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Paper:

Bias Correction in Typhoon and Storm Surge Projection Considering Characteristics of Global Climate Model MRI-AGCM3.2S

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The typhoons that so often rage across Japan's southwestern island, Kyushu, are expected to occur even oftener in the future due to global warming. Storm surge projections have been reported based on the super-high-resolution global climate model MRI-AGCM3.2S developed by Japan's Meteorological Research Institute (MRI). AGCM3.2S overestimates typhoon strength around Japanese islands, however, and this could lead to exaggerated storm surge projection. We therefore evaluate a bias correction method of typhoon strength considering the typhoon characteristics of AGCM3.2 in estimating maximum storm surge anomaly on the Ariake Sea coast. Our results indicated the possibility of storm surge anomaly of 2.8 m, exceeding the current design storm surge anomaly of 2.36 m at the innermost Ariake Sea.

Keywords: climate change, storm surge, MRI-AGCM3.2S, best track data, Ariake Sea

1. Introduction

Typhoons frequently hit Japan's southwest area, Kyushu Island. Especially the Ariake Sea in Kyushu Island, which opens on the west and extends north-south, has high risk of typhoon storm surges. Stronger typhoons due to global warming are expected to occur oftener in the future, requiring us to evaluate possible typhoons and resulting storm surges when considering how to reduce coastal disasters around the area.

Much research has been done on assessing storm surge risk in global warming scenarios. Hashimoto et al. (2005) and Kawai et al. (2006, 2009), for example, assessed the recurrence probability of storm surges using stochastic typhoon models [1–3]. Yoshino et al. (2007, 2009) and Murakami et al. (2011) evaluated a possible maximum storm surge if a typhoon takes the worst track [4–7]. Yasuda et al. (2011) evaluated possible changes in storm surge anomaly quantitatively by using extremal statistics directly inputting projected climate change values [8]. Kiri et al. (2004) estimated storm surges using a typhoon model to predict storm surges in the Ariake Sea [9].

Based on possible climate projected values computed by super-high-resolution global climate model MRI-AGCM 3.2S, developed by Japan's Meteorological Research Institute (MRI) [10], we extracted strong typhoons that may hit the Ariake Sea. We also estimated storm surge anomaly resulting from such typhoons along the Ariake Sea coast.

MRI-AGCM3.2S is considered able to reproduce tropical storms in the northwest Pacific Ocean accurately [8, 11]. The accuracy is confirmed in **Table 1**, which compares average characteristics of typhoons extracted from the current climate data computed by the AGCM (hereafter, AGCM current) with those of the best track (BT) data of the Japan Meteorological Agency (JMA) in the region drawn around with blue line in **Fig. 1**. On the other hand, **Table 2** shows comparison of typhoon characteristics extracted from the AGCM current with those of BT around the Japanese islands, northern latitude above 30° drawn around with green line in **Fig. 1**. As seen in **Table 2**, the AGCM current is too strong. Thus projected storm surges would be exaggerated if the AGCM values are directly applied to storm surge projection.

In the paper, we discussed a bias correction method of typhoon strength in AGCM3.2S by comparing the values of MRI-AGCM3.2S with BT. We also evaluated a maximum storm surge anomaly on the Ariake Sea coast by correcting bias of the typhoons with the proposed method.

2. MRI-AGCM3.2S Overview

MRI-AGCM3.2S is an updated super-high-resolution global climate model developed by Japan's Meteorological Research Institute during the Innovative Program of Climate Change Projection for the 21st Century. Climate projection experiments were conducted for current (1979-2003), near future (2015-2039), and future (last 25 years

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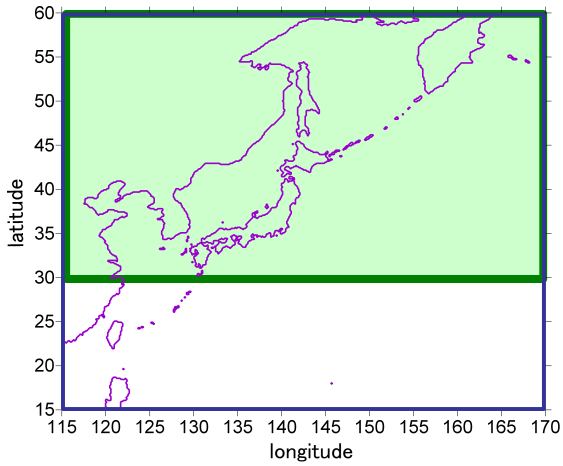

Fig. 1. AGCM data region.

