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Future Projection of Tropical Cyclone Precipitation over Japan with a High-Resolution Regional Climate Model

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Abstract

This study evaluates possible changes in tropical cyclone (TC) precipitation over Japan under a future warmer climate using an ensemble projection generated by a non-hydrostatic regional climate model with a resolution of 5 km (NHRCM05) under the RCP8.5 scenario. NHRCM05 reproduces TC precipitation and TC intensity more accurately than does a general circulation model with a resolution of 20 km. The number of TCs approaching Japan is projected to decrease under the future climate, while the TC precipitation rate increases. As these two effects cancel each other out, total TC precipitation, and the frequency of the moderate TC precipitation that is usual under the present climate, show no significant change. On the other hand, the frequency of extreme TC precipitation increases significantly because the intensification in the TC precipitation rate outweighs the reduction in TC frequency. The increase in the TC precipitation rate is caused primarily by the increase in water vapor around the TCs, which in turn results from the change in environmental water vapor. The intensification and structural changes to TCs also contribute to the enhanced TC precipitation.

Keywords tropical cyclone, extreme precipitation, future projection
1. Introduction

The heavy rainfall generated by tropical cyclones (TCs) causes serious problems in affected areas, but is also important in maintaining water resources. Satellite observations show that TC precipitation accounts for about 11% of total precipitation in the northwestern Pacific, and in some areas, such as Taiwan, the contribution of TC precipitation exceeds 30% (Jiang and Zipser 2010). Utusmi et al. (2017) classified precipitation in the area between 60°S and 60°N according to the weather systems that generated the precipitation and showed that TC precipitation accounts for about 10% of precipitation in southwestern Japan, which is greater than in other regions at similar latitudes. Kamahori and Arakawa (2018) demonstrated that TC precipitation accounts for 15% or more of precipitation in several areas of Japan located in eastward or southeastward topographic inclines.

TCs frequently cause extreme rainfall (e.g., Nakano et al. 2010; Kanada et al. 2017). Tsuguchi and Kato (2014) showed that in Japan, more than 30% of heavy precipitation is caused by TCs. Utsumi et al. (2017) showed that the contribution of TCs to extreme precipitation is more than that to the total precipitation. They classified extreme precipitation according to the temporal scale, and demonstrated that the contribution of TCs is greatest for 24-hour to 72-hour precipitation.

The changes in TC activity under a future warmer climate have attracted much attention and many projections have been made using general circulation models (GCMs) (Knutson et al. 2010; Christensen et al. 2013; Walsh et al. 2016). Many GCMs project that
the total number of TCs will decrease under the future climate. Although regional projections contain large variability, in the northwestern Pacific, many studies have projected that the total number of TCs will decrease but that the proportion of severe TCs (i.e., those with very destructive winds) will increase (e.g., Sugi et al. 2016; Yoshida et al. 2017). In addition, the intensity of the rainfall generated by these TCs is also likely to increase (e.g. Hasegawa and Emori 2005; Yamada et al. 2017; Yoshida et al. 2017). The change in the total precipitation caused by TCs depends on the balance between the change in the number of TCs and precipitation rate. Lui et al. (2018) showed that the combined effect of these two competing factors leads to a reduction of total precipitation caused by TCs in southern Japan, where the reduction of TC number surpasses the intensification of rainfall rate.

Under the future climate, extreme precipitation is projected to increase over Japan (Sasaki et al. 2012). Kanada et al. (2017) performed a pseudo global warming simulation for a TC that caused serious flooding in northern Japan and demonstrated that the intensity of the precipitation associated with TCs will increase under the future climate. Ikema et al. (2010) analysed daily precipitation in Okinawa and showed that the frequency of heavy precipitation (>75 mm per day) is increasing over time. They concluded that this is related to the decrease in the moving speed of TCs. On the other hand, Kitoh and Endo (2016) showed that the annual maximum daily precipitation (Rx1d) associated with TCs will decrease in the future owing to a reduction in TC number. Using large-ensemble simulation,
Kitoh and Endo (2019) showed that the median of Rx1d associated with TCs around Japan will decrease in the future whereas 90- and 99- percentile values of Rx1d will increase.

These results indicate that the frequency of extreme precipitation will be affected not only by the change in precipitation rate, but also by changes in the number of TCs and their moving speed. Therefore, the changes to the frequency of extreme precipitation associated with TCs, and its contribution to the total frequency of extreme precipitation, remain to be clarified.

