

FUTURE PROJECTION OF MAXIMUM POTENTIAL STORM SURGE CONSIDERING SST BIAS FOR CMIP6 HIGHRESMIP EXPERIMENT

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INTRODUCTION

The IPCC AR6 indicated that the ratio of strong tropical cyclones (TCs) will increase due to climate change, and consequently, the intensified TCs will increase the risk of storm surges. Storm surge is an extremely low-frequency and high-impact event because it depends on the combination of TCs' intensity, size, path, and speed to the bay. Such an event needs to be discussed in terms of frequency and intensity for climatological study. On the other hand, climate projection is getting longer due to increasing ensemble members facing uncertainty. Therefore, it is difficult to project future changes in a particular region with a large climate projection. Mori et al. (2021) proposed a framework to estimate future changes in the worst class of TCs using the MPI (Maximum Potential Intensity) theory and future changes in the worst class of storm surge height using the MPS (Maximum Potential Storm surge height) model. However, TC translation is not considered in MPI theory. Therefore, there is a spatial difference between the theoretical MPI and the real value of TCs' intensity. This study develops an improved MPI-MPS framework with a threshold SST (Sea Surface Temperature) to overcome the difference.

METHODOLOGY

The MPI-MPS framework proposed by Mori et al. (2021) is shown in Figure 1. First, the maximum potential intensity of TCs in a given environmental field is estimated using MPI (Emanuel et al., 2002). The maximum potential intensity (maximum potential pressure P_m and maximum potential wind speed V_m) is estimated using SST, sea level pressure (SLP), vertical profiles of atmospheric temperature and relative humidity as

$$V_m^2 = \frac{C_k T_S}{C_D T_0} (CAPE_m^* - CAPE_{env}) \quad (1)$$

$$R_d T_S \ln \frac{P_{env}}{P_m} = \frac{1}{2} V_m^2 + (CAPE_m - CAPE_{env}) \quad (2)$$

where T_S is the SST, T_0 is the tropopause temperature, CAPE is convective available potential energy, C_D and C_k are the momentum and heat exchange coefficients at the sea surface, and R_d is the gas constant for dry air. Superscript * means the saturated condition, subscript m means the value of RMW (Radius of Maximum Wind speed), and subscript env is the environmental field value. Basically, MPI highly depends on SST. Each bay's theoretical upper limit of storm surge height is estimated using the MPI. In the MPS model (Mori et al., 2021), pressure-induced and wind-induced storm surge heights were individually calculated, assuming the worst-case TC track, a steady-state, and the TC translation speeds with the long-wave velocity in the bay. Pressure-induced surges occur when the translation speed of TCs (V_T) is close to the long wave velocity (C) in the bay, which means

the Proudman resonance is expected. Assuming that a pressure wave of $\Delta P = \phi(t-x/C)$ travels along the channel from the entrance ($x=0$) of a one-dimensional channel with depth h connecting to the sea, a pressure-induced surge ζ_p is given as

$$(\zeta_p)_{V_T \rightarrow C} = \frac{1}{\rho_w g} \left\{ \phi \left(t - \frac{x}{C} \right) - \frac{x}{2C} \phi' \left(t - \frac{x}{C} \right) \right\} \quad (3)$$

where ρ_w is the seawater density and g is the acceleration of gravity. Pressure-induced surges are estimated by considering Myers' parametric TC pressure distribution in equation (3). Wind-induced surges occur when the wind blows toward the shore for a long time and reaches a steady state. Considering the balance between wind stress and gravitational force, a wind-induced surge ζ_w is given as

$$\frac{d\zeta_w}{dx} = \frac{\rho_a}{\rho_w g} \cdot \frac{K}{h(x)} \cdot U^2 \quad (4)$$

where ρ_w is the air density, K is the tuning parameter by a dynamical model, h is the water depth, and U is the wind speed. MPS can finally be estimated by the linear combination of a pressure-induced surge and a wind-induced surge.

DATA SET

This study used the climatic data on the CMIP6 HighResMIP (High-Resolution Model Intercomparison Project) experiment, which was evaluated specifically for TCs in IPCC AR6. This data set focuses on the intercomparison of TCs' intensity under the RCP8.5 scenario from 1950 to 2050 (2099), providing high-resolution data and estimating the effect of atmosphere-ocean coupling with AGCM (Atmospheric Global Climate Model) and AOGCM (Atmosphere-Ocean Global Climate Model). In this study, a total of 30 GCMs were used, which means all applicable GCMs for the framework were used. AGCM was given the same SST at each model based on observation, while AOGCM was given different ones. The differences in projection between the AGCM and the AOGCM were analyzed in detail.

