Does the Atmospheric Global Model MRI-AGCM3.2 Perform Better than CMIP6 Atmospheric Models in Simulating Precipitation?

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**Does the atmospheric global model MRI-AGCM3.2 perform better than CMIP6
atmospheric models in simulating precipitation?**

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Abstract

The performance of the Meteorological Research Institute-Atmospheric General Circulation model version 3.2 (MRI-AGCM3.2) in simulating precipitation is compared with that of global atmospheric models registered to the sixth phase of the Coupled Model Intercomparison Project (CMIP6). The MRI-AGCM3.2 with the grid size of 20-km and 60-km and 36 CMIP6 models are forced with observed sea surface temperature for 20-year period from 1995 to 2014. The horizontal resolution of the MRI-AGCM3.2 is relatively finer than CMIP6 models. As for global domain, the reproducibility of MRI-AGCM3.2 models are better than or equal to CMIP6 models in simulating geographical distribution of annual precipitation and intense precipitation events. Models with higher horizontal resolution tend to be better than those with lower resolution in simulating global precipitation. As for East Asia, the performance of MRI-AGCM3.2 models are better than or equal to CMIP6 models in simulating summertime monthly precipitation and the seasonal march in the Japanese rainy season, and extreme precipitation events. Higher horizontal resolution models also tend to perform better than lower resolution models in simulating precipitation over East Asia. The advantage of models with higher horizontal resolution over those with lower resolution in reproducing precipitation is more evident over East Asia than over the globe.

(202 words, Limitation : 150 to 250 words)

Keywords Precipitation; Global atmospheric model; High horizontal resolution model; CMIP6

1 Introduction

The performance to simulate current-day climatology by Atmospheric General Circulation Models (AGCMs) is usually assessed by specifying the observed sea surface temperature (SST) as a underlying boundary condition. This sort of simulation is called an Atmosphere Model Intercomparison (AMIP)-type experiment. Lau et al. (1996), Lau and Yang (1996), Liang et al. (2001), Kusunoki et al. (2001) and Kusunoki (2018a) analyzed AMIP-type experiments by AGCMs and reported that simulated precipitation in summer is smaller than observations over East Asia based on AMIP-type experiments. Also, Kang et al. (2002) and Kusunoki 2018a) indicated that most AGCMs do not reproduce the northward marching of summertime rainy band over East Asia.

However, Kusunoki et al. (2006), Kitoh and Kusunoki (2008) and Kusunoki 2018a) revealed that AGCMs with higher horizontal resolution perform better than those with lower horizontal resolution with respect to summer precipitation over East Asia. In the case of simulating heavy rainfall events, Kusunoki et al. (2006) and Randall et al. (2007) indicated the advantage of AGCMs with higher horizontal resolution over those with lower horizontal resolution.

We have been developing a high horizontal resolution global atmospheric model called the Meteorological Research Institute – Atmospheric General Circulation Model (MRI-AGCM) since year 2002. In view of the advantages of higher horizontal resolution models over lower ones in simulating precipitation over East Asia, a series of global warming projections such as Kusunoki et al. (2006, 2011), Kusunoki and Mizuta (2008, 2012, 2013), Endo et al. (2012), Okada et al. (2017), Kusunoki (2017, 2018b, c), Chen et al. (2019), Lui et al. (2019) and Kusunoki and Mizuta (2021) utilized the 20 km

grid spacing version of MRI-AGCM (hereafter referred to as the 20-km model) and the 60 km grid spacing version of MRI-AGCM (the 60-km model). The details of these studies are summarized in Table 1 of Kusunoki and Mizuta (2021). Furthermore, Kamiguchi et al. (2006), Kitoh et al. (2009), Kusunoki et al. (2006), Kusunoki and Mizuta (2008), Endo et al. (2012), Kitoh and Endo (2016), Kusunoki (2018b) and Lui et al. (2019) projected future changes in heavy rainfall events with the 20-km and 60-km models. Focusing the tropical region, Fábrega et al. (2013), Nakaegawa et al. (2014a, b, c), Pinzón et al. (2017), Kusunoki et al. (2019) and Martínez et al. (2020) investigated future climate change projected with the 20-km and 60-km models.

Kusunoki et al. (2018a) compares the performance of the 20-km and 60-km models with those of AGCMs participated in the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012). The 20-km and 60-km models performs better than the CMIP5 AGCMs in simulating precipitation over East Asia (Kusunoki et al. 2018a). As for global distribution of precipitation, Kusunoki (2017) reported that the 60-km model performs better than the CMIP5 AGCMs.

