How will the onset and retreat of rainy season over East Asia change in future?

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Future change of the rainy season over East Asia region is investigated using the high horizontal resolution global atmospheric model called the Meteorological Research Institute-Atmospheric General Circulation Model (MRI-AGCM) version 3.2S (20-km grid) and 3.2H (60 km). Higher reproducibility of precipitation during East Asian rainy season gives reliability of future projections. For the present-day simulations (1983–2003, 21 years), the models are forced with observed historical sea surface temperature (SST). For the future simulations (1979–2099, 21 years), the models are forced with future SST projected by Atmosphere–Ocean General Circulation Models (AOGCMs) participated to the fifth phase of the Coupled Model Intercomparison Project (CMIP5). In order to estimate the uncertainty of future change, we execute ensemble simulations with three kinds of cumulus convection schemes and four kinds of SST distributions using 60-km version to meet the limitation of computer resources. For each grid point, the onset and retreat of rainy season are defined from time evolution of pentad mean precipitation. The onset of rainy season becomes earlier in most regions over East Asia, but onset will delay in some area of western Japan. Retreat delays over China and Korea. Duration increases in most part of East Asia especially over China and Korea. This can be caused by enhanced water vapor transport from the tropics. The delay of onset over western Japan can be attributed to the decrease of water vapor transport associated with the southward shift of the subtropical high. Future change presented in higher horizontal resolution compared with previous studies is useful for impact, adaptation and mitigation studies of global warming.

KEYWORDS
future change in the onset, retreat and duration of rainy season, global warming projection, precipitation, rainy season over East Asia

INTRODUCTION

The rainy season or rainy zone during summer in East Asia region is referred to as the Baiu in Japan, the Mei-yu in China and the Changma in Korea. The rainy season provides plenty of water resources that benefit both human society and natural ecosystem. In contrast, severe precipitation events in the rainy season often bring about natural disasters such as flood, mudflow and land slide. Climate change is likely to increase some of the future extreme weather events. Therefore, the future change in the rainy season due to global warming is of concern to the people and society over East Asia.

The method to objectively define the onset and retreat date on a grid point base can be classified into three categories. The first method is to use the absolute value of time evolution of pentad mean precipitation. The second method uses fractional precipitation normalized by the maximum and minimum of the annual cycle of precipitation. The third method makes use of fractional accumulated precipitation normalized by the total annual precipitation. For details of these methods, see Text S1 and Table S1.
Kitoh and Uchiyama (2006) have applied the second method to the global warming projections by Atmosphere–Ocean General Circulation Models (AOGCMs) participated to the third phase of the Coupled Model Intercomparison Project (CMIP3). They revealed that retreat will delay over the southern part of Japan and around Taiwan. The reproducibility of seasonal mean precipitation, seasonal march of rainy season and extreme precipitation events over East Asia by models of higher horizontal resolution is generally higher than by lower horizontal resolution models (Kusunoki and Arakawa, 2015). Therefore, we have been using a higher resolution Meteorological Research Institute - Atmospheric General Circulation Model (MRI-AGCM) with the grid sizes of 20 and 60 km to project future change of summer monsoon precipitation in East Asia region. The horizontal resolution of MRI-AGCM is much higher than those of conventional AGCMs used in climate change studies. The advantage of MRI-AGCM over coarser horizontal resolution models in simulating summertime precipitation and rainy season over East Asia was also stressed in previous studies by Kusunoki et al. (2006), Kitoh and Kusunoki (2007) and Kusunoki (2016). Using the MRI-AGCMs forced with future sea surface temperature (SST) predicted by AOGCMs of CMIP3, Kusunoki et al. (2006), Kusunoki and Mizuta (2008), Kusunoki et al. (2011) indicated that the retreat of rainy season will delay over Japan in a warmer climate. These studies investigated the change in the seasonal march of rainy season by analyzing the longitudinal average of time-latitude distribution of pentad mean precipitation and the time series of regional averaged pentad precipitation. Kusunoki and Mizuta made an additional analysis on a grid point base similar to the method of Kitoh and Uchiyama and found the delay of retreat over Japan. All the studies with MRI-AGCMs (Kusunoki et al., 2006; Kusunoki et al., 2011; Kusunoki and Mizuta, 2012) are consistent with Kitoh and Uchiyama in that retreat delays over Japan.

