# SENSITIVITY OF FUTURE TROPICAL CYCLONE CHANGES TO STORM SURGE AND INUNDATION –CASE STUDY IN ISE BAY, JAPAN-

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In several decades, climate change has been occurred due to warmer sea surface condition, and tropical cyclone will become more intense in the future. That means the storm surge risk is more increased. It is necessary to be an evaluation of the risk of the storm surge with inundation. In this study, numerical storm surge simulation with inundation of high-resolution are carried out and the influence of climate change on storm surge are simulated.

*Keywords: storm surge, inundation, tropical cyclone, climate change*

## Introduction

According to recent issued as IPCC 5th Assessment Report (AR5) and Special Report for Extreme Weather (SREX), numbers of studies have been conducted on the impact assessment of extreme natural disasters due to climate change. The AR5 reported that tropical cyclones will become more intense due to warmer sea surface condition in the future, although the number of tropical cyclone will be decreased. With the strength change of the tropical cyclones, it is necessary to make an assessment of storm surge from present to the future climate. On the other hand, it takes more than a decade to design and construct coastal defense system generally. Storm surge is one of the important factors to design coastal defense facilities at middle latitude of the Pacific and Atlantic Ocean, and the estimation of storm surge and potential risk of inundation are required to assess the impact on social and economic activity under climate change in the future. Therefore, it is important to estimate changes of storm surge risk under the future climate condition in advance.

There are several researches of impact assessment on climate changes. Warner et al (2012) evaluated the probability of flooding in sea level rise from the concept of extreme value statistics at Galveston Bay, Texas. On the other hand, projection of future tropical cyclone characteristics was estimated using a stochastic typhoon model (Mori,2012). And the future storm surge risk in East Asian using the result of a state-of –the art atmospheric GCM (AGCM) was assessed by Yasuda et al (2014).

In this study, numerical storm surge simulations with inundation over the land were conducted targeting the Ise Bay including Nagoya of Japan, which suffered the most severe storm surge disaster in 1959. Future changes of typhoon characteristics are analyzed to estimate possible increase change of intensity, generation numbers, and tracks in the Pacific Ocean, and influence of climate change on storm surge in the Ise Bay are simulated as a case study.

## Methodology

First, analysis of future changes of tropical cyclone have been carried out based on climate model. Future changes of tropical cyclone, typhoon, activity at the end of 21st century are analyzed based on a series of single model sea surface temperature (SST) and perturbed physics (PP) ensemble MRI-AGCM-3.1S, 3.1H, 3.2S and 3.2H developed by Japan Metrological Research Institute for the CMIP5 (Coupled Model Intercomparison Project Phase 5) of IPCC AR5. The results of analysis for each ocean basins are shown in Figure 1. The names of ocean basin are denoted by acronym and the East Asia denoted as WP (the Western Pacific). The number of typhoons will be decreased in the future almost all basins. In addition, the future cyclogenesis centroids will move toward the center of the Pacific Ocean basin in the range of 1–3 degrees depends on the latitude (Mori et al. 2013). These future trends of latitudinal central pressure are added to the present climate condition.

This study are carried out a series of numerical simulations of against historical extreme storm surge and future climate. The target of storm surge is typhoon Vear landfall in Isebay around Aichi prefecture (see Figure 2 later). First, the validation of surge heights and inundation characteristics are

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compared with the historical record, Finally, the storm surge under the future climate condition is simulated considering the analysis of the latest global climate model results.

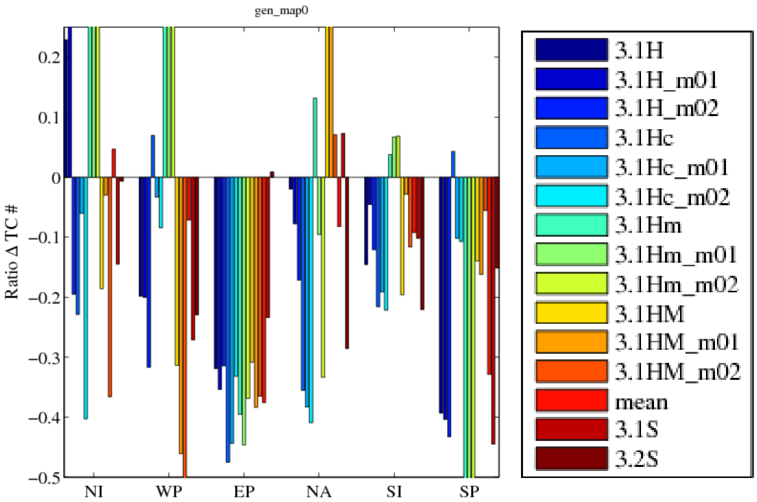



**Figure 1 Number of cyclogenesis change from present to future climate analyzed by SST ensemble experiments of MRI-AGCM-3.1H (Mori, 2012)**

