EVALUATION OF BIAS CORRECTION METHODS FOR DETERMINING FUTURE DESIGN WAVE HEIGHT BASED ON MEGA-ENSEMBLE CLIMATE PROJECTION

Kunihiro Watanabe[1], Fuminori Kato[1], Koichi Hosaka[2], Takehito Zaha[2] and Toshimitsu Takagi[2]

Mega-ensemble climate projection results are expected to be used for investigating future changes in design condition, such as wave height and storm surged. However, climate models are known to have some uncertainties making bias correction necessary. We performed wave modeling was performed based on typhoon tracks extracted from mega-ensemble projections. Three bias correction methods were investigated, and the variation induced by these methods was evaluated. The corrected future wave heights showed variations among various locations, and they were larger than the variations caused by the difference in bias correction methods for the return periods of 1/30 and 1/50. This result suggests that appropriately selecting a correction method is not a significant issue in coastal planning.

Keywords: climate change; typhoon; wave modeling; bias correction

INTRODUCTION

In 2020, the basic policy for coastal protection in Japan was revised to adapt to the anticipated climate change. According to this policy, coastal managers are required to revise the basic coastal protection plan for each coastal unit considering the average value of future projections under the RCP2.6 scenario by 2025. The RCP2.6 scenario is one of the representative concentration pathway scenarios considered in the Fifth Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC).

The height of the coastal dike and sea wall is the most important parameter for preventing coastal disasters and is designed besed on the high water level and wave run-up height in Japan. Thus, future changes in storm tides and waves must to be estimated to revise coastal protection plans. In most cases, the design parameters for shore protection facilities in Japan are determined in two ways. The first is a scenario-based method. The parameters are determined by simulating storm surges and high waves induced by typical typhoons, such as those previously experienced. Accordingly, future parameters can be estimated using numerical simulations that consider future changes in the central pressure of typhoons.

The second is a probability-based method. In this method, each parameters with 30- or 50-years return period is calculated using extreme statistics analysis based on the observed data. A large number of wave projections are necessary to estimate future changes in wave height. Mega-ensemble climate projection results can be used to investigate future changes in design conditions, such as wave heights and storm surges. However, climate models have a few uncertainties, necessitating bias correction (Fujuta et al. 2019, Morim et al. 2019, Nosaka et al. 2020).

In this study, we perfomed wave modeling based on typhoon tracks extracted from mega-ensemble projections, investigated three bias-correction methods, and evaluate the variations induced by these methods.

MATERIALS AND METHOD

Mega-Ensemble Climate Projections

For wave modeling, the database for policy decision-making for future climate change (d4PDF) was used as the mega-ensemble climate projection results. The d4PDF database enables us to discuss the uncertainty arising from the internal variability in future changes during extreme weather and climate events (Mizuta et al. 2017). The d4PDF contains two types of results: AGCM and RCM. The AGCM consists of global warming simulations conducted using a global atmospheric model with a horizontal grid spacing of 60 km. The RCM consists of regional downscaling simulations covering the Japanese area using a regional climate model with 20 km grid spacing. We used the result of historical climate simulations and plus 4 ° celsius future climate simulations based on AGCM because RCM is known to have some difficulties when representing typhoons. Althoug basic coastal protection plan is required to assume plus 2 ° scenario (RCP2.6), we used 4 ° scenario because future change in wave height is clearer than 2 ° scenario. The historical climate simulation comprised 100 members over 60 years (1951 – 2010). The plus 4 ° future climate simulation considers 90 members over a 60 year projection assuming that the

[1] National Institute for Land and Infrastructure Management, 1 Asahi, Tsukuba City, Ibaraki, 305-0804, Japan
[2] Yachiyo Engineering Co.,Ltd., 5-20-8 Asakusabashi, Taito-ku, Tokyo, 111-8648, Japan

climate is 4 ° warmer than the pre-industrial climate. In this study, we named these datasets as “present dataset” and “future projection”, respectively.

