EARLY ONLINE RELEASE

This is a PDF of a manuscript that has been peer-reviewed and accepted for publication. As the article has not yet been formatted, copy edited or proofread, the final published version may be different from the early online release.

This pre-publication manuscript may be downloaded, distributed and used under the provisions of the Creative Commons Attribution 4.0 International (CC BY 4.0) license. It may be cited using the DOI below.

The DOI for this manuscript is
DOI:10.2151/jmsj.2019-007

J-STAGE Advance published date: October 29th, 2018
The final manuscript after publication will replace the preliminary version at the above DOI once it is available.
Future Changes in Precipitation Extremes Associated with Tropical Cyclones Projected by Large-Ensemble Simulations

Akio Kitoh$^{1,2}$, and Hirokazu Endo$^2$

$^1$Japan Meteorological Business Support Center, Tsukuba, Japan

$^2$Meteorological Research Institute, Tsukuba, Japan

Corresponding author: Akio Kitoh, Japan Meteorological Business Support Center, Tsukuba, Ibaraki 305-0052, Japan. E-mail: kitoh@jmbsc.or.jp.
Abstract

Future changes in precipitation extremes and role of tropical cyclones are investigated by a large ensemble experiment, 6,000 years for the present and 5,400 years under +4 K warming, with a 60-km mesh atmospheric general circulation model (MRI-AGCM3.2). As in the previous findings by the authors, the annual maximum 1-day precipitation total (Rx1d) is projected to increase in the future warmer world almost all over the world, except in the western North Pacific where a projected decrease of tropical cyclone frequency results in only small change or even reduction of Rx1d. Furthermore, the large ensemble size enables us to investigate changes in the tails of the Rx1d distribution. It is found that 90- and 99-percentile values of Rx1d associated with tropical cyclones will increase in a region extending from Hawaii to the south of Japan. In this region, interannual variability of Rx1d associated with tropical cyclones is also projected to increase, implying an increasing risk of rare heavier rainfall events by global warming.

Keywords: precipitation extremes, tropical cyclone, global warming, AGCM, large ensemble
1. Introduction

Global warming leads to changes in various aspects of extreme weather and climate events. It is assessed that the frequency of heavy precipitation will likely increase in the 21st century over many areas of the globe (IPCC 2012). Heavy precipitation associated with tropical cyclones (TCs) is also likely to increase with continued warming (IPCC 2012).

There are modeling activities to project future climate by global atmosphere-ocean coupled general circulation model (AOGCM) such as the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al. 2012). It is projected that the change rate of heavy precipitation amounts will become more than that of mean precipitation (Tebaldi et al. 2006; Sillmann et al. 2013b). The CMIP5 models reasonably reproduce the present-day spatial distributions of various precipitation indices but the magnitude of precipitation extremes is underestimated (Sillmann et al. 2013a). It is discussed that high-resolution model is needed to reproduce weather and climate extremes and to project their future changes (Kitoh et al. 2016). In low-latitudes, TCs have important contributions to heavy precipitation (e.g., Kamahori 2012). Therefore, models should reasonably reproduce TCs and associated precipitation to properly project future climate changes.

We have been using a high-resolution global atmospheric general circulation model (AGCM) version 3.2 developed at the Meteorological Research Institute (MRI) (MRI-AGCM3.2, Mizuta et al. 2012) to project future changes in weather and climate extremes such as TCs, heavy precipitation and strong winds. Our experiment strategy is described in Kitoh et al. (2009). The present-day climate is forced by interannually varying observed monthly sea surface temperature (SST), while the future climate is forced by the SST where the projected future changes of monthly mean SST climatology by AOGCMs in the CMIP5 or CMIP3 experiments are added to the present-day SST.

Kitoh and Endo (2016a) used the four-member ensemble simulations with different
SST patterns using the 20-km mesh MRI-AGCM3.2 at the end of the 21st century (2075-2099) under the RCP8.5 scenario. They found that heavy precipitation increases in all regional domains over land, even where mean precipitation decreases. Using the same data, Kitoh and Endo (2016b) analysed the annual maximum 1-day precipitation total (Rx1d) and its relation with TCs. Rx1d is projected to increase in future, with larger increase over the regions where it is climatologically large. The exception is the western North Pacific where there is only small change or even reduction of Rx1d is projected. This is mainly related to a decrease of TC frequency in this region. On the other hand, interannual variability of Rx1d in the western tropical Pacific increases associated with El Niño (note that in the experiment the same interannual variability in SST is given in the future climate as in the present-day climate). However, a sample size of the experiment is small and the statistical significance of projected changes is low. In order to discuss the statistical significance of Rx1d changes, a large ensemble size is needed.