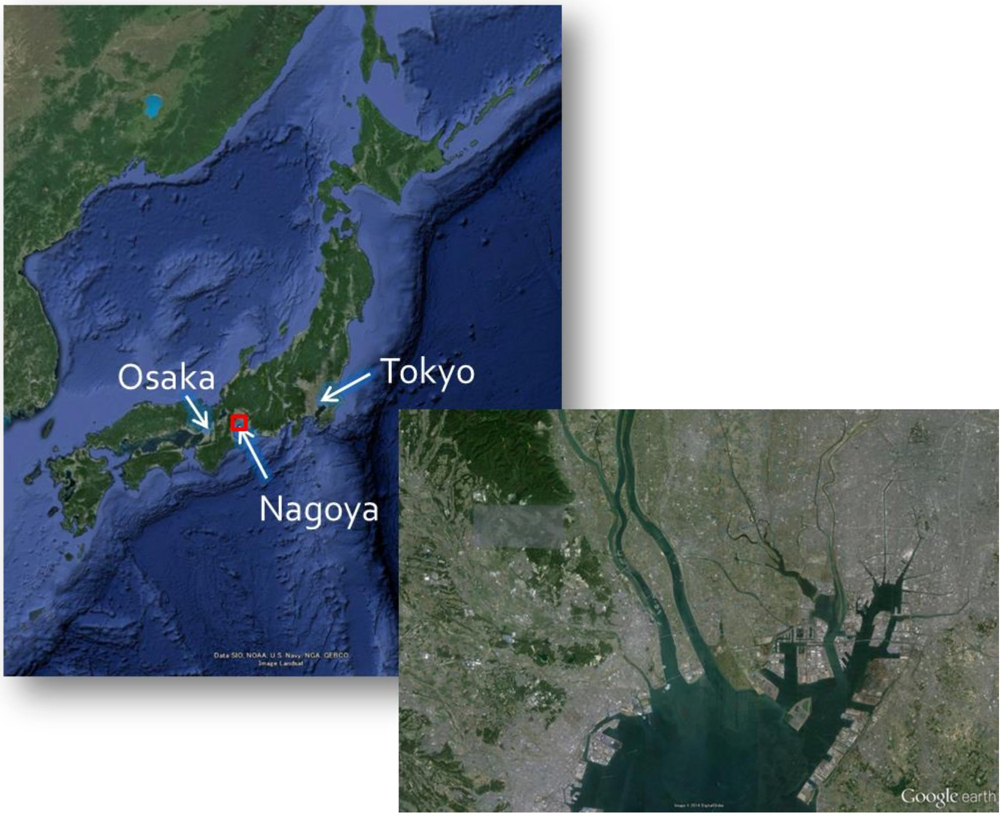



**Figure 2 Targeting area of storm surge around Nagoya of Japan**

### Storm surge simulations

Storm surge simulation is used full coupled Surge-Wave-Tide coupled model (SuWAT) developed by Kim et al (2008). The SuWAT model which consists of storm surge module by the nonlinear shallow water equation and wave module by spectral wave model SWAN considering tidal effects at the lateral boundary. The detail of model should be referred by Kim et al. (2008). In order to simulate with inundation on landside, The model was modified to take into account overflow into the land considering the bottom roughness based on land use data as shown in Figure 3 (Nagoya city at Aichi Prefecture). The wave model were basically not used and the atmospheric forcing is given by empirical typhoon model for reduction of computational cost in this study. The atmospheric pressure field is estimated by Mitsuta and Furita (1986) model, the wind field is simulated by Myers at al., (1961).