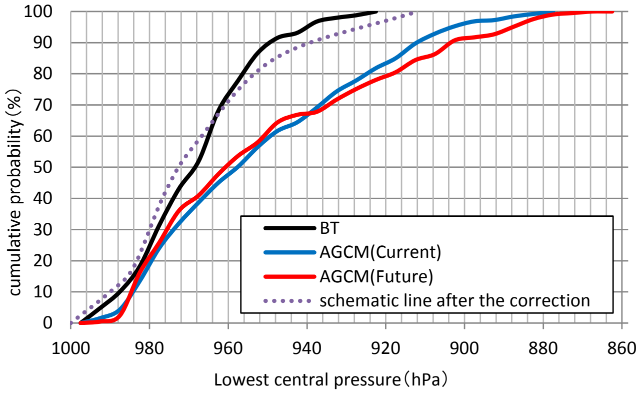

Fig. 2. Cumulative distribution of lowest typhoon central pressure values around the Japanese islands.

Table 1. Comparison of current typhoon characteristics.

	BT	MRI-AGCM3.2S	
		Current	Future
Total number	426	361	306
Average number per year	17.04	14.44	12.24
Average value of the lowest central pressure of each typhoon	951.8hPa	941.7hPa	939.2hPa
Lowest central pressure	870.0hPa	865.9hPa	945.4hPa

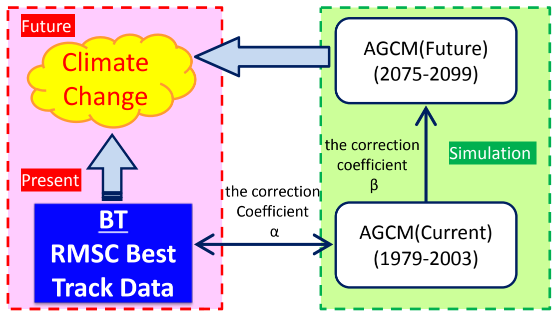

Fig. 3. Estimation procedure of future typhoon strength.

Table 2. Comparison of current typhoon characteristics around the Japanese islands.

	BT	MRI-AGCM3.2S	
		Current	Future
Total number	248	253	205
Average number per year	9.92	10.12	8.20
Average value of the lowest central pressure of each typhoon	968.2hPa	950.1hPa	948.6hPa
Lowest central pressure	925.0hPa	875.2hPa	867.0hPa

of 21st century; 2075-2099) under the IPCC SRES-A1B emission scenario. This holds that atmospheric greenhouse gas concentration will roughly double by the end of the 21st century compared to that at the end of the 20th century.

In this study, typhoons were extracted from climate projection values, mean sea level pressure every 6 hours, for current and the future. Typhoons were assumed to be generated at points where a minimum pressure of 985 hPa or less in the southern area below 35° in northern latitude, and disappeared where central pressure exceeded 995 hPa. Experiments were conducted using mean sea level pressure in 1979-2003 and 2075-2099 in the area between eastern longitudes 114.938-170.063 and between northern latitudes 14.898-63.061.

3. Estimation of Future Typhoon Strength

Figure 2 shows the cumulative distribution of lowest central pressure for the periods in **Table 2**. Compared with BT shown in solid black line in **Fig. 2**, based on actual typhoons vs. AGCM current computed with current climate conditions, AGCM current shown in blue line is much stronger. Because the difference between AGCM future shown in red line and AGCM current reflects the impact of global warming, the distribution of the dotted purple line is considered as appropriate for future typhoon strength. As shown in **Fig. 3**, this study estimates future typhoon strength using two methods: (1) Comparing the cumulative distribution of AGCM current with that of BT to determine correction coefficient α. Then, correcting the central pressure of typhoons in AGCM future with α to estimate future value of the central pressure of typhoons. And (2) Comparing the cumulative distribution of AGCM future with that of AGCM current to determine correction coefficient β. Then, correcting the central pressure of typhoons in BT with β to estimate corrected future value of the central pressure of typhoons.