Most previous projections of TC precipitation have been performed using GCMs (e.g., Yoshida et al. 2017). However, TC precipitation is strongly affected by complex topography, such as that found in Taiwan (Lin et al. 2002) and Japan (Kamahori and Arakawa 2018), and a high-resolution model is needed to express this topographical effect on TC precipitation (Wu et al. 2002). Unfortunately, it is difficult to perform such high-resolution simulations using a GCM because of the limitations imposed by the availability of computer resources. However, dynamical downscaling can be used to simulate such complex topographical effects. Previous studies have demonstrated that dynamical downscaling using a high-resolution non-hydrostatic regional climate model (RCM) can realistically reproduce total precipitation and extreme precipitation over Japan (Kanada et al. 2010; Sasaki et al. 2011; Nakano et al. 2012; Murata et al. 2015; Murata et al. 2017). Thus, RCM simulations offer a promising approach to the more accurate evaluation of changes in TC precipitation as the climate continues to warm.
Recently, evaluation of the changes in TC precipitation using dynamical downscaling by an operational hurricane model (Knutson et al. 2015) or an RCM has been started (Huang et al. 2016; Nishizawa et al. 2018). Among them, Nishizawa et al. (2018) evaluated the future changes in TC precipitation over Japan. However, they performed a dynamical downscaling from only one member of ensemble simulations. TCs have both a low occurrence frequency and large internal variability. In addition, the change in the number and distribution of TCs vary depending on the distribution of SST change (e.g., Knutson et al. 2010; Christensen et al. 2013; Walsh et al. 2016). Therefore, more evaluation should be performed to obtain more reliable estimation of the future changes in TC precipitation over Japan.

In this study, we evaluate these potential changes to TC precipitation over Japan using a high-resolution dynamical downscaling projection. The remainder of this paper is organized as follows. Our data and methodology are described in section 2, and the performance of the downscaling is evaluated in section 3. The future projection of TC precipitation is demonstrated in section 4, the factors that control the future change in TC precipitation are discussed in section 5, and our concluding remarks are provided in section 5.

2. Data and Methodology

2.1 Model
We used the non-hydrostatic regional climate model (NHRCM), which is a climate version of the Japan Meteorological Agency Non-Hydrostatic Model (JMA-NHM; Saito et al. 2006), for the dynamical downscaling. The specifications of the NHRCM were described by Sasaki et al. (2008), Nakano et al. (2012), and Murata et al. (2015).

The NHRCM includes a spectral nudging scheme (Nakano et al. 2012) that is based on a spectral boundary coupling scheme (Kida et al. 1991; Sasaki et al. 2000) for climate simulations. Large-scale wave components (wavelength > 1000 km) of horizontal momentums and potential temperature above a height of 7 km are replaced with weighted averages of the values in inner and outer models by the spectral nudging scheme. The weighting factors for inner and outer models are 0.94 and 0.06, respectively. It reduces difference in the TC position between outer and inner models, while it little affects TC intensity in the inner model (Nakano et al. 2012).

2.2 Experimental design

The experimental design used in this study was described by Murata et al. (2015). The model domain of the NHRCM has 527 × 804 grid points with a grid spacing of 5 km (NHRCM05), which covers Japan (Fig. 1). Time-slice simulations were conducted for 20-year periods between 1980 and 2000, and between 2076 and 2096, for the present and future climate, respectively. For each simulation, NHRCM05 was initialized on 21 July and then run until 1 September the following year. The results from the first 42 days were
excluded as model spinup. Boundary conditions for NHRCM05 were derived from a
simulation using an atmospheric GCM with a 20-km horizontal resolution (MRI-AGCM3.2S,
hereafter referred to as AGCM20; Mizuta et al. 2012).

For the future climate simulation, four ensemble simulations, in which different
boundary conditions were used, were conducted under the representative concentration
pathway (RCP) 8.5 scenario for greenhouse gas concentrations. The four boundary
conditions were generated from AGCM20 simulations with four different sea surface
temperature (SST) fields (Mizuta et al. 2014). The control SST field was the ensemble
mean SST from the end of the 21st century generated by the Coupled Model
Intercomparison Project Phase 5 (CMIP5) models (referred to as C0). The other three SST
fields were generated by cluster analyses for the CMIP5 SSTs based on the spatial patterns
of the changes in the annual-mean SST in the tropics (referred to as C1, C2, and C3).