According to the protocol of the sixth phase of the Coupled Model Intercomparison Project (CMIP6; Eyring et al. 2016), the AMIP-type experiments were conducted by AGCMs which participated in the CMIP6. However, the reproducibility of the 20-km and 60-km models in simulating precipitation is not yet compared with that of the CMIP6 AGCMs. Therefore, the aim of this paper is to verify the reproducibility of precipitation by the 20-km and 60-km models and the CMIP6 AGCMs. The performances of these models are compared focusing on geographical distribution of precipitation over the globe and over East Asia, the time evolution of summertime rainy

season in East Asia region.

2 Models and Experiments

2.1 The MRI-AGCM3.2 models

The MRI-AGCM version 3.2 (MRI-AGCM3.2) has been developed for climate simulations with high horizontal resolution. In this study, we used the 20 km grid spacing version MRI-AGCM3.2S (the 20-km model) and the 60 km grid spacing version MRI-AGCM3.2H (the 60-km model). Both version consist of 60 vertical levels. The top level is 0.01 hPa equivalent to a altitude of about 80 km. We adopted the cumulus convection scheme called the “YS scheme” (Yoshimura et al. 2015) which is developed from the method of Tiedtke (1989). Endo et al. (2012), Kusunoki (2016), Kusunoki (2018b, c) and Okada et al. (2017) used the 20-km model to investigate future precipitation changes in the Asian region. Kusunoki et al. (2019) utilized the 20-km model to project future precipitation changes in the tropics.

Because the 20-km model requires enormous supercomputer resources, large ensemble simulations is not easily feasible with the 20-km model. In contrast, the calculation speed by the 60-km model is 5 times larger than that of the 20-km model. Ensemble simulations with the 60-km model enable us to evaluate the uncertainty of future precipitation changes over Asian regions (Endo et al. 2012; Kusunoki and Mizuta 2013; Kusunoki 2018b, c; Kusunoki and Mizuta 2021), over the globe (Kusunoki 2017) and in the tropics (Kusunoki et al. 2019). Moreover, the 60-km model is used in the massive ensemble global warming simulations of about 100 members called the Database for Policy Decision-Making for Future Climate Change (d4PDF; Mizuta et al.

2017; Ishii and Mori 2020; Kusunoki and Mizuta 2021).

2.2 The CMIP6 atmospheric models

We used 36 global atmospheric models (Table 1) which participated in the CMIP6 coordinated for the sixth assessment report of Intergovernmental Panel on Climate Change (IPCC AR6; IPCC 2021). The grid spacing of models ranges from 56 to 313 km (Table 1, the last column).

2.3 Sea surface temperature and sea ice

According to the procedure of the High Resolution Model Intercomparison Project (HighResMIP ; Haarsma et al. 2016) implemented in the CMIP6, the MRI-AGCM3.2 models are forced by observed sea surface temperature (SST) and sea ice concentration of the Hadley Centre Sea Ice and Sea Surface Temperature data set 2 (HadISST 2; Rayner et al. 2003) for 20 years from year 1995 to 2014. We have conducted one simulation by the 20-km model (simulation name SPD) and four simulations by the 60-km model (simulation name HPD) giving four different atmospheric initial conditions. The first character in simulation name indicates horizontal resolution of model (S; 20 km, H; 60 km). The second character 'P' denotes present-day or historical simulation. The third character 'D' indicates the simulation code for the HighResMIP. These simulations correspond to AMIP-type simulations which evaluate the performance of atmospheric models.

The CMIP6 global atmospheric models are also forced by the HadISST2 for 20 years from year 1995 to 2014 according to the protocol of AMIP simulation in the Diagnostic,

Evaluation and Characterization of Klima (DECK ; Eyring et al. 2016) experiments (klima is Greek for “climate”) within the frame work of the CMIP6. For further technical details of external forcing such as aerosols and ozone for the HighResMIP experiments and the AMIP simulation in CMIP6 DECK experiments, see Table 1 in Haarsma et al. (2016).

3 Observational data of precipitation

We verified model performance using the One-Degree Daily data (1dd) of the Global Precipitation Climatology Project (GPCP) v1.3 provided by Huffman et al. (2001) for 22 years from 1997 to 2018. Horizontal grid size is 1.0 degree in longitude and latitude corresponding to a distance of about 111 km at the equator. Considering the horizontal resolutions of the 20-km and 60-km models are relatively higher than generally used atmospheric models, we selected the GPCP 1ddv1.3 precipitation because of its higher horizontal resolution. However, the GPCP 1ddv1.3 data only cover the part of target period of model simulations from 1997 to 2014. Pentad and monthly data are derived from daily precipitation data. For the evaluation of model skills, all model data were interpolated to the 1-degree grid of the GPCP 1dd.