Figure 4 plots the difference between the central pressure of AGCM current and BT in each cumulative probability. The relationship between AGCM current and BT was approximated as the solid line and regarded as correction coefficient α for bias correction of the typhoon central pressure in the AGCM future values. As seen in **Fig. 4**, the difference between AGCM current and BT increases from the cumulative probability of 30%, so the correction coefficient α for bias correction was set to change from 30% with a linear equation as seen in **Fig. 4**. **Fig. 5** plots the difference between the central pressure

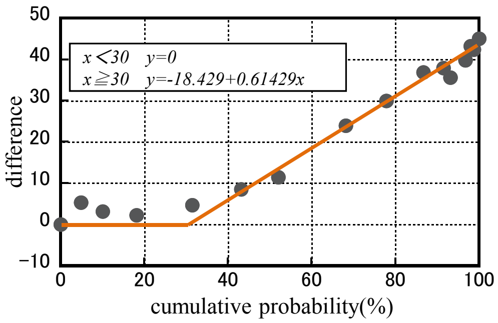

Fig. 4. Differences between the central pressure of AGCM current and BT in each cumulative probability.

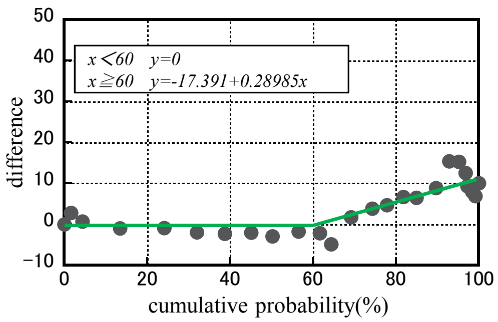

Fig. 5. Differences between the central pressure of AGCM future and AGCM current in each cumulative probability (%).

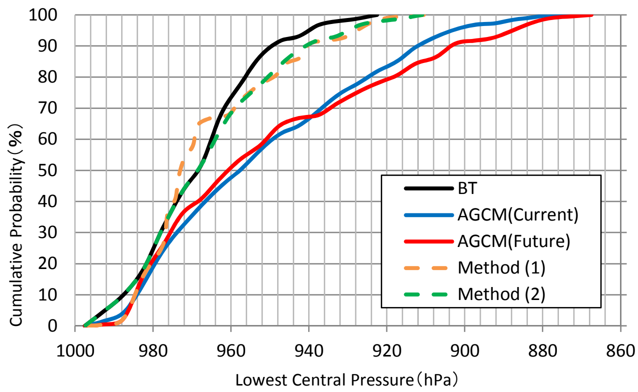

Fig. 6. Cumulative distribution of lowest typhoon central pressure values around the Japanese islands after bias correction.

of AGCM future and AGCM current in each cumulative probability to determine bias correction coefficient β.

In addition, although not discussing here, as an alternative method, ratios of central pressure between two values could also be applied for bias correction. Thus we tried the methods as well, but we could not identify any major differences in the two correction methods.

Figure 6 shows the cumulative distribution of central pressure for future typhoons using obtained correction coefficients (solid line: distribution before correction; broken line: distribution after correction). Method (1), yellow broken line, shows corrected AGCM future values using correction coefficient α, while Method (2), green broken line, shows corrected BT using future variation coefficient β. Method (1) and Method (2) almost overlap in the range of central pressure below 960 hPa, which is important in estimating storm surges and waves in severe sea conditions.

4. Storm Surge Projection

4.1. Computation of Storm Surges

In storm surge computations, FVCOM (Finite Volume Coastal Ocean Model) version 2.7 was used with external forces (input values) including wind and atmospheric pressure computed by an empirical typhoon model that uses the Myers pressure distribution model. FVCOM, an unstructured-grid ocean flow model, uses 3-dimensional finite volume developed by Chen et al. (2003) of Massachusetts Dartmouth University. This model offers variable grids of different sizes from several 10 km for representing Open Ocean to several 10 m for representing complicated topography on a coast [12].

In this study, FVCOM was modified to reflect changes in atmospheric pressure fields for storm surge computations by incorporating atmospheric pressure change into the pressure term in the momentum equation since the original model did not consider atmospheric pressure changes. Wind fields are incorporated in the FVCOM momentum equation using bulk equation (Eq. (1)) as tangential sea surface stress.

$$\begin{cases} \tau_x = \rho_a C_d u_{10}\sqrt{u_{10}^2+v_{10}^2} & (east-west) \\ \tau_y = \rho_a C_d v_{10}\sqrt{u_{10}^2+v_{10}^2} & (north-south) \end{cases} \quad (1)$$

where τ_x [N/m^2] is the east-west tangential stress component, τ_y [N/m^2] is the north-south tangential stress component, ρ_a [Kg/m^3] is air density, C_d is the sea surface drag coefficient, and u_{10} [m/s] and v_{10} [m/s] are east-west and north-south components of wind velocity 10 m above the sea surface.