2.3 TC detection

Although a number of TC detection scheme have been proposed, a scheme for model
datasets with a fine grid length is lacking. To identify the TCs generated by NHRCM05, we
developed a new TC detection scheme designed for high-resolution RCM (Murata et al.
2019). In this scheme, sea level pressure and surface wind speed are used for the vortex
detection but relative vorticity at 850 hPa, which is used in many previous schemes (e.g.
Murakami et al. 2012), is not used in order to reduce the resolution dependency. In addition,
This level is underground in some mountainous regions in Japan. This scheme distinguishes TCs from other low pressure systems based on parameters associated with the axisymmetry of the vortex and warm core structure. These parameters are calculated using the layer thickness between 500 and 300 hPa. Note that the scheme does not use the parameters from each time step, but uses the parameters averaged over the vortex lifetime. The thresholds for these parameters are determined based on the comparison between observation and downscaling datasets forced by a reanalysis. To avoid the effect of the horizontal boundary, the detection of TCs was performed only in the domain away from the boundary (Fig. 1). The detection scheme of Murakami et al. (2012) was used for the detection of TCs from AGCM20.

We also evaluated the precipitation caused by TCs that experienced an extratropical transition. In the best track data, the location of a cyclone changed from a TC is recorded regardless of its maximum wind speed. Therefore, TCs were tracked for as long as they maintained a sea level pressure (SLP) minimum that was 2 hPa lower than the surroundings and remained in the domain for TC detection after they no longer satisfied the criteria for TC.

2.4 TC precipitation

We examined only the precipitation caused by the TCs themselves, although TCs cause predecessor rainfall events (PRE) in the remote area by transporting huge amounts
of water vapor from the Southern Ocean (Galarneau et al. 2010). We defined TC precipitation as precipitation that falls within a 500 km radius of the TC center, as precipitation is concentrated within a 5° radius of the TC center (Kamahori 2012). This definition is consistent with previous studies (e.g., Dare et al. 2012; Kito and Endo 2016).

We defined the TC period as that during which the observation station or model grid point was within 500 km of the center of the TC. The TC precipitation for each observation station or model grid point was defined as a precipitation that occurs during the TC period. The TC precipitation rate was calculated by dividing the total TC precipitation by the total TC period. A daily TC precipitation was obtained by summing up the TC precipitation from 00 UTC to 00 UTC on the next day.

We also evaluated the radial distribution of the TC precipitation that are calculated as follows: First, the total TC precipitation and the total TC period of an observation station or a model grid point are divided into several bins according to the relative location of the point to the TC center (i.e. direction and distance from the TC center). Second, the divided TC precipitation and TC period are averaged over all observation stations or corresponding model grid points. Finally, the TC precipitation rate in each bin is calculated by dividing averaged TC precipitation by averaged TC period for the bin.

2.5 Observational data

We evaluated the performance of NHRCM05 by comparing the result of its present-day
climate simulation with ground-based observational data for the same period. The data used were from the automated meteorological data acquisition system (AMeDAS) administered by the JMA. AMeDAS comprises a dense network of meteorological stations that are located throughout Japan at an average interval of 17 km (Fig. 1), and we obtained precipitation data from about 1300 stations. The temporal resolution of the AMeDAS data is 1 h, which is equal to that of the model output. For comparison, we used the land grid point of the model nearest to the location of each AMeDAS station. These stations were divided into seven regions (Fig. 1) as follows: NJ: Japan Sea side of northern Japan; NP: Pacific Ocean side of northern Japan; EJ: Japan Sea side of eastern Japan; EP: Pacific Ocean side of eastern Japan; WJ: Japan Sea side of western Japan; WP: Pacific Ocean side of western Japan; and SI: Nansei Islands, using the same procedure as Murata et al. (2015) and averages were calculated for each region. For the observed TC tracks, we used the Regional Specialized Meteorological Center (RSMC) Tokyo best track data.

3. Evaluation of present-day climate simulation

In this section, we evaluate the performance of NHRCM05 by comparing the present-day climate simulations generated by the model with the observational data. As the simulation of the present-day climate by NHRCM05 is not a perfect boundary simulation in which reanalysis data are used as the boundary conditions, we were unable to directly compare each TC generated by NHRCM05 with the RSMC best track data. Instead, we
used the 20-year average values. For the comparison, we also evaluated the performance of AGCM20. TC detection by NHRCM05 is performed within the domain shown in Fig. 1. For the observation and AGCM20, only TCs that passed the same domain as NHRCM05 were analysed.

First, we evaluate the performance of the new TC detection scheme. In the dynamical downscaling, TCs detected in AGCM20 are expected to be found in NHRCM05 although there is a possibility that NHRCM05 produces its own TCs that are not found in AGCM20. The locations of TCs in NHRCM05 and AGCM20 are compared every 6 hour. If the TCs are located within 200km for more than 3 time steps, these TCs are judged to be identical. 112 and 118 TCs were detected in NHRCM05 and AGCM20, respectively, and 88 TCs were judged to be identical. Thus, most of the TCs in AGCM20 were reproduced in NHRCM05 and detected by the new TC detection scheme, indicating that the performance of the new TC detection scheme for RCMs developed by Murata et al. (2019) is comparable to the TC detection scheme for GCMs developed by Murakami et al. (2012). We also examined TCs that were detected in only one of either NHRCM05 or AGCM20. Cyclones corresponding to such TCs were found in both model but they are not judged to be a TC in either model because their intensity or structure did not satisfy the criteria for the model.