As ensemble size should be limited with the 20-km model due to computational cost, we made large ensemble simulations with the 60-km model as “Database for Policy Decision Making for Future Climate Change” (d4PDF) (Mizuta et al. 2017). Although the 60-km model, compared to the 20-km model, has limitation to quantitatively reproduce TC intensity, spatial pattern and amount of precipitation extremes are reasonably simulated (Endo et al., 2012).

Mizuta et al. (2017) described experimental details and preliminary findings of d4PDF. Yoshida et al. (2017) investigated future changes in global TC activity. They showed an increase of very intense (category 4 and 5) TC occurrence in the region to the south of Japan, and a global mean increase of lifetime maximum surface wind speeds and precipitation. Endo et al. (2017) investigated precipitation extremes in East Asia and showed that Rx1d robustly increases throughout East Asia. They also showed that spatial patterns of
future SST changes affect Rx1d quantitatively over oceanic regions in East Asia including Japan, Korea and coastal China, through modulation of TC activity.

In this paper, future changes of Rx1d and TC-associated Rx1d are analyzed using large ensemble d4PDF data. Not only the mean but also tails of the distribution are investigated. Model and experiment setup are described in Section 2. Model performance to reproduce Rx1d and its relation with TC in the present-day climate are examined in Section 3. Section 4 investigates their future changes at the 4K warmer world corresponding to the end of the 21st century. Summary and discussions are given in Section 5.

2. Model and experiment

a. MRI AGCM

The model used is a 60-km mesh version of the MRI-AGCM3.2 (Mizuta et al. 2012), which has 64 layers in the vertical with a top at 0.01 hPa. A mass-flux type cumulus parameterization scheme (Yoshimura et al. 2015) is used. This model has been used to investigate future changes of precipitation (Endo et al. 2012; Kusunoki and Mizuta 2013; Kusunoki 2017) and TC (Murakami et al. 2012b; Sugi and Yoshimura 2012).

b. Experiment: d4PDF

Experimental design and some preliminary results of the “Database for Policy Decision Making for Future Climate Change (d4PDF)” are shown in Mizuta et al. (2017), Matsueda and Endo (2017), Endo et al. (2017), and Yoshida et al. (2017).

The present-day climate experiment is conducted for the period 1951 to 2010, in which the observed inter-annually varying monthly-mean SST and sea-ice concentration (COBE-SST2) (Hirahara et al. 2014) are used as the lower boundary conditions. A 100-member ensemble simulation is conducted with different atmospheric initial conditions as
well as small perturbations in SST ($\delta$SSTs). Here the typical magnitude of $\delta$SST is set to be below the observed uncertainty in monthly time scale, which is 0.2 K, for example, over the western tropical Pacific.

For the future climate experiment, a 60-year integration with 90 members is conducted corresponding to conditions around the 2090s under the RCP8.5 scenario. The prescribed global-mean surface air temperature (SAT) in the future climate is 4.1 K warmer than the pre-Industrial level or 3.6 K warmer than the present climate (1951–2010). The future SST is a sum of CMIP5 AOGCM-projected SST anomalies ($\Delta$SSTs) and the observed SST after removal of the long-term trend component. To cover uncertainty of future SST projections, six different $\Delta$SSTs (CCSM4, GFDL-CM3, HadGEM2-AO, MIROC5, MPI-ESM-MR, and MRI-CGCM3, denoted as CC, GF, HI, MP, MP, and MR SST, respectively) are selected based on cluster analysis of tropical $\Delta$SSTs. The $\Delta$SSTs are normalized to give a global-mean SAT 4 K warmer than the pre-Industrial level. For each of the six $\Delta$SSTs, 15-member ensemble runs are conducted using different atmospheric initial conditions and different $\delta$SSTs (i.e., 90 members in total). In total, we used 6,000 years data for the present climate, and 5,400 years data for the future climate.