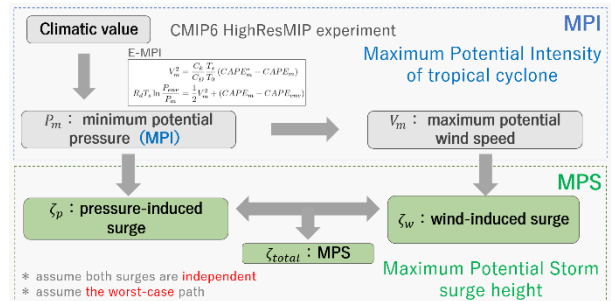


Figure 1: Schematic view of the MPI-MPS framework

FUTURE CHANGES IN THE INTENSITY OF TROPICAL CYCLONES

To characterize GCMs in the HighResMIP experiment, the spatial pattern of the GCMs under the past climate was investigated based on MPI compared with historical atmospheric reanalysis (JRA55). The correlation coefficients were above 0.81 for all GCMs and all ocean regions, which means the spatial pattern generally agreed regardless of whether GCM is AGCM or AOGCM. In addition, to examine the quantitative differences, the spatial RMSE (Root Mean Square Error) compared with JRA55 was calculated. In AGCM, a model has a systematic bias for all ocean regions, which was a few times larger than that of other GCMs. Even in AOGCM, this trend was also observed in all ocean regions except the WNP (Western North Pacific). These values showed there were highly reproducible areas under the past climate for each GCM. Then, using the inverse of these biases as the weight of the ensemble mean, time-series changes in MPI were investigated (Figure 2). In the Northern Hemisphere, the MPI gradually strengthened from past to future, up to about 940 hPa by 2050, especially in WNP and NA (North Atlantic). In addition, the most significant trend is a strengthening of about 7 hPa in NA over about 100 years.

UPDATING MPI-MPS FRAMEWORK AND APPLICATION TO FUTURE PREDICTION OF STORM SURGE HEIGHTS

In the original MPI-MPS framework (Mori et al., 2021), MPI on the average of the four points closest to the target bay was used as an input variable of MPS. However, it is undeniable that the MPI may be rather weak values compared to the actual maximum development values of TCs, particularly in above middle latitudes because the MPI theory does not include the effect of typhoon movement. Then, the spatial differences in WNP between the MPI from JRA55 and the highest development intensity of TCs from IBTrACS (International Best Track Archive for Climate Stewardship), which is observation data were investigated. Figure 3 shows the relationship between the MPI and the typhoon's maximum development intensity in WNP as the latitudinal distribution with SST distribution. It should be noted that the values in this figure were averaged in the longitude direction due to the high dependence of MPI on SST, which made them weaker compared to the actual input MPI value. However, it is enough to see the gap. MPI has greatly underestimated the observation north of 35 °N, where there are major Japanese bays, Tokyo Bay, Ise Bay, and Osaka Bay. Therefore, in the new MPI-MPS framework, SST is used as a threshold, and when SST is less than 25 degrees, MPI at 25 degrees SST is used as an input for storm surge calculation. The calculated MPS at Tokyo Bay is shown in Figure 4 using the new framework with the threshold SST. Compared to the original framework, the underestimation of storm surge heights has been mitigated, which is more in line with the purpose of this study, the maximum potential storm surge. This result highlights the importance of adaptation measures to consider storm surge future changes in addition to sea level rise under a warming climate.

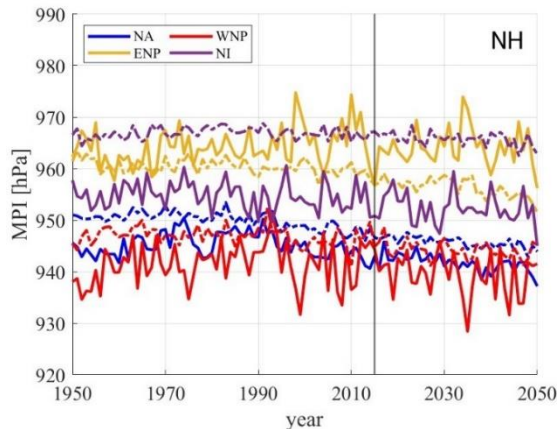


Figure 2: Time series of ensemble-averaged MPI considering bias of GCMs in the North Hemisphere (legend: abbreviation for each ocean region, solid line: AGCM, dotted line: AOGCM)

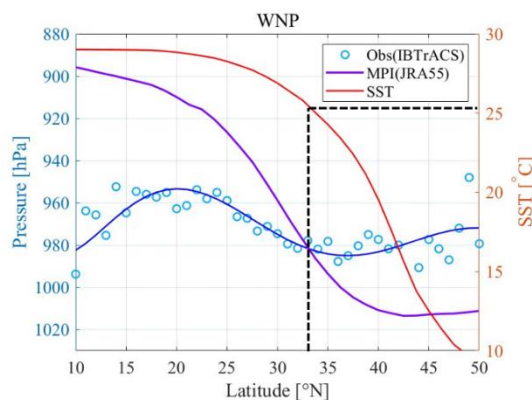


Figure 3: The relationship between the theoretical intensity of typhoons from JRA55 and observed intensity from IBTrACS in WNP with SST in the latitudinal direction

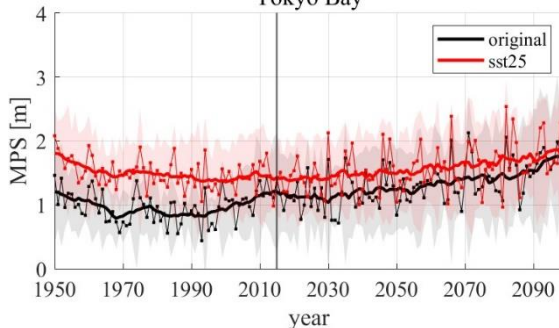


Figure 4: Future change of Maximum Potential Storm surge heights in Tokyo Bay using MRI-AGCM3.2S (black: original MPS, red: MPS in this study, background shade: monthly variations, Sep. to Oct.)

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- N. Mori et al. (2021): Future projection of maximum potential storm surge height at three major bays in Japan using the maximum potential intensity of a tropical cyclone. *Climatic Change*, 164(3), 1-18.
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