Wave Modeling

Case studies were conducted at Tosa Bay, located south of Kochi Prefecture, Japan. This area is the typhoon-prone area, and the design parameters for shore protection facilities were determined by typhoon. Typhoon tracks were extracted from a tropical cyclone dataset (Webb et al. 2019) based on the d4PDF (Fig. 1). The present tracks were obtained from simulations under historical climate conditions (over 60 years, 100 members), and future tracks were derived from a projection made under future climate conditions, assuming a climate 4 ° warmer than the pre-industrial climate (over 60 years, 90 members). Typhoon tracks with the lowest central pressure of < 990 hPa were selected for wave calculation. The wind fields were calculated based on the typhoon track data using the Myers model (Myers 1954). Typhoon-induced waves were calculated using SWAN Cycle III Version 40.31 (Booij et al. 1999) at the Tobara wave station and 11 sites along the 200-m water depth line (Fig. 2). SWAN is one of the open-source models and is used in many researches. The model domain covered the entire typhoon track, from 125°E to 145°E longitude and from 20°N to 37°N latitude, and the grid sizes were 5 km and 15 km, respectively, as shown in Fig. 3. The radius of the typhoons, r_0, were assumed from the central pressure of typhoon P_c using Eq. 1 as proposed by Kawai et al. (2005).

$$r_0 = 94.89exp\left(\frac{P_c - 967}{61.5}\right) \quad (1)$$

The coefficients for translating the gradient wind speed and wind speed induced by typhoon movement to sea surface wind speed, C1 and C2, were 0.70. The angle between the sea surface wind and pressure conterline was 30°. These parameters were determined through the hindcast calculation of Typoons 200310 (ETAU), 200514 (NABI), and 201824 (TRAMI), which caused a remarkably heightened wave at the Tobara observatory. The track data for these typhoons were obtained using Digital Typhoon (http://www.digital-typhoon.org/). We reduded calculation time by appling the resolution of wave frequency and direction, 15 grids (0.03 – 1.0 Hz) and 16 grids (0 – 360°) , respectively.

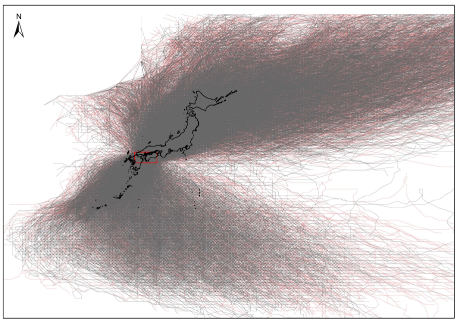

Figure 1. Tracks of tropical cyclones extracted from the present dataset (black lines) and future projection (red lines) of climate.

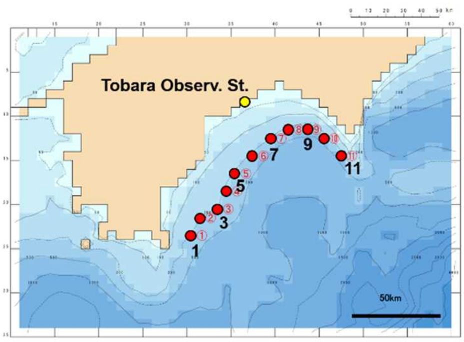

Figure 2. T Locations of Tobara wave observation station and 11 sites.

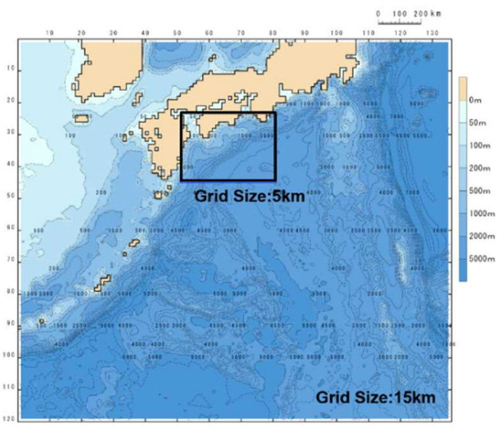

Figure 3. Computation domain and grid sizes.