Figure 2 compares observed and simulated TC distribution. TC numbers to the south of 30°N are smaller than those recorded in the best track data in both models (Fig. 2f), and this can be attributed to the influence of AGCM20 because the TC tracks generated by
NHRCM05 are dominated by AGCM20. This bias was pointed out in a previous study (Murakami et al. 2012). Note that TC number in NHRCM05 near the boundary of the domain might be underestimated because some TCs passed through the domain in a period shorter than a threshold for the detection. To the north of 30°, both positive and negative biases are found in both models (Fig. 2d and 2e). In a larger scale average, there are no systematic bias between 30°N and 40°N and negative bias to the north of 40°N in NHRCM05. In AGCM20, TC number is underestimated between 30°N and 35°N and to the north of 40°N. The negative bias to the north of 40°N in AGCM20 is larger than that in NHRCM05. NHRCM05 reproduces the minimum central SLP of the TCs well, but there is a negative bias in AGCM20, indicating an overestimation of TC intensity in AGCM20 (Fig. 3).

Annual TC precipitation is larger on the Pacific side than the Japan Sea side. (Fig. 4a). More than 400 mm of TC precipitation per year is observed on the southern slopes of the mountains on Kyushu and Shikoku Islands, which is about 20% of the total precipitation in these areas. Although annual TC precipitation in northern Japan is less than 100 mm, the contribution of TC precipitation to total precipitation is about 8% on the Pacific side (not shown). These results are consistent with the results in Kamahori and Arakawa (2018). The overall distribution of TC precipitation is reproduced by the models (Fig. 4b and 4c).

The bias and Taylor’s skill score (Taylor 2001) in TC precipitation in the models for each region are summarized in Table 1. Since the bias in annual TC precipitation is caused by a combination of the biases in TC tracks and TC precipitation rate, we also calculated
bias and skill score for TC precipitation rate to exclude the effect of the difference in TC
tracks between observation and models. Bias [%] is defined as $100 \times (m/o - 1)$, where $o$
and $m$ are the annual precipitation values for the observations and model simulations,
respectively. The Taylor’s skill score is a combination of the spatial variance and spatial
correlation and ranges from 0.0 (no skill) to 1.0 (perfect skill) (Taylor 2001).

In NHRCM05, the biases of total TC precipitation are less than 15% in the regions
except northern Japan, while negative biases of TC precipitation rate are found in several
regions. In AGCM20, although there are negative biases of total TC precipitation in several
regions, the biases of TC precipitation rate are smaller than those in NHRCM05. However,
skill scores of NHRCM05 for both total TC precipitation and TC precipitation rate are better
than those of AGCM20 in many regions including whole Japan, especially in EP, WP, and SI
regions where large TC precipitation is observed. This indicates that the reproducibility of
the spatial distribution of TC precipitation in NHRCM05 is better than AGCM20. For
example, the 400 mm of TC precipitation on Kyushu and Shikoku Islands was reproduced
by NHRCM05 (Fig. 4b). Such large TC precipitation was observed on several neighboring
AMeDAS stations, the spatial interval of which is comparable to a grid interval of AGCM20,
indicating that such large TC precipitation were observed over an area comparable to a grid
of AGCM20. However, for AGCM20 the TC precipitation simulated over these regions was
slightly underestimated. Although the negative bias in the TC number in AGCM20 between
30°N and 35°N (Fig. 2e and 2f) accounts for some portion of this underestimation, TC
precipitation rates in these regions are also underestimated in AGCM20. In these regions, contribution of TC precipitation out of 200km from TC center in the eastern half of TC, where topographical uplifting of humid southerly occurs, is relatively large (not shown), which is underestimated in AGCM20. The horizontal resolution of AGCM20 is too low to resolve the topography of Japan; thus, this topographical effect on TC precipitation is not expressed completely by AGCM20. This leads to a slightly weak contrast between the Pacific side and the Japan Sea side (Fig. 4c).

Figure 5 shows the average radial distribution of the TC precipitation rate and TC period. Since more TCs are observed to the south of Japanese Islands, TC period for NE and NW quadrants are larger than those for SE and SW quadrant. TC precipitation is most intense northeast of the center because the humid southeasterly associated with the TCs is uplifted by the topography of Japan (Fig. 5b). In addition, the asymmetry of the friction in the boundary layer caused by TC movement (Lonfat et al. 2004), the vertical shear of the zonal wind at mid-latitudes (Chen et al. 2006), and the extratropical transition of the TCs (Evans et al. 2017) also affect the asymmetry of TC precipitation.