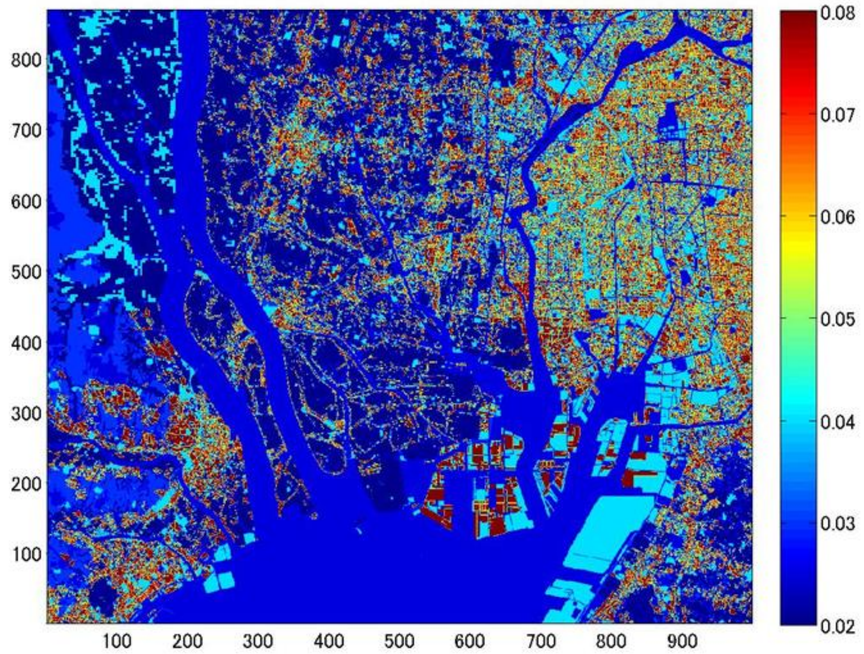



Figure 3 Spatial distribution of bottom roughness based on land use data by Japan Geographical Survey Institute (GSI).

The SuWAT employs nesting scheme, the four domain nesting results for the historical analysis is shown in Figure 4. The spatial resolution of the coarsest domain is 12,150m and the finest domain resolution is 450m. The maximum storm surge height of typhoon Vera (1959) is shown in Figure 5. Although the maximum surge height is 3.45m by historical record at Nagoya port, the numerical result is 4.26m. We introduced the reduction coefficient into the super gradient wind to adjust the hindcast to the observation. The maximum storm surge result and the time series of surge height are shown in Figure 6. From Figure 6, the numerical results (blue line) show good agreement with observation (black line).