The skill of model performance depends on the selection of observational data, because observations have uncertainty (Sperber et al. 2013). The pentad data of the GPCP v2.2 and the monthly data of the GPCP v2.3 provided by Adler et al. (2003) are used for 20 years from 1995 to 2014. These data cover the whole period of simulations (1995-2014). The grid size is 2.5 degree which is equal to a spacing of about 278 km at the equator.

The pentad mean and monthly mean dataset of the Climate prediction center Merged Analysis of Precipitation (CMAP) provided by Xie and Arkin (1997) are also selected for 20 years through 1995 to 2014. The grid spacing is 2.5 degree.

Table 3 summarizes the features of observational data for verification.

4 Global precipitation

4.1 Geographical distribution

The global distributions of annal precipitation (PAV, Table 3) are compared in Fig.1. In the GPCP 1dd observation (Fig. 1a), precipitation is large over the Indian Ocean, over the tropical area of the Pacific Ocean and the Atlantic Ocean, and over the Amazon. Similar feature also appears in the GPCP data of 2.5 degree grid interval (Figs. 1b). Precipitation by the CMAP of 2.5 degree grid interval (Fig. 1c) is larger than other observations (Figs. 1a-b) over the Indian Ocean and the Maritime continent.

appears in other observations with some differences (Figs. 1b).

The 20-km model (SPD, Fig. 1d) and the 60-km model (HPD, Fig. 1e) tend to overestimate precipitation over the maritime continent and the South Pacific Convergence Zone (SPCZ). This excessive precipitation is also found in the CMIP6 models (Fig. 1f-h). The overestimations of precipitation in the tropic over the Pacific Ocean are also confirmed by bias distribution against the GPCP 1dd observation (Fig. S1).

4.2 Skill evaluation

In Fig. 2, the performance of models as for PAV are quantitatively evaluated by

objective skill measures based on the GPCP 1dd (green circle). The location of green circle means perfect simulation. Figure 2a shows the bias and root mean square error (RMSE) of simulations. All models show positive bias partly due to the overestimation of precipitation over the Pacific Ocean (Figs. 1 and S1). Black circles in Fig. 2 indicates the multi-model ensemble (MME) average skill which is based on the 2-dimensional global spatial distribution of precipitation constructed with the MME mean of CMIP6 models (Fig. 1f). Black squares in Fig. 2 display the average of the skill of each CMIP6 models (AVM). In the case of linear skill measures such as bias (Fig. 2a, horizontal axis), the MME average is identical to the AVM. The biases of the 20-km model (red S) and the 60-km model (purple H) are slightly larger than the MME average (black circle) and the AVM (black square) of CMIP6 models (Fig. 2a).

The RMSE (Fig. 2a, vertical axis) of the 20-km and 60-km models are relatively smaller than those of CMIP6 models. Since RMSE is a nonlinear skill measure, the MME average (black circle) differs from the AVM (black square). The MME average of CMIP6 models (black circle) is almost higher than the RMSEs of all individual CMIP6 models (black characters). This advantage of MME average is consistent with previous studies such as Lambert and Boer (2001), Gleckler et al. (2008), Reichler and Kim (2008), Kusunoki and Arakawa (2015) and Kusunoki (2018a).

To show the uncertainty of observation, the GPCP data of 2.5 degree grid interval (green square) and the CMAP data of 2.5 degree grid interval (green diamond) are also plotted as well as the GPCP1dd (green circle). The uncertainty (spread) among observations (three green marks) are smaller than the magnitudes of bias and RMSE by models.

Figure 2a is the Taylor diagram (Taylor 2001) which demonstrates the spatial correlation coefficient between model simulations and observation as well as spatial standard deviation. The distance measured from the origin point is the standard deviation of a simulated spatial distribution standardized by the observed standard deviation. The radial distance of one means perfect simulation. The angle from the y-axis implies the spatial correlation coefficient. The perfect simulation coincides with the location of green circle. The spatial correlation coefficients of the 20-km (red S) and 60-km (purple H) models are relatively larger than those of individual CMIP6 models. The spatial correlation coefficient of the MME average (black circle) of CMIP6 models is almost higher than any other models. The symbols of all the models are plotted outer area of the radius one quadrant. It means that spatial variability of all simulations is overestimated.