The average precipitation rates over the whole area within 500 km of the TC center are 1.53, 1.31, and 1.53 mm hour$^{-1}$ in observation, NHRCM05, and AGCM20, respectively. Although the bias in average TC precipitation rate in AGCM20 is smaller than that in NHRCM05, the representation of the radial distribution of TC precipitation in NHRCM05 is better than that in AGCM20. On the north side of the TCs (Fig. 5a and 5b), although both
NHRCM05 and AGCM20 overestimate precipitation near the center and underestimate precipitation far from the center, the overestimation near the center in NHRCM05 is much smaller than that in AGCM20. The observed precipitation rate is largest at 25-50 km and 50-75 km of the center of the TCs on the northwest and northeast quadrants, respectively. NHRCM05 reproduces this distribution, whereas the maximum precipitation generated by AGCM20 is found farther away from the center. We believe that this is caused by the coarser resolution of AGCM20, which cannot reproduce the inner-core structures of a TC (Kanada et al. 2013). The coarser resolution of AGCM20 might lead to an error in the calculation of relative location of the grid point from TC center. However, this error is expected to be cancel out in the average. On the south side of the TCs, where precipitation is less intense than on the north side, the bias in NHRCM05 is smaller than that in AGCM20 except near the center on the southwest side of the TCs, where NHRCM05 simulates weaker precipitation than seen in the observations.

Next, we will evaluate the performance related to the extreme precipitation caused by TCs (Fig. 6). Note that AGCM20 underestimate the frequency of hourly precipitation larger than 50mm hour\(^{-1}\) when compared with AMeDAS observation due to its coarse resolution (Sasaki et al. 2012). The contribution of TCs to intense hourly precipitation (>30mm hour\(^{-1}\)) is about 20% in Japan (Fig. 6a and 6c). The frequency of intense TC precipitation and its contribution are higher on the Pacific side than the Japan Sea side (not shown). Although both NHRCM05 and AGCM20 overestimate the frequency of intense hourly TC
precipitation, the bias in NHRCM05 is smaller than that of AGCM20. (Fig. 6a). This is related to the overestimation of precipitation rates near the center on the north side of the TCs (Fig. 5). NHRCM05 also overestimates the frequency of intense hourly precipitation caused by non-TC systems by almost the same proportion as that of TC precipitation. Consequently, the contribution of TCs generated by NHRCM05 agrees very well with the observations (Fig. 6c). In contrast to NHRCM05, AGCM20 underestimates the frequency of intense precipitation associated with non-TC systems and the contribution of TCs in AGCM20 is much larger than seen in the observations (Fig. 6c).

The contribution of TCs to daily precipitation is larger for more intense precipitation (Fig. 6b and 6d). The contribution of TCs to intense daily precipitation larger than 100 mm is about 20%, and that to daily precipitation larger than 200 mm is 30%. Similar to the hourly precipitation, the frequency of extreme TC precipitation and its contribution are higher on the Pacific side than on the Japan Sea side (not shown). Both NHRCM05 and AGCM20 accurately reproduce the frequency of extreme daily TC precipitation (Fig. 6b) and the contribution of TCs (Fig. 6d). This result might arise because the overestimation near the center and underestimation in the surrounding area cancel each other out (Fig. 5).

4. Projection of TC precipitation under the future climate

Overall, NHRCM05 reproduces TC precipitation under the present climate reasonably well. Consequently, we evaluated the projected change in TC precipitation under the
warming climate from a projection made using NHRCM05. Figure 7 shows the changes in annual TC precipitation, TC period, and TC precipitation rate, averaged over each region. The change (%) was defined as $100 \times (f/p - 1)$, where $p$ and $f$ are the values for the present and future climate, respectively. The future projection of each ensemble member and the ensemble mean are indicated in the figure. Statistical significance was evaluated using bootstrapping.

The change in total TC precipitation depends on the changes to the TC period and TC precipitation rate. As AGCM20 projects a decrease in TC number around Japan (Murakami et al. 2012; Kito and Endo 2016), the TC number generated by NHRCM05 decreases under the future climate (not shown). Consequently, the TC period decreases in all regions for all members (Fig. 7b). The ensemble mean shows a significant decrease of TC period at the 5% level in SI, WP, WJ, EJ, and across the whole of Japan. On the other hand, the TC precipitation rate increases in all regions for almost all members (Fig. 7c). The changes for the ensemble mean are statistically significant at the 5% level in all regions except NJ and EJ. As the decrease in TC period and the increase in TC precipitation rate cancel each other out, there is no robust change in annual TC precipitation (Fig. 7a).