Kusunoki (2017) have indicated the delay of onset in the global warming projection using MRI-AGCMs forced with the future SSTs of AOGCMs registered in the fifth phase of the Coupled Model Intercomparison Project (CMIP5). This result contrasts to previous studies (Kusunoki et al., 2006; Kusunoki et al., 2011; Kusunoki and Mizuta, 2012) which reported the delay of retreat. The difference may originate in difference of cumulus convection scheme used in MRI-AGCM, forced SST distribution and emission scenario. The purpose of this paper is to investigate the change in rainy season on a grid pint base which is different from the method used by Kusunoki (2017) in order to enhance the reliability of future projection.

2 | EXPERIMENTAL DESIGN

The model used in this study is the MRI-AGCM version 3.2 (MRI-AGCM3.2) (Mizuta et al., 2012). The number of vertical levels is 60 with a 0.01 hPa top corresponding to an altitude of approximately 80 km. We utilized two models with different grid spacing of 20-km (MRI-AGCM3.2S; the 20-km model) and 60-km (MRI-AGCM3.2H; the 60-km model). As for cumulus convection, we implemented the “Yoshimura scheme” (YS) (Yoshimura et al., 2015). In order to evaluate the sensitivity of precipitation change on cumulus convection scheme, we also implemented the Arakawa–Schubert (AS) scheme (Randall and Pan, 1993) and the Kain–Fritsch (KF) scheme (Kain and Fritsch, 1990) into the 60-km model as well as the YS scheme. However, we could not execute the simulation of the 20-km model with the AS and KF schemes owing to the limitation of computer resource, because the 20-km model requires huge calculation time and enormous data storage. In the present-day simulation from 1983 through 2003 (21 years), historical observed SST (Rayner et al., 2003) was prescribed to the models. Ensemble simulations were executed starting from two different atmospheric initial conditions. In the future simulation from 2079 through 2099 (21 years), the distributions projected by AOGCMs which participated the CMIP5 were prescribed to the models. We prepared four SST distributions for future simulations (Mizuta et al., 2014) to evaluate sensitivity of precipitation change to SST. The first one is the multi-model ensemble (MME) mean of AOGCMs in CMIP5. Projected changes in SST by MME mean are superposed on the observations. Furthermore, we have conducted clustering analysis to separate 28 CMIP5 models into three groups, using the future change in annual mean SST over the tropics predicted by CMIP5 models (Figure S1). We assumed the emission scenario of Representative Concentration Pathway (RCP) 8.5 (Collins et al., 2013). Table 1 summarizes the experimental design which is identical to that used by Kusunoki (2017). See Kusunoki (2017) for further details of experimental design.

All the simulated precipitations were interpolated to the grids points (1° in longitude and latitude) of the one-degree daily data (1dd) of the Global Precipitation Climatology Project (GPCP) v1.2 (Huffman et al., 2001).

3 | DEFINITION OF RAINY SEASON

We define the rainy season in East Asia region corresponding to the method 1 in Table S1 by the following three steps. First, we defined the Asia Summer Monsoon (ASM) region as the area where the summer precipitation (June–August) is equal to or greater than 4 mm/day and the summer precipitation is equal to or greater than the winter precipitation (December–February). In the Hokkaidou Island of northern Japan (140°–146°E, 41°–46°N), rainy season does not exist. Therefore, we chose the threshold value as 4 mm/day for the purpose of excluding the Hokkaidou Island. The blue region in Figure S2 shows the ASM region.
Second, we analyzed the climatology of pentad mean precipitation at each grid point included in the ASM region. A dashed horizontal line in Figure 1 is an example of threshold value ($tv$) to detect the onset and retreat of rainy season. The pentad date in which precipitation exceeds the threshold value is specified as the onset pentad number. Similarly, the pentad date where precipitation drops below the threshold value after onset is defined as the retreat pentad. In case of original time series (black line), the onset and retreat are different from observations by the Japan Meteorological Agency (JMA). The red line is an example of smoothed time series including the annual average and the leading terms ($kx$) of Fourier harmonics of whole 73 pentad precipitation. This smoothed red line defines the onset as the pentad 32 (5–9 June) and the retreat as the pentad 41 (19–24 July) which well matches with the observation. The dates of pentad numbers are defined in Table S2.