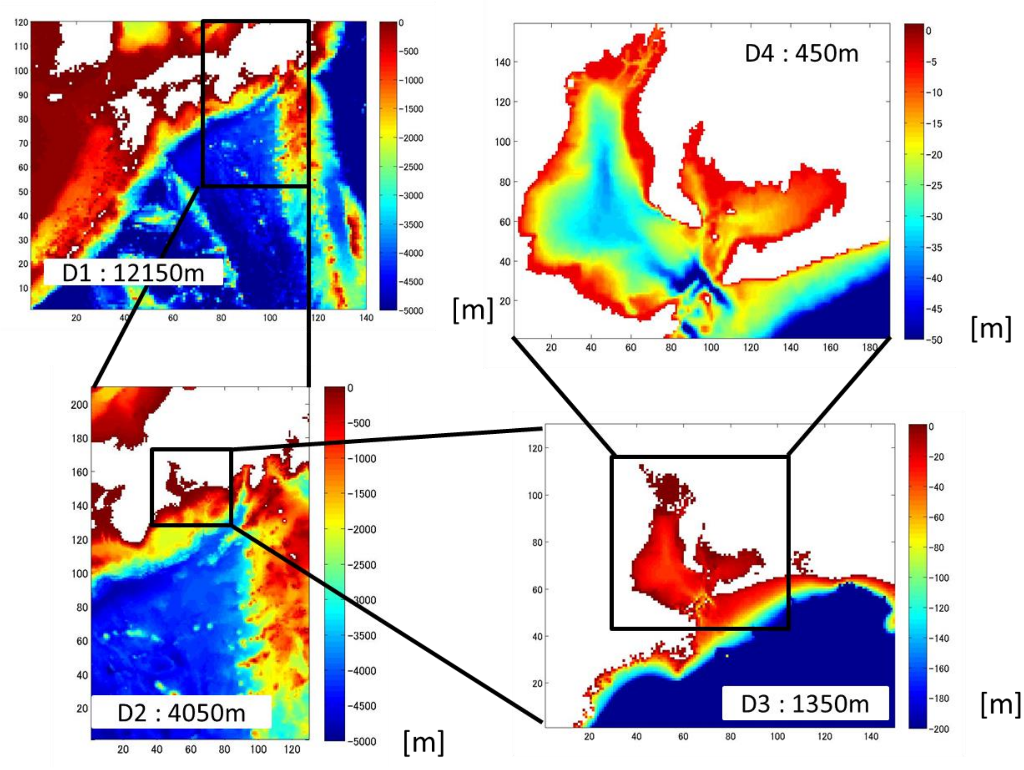



**Figure 4 Outline of nesting domains**

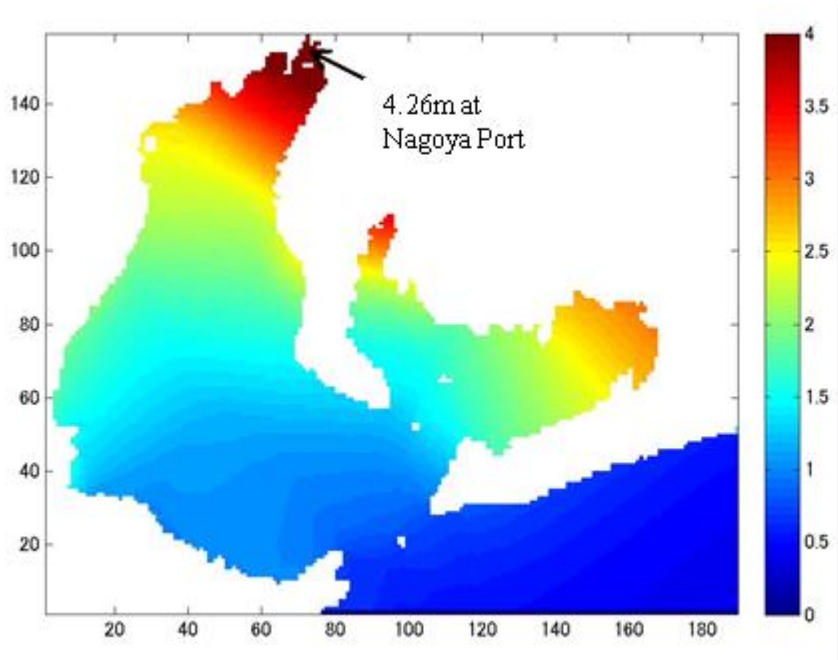



**Figure 5 Maximum storm surge height in domain 4**

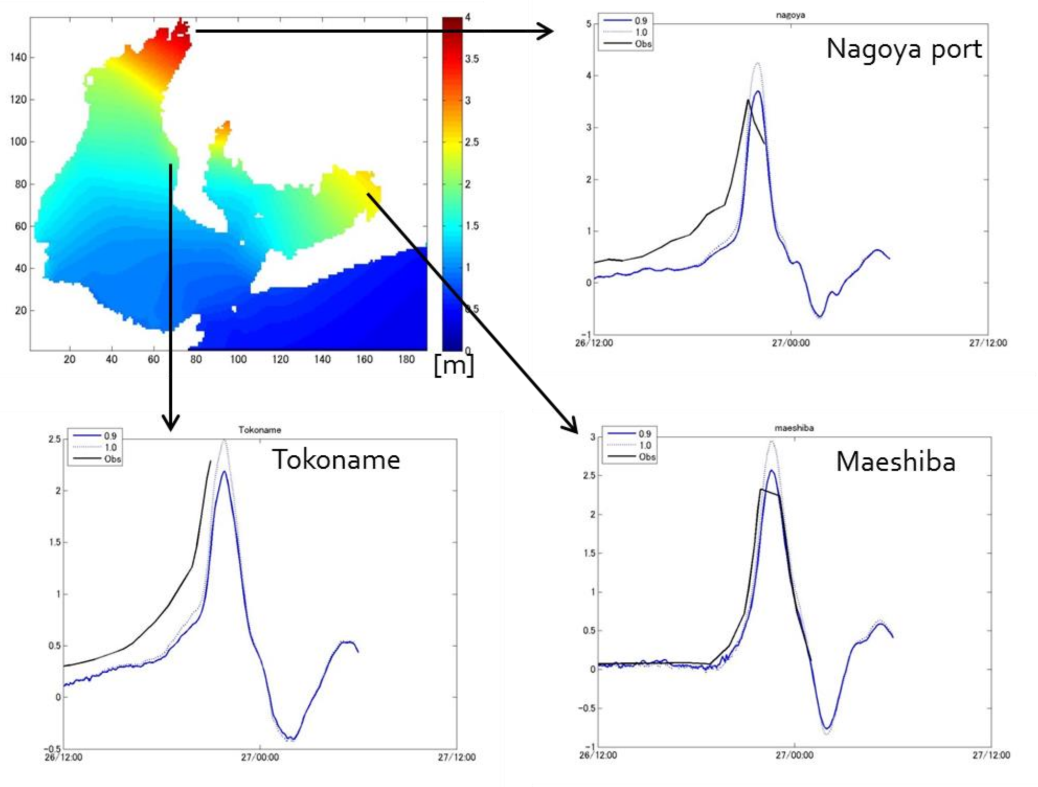



**Figure 6 Maximum surge height and time series with the calibration**
**(Blue line is simulation, black line is observation)**

In order to calculate the storm surge flooding on the land, we need higher resolution onshore. For the inundation simulation, the six level-domains from the resolutions of 7,290 m to 30 m were used as shown in Figure 7. The only finest domain is considered inundation over the land. The depth and sea wall condition are different between the present and past condition. Thus we needed to assume the past condition. These are estimated from historical record and present and past sea wall condition using the simulation are shown in Figure 8. The details of sea wall condition are as follows that the sea wall of more than 5m has been cut to 5m, and 5.0m to 3.5m has been cut to 3.5m. Also, reclaimed land was removed.

The result of hindcast of the storm surge of typhoon Vera and the inundation area by historical record are shown in Figure 9 and 10, respectively. The legend of Figure10 is inundation period. It is confirmed that the flooding into the land, and maximum surge height is 3.24 m at Nagoya port. The storm surge and inundation area by the hindcast show good agreement with historical record approximately.