Bias Correction

The procedure for the bias correction of the projected future wave is shown in Fig. 4. The exceedance probabilities of the wave heights calculated from the present dataset were compared with the values observed for 50 typhoons at Tobara Station. Wave heights were hindcasted at 11 sites based on the relationship between the wave heights calculated for the present dataset at Tobara Station and each site (Fig. 5). These relationships are expressed by Eq. 2 as follows:

$$y_h = ax_h^2 + bx_h + c \quad (2)$$

where x_h and y_h represent the calculated wave heights at the Tobara observatory and each site, respectively. The values of the coefficients a, b, and c are reported in Table 1.

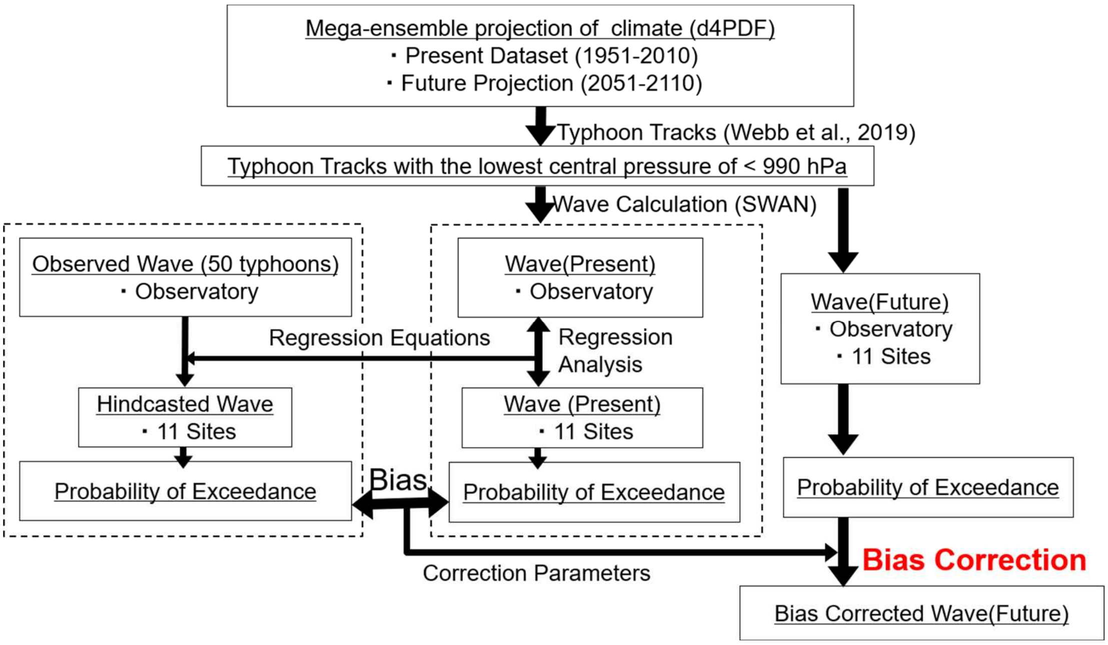

Figure 4. Flow of the bias correction regarding the projected future waves.

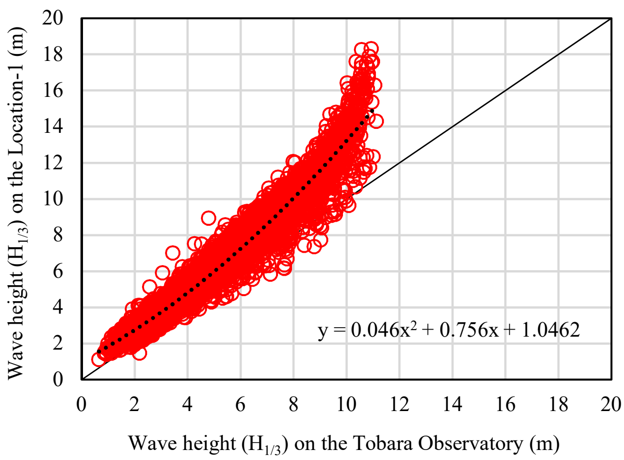

Figure 5. Relationship between wave height calculated at the Tobara Observatory and Site-1 based on the present dataset.

Table 1. Coefficients of the regression equation used for estimating the wave height on each site.