c. Observation data

In order to investigate precipitation extremes associated with TC, we use daily precipitation data. For observed precipitation data, we use Tropical Rainfall Measuring Mission (TRMM) 3B42 product in version 6 (Huffman et al. 2007), CMORPH (Climate Prediction Center morphing method) (Joyce et al. 2004), GSMaP (Global Satellite Mapping of Precipitation) (Ushio et al. 2009), PERSIANN (Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks) (Sorooshian et al. 2000), and GPCP-1dd (Global Precipitation Climatology Project with a 1-degree by 1-degree grid) (Huffman
and Bolvin 2009). The spatial resolution of data is 0.25 degree for TRMM 3B42, CMORPH, GSMaP, and PERSIANN, while is is 1.0 degree for GPCP-1dd. For the observed TC tracks, we use International Best Track Archive for Climate Stewardship (IBTrACS) v03r06 (Knapp et al. 2010). This TC tracks dataset used in this study covers the 15-year period 1998-2012.

3. Present-day Rx1d and its relation with tropical cyclones

The 60-km mesh version of MRI-AGCM3.2 shows good skill in simulating monsoon circulations and precipitation (Endo et al. 2012; Mizuta et al. 2017). The model successfully reproduces the pattern as well as the amount of both mean and extreme precipitation globally and regionally (Endo et al. 2012; Kusunoki 2016, 2017). The model also reproduces various characteristics of TC such as their intensity and global distribution (Yoshida et al. 2017).

Figure 1 compares observed Rx1d and simulated Rx1d by the 60-km mesh MRI-AGCM3.2. All are 10-year averages from 2001 to 2010. Model data is also based on one-member for the same period. The observed estimations show large Rx1d over the western North Pacific, Bay of Bengal, Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ). There is large uncertainty among different observation-based estimates. The areal averages of Rx1d between 50°S and 50°N are 75.4 mm (TRMM), 65.6 mm (CMORPH), 79.6 mm (GSMaP), 49.0 mm (PERSIANN), and 39.3 mm (GPCP-1dd). The uncertainty range is factor 2 from the least GPCP to the largest GSMaP. The 60-km mesh MRI-AGCM3.2 (Fig. 1f) reproduces the observed Rx1d reasonably with the areal average amount (58.0 mm) within the observed uncertainty range.

Figure 2a and 2b show the observed Rx1d and Rx1d associated with TCs (Rx1d-TC), respectively, based on TRMM 3B42 data during 1998-2012. We calculated Rx1d-TC from daily precipitation within 500 km from the TC center, as precipitation around TCs is concentrated within a 5-degree radius from the TC center (Kamahori 2012). From this
definition, the distribution of Rx1d-TC corresponds to that of TC themselves. Its magnitude is large over the western North Pacific around 10°N-25°N and over the eastern North Pacific off Mexico. Figure 2c shows that the distribution of Rx1d not associated with TCs (Rx1d-nTC) is similar to that of Rx1d. The exception is found in the western tropical Pacific near the Philippines, where magnitude is significantly less than Rx1d.

Figures 2d, 12e and 2f are simulated counterparts to Figs. 2a-c by the 60-km mesh MRI-AGCM3.2 averaged for 6,000 year. The 60-km mesh MRI-AGCM reproduces the observed Rx1d, Rx1d-TC and Rx1d-nTC but with magnitude slightly underestimated compared with TRMM data. In particular, simulated Rx1d-TC resembles the observed features over the Pacific and the Indian Oceans. Simulated Rx1d-TC, however, is greatly underestimated over the North Atlantic Ocean. This failure is associated with poor TC reproducibility over the North Atlantic Ocean as noted by Murakami et al. (2012b), but the reason is not clarified. The 20-km mesh version of MRI-AGCM3.2 better simulates TC frequency (Murakami et al. 2012a) and Rx1d-TC (Kitoh and Endo 2016b). It is noted that quantitative accuracy of TRMM data is debatable (Huffman et al. 2007). For example, using Pacific atoll and island precipitation dataset, Chen et al. (2013) show that TRMM 3B42 tends to overestimate heavy precipitation frequency at atoll sites but underestimate it at coastal and island sites with high elevation.

4. Future changes

Using the 20-km mesh version of MRI-AGCM3.2, Kitoh and Endo (2016b) showed that changes in Rx1d in the future climate generally follow the climatological pattern in Rx1d. There are large increases in Rx1d over the central-eastern equatorial Pacific, the equatorial Atlantic Ocean, south and east off Japan and SPCZ. An exception is the western tropical Pacific, where Rx1d is climatologically large but future change is small or even
negative. This peculiar change is considered to be related to changes in TC activity there (Kitoh and Endo 2016b).