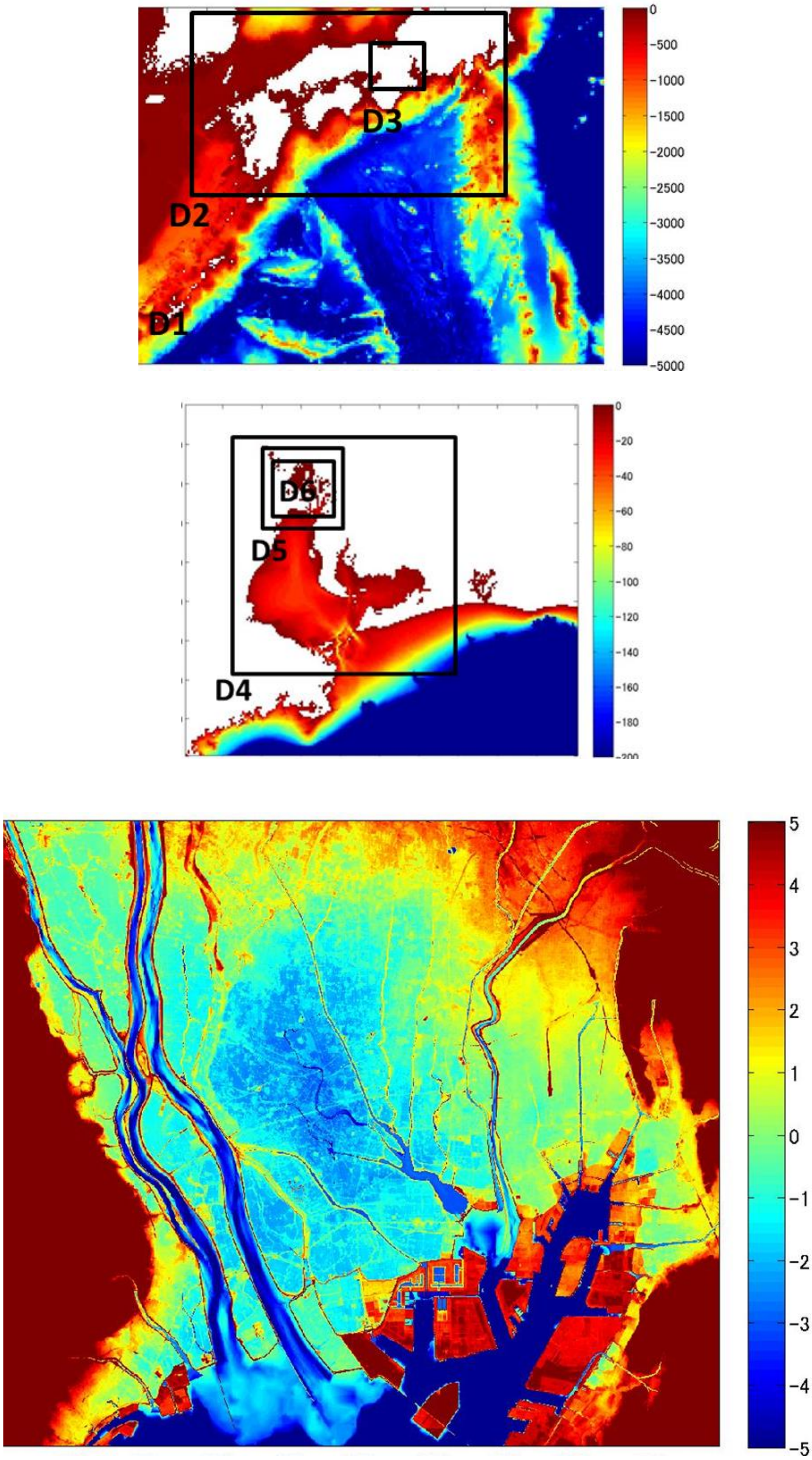
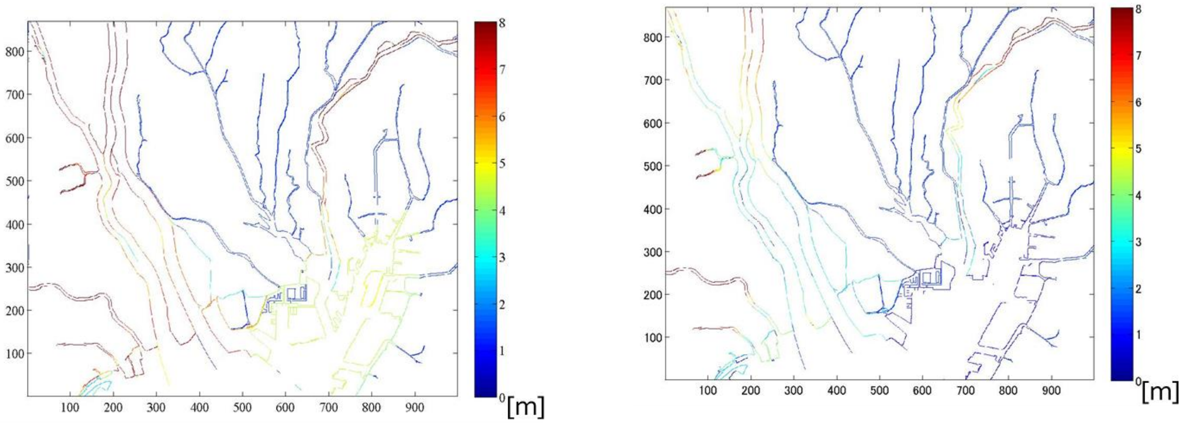
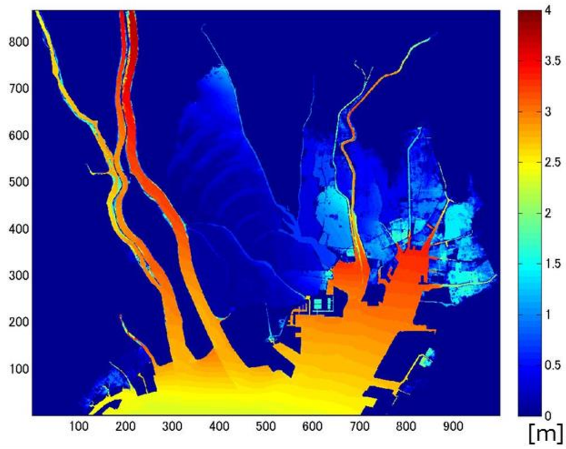



**Figure 7 Setup of nesting domains for inundation simulation**




(a)Present sea wall condition (b) past sea wall condition

Figure 8 Sea wall heights



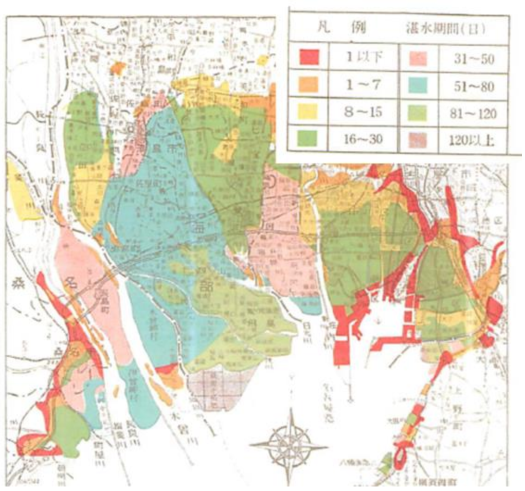




Figure 9 Maximum surge height f of typhoon Vera

Figure 10 Inundation area by historical record (reference)