Site number	Cofficients		
	a	*b*	*c*
1	0.0460	0.7560	1.0462
2	0.0494	0.7078	1.1447
3	0.0555	0.6577	1.3197
4	0.0593	0.6092	1.3986
5	0.0621	0.5686	1.4544
6	0.0668	0.5112	1.5809
7	0.0668	0.4936	1.6243
8	0.0678	0.4693	1.6652
9	0.0663	0.4841	1.6652
10	0.0583	0.5834	1.5450
11	0.0482	0.6921	1.3445

The differences in wave heights were applied to bias corrections based on quantile mapping methods (Wang and Chen 2014). In this study, three types of bias correction methods, namely, method-1 (Eq. 3), method-2 (Eq. 4), and method-3 (Eq. 5) can be expressed as follows:

$$\tilde{x}_{p.ad} = x_o + F_p^{-1}\left(F_p(x_p)\right) - F_m^{-1}\left(F_p(x_p)\right) \tag{3}$$

$$\tilde{x}_{p.ad} = x_m \times F_o^{-1}\left(F_p(x_p)\right)/F_m^{-1}\left(F_p(x_p)\right) + F_p^{-1}\left(F_p(x_p)\right) - F_m^{-1}\left(F_p(x_p)\right) \tag{4}$$

$$\tilde{x}_{p.ad} = x_p \times F_o^{-1}\left(F_p(x_p)\right)/F_m^{-1}\left(F_p(x_p)\right) \tag{5}$$

where F_o and F_m are the cumulative distribution functions (CDF) of the observations and models in the reference period, respectively, and F_p is the CDF of the model for the future projection period. $\tilde{x}_{p.ad}$, x_o, x_m, and x_p denote the wave heights for bias-corrected future projections, observations, present models, and future projections, respectively. Quantile mapping assumes that the future distribution of the variable of interest is similar to that of the reference period.

Using method-1 (Eq. 3), the bias-corrected future wave height was obtained by adding the difference between the present dataset and future projection to the observed wave height (Fig. 6a). In method-2 (Eq. 4), the wave height of the present dataset was adjusted to the observed height, and the difference between the present dataset and future projections was added to the adjusted present dataset (Fig. 6b). In method-3 (Eq. 5), the difference between the observed data and present dataset was evaluated as a ratio, and future projections were corrected using this ratio (Fig. 6c).

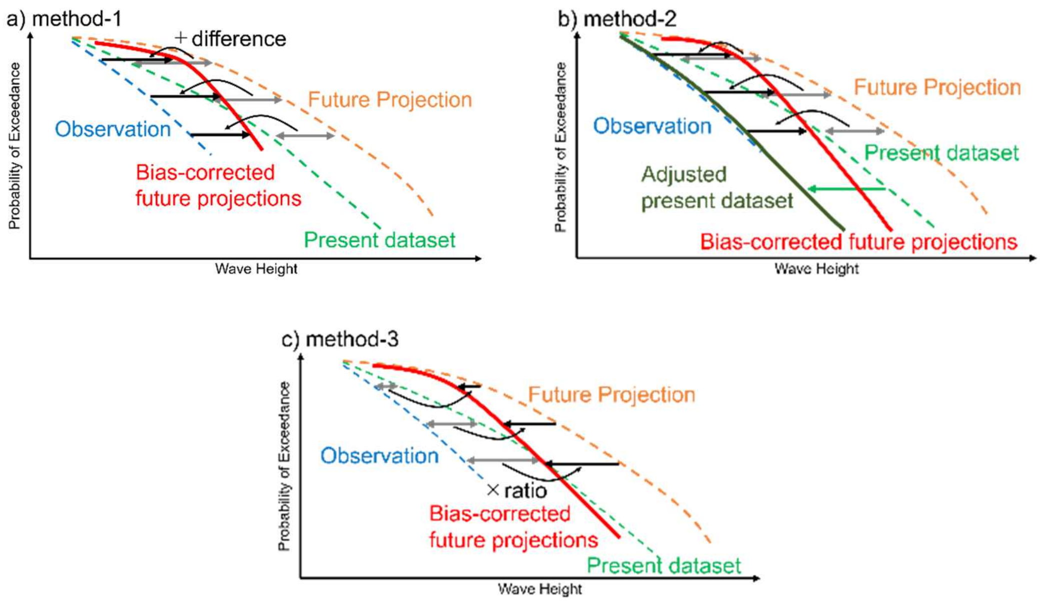

Figure 6. Schematics of bias correction methods.