Next, we evaluated the likely future changes in extreme precipitation caused by TCs. Figure 8 shows the change in the frequency of precipitation associated with TCs. All ensemble members show increases in the frequency of intense hourly and daily precipitation. On the other hand, the frequency of weak TC precipitation decreases due to
the reduction in the number of TCs approaching Japan. These results indicate a greater risk
of extreme precipitation from any single TC under the future climate.

To evaluate extreme precipitation, we defined indices of extreme precipitation for each
region; i.e., the precipitation, including both TC and non-TC precipitation, that occurred 5
and 0.5 times per year per station under the present climate averaged over each region
over 20 years. Hereafter, these indices are referred to as P5 and P05, respectively. On
average, precipitation greater than P5 and P05 occurs 100 and 10 times, respectively, per
point in each region over 20 years. P5 and P05 are large towards the south, and larger on
the Pacific side than the Japan Sea side (Fig. 9), which is consistent with the results of

There is no robust change in the frequency of the hourly precipitation larger than P5
across the whole of Japan or for each region (Fig. 9a). On the other hand, the frequency of
the hourly precipitation larger than P05 in the ensemble mean for the whole of Japan shows
a significant increase at the 5% level, although the rate of increase varies considerably
among the ensemble members (Fig. 9b). Three or four of the four ensemble members
show increases in the frequency of the precipitation larger than P05 in all regions. The
changes for the ensemble mean are statistically significant at the 5% level in all the regions
except EJ.

Similar to the hourly precipitation, the frequency of the daily precipitation larger than P5
does not show any robust change (Fig. 9c). In contrast, two ensemble members show
significant increases in the frequency of the daily precipitation larger than P05 for the whole
of Japan, although the significance level for the ensemble mean is less than 5% (Fig. 9d).

The frequency of the daily precipitation larger than P05 shows an increase in most of the
ensemble members in all regions. A statistically significant change in the ensemble mean is
evident in NJ, NP, and EP, where the rate of change is greater than in the other regions.

Thus, the risk of heavy TC precipitation is likely to rise in northern Japan.

The change in the frequency of extreme precipitation depends on the balance between
the changes in the TC period and precipitation rate. For the moderate precipitation that
sometimes occurs under the present climate, the decrease in TC period and the increase in
TC precipitation rate cancel each other out. Thus, the frequency of the precipitation larger
than P5 shows no significant change. For the very intense precipitation that is rare under
the present climate, on the other hand, the increase in TC precipitation rate overcomes the
effect of the reduction in the TC period. Therefore, the frequency of precipitation shows an
increase despite the reduction in the number of TCs approaching Japan.

It should be noted that the future change in TC precipitation seems to be affected by
the horizontal distribution of the SST change. The SST change around Japan is larger in C2
and C3 than in C0 and C1 (Mizuta et al. 2014; Murata et al. 2015). This is consistent with
the changes in the rate and frequency of extreme TC precipitation; i.e., they are larger in C2
and C3 than in C0 and C1.
5. Discussion

Under the future climate, the increase in SST leads to an increase in the amount of water vapor in the atmosphere (Fujita et al. 2017). The mean total precipitable water for the TC season (May–October) increases by about 12 kg m\(^{-2}\), which corresponds to between 30% and 40% of the value for the present climate. (Fig. 10b). The rate of change shows a uniform increase towards the north, which is consistent with the SST change (Murata et al. 2015). The water vapor around the TCs also increases by 10–20 kg m\(^{-2}\) (Fig. 10a). This equates to an increase of between 20% and 30%, which is smaller than the environmental change. The change in the water vapor for the TC period is affected by the tropics where the TCs generated because they brings air in the tropics when they approach Japan. The SST change in the tropics is smaller than around Japan (Mizuta et al. 2014). Therefore, the change rate in total precipitable water for TC period is smaller than the environmental change rate around Japan. The change in the water vapor is slightly less than the change in the TC precipitation rate (30%–35%). In contrast to the uniform meridional gradient seen in the TC-season mean, the increase rate of water vapor over the TC period shows a more complicated distribution. A contrast is evident between the Pacific side and the Japan Sea side: it is about 30% on the Pacific side, but less than 25% on the Japan Sea side of eastern and northern Japan. This is consistent with the result that the increase in the TC precipitation rate is small in the EJ and NJ regions.