Figure 3a shows the future changes in the median (50-percentile) value of Rx1d with the 60-km mesh MRI-AGCM3.2. Most of the world will experience larger Rx1d in a warmer world. However, being consistent with the 20-km model results, there are some regions where Rx1d is projected to decrease in a future warmer world, including the western tropical Pacific around the Philippines between the equator and 20°N. This is mainly due to a decrease in Rx1d-TC (Fig. 3d) brought by reductions in TC frequency.

The SST change pattern can affect future precipitation changes in the tropics (Xie et al. 2010; Ose and Arakawa 2011). In this experiment, as described in Section 2b, six different geographical patterns of future SST changes (ΔSSTs) are used to cover the most part of the CMIP5 model uncertainty. Changes in Rx1d, Rx1d-TC and TC frequency in each six sub-ensembles are shown in Fig. 4. Spatial patterns are similar each other with some differences in magnitude. Prescribed SST anomalies in the equatorial Pacific should be the main reason of difference among sub-ensembles. For example, the El Niño-like ΔSSTs (HA, MP and MR SST) result in an intensification of mean and extreme precipitation over the central and eastern equatorial Pacific region (Mizuta et al. 2017). All six experiments with different SST patterns consistently show a decrease in Rx1d-TC around the Philippines, although its magnitude varies greatly between -0.7 mm (MR SST) and -3.4 mm (MI SST). The sub-ensemble with large decrease in TC frequency over the western tropical Pacific (MI SST) leads to large decrease in Rx1d-TC and then Rx1d there. Similarly, the sub-ensemble with increase in TC frequency around Hawaii (HA SST) leads to increase in Rx1d-TC and then Rx1d there. Therefore, there is regionally non-negligible effect of different SST pattern changes on future Rx1d changes.
The above result in Fig. 3a is based on the median values of Rx1d within 6,000 and
5,400 years of the present and future simulations, respectively, where Rx1d is defined in each
year. Extremely large Rx1d may increase more than the mean Rx1d in the future. Figures 3b
and 3c show the future changes in the 90- and 99-percentile values of Rx1d. Their changes in
global mean values are +26.4 mm and +45.2 mm, respectively, which are much larger than
+10.2 mm of the change in the 50-percentile value. As it may not be surprising that the
absolute change in more extremes is larger than that in the mean or median, the changing
ratio is also calculated. Global mean ratio of the changes relative to the present-day value is
+27.5%, +34.2%, and +39.6% in the 50-, 90-, and 99-percentile values of Rx1d, respectively.
Larger increasing rate for higher percentiles by global warming is consistent with previous
findings (O’Gorman, 2012; Scoccimarro et al. 2013; Sillmann et al. 2013b).

Areal coverage with positive or negative Rx1d changes differs at different threshold
percentiles. Area with positive changes in the 50-, 90-, 99-percentile values of Rx1d is
84.6%, 93.2%, 96.3% of the world, respectively. This indicates that more and more regions
will experience extremely intense precipitation in the future. Even where the mean/median
Rx1d is projected to decrease, magnitude of rare events such as once-in-10-year or once-in-
100-year events can increase in the future warmer world.

Figures 3d, 3e and 3f show the future changes in the 50-, 90-, and 99-percentile
values of Rx1d-TC. The 50-percentile (median) value of Rx1d-TC is projected to decrease
almost all over the world, except for some small regions around Hawaii and the subtropical
North Atlantic. The 90-percentile value of Rx1d-TC will decrease in the tropics as in the 50-
percentile value, while it shows an increase in a region extending from the west coast of
Mexico to the south of Japan. Distribution of the changes in 90-percentile values of Rx1d-TC
is similar to that of frequency changes of category 4-5 TCs in this experiment (see Fig. 2f in
Yoshida et al. 2017). Future weakening of the vertical shear of horizontal wind is considered as a plausible reason for the intense TC changes in those regions.

Global mean change of the 90-percentile value of Rx1d-TC is negative (decrease in the future), but that of the 99-percentile value is positive (increase in the future). Except for the western tropical Pacific and the Indian Ocean where future change is negative, large increase of extremely intense Rx1d-TC is projected in the Northern Hemisphere subtropics (Fig. 3f). Coastal regions in East Asia including Japan and Taiwan, Hawaii, western Mexico, northern Arabian Sea, Madagascar, northwestern Australia, southeastern Brazil, northeastern America, and western North Africa are among regions with increasing very rare extreme precipitation events associated with TCs.