The drag coefficient of sea surface C_d was calculated using Honda and Mitsuyasu equation (Eq. (2)), formulated based on wind data below 25 m/s.

$$C_d(U_{10}) = \begin{cases} \left(1-1.890\times U_{10}\times 10^{-2}\right)\times 1.28\times 10^{-3} & (U_{10}\leq 8.0 \text{ m/s}) \\ \left(1+1.078\times U_{10}\times 10^{-1}\right)\times 5.81\times 10^{-3} & (U_{10}\geq 8.0 \text{ m/s}) \end{cases} \quad (2)$$

where U_{10} [m/s] is wind velocity 10 m above sea surface. According to Powel et al. (2003) and Yokota et al. (2011), however, the drag coefficient C_d is expected to decrease due to spray generation under wind conditions exceeding 30 m/s, resulting in overestimated values based on the proposed Eq. (2) [13, 14]. In this study, we therefore estimated storm surges with a constant drag coefficient C_d for above 30 m/s for future climate conditions.

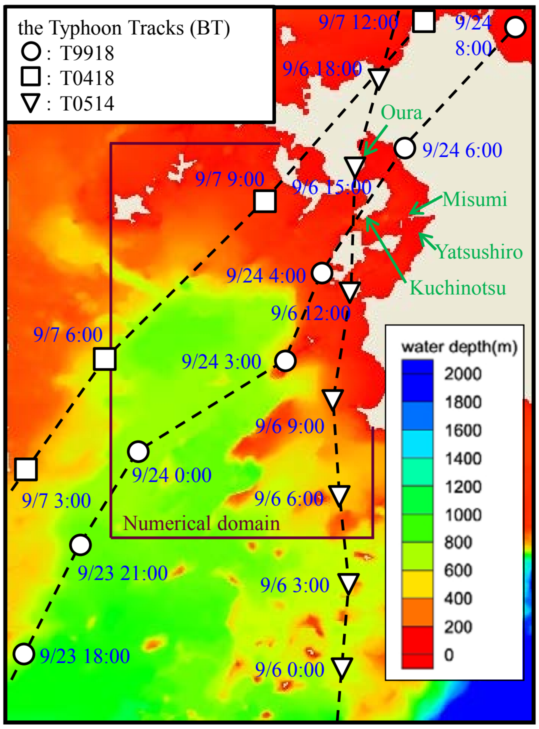

Fig. 7. Water depth distribution and typhoon tracks in computation area.

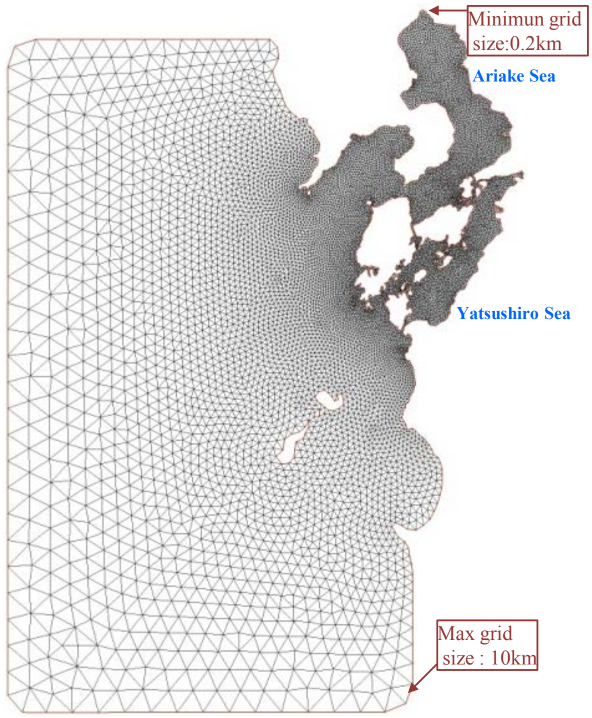

Fig. 8. FVCOM computation grids.

It should be noted that, in the following, we estimates storm surge anomaly from the mean sea level without considering astronomical tide.