The future change in the atmospheric environment does not always lead to
intensification of precipitation, as in some cases, the increase in water vapor is cancelled out by the suppression of convection due to the thermal stability enhancement (Hibino et al. 2018). To evaluate the effect of the stability change, we calculated vertical profiles of potential temperature and equivalent potential temperature around TC under the present and future climate (Fig. 11). The potential temperature change is larger in the upper level, resulting in the enhanced stability. On the other hand, because the change in water vapor is largest in the lower level, the change in the equivalent potential temperature is also largest at this level. The difference between the equivalent potential temperature in the lowest level (1000 hPa) and the saturated equivalent potential temperature above is larger under the future climate than under the present climate (Fig. 11b), which indicates a larger convective available potential energy (CAPE) around TCs under the future climate. Therefore, for TC precipitation the effect of the increase in water vapor overcomes the enhanced stability.

In addition to the change in water vapor, the change in TC intensity also affects the TC precipitation rate (Hasegawa and Emori 2005). The minimum SLP of TCs decreases under the future climate (Fig. 12a), indicating an increase in the occurrence of stronger TCs in the Japan region. The average wind speed around TCs increases by 5-10% (not shown). The composite effect of the changes in water vapor and wind speed corresponds to about 25-35% increase in water vapor flux, which is roughly consistent with the change in the TC precipitation rate. This seems to cause the higher rate of increase in TC precipitation compared with total precipitable water. The change in SLP is larger at higher latitudes. The
increase in SST, which is also larger at higher latitudes (Murata et al. 2015), allows the TCs to travel farther north while maintaining their intensity. In addition, the fraction of TCs that transform into extratropical cyclones decreases north of 35°N under the future climate (Fig. 12b). This seems to be related to the northward shift of the jet stream under the future climate (Ito et al. 2016), as well as the SST change. These changes in TC intensity and structure over northern Japan are likely to be related to a larger change in the frequency of the daily P05 (Fig. 9d). Note that no significant change was found in the moving speed of the TCs.

6. Concluding remarks

We evaluated potential changes in TC precipitation over Japan under a future warmer climate using an ensemble projection generated by a 5-km-resolution non-hydrostatic regional climate model under the RCP8.5 scenario. The reproducibility of TC precipitation and TC intensity were improved by dynamical downscaling using NHRCM05 when compared with the results obtained from a global climate simulation generated using AGCM20.

The number of TCs approaching Japan is projected to reduce, whereas the TC precipitation rate increases under the future climate. This is consistent with the projection by AGCM20 (Lui et al. 2018) and the projections using dynamical downscaling (Knutson et al. 2015; Huang et al. 2016; Nishizawa et al. 2018). The frequency of moderate TC
precipitation, which sometimes occurs under the present climate, does not change significantly because of the cancelation of these two contrary effects. On the other hand, the frequency of extreme TC precipitation, which is rare under the present climate, increases significantly because the intensification of the TC precipitation rate overcomes the reduction in TC number. This indicates that the probability of extreme precipitation associated with any single TC will increase under the future climate. Therefore, the risk of the hazard due to TC precipitation rises under the future climate despite the reduction in the number of TCs approaching Japan. This projected increase in TC precipitation rates is driven mainly by the increase in water vapor around TCs, which is caused by the increase in environmental water vapor. The intensification of, and structural changes in the TCs also contribute to the increase in TC precipitation rate.

The changes in the total TC precipitation and the frequency distribution depend on the balance between two competing factors: reduction in TC number and intensification of TC precipitation rate. In Nishizawa et al. (2018), in which dynamical downscaling data for the projection by AGCM20 with C0 SST distribution was used, the reduction of TC number surpasses the intensification of precipitation, and a reduction of total TC precipitation are projected, which is consistent with our result for C0 SST. Using the projection by AGCM20 that is used for the boundary condition of NHRCM05, Kitoh and Endo (2016) showed that the annual maximum daily precipitation associated with TCs will decrease in the future owing to a reduction in TC number. Lui et al. (2018), in which the same AGCM20, except
with different SST and different emission scenario, was used, projected reductions of total TC precipitation and the frequency of the daily TC precipitation less than 200mm, while significant reduction was not found in the frequency of the daily TC precipitation larger than 200mm. This is consistent with our result that the contribution of the intensification of the TC precipitation rate is larger for the frequency of more intense precipitation.

We have evaluated the changes in precipitation caused by the TCs themselves. However, TCs also cause PRE in remote areas because they transport huge amounts of water vapor (Galarneau et al. 2010). Kanada et al. (2017) demonstrated the enhancement of PRE under the future climate; however, their analysis focused on one TC only. Statistical analysis of possible changes to PRE will be necessary in future work.