The return periods (R) were calculated from the exceedance probability and average number of typhoons per year (λ) based on the equations stated below:

$$R = \frac{1}{\lambda(1 - F_m)} \quad (6)$$

where F_m denotes the non-exceedance probability.

RESULTS

Number of Typhoon Tracks

A total of 7352 tracks were extracted from the tropical cyclone dataset created based on the d4PDF (Fig. 1). 4,608 tracks were extracted from the present dataset, whereas the remaining tracks originated from future projections (Table 2). The annual average number of extracted typhoons decreased to 66 % of the present value in the future climate. However, the annual average number of typhoons was 2.174 for the observed data, approximately 2.8 times that of the present dataset.

Table 2. Number of typhoon tracks contained in 3 datasets.

	Observed	Present dataset	Future projection
Number of typhoon tracks	50	4,608	2,744
Period (year)	23	6,000	5,400
Number of typhoon tracks (/year)	2.174	0.768	0.508
Corrected number of typhoon tracks (/year)	-	2.174	1.438

Exceedance Probability of Wave Height

The wave heights simulated by the present model were greater than the observed wave heights (Fig. 7). In this study, we considered these differences as bias induced by the climate model and wave modeling and conducted bias correction. The differences between the simulation and observed results were greater for smaller probabilities (Fig. 7). These relationships were observed at 11 sites (Fig. 8). Based on these results, we selected the quantile mapping method for bias correction, because different correction values should be applied according to the exceedance probability of the wave.

The future wave heights increased compared to the present wave heights estimated cosidering the same exceedance probability (Fig. 8). The exceedance probability distributions of the corrected future wave heights were similar for the three correction methods (Fig. 9).

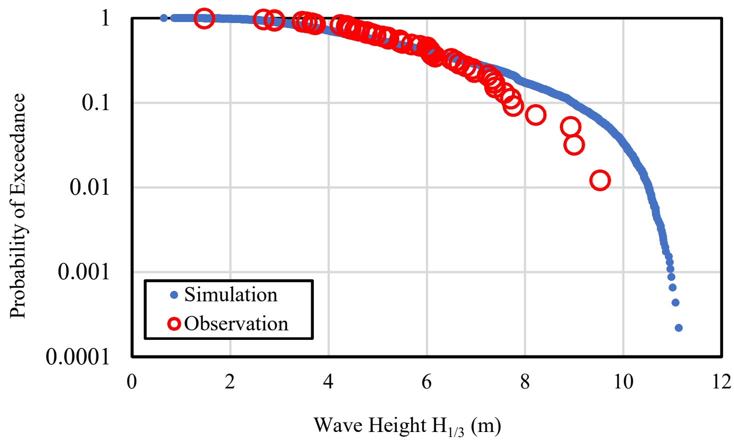

Figure 7. Exceedance probabilities of wave heights at the Tobara wave observatory.

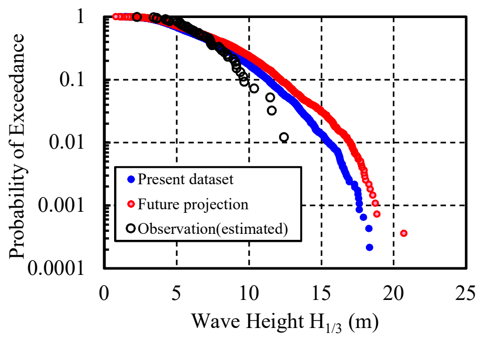

Figure 8. Exceedance probabilities of wave heights calculated using present dataset and future projection at the Site-1.