As external forces for storm surge computations with AGCM3.2S, the given data for atmospheric pressures of every 20 km and 6 hours and wind velocities of every 20 km and 1 hour are too coarse in time-space resolution for accurate computations of storm surges in the Ariake Sea. We therefore interpolated the data with higher time-space resolution of every 1 km and 1 hour using the following Myers's typhoon model Eq. (3) based on the atmospheric pressure data extracted from AGCM3.2S data.

$$P(r) = P_0 + \Delta P \exp\left(-\frac{TR}{r}\right) \quad . \; . \; . \; . \; . \; . \; . \; (3)$$

where P_0 [hPa] is central pressure, ΔP [hPa] is the descent of central pressure ($\Delta P = 1013 - P_0$), TR [km] is the maximum wind velocity radius, and r [km] is the distance from the center.

4.2. Accuracy Evaluation of Storm Surges

To evaluate accuracy of storm surge estimates, computations were carried out for past typhoons that caused significant storm surge anomaly in the Ariake Sea and nearby Yatsuchiro Seas.

4.2.1. Computation Area and Grids

Figure 7 shows water depth distribution and typhoon tracks in the computation area. **Fig. 8** shows unstructured computation grids. Coast lines were determined based on digital national land information data and water depth data were interpolated from hydrographic isoline data published by the Japan Coast Guard (JCG).

Mean sea level above the hydrographic datum (Z_0) was corrected in the Ariake Sea and Yatsushiro Seas. The computation area was determined so that Open Ocean effects are properly taken into account for accurate storm surge computations in the Ariake Sea and Yatsushiro Seas following the results of Kinashi et al. (2012) [15]. Grid sizes were set 0.8 km for inner bays and gradually increased for Open Ocean up to 10 km at a maximum.

4.2.2. Computation Conditions

Table 3 lists major computation conditions for FVCOM. Three typhoons with different tracks, T9918, T0418, and T0514, causing significant storm surge anomaly in the Ariake Sea and Yatsushiro Seas were selected. Atmospheric pressures and wind velocities were estimated for each typhoon with an interval of 1 km based on the best track data provided by the JMA. The wind reduction coefficient was set to be a constant of 0.66. Computations for storm surges were from Sep. 23, 1999, 01:00, to Sep. 24, 21:00, for T9918; from Sep. 6, 2004, 01:00 to Sep. 8, 15:00, for T0418; and from Sep. 5, 2005, 1:00, to Sep. 7, 18:00, for T0514 with a spin up computation time of 24 hours. Note that input values for wind and atmospheric pressure were interpolated based on FVCOM computational interval time.

4.2.3. Discussion on the Results

Figure 9 compares observed and estimated values for maximum storm surge anomaly at Kuchinozu, Misumi,

Table 3. Computation conditions for FVCOM.

Horizontal grid sizes	0.8 ~10 km
Number of vertical layers	10
Sea water density	Constant (20C°, 30psu)
Open boundary condition	Sea surface level boundary (conversion from atmospheric pressure change into amount of change in water level)
Estimation of atmospheric pressures and winds	Typhoon model (every 60 min)
Time interval of calculation	1.0sec

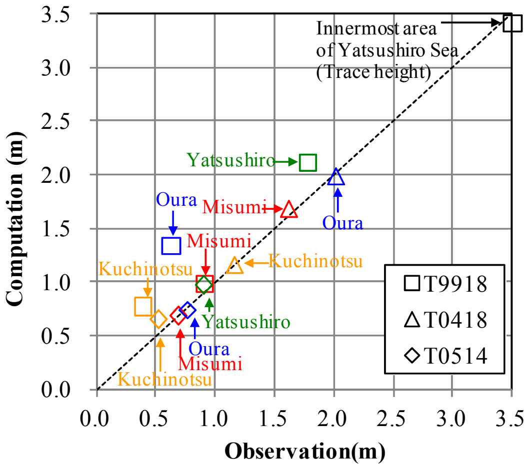

Fig. 9. Comparison of maximum storm surge anomalies.

Oura, Yatsushiro, and the innermost Yatsushiro Sea. The anomaly at the innermost Yatsushiro Sea is based on field observation values by Takigawa (2000) [16]. While, those at the other locations were based on observation data carried out by the JMA and JCG. The estimated values are roughly correlated with the observed values, although estimates for T9918 are larger than those observed by several 10 s of cm at Kuchinozu, Oura, and Yatsushiro. However, the computations with FVCOM are considered sufficiently accurate.