The number, track, and intensity of TCs simulated in the RCM are strongly affected by the parent GCMs. The GCM projections vary significantly among the various models. They also vary depending on the distribution of SST change (e.g., Knutson et al. 2010; Christensen et al. 2013; Walsh et al. 2016). Moreover, TCs have both a low occurrence frequency and large internal variability. The number of runs used to generate the ensemble in the present study may have been insufficient, although our results are qualitatively consistent with the results of a large-ensemble simulation using a GCM (Yoshida et al. 2017; Kitoh and Endo 2019). The present results show that downscaling with a high-resolution RCM is a promising approach to the accurate evaluation of TC precipitation. Therefore, dynamical downscaling of the results of multi-ensemble and multi-GCM
simulations will be necessary if we are to reduce the uncertainty in the changes to TC precipitation under a future warmer climate.

Acknowledgments

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Fig. 2 Average number of TC locations within a 2° × 2° grid in a year calculated from 6 hourly data for the (a) best track, (b) NHRCM05, (c) AGCM20 data, (d) difference between NHRCM05 and best track, and (e) the difference between AGCM20 and best track. The black polygon indicates the domain in which TC detection was performed for NHRCM05. (f) The bias of TC number averaged over 5° in latitude. Bias [%] is defined as 100 × (m/o − 1), where o and m are the TC numbers for the best track and model simulations, respectively.

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Fig. 5 Radial distribution of TC precipitation rate (mm yr$^{-1}$) averaged in 50-km bins for the (a) northwest, (b) northeast, (c) southwest, and (d) southeast quadrants of the TCs.

Fig. 6 (a), (b) Excess frequency (event yr$^{-1}$) of TC precipitation (solid lines) and all precipitation (dashed lines) over the whole of Japan for (a) hourly precipitation and (b) daily precipitation. (c), (d) Contribution of TC precipitation to the excess frequency of all precipitation for (c) hourly precipitation and (d) daily precipitation. The contribution was calculated by dividing the frequency of TC precipitation by that of all precipitation.

Fig. 7 Future changes in (a) annual TC precipitation (%), (b) annual TC period (%), and (c) TC precipitation rate (%) defined as 100 $\times$ (future/present − 1), for each region projected by NHRCM05. ‘ALL’ denotes the whole of Japan. ‘Mean’ denotes the ensemble mean, and C0, C1, C2, and C3 denote individual ensemble members. Filled circles denote statistically significant changes (5% level).

Fig. 8 Excess frequency (event yr$^{-1}$) of TC precipitation over the whole of Japan projected by NHRCM05 for (a) hourly precipitation and (b) daily precipitation. ‘Present’ denotes the present climate. ‘Mean’ denotes the ensemble mean for the future climate, and C0, C1, C2, and C3 denote individual ensemble members. (c) and (d) are closeup views of (a).
and (b), respectively.

Fig. 9 As for Fig. 7, but for the excess frequencies of (a) P5 for hourly precipitation, (b) P05 for hourly precipitation, (c) P5 for daily precipitation, and (d) P05 for daily precipitation. The values of P5 and P05 for each region are shown in the figures. P5 and P05 are defined in the main text.

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Fig. 11 (a) Area-average of vertical profiles of potential temperature (K; solid), equivalent potential temperature (K; dashed), and saturated equivalent potential temperature (dotted) averaged for TC period. The area-averages were calculated over the domain shown in Fig. 10. ‘Present’ (gray) denotes the present climate and ‘Future’ (K; black) denotes the ensemble mean for the future climate. (b) The difference between equivalent potential temperature at 1000 hPa and saturated equivalent potential temperature at each level.

Fig. 12 (a) Minimum central pressure of TCs (hPa) averaged in bins of 5° latitude. ‘Present’ (gray) denotes the present climate and ‘Future’ (black) denotes the ensemble mean for the future climate. (b) As for (a), but for the fraction of TCs ($\%$) that transformed into
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Fig. 2 Average number of TC locations within a $2^\circ \times 2^\circ$ grid in a year calculated from 673 hourly data for the (a) best track, (b) NHRCM05, (c) AGCM20 data, (d) difference between NHRCM05 and best track, and (e) the difference between AGCM20 and best track. The black polygon indicates the domain in which TC detection was performed for NHRCM05. (f) The bias of TC number averaged over $5^\circ$ in latitude. Bias [%] is defined as $100 \times (m/o - 1)$, where o and m are the TC numbers for the best track and model simulations, respectively.
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(a) Total TC precipitation

<table>
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<th>Region</th>
<th>NHRCM05 (Bias %)</th>
<th>AGCM20 (Bias %)</th>
<th>NHRCM05 (Taylor’s skill score)</th>
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(b) TC precipitation rate

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