Finally, it was simulated the storm surge by pseudo global warming scenario with the worst course of typhoon Vera. A series of simulations are carried out under the intensified central pressure obtained from analysis of CMIP5 and the changed typhoon track considering the analyzed typhoon characteristics changes as the pseudo global warming experiments. The worst course of typhoon Vera was estimated by shifted and rotated of the track in Figure 11.

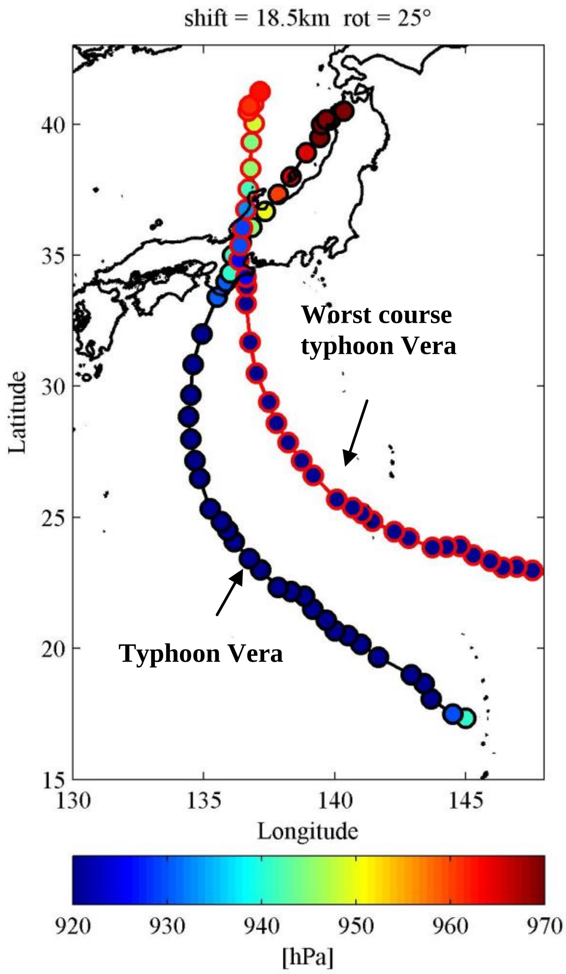



**Figure 11 The worst course of typhoon Vera**

In this simulation, the same six domain nesting was used in Figure 7. First, Vera under the present depth and sea wall condition was simulated and compare with historical record. Figure 12 shows the numerical result of maximum surge height and inundation area of calculation. The storm surge run up along the river, and it was source of flooding at the upstream of the river. A series of storm surge by extreme typhoons considering the track changed worst course was simulated by pseudo warming experiments. The results of extreme typhoon with worst course shows that the maximum surge height becomes larger and inundation area is increased significantly as shown in Figure 13. The result indicates that the storm surge disaster will be increased when the typhoon will intensify in the future climate condition. When typhoon will intensify, the maximum surge heights will become larger in the range of 1.3 to 1.0m. The future change of inundation area due to storm surge will increase about 30% significantly.