4.3. Extraction of Typhoons in Future Climate

Typhoons that may cause severe storm surges in the Ariake Sea are extracted from AGCM future values. Then storm surges were computed based on corrected atmospheric pressure data so that cumulative distribution of typhoon central pressures followed the yellow broken line, method (1), in **Fig. 6**. That is, in this study, we used method (2), which corrects AGCM future values considering global warming. On the other hand, if the correction coefficient β is applied to BT data following method (2), future typhoons turn out to be estimated based on past typhoons, thus failing to consider changes in the number and tracks of typhoons due to global warming.

Figure 10 shows an example of typhoon track included in AGCM future data. In the experimental climate projection data, this typhoon is generated on August 9, 2076,

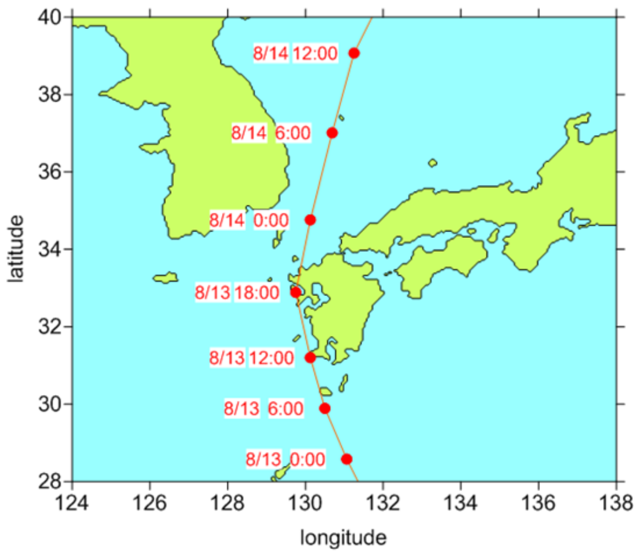

Fig. 10. An example of typhoon track in the future climate.

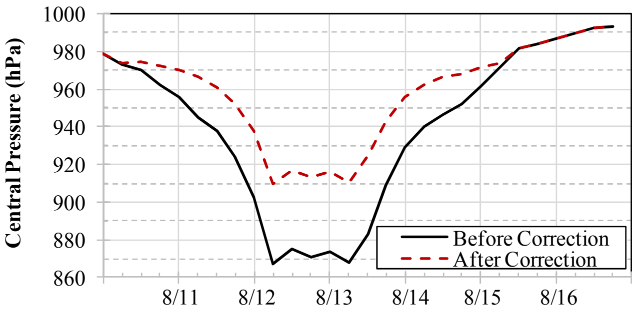

Fig. 11. Correction of central atmospheric pressure of a typhoon in AGCM future data.

and passes on the west side of Kyushu through the Ariake Sea at 18:00 on August 13, 2076. According to Kinashi et al. (2012), this typhoon may cause the largest storm surge anomaly in the innermost Ariake Sea among typhoons that may hit the area in the last quarter of the 21st century (2075-2099) [17]. **Fig. 11** shows temporal changes in the typhoon central pressure before and after correction using climate model correction coefficient α. The lowest central pressure changed from 867 hPa to 910 hPa after correction, indicating decreased typhoon strength.

4.4. Setting the Maximum Wind Velocity Radius of Future Climate Typhoons

AGCM future atmospheric pressure distribution was compared to that computed by the Myers equation with different maximum wind velocity radius (TR) before and after correction to obtain the radius with the smallest error. The error was defined as the sum of the differences of atmospheric pressures at each grid point every 20 km in an area of 1,000 km square at the typhoon center.

Figures 12 and **13** show atmospheric pressure distributions around the typhoon at 18:00 on August 13, 2076, (AGCM future and Myers) as an example of estimated

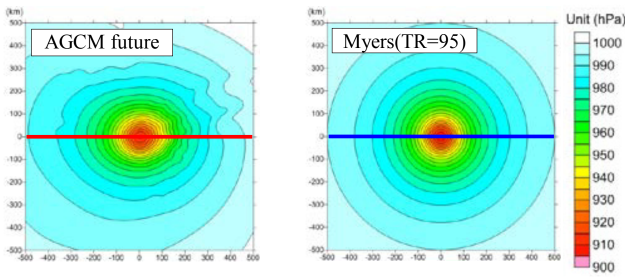

Fig. 12. An example of atmospheric pressure distribution in estimating maximum wind velocity radius before correction.