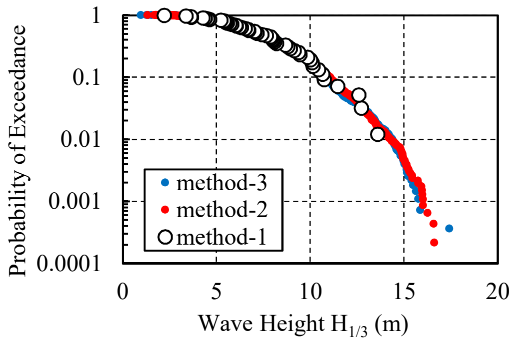

Figure 9. Exceedance probabilities of future wave heights corrected by the 3 methods at Site-1.

The relationship between the return periods and wave heights is shown in Fig. 10. Estimated future wave heights decreased for return period of one year, and increased for return periods over five years. This relationship was coinsided among 3 bias correction methods, and the variation of change rate in wave height was little (Table 3).

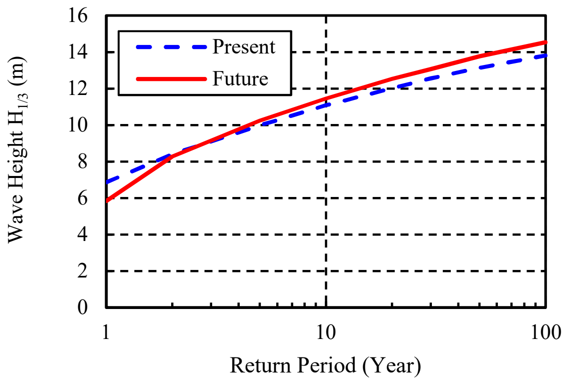

Figure 10. Relationship between the wave height and return periods. Wave heights were corrected by method-2, and averaged among 11 sites.

Table 3. Estimated change in wave height for each return periods. Averaged values among 11 sites are shown, upper and lower ranges are shown in parentheses.

	Wave height change (Future / Present)		
Return Period (year)	Method-1	Method-2	Method-3
1	0.86 (0.85-0.87)	0.85 (0.83-0.88)	0.85 (0.83-0.88)
5	1.02 (1.01-1.03)	1.03 (1.00-1.04)	1.01 (1.00-1.03)
10	1.04 (1.03-1.05)	1.03 (1.02-1.04)	1.01 (1.00-1.02)
30	1.06 (1.05-1.07)	1.04 (1.02-1.06)	1.04 (1.02-1.06)
50	1.07 (1.05-1.08)	1.05 (1.04-1.06)	1.04 (1.01-1.06)
100	1.07 (1.06-1.09)	1.05 (1.03-1.07)	1.05 (1.01-1.06)

Fig. 11 shows the distribution of the bias-corrected future wave heights for each return period. The wave heights varied among the 11 sites, and the variations were larger than those caused by the difference in the bias correction methods for return periods of 1/30, 1/50, and 1/100. Variations among the three bias correction methods were lower at site 9 than those at the other sites (Fig. 11). The wave height corrected by method-1 tends to be larger than corrected by the other two methods.

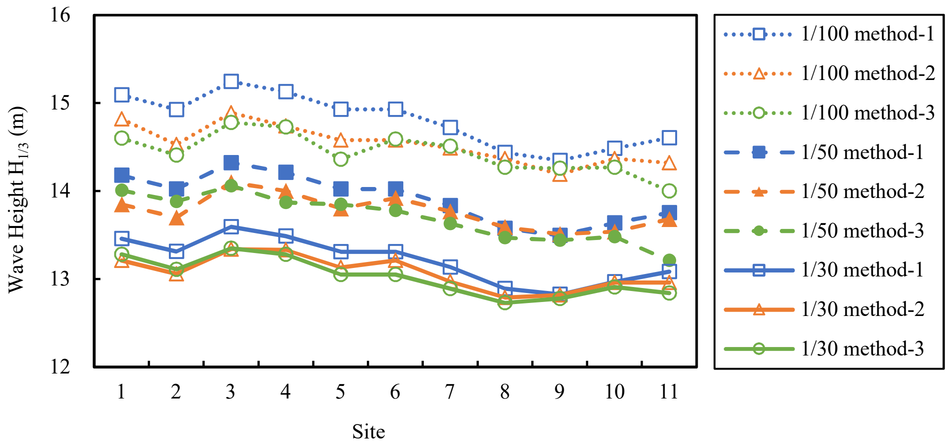

Figure 11. Distribution of projected future wave heights with each return period. The bias correction methods applied are denoted as method-1, method-2, and method-3.