In summary, Fig. 2 indicates that the reproducibility of the 20-km and 60-km models are equivalent to or better than CMIP6 models in simulating global distribution of PAV. This is similar to the result of previous studies on CMIP5 models (Kusunoki 2017 ; Fig. 1) which reported the advantage of the 60-model over CMIP5 atmospheric models in simulating global distribution of PAV.

4.3 Extreme precipitation events

Table 3 shows the definition of extreme precipitation indices used for verification based on Frich et al. (2002). The maximum 5-day precipitation total (R5d) is often used to define heavy precipitation events leading to water related disaster such as inundation and landslide. The maximum 1-day precipitation total (R1d) is widely used to define

extreme precipitation events happening once a year. On the other hand, maximum consecutive dry days (CDD) is an index estimating the possibility of dry condition ought. PAV is also included in Table 3 for comparison.

Figure 3 compares the reproducibility of the 20-km and 60-km models with those of CMIP6 models as to four extreme indices. The spatial correlation coefficient of global distribution of extreme precipitation events is selected as skill measure. As for PAV, the spatial correlation coefficients of the 20-km and 60-km models are almost the same as that of the best CMIP6 model and the MME average (black circle). In the case of R5d, the skill of 60-km models (purple lines) are better than the AVM of CMIP6 models (thick long black line), but the skill of 20-km model (red line) is comparable to the AVM. As for R1d, the skill of the 20-km model (red line) is lower than the AVM. This might be partly attributed to the lower horizontal resolution of the GPCP 1dd observation (111 km) as compared to that of the 20-km model. In the case of CDD, the skills of 20-km and 60-km models are almost near to those of CMIP6 models. In terms of RMSE, the advantage of the 20-km and 60-km models are recognized only for PAV (Figure not shown).

4.4 Skill dependence on horizontal resolution

Figure 4 illustrates how the model skill depends on the horizontal resolution of models in the case of spatial correlation coefficient for global PAV. Models with small grid spacing, namely models with higher horizontal resolution, tend to show higher skill. The correlation coefficient between grid spacings and spatial correlations coefficient for global PAV is -0.463 which exceeds the 99% statistical significance level. Figure 5

shows how model performance depends upon on grid spacing for all four extreme events (Table 3). All four negative correlation suggests the advantage of higher horizontal resolution models over low resolution models, but statistical significance above 99% level is only recognized for PAV and R5d.

5 Precipitation over East Asia

5.1 Geographical distribution

The rainy season over Japan (the Baiu) starts in the middle of May and terminates in the end of July. Figure 2 compares observed precipitations with simulated precipitations in June. In the GPCP 1ddv1.3 observation (Fig. 6a), precipitation is larger over the Taiwan island, the southern part of China, the East China Sea and to the south of Japan, which corresponds to the Baiu rain band. This rainy zone is also presented in other observations with some differences (Figs. 6b-c). The 20-km model correctly reproduces the location of the Baiu zone, but the precipitation amount is apparently underestimated (Fig. 6d). The simulation by the 60-km model (Fig. 6e) is nearly the same as that by the 20-km model (Fig. 6d) with larger precipitation amount to the south of Japan as compared to the 20-km model.

The MME average of CMIP6 models also underestimates precipitation of the Baiu rain band (Fig. 6f). The spatial coefficient C of the best CMIP6 model is high as 0.837, but precipitation is still underestimated (Fig. 6g). The worst CMIP6 model shows erroneous excessive precipitation to the south of 25°N (Fig. 6h).

Figure 7 shows the objective skill scores of models for June precipitation over East Asia (Fig. 6). Most models underestimate precipitation (Fig. 7a, horizontal axis). In

terms of RMSE (Fig. 7a, vertical axis), the RMSE of the 20-km and 60-km models are relatively smaller than CMIP6 models and is smaller than the MME average of CMIP6 models (black circle). In the Taylor diagram (Fig. 7b), almost entire models are displayed inside the radius one quadrant. This mans the underestimation of spatial variability. The spatial correlation coefficients of the 20-km and 60-km models are relatively larger than those of CMIP6 models.

In the case of July which corresponds to the later half of the Baiu season, the reproducibility of the 20-km and 60-km models are also higher than CMIP6 models in simulating July precipitation over East Asia region with respect to bias, spatial variability and spatial correlation coefficient (Figs. S2-S3). Models with higher horizontal resolution tend to perform better than those with lower resolution in simulating monthly precipitation in warmer season over East Asia (Fig. S4).