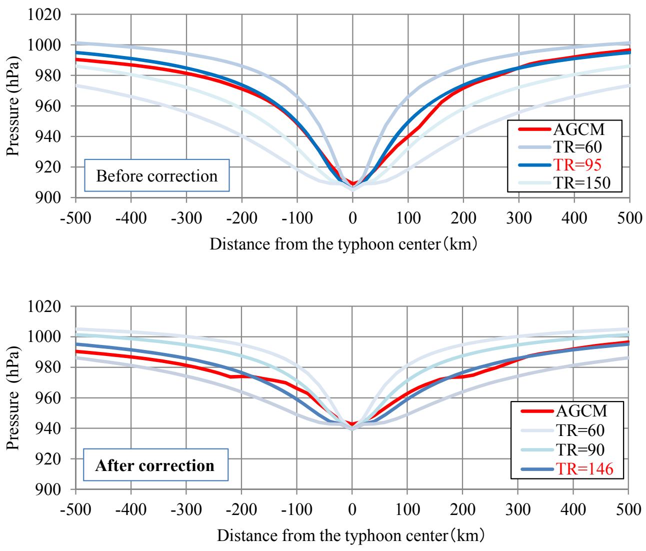

Fig. 13. Examples of cross-sections of atmospheric pressure distributions in west-east direction in estimating maximum wind velocity radius (upper; before correction, lower; after correction).

atmospheric pressure distribution. The dark and dilute blue lines in **Fig. 13** show cross-sections of atmospheric pressure distributions at different maximum wind velocity radii in upper and lower charts, before correction and after correction, respectively. Red lines in upper and lower charts show AGCM future atmospheric pressure distribution and that after correction using correction coefficient α. **Fig. 14** plots maximum wind velocity radii before and after correction on a correlation diagram of maximum wind flow radii and typhoon central pressure based on best track data for the last 50 years created by Yasuda et al. (2010). Distribution before and after correction falls within the BT distribution, confirming that maximum wind speed radii of the simulated typhoon are appropriate.

4.5. Estimation of Storm Surge in Future Climate

Figures 15 and **16** show maximum storm surge anomaly distribution as estimation results for future typhoons before and after correction. Anomaly increases toward innermost bay in both cases and generally decreases after correction.

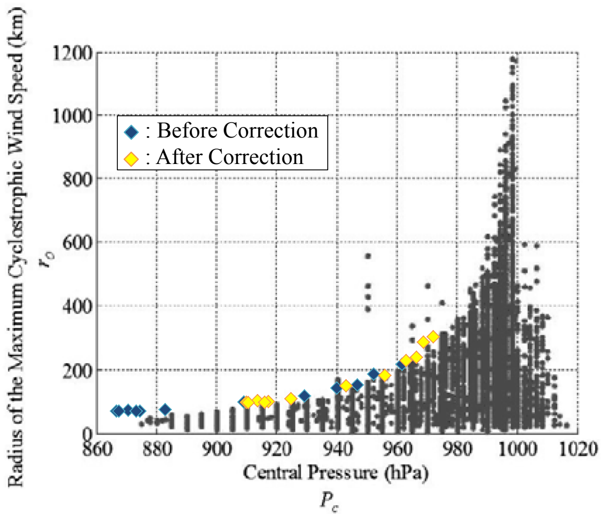

Fig. 14. Typhoon central pressure and maximum wind velocity radius. Black: BT, 1951-2000 [18].

Figure 17 compares the maximum anomaly of storm surges before and after correction at the innermost Ariake Sea (black point in **Figs. 15** and **16**).

At the innermost Ariake Sea, storm surge anomaly decreased from 5.07 m to 2.76 m after correction. The value after correction, however, exceeds that of design storm surge anomaly 2.36 m.

Note that this study is not sufficient for discussing future typhoon strengths and tracks because it is based on projection values assuming only one emission scenario, SRES-A1B of IPCC. Storm surge projection in the future should consider various changes in typhoon strength and tracks.

5. Conclusions

This study evaluated the accuracy of a storm surge estimation using FVCOM targeting the Ariake Sea by reproduction computation of past storm surges. A storm surge along the Ariake Sea coast was estimated from experimental future climate projection data based on a global warming scenario. In summary, the strength of typhoons that may hit the Japanese islands was estimated based on proposed correction coefficients, α and β, by comparing the cumulative distribution of the lowest values of typhoon central pressure extracted from BT and MRI-AGCM3.2S. Typhoons that may cause significant storm surges in the Ariake Sea and Yatsushiro Seas were extracted from future AGCM typhoons. Storm surges were calculated by correction using correction coefficient α (method (1)). Result suggest that a storm surge anomaly of 2.8 m exceeding the value of current design tide anomaly 2.36 m may occur at the innermost Ariake Sea, although storm surge values decreased considerably after correction. Note that this study does not cover occurrence probability and thus does not show that the return periods of storm surges exceeding the current design anomaly were shorter than given periods.