Future changes in the 50-, 90-, and 99-percentile values of Rx1d-nTC are shown in Figs. 3g, 3h and 3i. They are similar to those of Rx1d, but regions with negative changes are narrower than in Rx1d, because reduction of TC frequency does not affect Rx1d-nTC. As Fig. 3 reveals, a sign of TC-associated Rx1d changes depends on the threshold percentile. Figure 5 shows the largest percentile value in each grid point at which future changes in Rx1d and Rx1d-TC change their sign. Here this threshold point is defined as the first percentile at which the future value becomes lower than the present-day value by searching backward from the maximum value. The threshold point is calculated for 900 years in 36 combinations of the six future experiments with different ΔSSTs and six non-overlapping 900-year periods of the present-day experiment. The average values of 36 cases are shown in Fig. 5.

In the mid- and high-latitudes, future Rx1d will increase even at less than 10-percentile threshold. As is shown in Fig. 5a, over most of land area, the threshold is found to be below 33-percentile. Rx1d only above the 66-percentile will increase in the future over the
It is interesting to find that red colors appear over the eastern Tibetan Plateau, where the largest Rx1d in the future is less than that in the present (this spot can be seen in Fig. 3c). Kitoh and Arakawa (2016) investigated the future changes in water budget over the eastern and the western Tibetan Plateau simulated by the 20-km mesh MRI-AGCM. They noted a projected drying at the surface in the eastern Tibetan Plateau. The drying surface condition, which also occurs in the 60-km model, may have resulted in least occurrence of extremely heavy precipitation there in the future climate.

Figure 5b reveals that the threshold percentile from negative to positive changes in Rx1d-TC is more than 50-percentile except around Hawaii as already indicated in Fig. 3d. It is over 80-percentile in the tropical Indian and western Pacific regions including East Asia around Japan and eastern China, and over the southeastern USA. In those regions, our model results suggest that extreme TC-associated precipitation once in 5 years will become more intense in a future warmer climate.

Large changes in extreme precipitation would lead to changes in interannual variability. Figures 6a and 6b show the interannual standard deviations of the present-day Rx1d and Rx1d-TC, respectively. Distribution of standard deviations of Rx1d-TC (Fig. 6b) is similar to the distribution of Rx1d-TC itself (Fig. 2e). Coefficient of variability (standard deviation divided by mean) of Rx1d-TC is close to 1 around the main TC active regions. On the other hand, standard deviations of Rx1d (Fig. 6a) are much smaller than Rx1d itself (Fig. 2d). Globally averaged coefficient of variability of Rx1d is about 0.5. This is because variability of Rx1d-nTC is smaller than that of Rx1d due to large variability of TC occurrence. As Rx1d consists of Rx1d-TC and Rx1d-nTC, coefficient of variability of Rx1d becomes smaller than that of Rx1d-TC.
Figures 6c and 6d show the future changes in interannual standard deviations of Rx1d and Rx1d-TC, respectively. The largest increase in Rx1d variability is found over the equatorial Pacific. In this experiment, the same SST variability, such as El Niño and La Niña, is prescribed in the present as well as in the future. Moisture rich future atmosphere would have resulted in large precipitation response to El Niño and La Niña (Kitoh and Endo 2016b). Other regions with increased Rx1d variability include the Atlantic Ocean, India, and tropical Africa. It also increases over the region extending from Hawaii to the south of Japan is where interannual variability in Rx1d-TC also becomes larger in the future climate (Fig. 6d). This zone corresponds to where intense TCs will be more frequent in future (Yoshida et al. 2017) and the 90- and 99-percentile values of Rx1d-TC are projected to increase (Figs. 3e and 3f).