The superiority of the 20-km and 60-km models over CMIP6 models in simulating summer precipitation is similar to the results by Kusunoki (2018a) with respect to CMIP5 models.

5.2 Seasonal march of the rainy season over Japan

Figure 8 depicts the seasonal march of the Japanese rainy season (the Baiu) based on longitudinal averaged pentad precipitation over Japan. In the GPCP 1ddv1.3 observation (Fig. 8a), the Baiu starts in the middle of May at latitude around 25°N. The Baiu migrates northward till the middle of July at latitude around 37°N. Other observations show similar northward migration of the Baiu (Figs. 8b-c). In the 20-km model (Fig. 8d), precipitation of the Baiu is underestimated and northward migration is not clear. The

60-km model (Fig. 8e) seems to simulate larger precipitation in the Baiu season than the 20-km model (Fig. 8d). The MME average CMIP8 models apparently underestimate precipitation and the location of the Baiu is shifted to north as compared to observation (black contour). Even the best CMIP6 model underestimate precipitation amount of the Baiu (Fig. 8g). The worst model shows the erroneous location of Baiu (Fig. 8h).

In terms of objective skill scores (Fig. 9), most models underestimate precipitation (Fig. 9a, horizontal axis). The RMSEs of the 20-km and 60-Km model are relatively less than those of individual CMIP6 models and the MME average of CMIP6 model (Fig. 9a, vertical axis). Most models underestimate spatial variability (Fig. 9b). The spatial correlation coefficients of the 20-km and 60-km models are relatively higher than those of individual CMIP6 models and the MME average of CMIP6 model (Fig. 9b). Models with higher resolution tend to perform better than those with lower horizontal resolution in simulating the seasonal march of rainy season over Japan (Fig. 10). The correlation coefficient between grid spacings and spatial correlations coefficient for seasonal march of the Baiu is -0.520 which is larger than the 99% statistical significance level.

In summary, the reproducibility of the 20-km and 60-km models is better than CMIP6 models in simulating the seasonal march of the Japanese rainy season. This is similar to the results by Kusunoki (2018a) with respect to CMIP5 models.

5.3 Extreme precipitation events

Figure 11 compares the performance of models in simulating extreme precipitation events over East Asia. The skills of 20-km and 60-km models are equivalent to or better

than those of CMIP6 models for all four indices. The advantage of the 20-km and 60-km models (Fig. 11) are more evident than global case (Fig. 3).

Figure 12 depicts how the model skill depends on the horizontal resolution of models in the case of spatial correlation coefficient for four extreme precipitation indices over East Asia. Large negative correlation coefficients for all four indices imply the advantage of higher horizontal resolution models over lower resolution models. Magnitude of statistical correlation coefficients and significance levels of all four indices over East Asia (Fig. 12) are larger than those over the globe (Fig. 5). This suggests that the advantage of higher horizontal resolution models is much more evident over East Asia than over the globe.

Why higher horizontal resolution models performs better over East Asia region? The Baiu rain band is characterized by multi-scale phenomena where the meso-scale disturbances (less than 100 km) are embedded in larger synoptic scale structure (Ninomiya and Akiyama 1992) . Intense rainfall events often occur in such small scale structures in the Baiu rain band. Tropical cyclones are also characterized by small scale structure such as rain bands and convective cells embedded in larger synoptic scale structure (Houze 2010). Intense rainfall events over East Asia is often caused by meso-scale convective disturbances associated with the Baiu rainy season and tropical cyclones (typhoons). Apparently, higher horizontal resolution models have the advantage over lower resolution models in simulating these small scale disturbances.

6 Comparison with CMIP5 models

Figure 13 compares the performances of the 20-km and 60-km models with those of

CMIP5 and CMIP6 global atmospheric models with respect to the global distribution of annual precipitation. All the simulations are based on AMIP-type experiments. Since most CMIP5 model simulations terminate at year 2008, the target period of comparison is selected for 20 years from 1981 to 2000. In Fig. 12, the performances of CMIP6 models are better than those of CMIP5 models in terms of AVM and MME. CMIP6 was accomplished about 10 years after CMIP5. Figure 12 suggests the climate models were apparently improved during this last decade due to continuous and great efforts by climate modelling scientists. The 20-km and 60-km models perform relatively better than CMIP5 and CMIP6 models in simulating the spatial pattern of global annual precipitation.