DISCUSSION

Number of Typhoon Tracks

Differences in the annual number of typhoons between the observation and present datasets have also been reported for the entire coastal region of Japan (Arimura et al. 2021). The annual number of typhoon formation was 15.3 for present dataset, while 15.9 typhoon formations were observed with a difference of 4 %. Igarashi et al.(2022a) reported 3.97 and 3.10 as the annual number of typhoon for observation and present datasets, respectively, on Ise Bay, located east of Tosa Bay. These results suggest that the annual number of simulated typhoons tends to be lower than the number of observations.

These differences may be due to the track detection methods developed by Shimura et al. (2017) and used by Webb et al. (2019). Because Shimura's method aimed to detect tropical cyclones on a global scale, it was calibrated to be consistent with the global number of cyclones and typhoons. This is consistent with the results obtained by Arimura et al.(2021), who found that the differences were relatively small for the entire coastal region of Japan.

Methods configured for the regional scale should be developed to utilize d4PDF climate data for coastal planning because the return period of wave height strongly depends on the annual number of typhoons.

Bias Correction Method

The distributions of exceedance probabilities were similar among the three correction methods (Fig. 9). Although the return periods of the wave height differed between method-1 and the other two methods (Fig. 11), these differences were small compared to the variation over the 11 sites (Table 3). This suggests that appropriately selecting a correction method is not a significant issue in coastal planning.

Arimura et al. (2021) attempted bias correction on the central pressure of a typhoon, whereas bias correction was performed on the exceedance probability of wave height in this study. Although Arimura's method is simpler than our procedure, it can not avoid the bias generated by wave calculations. Some unpublished data show that wind speeds calculated based on the Myers typhoon model tend to be lower than those provided by d4PDF. Moreover, this method can not be applied to coastal regions where the design wave is determined by various climatic events, except for typhoons. Our bias correction procedure resolves these problems. However, the exceedance probability of the observed wave height for the planning site must be obtained, which usually requires an additional hindcast calculation of the waves. Both Arimura's and our method have certain advantages and disadvantages; thus, how the parameters should be selected as targets of bias correction should be further discussed.

Handling of Big Data

In this study, wave modeling was conducted on a 5 km grid, which was too coarse to calculate the storm tide. The grid size should be finer than 90 m when calculating the storm tide on the coast facing the open ocean because wave set up is an important factor that enlarges the storm tide; thus, a simulation based on detailed near-shore topography is required. However, the large data size of d4PDF makes this difficult. Although typhoon tracks extracted by Webb et al. (2019) are a type of summized d4PDF data, we could not avoid making the grid size coarse owing to the simulation cost.

A modified method, which can estimate the wave height and storm tide based on parameters such as the central pressure and velocity of typhoons and winds, was proposed to enable coastal managers to utilize the d4PDF (Igarashi et al. 2022b). A greater variety of methods are expected to be proposed, the accuracy and applicability of which can be evaluated from this perspective.

Future Change in Wave Height

This study demonstrated the future increase in wave height in Tosa Bay. The degree of increase tended to be larger in the lower probabilities, and 50 years return period of wave height was predicted to increase 4–7 % compared to present condition. This result should be treated carefully because wind speeds were calculated from the center pressure and diameter of typhoons using the Myers typhoon model, and this assumption may not be applicable to future typhoons. Recently, Lai and Toumi (2003) reported that tropical cyclones have become shallower over time owing to changes in environmental conditions such as sea surface temperature, vertical wind shear, and relative humidity.

Notice for Practical Use

Climate change is the most important factor in planning future coastal management, based on which a significant amount of research is being conducted worldwide. The contributions of many researchers have enabled us to obtain reliable future change projections for the sea level. However, the reliability of future wave projections is insufficient for practical application in coastal management. Therefore, it necessary to simultaneously investigate multiple methods. Predictions of future climate change will be regularly updated. It is necessary to review the plan periodically based on the latest prediction results rather than sticking to the design values that were determined once.

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