5. Summary and discussions

A large ensemble experiment, 6,000 years for the present and 5,400 years for the future warmer world similar to the RCP8.5 scenario, is performed with the 60-km mesh MRI-AGCM3.2. The present-day simulation consists of 100 ensemble members for 60-year period (1951-2010), while the future simulation consists of 90 ensemble members for 60-year period at the end of the 21st century. The Rx1d will increase in the future world, except the western North Pacific. Small changes or even reduction of Rx1d there are mainly related to a projected decrease of TC frequency in a future climate in this region. This is qualitatively consistent with the former findings by Kitoh and Endo (2016b) with the 20-km mesh MRI-AGCM3.2. Further findings are obtained thanks to a large ensemble size of this experiment. Interannual variability of Rx1d increases over most of the western North Pacific. A reduction in interannual variability of Rx1d is confined near the Philippines. Moreover, 90- and 99-percentile values of Rx1d will increase over most of the world, implying an increasing risk of heavier rainfall events by global warming.
As we used the AGCM with fixed SST, one may concern about the effect of air-sea interaction on the results because it is widely known that ocean-atmosphere coupling process is essential in the western tropical Pacific at least for seasonal prediction (Wang et al. 2005). Ogata et al. (2015, 2016) made an experiment with the 60-km mesh MRI-AGCM3.2 to investigate air-sea interaction effects with an AOGCM with flux adjustment. Necessary flux adjustment values are obtained by nudging the SST toward the present and future SST used in the AGCM experiment. Figure 7 shows the future changes in Rx1d and Rx1d-TC in this experiment, which is very similar to Figs. 3a and 3d, respectively, obtained with the AGCM without air-sea interaction. Therefore, changes in heavy precipitation are not largely affected by air-sea interaction, although the mean precipitation changes are greatly affected by inclusion of air-sea interaction (not shown). This may be due to the fact that time scale of extreme precipitation such as Rx1d is very short. Ogata et al. (2015, 2016) however found the effect of air-sea coupling leads to more realistic TC distribution in the present-day climate simulation.

There are strength and weakness in our experiment (Mizuta et al. 2017). One of strength of d4PDF is its high resolution. Although it is coarser than the 20-km model used by Kitoh and Endo (2016b) and others, this global 60-km mesh is still grouped among high-resolution models in literature, which can reproduce TCs to a certain extent. Large ensemble size (6,000 years for the present and 5,400 years for the future) is the largest advantage of this data set. Uncertainty of future changes in SST is also considered. There are some weaknesses. Compared to the 20-km model version and observations, the strength of TC and associated precipitation is underestimated. As already mentioned, an air-sea coupling is not included, which may affect some of the TC characteristics (Ogata et al. 2015, 2016). Moreover, a use of one particular model does not cover a full spectrum of uncertainty. To overcome demerits of d4PDF experiment, a multi-model approach is desirable. Multi-model
high-resolution model experiments have started as the High Resolution Model Intercomparison Project (HighResMIP) (Haarsma et al. 2016), whose results would be available in a near future.

Acknowledgements

This work was conducted under the Integrated Climate Model Advanced Research Program (TOUGOU) of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan. This study used d4PDF produced with the Earth Simulator jointly by science programs (SOUSEI, TOUGOU, SI-CAT, DIAS) of MEXT.

References


Endo, H., A. Kitoh, R. Mizuta and M. Ishii, 2017: Future changes in precipitation extremes in East Asia and their uncertainty based on large ensemble simulations with a high-resolution AGCM. SOLA, 13, 7-12.


Mizuta, R., A. Murata, M. Ishii, H. Shiogama, K. Hibino, N. Mori, O. Arakawa, Y. Imada, K.
Yoshida, T. Aoyagi, H. Kawase, M. Mori, Y. Okada, T. Shimura, T. Nagatomo, M.
Tachikawa, K. Temur, Y. Kamae, M. Watanabe, H. Sasaki, A. Kitoh, I. Takayabu, E.
Nakakita, and M. Kimoto, 2017: Over 5,000 years of ensemble future climate
simulations by 60-km global and 20-km regional atmospheric models. Bull. Amer. 

Yukimoto, M. Hosaka, S. Kusunoki, T. Ose, and A. Kitoh, 2012a: Future changes in
tropical cyclone activity projected by the new high-resolution MRI-AGCM. J. Climate,
25, 3237-3260.

Murakami, H., R. Mizuta, and E. Shindo, 2012b: Future changes in tropical cyclone activity
projected by multi-physics and multi-SST ensemble experiments using the 60-km-mesh

on the frequency distribution of intense tropical cyclones over the northwestern Pacific.

coupling effect on intense tropical cyclone distribution and its future change with 60 km-

Nature Geosci., 5, 697-700.