As for monthly precipitation over East Asia, also the performances of CMIP6 models are better than those of CMIP5 models (Fig. S5). The 20-km and 60-km models perform relatively better than CMIP5 and CMIP6 models especially in warm season (Fig. S5). The performance of 20-km and 60-km models are better than or equal to CMIP5 and CMIP6 models in simulating R1d over East Asia (Fig. S6). The 20-km and 60-km models perform relatively better than CMIP5 and CMIP6 models in simulating the seasonal march of Japanese rainy season (Fig. S7).

7 Conclusions

Our results are summarized as follows.

1. The performance of MRI-AGCM3.2 models is higher than or equal to CMIP6 atmospheric models with respect to the geographical distribution of annual precipitation and intense precipitation over the globe.

2. Models with higher horizontal resolution perform better than those with lower resolution in simulating global precipitation.
3. The reproducibility of MRI-AGCM3.2 models is higher than or comparable to CMIP6 atmospheric models as to monthly precipitation, the seasonal march of Japanese rainy season and extreme precipitation events over East Asia.
4. Models with higher horizontal resolution perform better than those with lower resolution in simulating precipitation over East Asia.
5. The advantage of higher horizontal resolution models over lower resolution models is more evident over East Asia than over the globe.

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Statements and Declarations

The authors declare no competing interests.

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388 **Data availability**

389 The MRI-AGCM3.2 data are available at the website of the Earth System Grid
390 Federation (ESGF) ; <https://esgf.llnl.gov/>

391 The CMIP6 data are available at the website for the sixth phase of the Coupled Model
392 Intercomparison Project (CMIP6) supplied by the Program for Climate Model
393 Diagnosis and Intercomparison (PCMDI); <https://pcmdi.llnl.gov/CMIP6/>

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Table 1 Features of 36 CMIP6 models used in this study

No.	Label	Name in Table AII.5 of IPCC (2021)	Horizontal resolution and vertical levels ^a	Number of grids		Longitudinal grid spacing (km) at the equator ^b
				Longitude	Latitude	
1	a	ACCESS-CM2	G064L85	192	144	208
2	b	ACCESS-ESM1-5	G064L38	192	145	208
3	c	BCC-CSM2-MR	T106L46	320	160	125
4	d	BCC-ESM1	T042L26	128	64	313
5	e	CAMS-CSM1-0	T106L31	320	160	125
6	f	CanESM5	T042L49	128	64	313
7	g	CESM2	G096L32	288	192	139
8	h	CESM2-FV2	G048L32	144	96	278
9	i	CESM2-WACCM	G096L70	288	192	139
10	j	CMCC-CM2-SR5	G096L30	288	192	139
11	k	CNRM-CM6-1	T085L91	256	128	156
12	l	CNRM-CM6-1-HR	T240L91	720	360	56
13	m	CNRM-ESM2-1	T085L91	256	128	156
14	n	EC-Earth3	T170L91	512	256	78
15	o	EC-Earth3-AerChem	T170L91	512	256	78
16	p	EC-Earth3-CC	T170L91	512	256	78
17	q	EC-Earth3-Veg	T170L91	512	256	78
18	r	FGOALS-f3-L	G096L32	288	180	139
19	s	FGOALS-g3	T060L26	180	80	222
20	t	GFDL-CM4	G096L33	288	180	139
21	u	GFDL-ESM4	G096L33	288	180	139
22	v	IITM-ESM	T064L64	192	94	208
23	w	INM-CM4-8	G060L21	180	120	222
24	x	INM-CM5-0	G060L21	180	120	222
25	y	IPSL-CM6A-LR	G048L79	144	143	278
26	z	KIOST-ESM	G064L32	192	96	208
27	A	MIROC6	T085L81	256	128	156
28	B	MIROC-ES2L	T042L40	128	64	313
29	C	MPI-ESM1-2-HAM	T063L47	192	96	208
30	D	MPI-ESM1-2-HR	T128L95	384	192	104
31	E	MPI-ESM1-2-LR	T063L47	192	96	208
32	F	MRI-ESM2-0	T106L80	320	160	125
33	G	NESM3	T063L47	192	96	208
34	H	NorCPM1	G048L26	144	96	278
35	J	NorESM2-LM	G048L32	144	96	278
36	K	SAM0-UNICON	G096L30	288	192	139
	S	MRI-AGCM3.2S	T639L60	1920	960	21
	H	MRI-AGCM3.2H	T213L60	640	320	63

^a G means grid model. Two figures following after G indicate corresponding spectral wave number.
Figures following after T indicate the triangular truncation at the corresponding spectral wavenumber.
Two figures following after L indicate vertical levels.