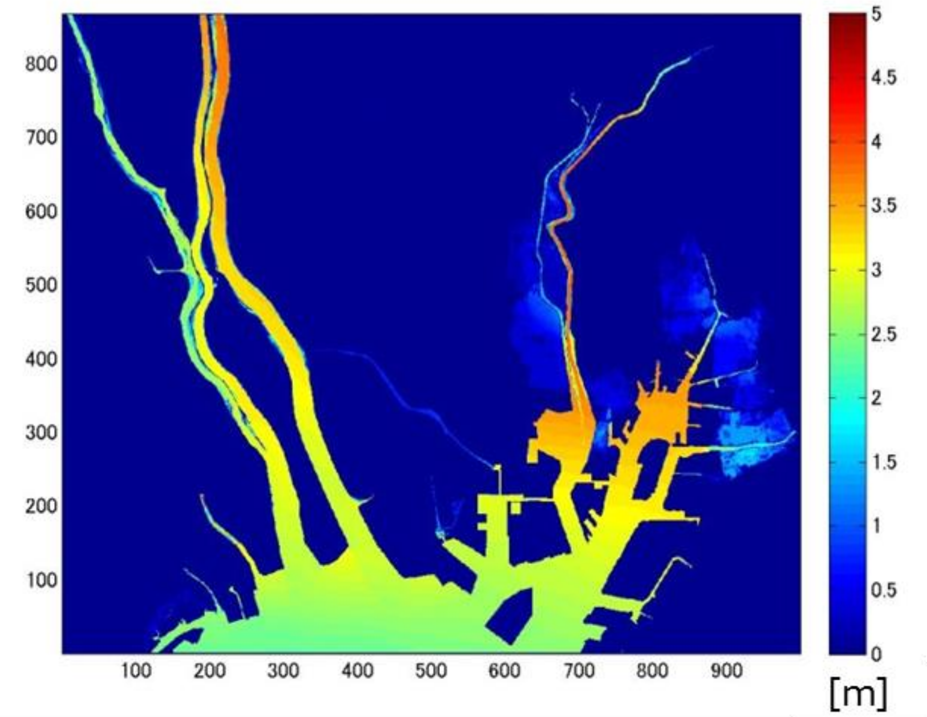



**Figure 12 The maximum storm surge for typhoon Vera**

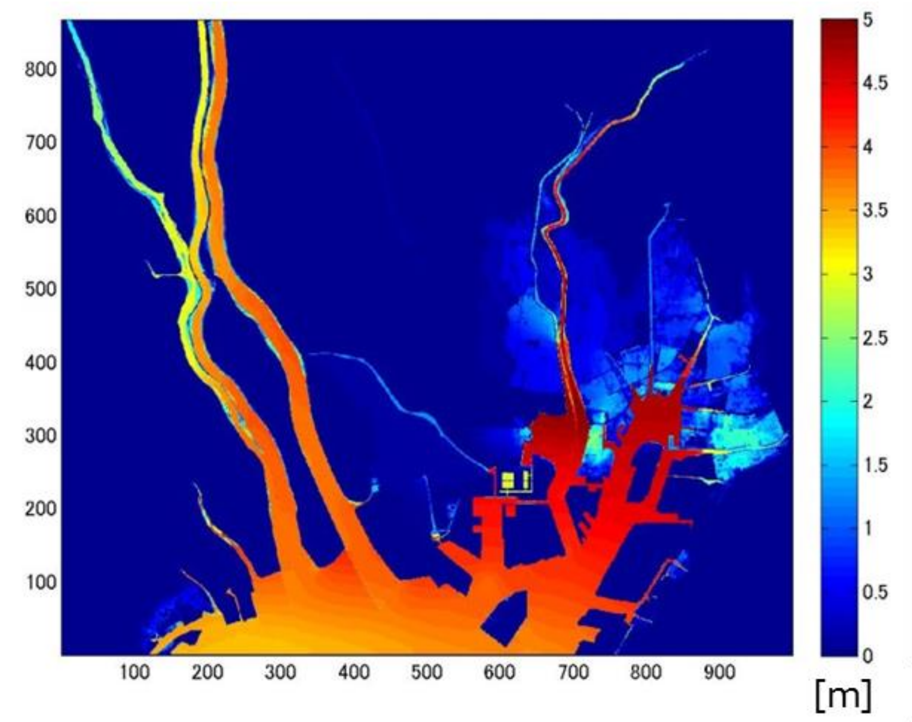



**Figure 13 The maximum storm surge for extreme typhoon Vera with the track changed worst course**

## Conclusions

In this study, numerical experiments of storm surge considering inundation over the land were conducted targeting the Ise Bay of Japan, which suffered severest storm surge disaster of Japan in 1959. This study has examined the sensitivity of future change of typhoon climate to storm surge and inundation, quantitatively. The future changes of typhoon characteristics were analyzed to estimate changes of intensities, generation numbers, and tracks in the Pacific Ocean, and influence of climate change on storm surge in the Ise Bay were simulated as a case study.

It is found that the local storm surge characteristic is significantly sensitive to the macro typhoon characteristics. The finding should be taken into account for design of coastal defense facilities against the inundation risk in the future climate.

## ACKNOWLEDGMENTS

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