Ose, T., and O. Arakawa, 2011: Uncertainty of future precipitation change due to global
warming associated with sea surface temperature change in the tropical Pacific. J.


Figure Captions

Figure 1. Rx1d climatology estimated by (a) TRMM-3B42, (b) CMORPH, (c) GSMaP, (d) PERSIANN, and (e) GPCP-1dd for the 12-year period between 2001 and 2010. For (f), Rx1d based on one-member 60-km mesh MRI-AGCM3.2 corresponds to 2001-2010 is plotted.

Figure 2. (a, b, c) Observed and (d, e, f) simulated climatology of (a, d) Rx1d, (b, e) TC-associated Rx1d, and (c, f) non-TC-associated Rx1d. Unit is mm.

Figure 3. Projected future changes (future minus present) (a, b, c) Rx1d, (d, e, f) Rx1d-TC and (g, h, i) Rx1d-nTC at (a, d, g) 50-percentile, (b, e, h) 90-percentile, and (c, f, i) 99-percentile thresholds. Unit is mm. Changes in statistically significant at 95% are color shaded. Hatches denote where all six members of different ΔSST pattern experiments have the same sign.

Figure 4. Future changes in (a-f) Rx1d, (g-l) Rx1d-TC, and (m-r) TC frequency. (a, g, m) CC, (b, h, n) GP, (c, i, o) HA, (d, j, p) MI, (e, k, q) MP, and (f, l, r) MR SST experiments. Units are mm for Rx1d and Rx1d-TC, and number per 60 years in each grid for TC frequency.

Figure 5. Largest percentile value in each grid point at which future changes in (a) Rx1d and (b) Rx1d-TC change sign. Those values are calculated for each experiment (different SST patterns) and then averaged.

Figure 6. (a) Interannual standard deviations of present-day Rx1d. (b) As in (a) but for Rx1d-TC. (c) Future changes (future minus present) of interannual standard deviations of Rx1d. (d) As in (c) but for Rx1d-TC. Unit is mm. Hatches denote where all six members of different ΔSST pattern experiments have the same sign.

Figure 7. Projected future changes (future minus present) of (a) Rx1d and (b) Rx1d-TC from the 60-km mesh MRI-AGCM with the effect of air-sea interaction. Unit is mm.
Figure 1. Rx1d climatology estimated by (a) TRMM-3B42, (b) CMORPH, (c) GSMaP, (d) PERSIANN, and (e) GPCP-1dd for the 12-year period between 2001 and 2010. For (f), Rx1d based on one-member 60-km mesh MRI-AGCM3.2 corresponds to 2001-2010 is plotted.
Fig. 2. (a, b, c) Observed and (d, e, f) simulated climatology of (a, d) Rx1d, (b, e) TC-associated Rx1d, and (c, f) non-TC-associated Rx1d. Unit is mm.
Fig. 3. Projected future changes (future minus present) (a, b, c) Rx1d, (d, e, f) Rx1d-TC and (g, h, i) Rx1d-nTC at (a, d, g) 50-percentile, (b, e, h) 90-percentile, and (c, f, i) 99-percentile thresholds. Unit is mm. Changes in statistically significant at 95% are color shaded. Hatches denote where all six members of different ΔSST pattern experiments have the same sign.
Fig. 4. Future changes in (a-f) Rx1d, (g-l) Rx1d-TC, and (m-r) TC frequency. (a, g, m) CC, (b, h, n) GP, (c, i, o) HA, (d, j, p) MI, (e, k, q) MP, and (f, l, r) MR SST experiments. Units are mm for Rx1d and Rx1d-TC, and number per 60 years in each grid for TC frequency.
Fig. 5. Largest percentile value in each grid point at which future changes in (a) Rx1d and (b) Rx1d-TC change sign. Those values are calculated for each experiment (different SST patterns) and then averaged.
Fig. 6. (a) Interannual standard deviations of present-day Rx1d. (b) As in (a) but for Rx1d-TC. (c) Future changes (future minus present) of interannual standard deviations of Rx1d. (d) As in (c) but for Rx1d-TC. Unit is mm. Hatches in (b) and (d) denote where all six members of different ΔSST pattern experiments have the same sign.
Fig. 7. Projected future changes (future minus present) of (a) Rx1d and (b) Rx1d-TC from the 60-km mesh MRI-AGCM with the effect of air-sea interaction. Unit is mm.