^b The minimum is 56 km ; CNRM-CM6-1-HR.
The maximum is 313 km ; BCC-ESM1, CanESM5, MIROC-ES2L.

CMIP6 stands for the sixth phase of the Coupled Model Intercomparison Project.

IPCC stands for Intergovernmental Panel of Climate Change.

Table 2 Observations of precipitation used for verification

Name	Time resolution	Spatial resolution in degree	Period (Number of years)	Region	Reference
GPCP 1ddv1.3	Day	1.0	1997-2018 (22)	Globe	Huffman et al. (2001)
GPCP v2.2	Pentad	2.5	1995-2014 (20)	Globe	Adler et al. (2003)
CMAP v1701	Pentad	2.5	1995-2014 (20)	Globe	Xie and Arkin (1997)
GPCP v2.3	Month	2.5	1995-2014 (20)	Globe	Adler et al. (2003)
CMAP v1705	Month	2.5	1995-2014 (20)	Globe	Xie and Arkin (1997)

GPCP stands for the Global Precipitation Climatology Project.

1dd stands for the One-Degree Daily data.

CMAP stands for the Climate Prediction Center Merged Analysis of Precipitation.

Table 3 Indices for extreme events of precipitation

Index	Name	Definition	Unit
PAV	Annual mean precipitation	Precipitation average for a year	mm day ⁻¹
R5d	Maximum 5-day cumulated precipitation	Maximum of consecutive 5-day precipitation in a year	mm
R1d	Maximum 1-day precipitation	Maximum of daily precipitation In a year	mm
CDD	Maximum consecutive dry days	Maximum number of consecutive dry days (precipitation < 1 mm) in a year	day

Fig. 1 The global distributions of climatological annual precipitation PAV (mm day^{-1}). **a-c** Observations (Table 2). **d** SPD. Averaged period is 20 years from 1995 through 2014. **e** Similar to **d** but for HPD. The first member of ensemble simulations is plotted. **f** Same as **d** but for the MME (multi-model ensemble) average of CMIP6 atmospheric models. **g** Same as **f** but for the best CMIP6 model. **h** Same as **g** but for the worst CMIP6 model. R, B, C in the panel captions in **d-h** denote model's skill scores against the GPCP 1ddv1.3 observation **a**. R : The root-mean square error (RMSE , mm day^{-1}). B: Bias (mm day^{-1}). C : Spatial correlation coefficient (nondimensional). The best and worst models are selected based on RMSE. Values of R, B and C are also plotted in Fig. 2.

Fig. 2 The skills of simulated annual precipitation over the globe. The GPCP 1dd v1.3 data (green circle) are used as reference observation. The target region is similar to Fig. 1. Green square and diamond symbols indicate additional observations (Table 2). Colored letters denote the MRI-AGCM3.2 models. Red S shows the 20-km model. Purple H shows all four members of the 60-km model simulations. Black letters indicate CMIP6 each models (Table 1). Black circles specify the MME average. Black squares

613 imply the mean skill scores of entire CMIP6 models (AVM). **a** The horizontal axis is
614 bias. The vertical axis is RMSE. Units are mm day^{-1} . The domain average of
615 observation is displayed above the panel. **b** The Taylor diagram (Taylor 2001). The
616 distance relative to the origin corresponds to the standard deviation of a simulated
617 pattern which is standardized based on the observed standard deviation. The angle
618 relative to the vertical axis means the spatial correlation coefficient. The standard
619 deviation of the observation in the domain is displayed above the panel.
620

Fig. 3 Spatial correlation coefficients of model simulations against the observation GPCP 1ddv1.3 as for the global distribution of precipitation indices (Table 3). Red lines display the 20-km model. Purple lines denote the 60-km model. Black bars show the CMIP6 each models. Black circles display the MME average of CMIP6 models. Thick black long lines indicate the AVM of CMIP6 models.

Fig. 4 Dependence of model skill on the grid spacing at the equator (Table 1, the last column). Red S ; the 20-km model, purple H ; the 60-km model, black character ; CMIP6 models. The skill measure is the spatial correlation coefficient C verified against the GPCP 1ddv1.3 observation for the global distribution of annual precipitation PAV. The correlation coefficient between C and grid spacing is -0.463 which is greater than the 99 % significance level. For the 60-km model, only the first member is chosen out of four ensemble simulation.