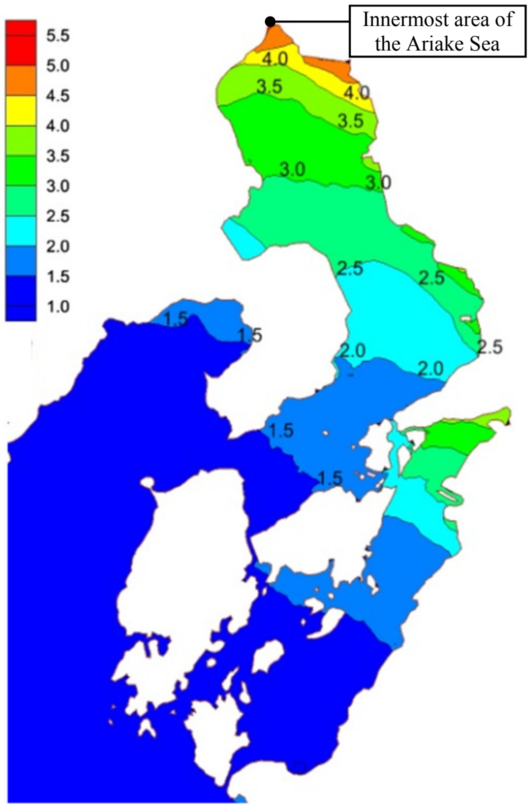

Fig. 15. Distribution of maximum storm surge anomaly of a typhoon before correction.

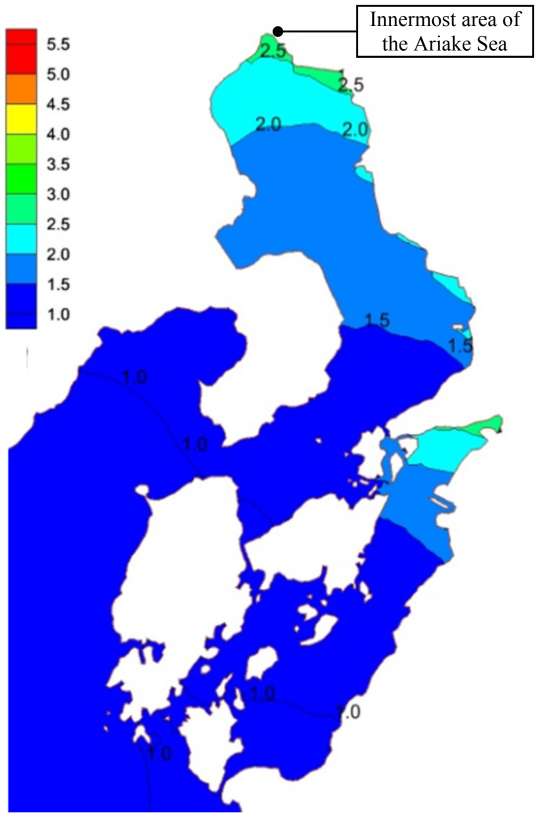

Fig. 16. Distribution of maximum storm surge anomaly of a typhoon after correction.

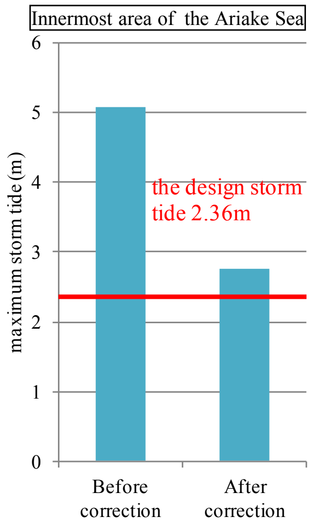

Fig. 17. Comparison of maximum storm surge distribution at the innermost Ariake Seas.

As discussed above, an appropriate correction method for typhoon projection data was proposed in this study by comparing experimental projection values in future climate, which overestimated typhoon strength, with the BT data as well as observed data.

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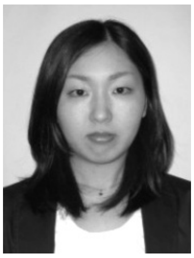

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