Fig. 5 Correlation coefficients between the skill and grid spacing based on two MRI-AGCM3.2 models and 36 CMIP6 models (Table 1) for 4 extreme indices (Table 3). For the 60-km model, only the first member is chosen out of four ensemble simulation. The skill measure is the spatial correlation coefficient C verified against the GPCP 1ddv1.3 observation for the global distribution of extreme indices. Horizontal lines show statistical significance levels. Scatter plot in the case of PAV is displayed in Fig. 4. Larger negative correlation coefficient means that the advantage of higher resolution model over low resolution model is much more evident.

Fig. 6 Similar to Fig. 1 except for June precipitation. The target region is East Asia (110-150°E, 20-50°N). The black box in **a** defines the target domain (125-142°E, 20-45°N) selected in Figs. 8-10.

Fig. 7 Similar to Fig. 2 except for June precipitation over East Asia (110-150°E, 20-50°N).

Fig. 8 Time evolution of pentad mean precipitation. Observations (Table 2). **d-h** Model simulations. climatological pentad mean precipitation. Simulated period is 20 years from 1995 to 2014. The target region (125–142°E, 20–45°N) is displayed by the black box in Fig. 6a. Plotted time span is from pentad 25 (1–5 May) to 43 (30 July - 3 August). Unit is mm day⁻¹. Similar to Fig. 1, R, B, C in the panel captions in **d-h** denote model's skill scores against the GPCP 1ddv1.3 observation **a**. Contour line of 8 mm day⁻¹ defines the Japanese rainy season based on the GPCP 1ddv1.3 observation **a**.

Fig. 9 Same as Fig. 2 but for the seasonal march of the Japanese rainy season (Fig. 8).

Fig. 10 Same as Fig. 4 but for the seasonal march of the Japanese rainy season (Figs. 8-9). The correlation coefficient between grid spacing and the pattern correlation coefficient for the seasonal march of precipitation is -0.520 , which is greater than the 99 % significance level.

Fig. 11 Similar to Fig. 3 except for East Asia (110-150°E, 20-50°N).

Fig. 12 Similar to Fig. 5 except for East Asia (110-150°E, 20-50°N).

Fig. 13 Comparison among 24 CMIP5 models (black), 36 CMIP6 models (green) and MRI-AGCM3.2 for global annual mean precipitation of the 20-year period from 1981 to 2000. Skill measure is spatial correlation coefficient against the GPCP 1ddv1.3 observation. For details of CMIP5 models, see Table 5 in Kusunoki and Mizuta (2021).

698 **Supplementary material**

699

700 Kusunoki, S., T. Nakaegawa, and R. Mizuta, 2022: Does the atmospheric global model
701 MRI-AGCM3.2 perform better than CMIP6 atmospheric models in simulating
702 precipitation? *Climate Dynamics*, doi:10.1007/s00382-???

703

Fig. S1 The biases of annual precipitation PAV (mm day^{-1}). **a** Reference observation GPCP 1ddv1.3 used for verification. **b** Bias of SPD averaged for 1995–2014 (20 years). **c** Similar to **b** except for HPD. **d** Similar to **b** except for the MME (multi-model ensemble) average of CMIP6 atmospheric models. **e** Similar to **d** except for the best CMIP6 model. **f** Similar to **d** except for the worst CMIP6 model. R, B, C in the panel captions in **b–f** denote model's skill scores against the GPCP 1ddv1.3 observation **a**. R : The root-mean square error (RMSE), B: Bias, C : Spatial correlation coefficient. The best and worst models are selected based on RMSE.

Fig. S2 Same as Fig. 6 but for July.

Fig. S3 Same as Fig. 7 but for July.

Fig. S4 Same as Fig. 5 but for monthly precipitation in East Asia region (110-150°E, 20-50°N).

Fig. S5 Comparison among CMIP5 AVM (black line), CMIP6 AVM (green line), SPD (red circle) and four HPDs (purple circles). Skill measure is spatial correlation coefficient for monthly precipitation in East Asia (110-150°E, 20-50°N). Target period is 20 years from 1981 to 2000.

Fig. S6 Comparison among individual CMIP5 models (black line), individual CMIP6 models (green lines), SPD (red line) and four HPDs (purple line). Skill measure is spatial correlation coefficient for R1d in East Asia (110-150°E, 20-50°N). Thick long lines show AVM. Circles show MME average. Target period is 20 years from 1981 to 2000.

Fig. S7 Same as Fig. S6 but for the seasonal march of the Japanese rainy season 'Baiu' based on the time evolution of pentad precipitation averaged over the longitude 125-142°E. Target pentad period and latitude is the same as Fig. 8.