Third, using smoothed time series, we selected the grid points where precipitation maximum appears between the pentad number 25 (1–5 May) and the pentad number 54 (23–27 September).

We selected the values $kx = 12$ and $tv = 6.5$ mm/day by best fitting to the JMA observations of onset and retreat (see Text S2 and S3 for detail). We applied these values to all the grid points in the ASM region (Figure S2).

### 4 | Future Change in Rainy Season

According to the procedure described in the previous section, the spatial distributions of onset pentad are defined by the GPCP 1dd v1.2 data (Figure 2a). The ASM regions defined by the present-day simulations well reproduce the observation in broad scale over Asia, but the ASM regions in the models are slightly different among simulations (Figure S7). Figure 2b shows the distribution of onset pentad by the simulation SPYS01, which resembles the observation over Japan (Figure 2a) with some discrepancy around Taiwan. In some area over the Hokkaidou Island of northern Japan (140–146°E, 41–46°N), model erroneously defines onset which does not exist in reality (Figure 2a). We calculated the future change where both onset and retreat exist. In the future, onset becomes earlier in most part of East Asia (blue), while onset delays around Japan (Figure 2d) and to

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**TABLE 1** Definition of simulation names

| Present-day climate from 1983 through 2003, 21 years |
| Model | Grid size (km) | Cumulus convection | Observed historical sea surface temperature (SST) | Ensemble size |
|-------|----------------|---------------------|-----------------------------------------------|---------------|
| MRI-AGCM3.2S | 20 | YS | SPYSnn\(^{c}\) | 2 |
| MRI-AGCM3.2H | 60 | YS | HPYSnn | 2 |
| MRI-AGCM3.2H | 60 | AS | HPASnn | 2 |
| MRI-AGCM3.2H | 60 | KF | HPKFn\(^{n}\) | 2 |

| Future climate from 2079 through 2099, 21 years |
| Model | Grid size (km) | Cumulus convection | SST taken from RCP8.5 future simulations by the CMIP5 AOGCMs |
|-------|----------------|---------------------|--------------------------------------------------|
|       | Cluster 0 | Cluster 1 | Cluster 2 | Cluster 3 |
| MRI-AGCM3.2S | 20 | YS | SFYSC0 | SFYSC1 | SFYSC2 | SFYSC3 | 1 |
| MRI-AGCM3.2H | 60 | YS | HFYSC0 | HFYSC1 | HFYSC2 | HFYSC3 | 1 |
| MRI-AGCM3.2H | 60 | AS | HFASC0 | HFASC1 | HFASC2 | HFASC3 | 1 |
| MRI-AGCM3.2H | 60 | KF | HFKFC0 | HFKFC1 | HFKFC2 | HFKFC3 | 1 |

*Note.* First character of simulation name represents horizontal resolution: S = 20 km, H = 60 km. Second character represents the target period: P = Present-day, F = Future. Third and fourth characters represent the type of cumulus convection scheme. RCP, representative concentration pathway; CMIP5, The fifth phase of the coupled model intercomparison project; AOGCM: atmosphere-ocean general circulation model; MME: multi-model ensemble.

\(^{a}\) Yoshiumura (YS); Yoshiumura et al. (2015) Arakawa-Schubert (AS); Randall and Pan (1993). Kain-Fritsch (KF); Kain and Fritsch (1990).

\(^{b}\) HadISST1: the Hadley Centre sea ice and SST data set version 1 (Rayner et al., 2003).

\(^{c}\) nn represents the ensemble member integrated from different atmospheric initial conditions; nn = 01, 02.
The delay of onset in some area in the western part of Japan is consistent with Kusunoki (2017). Similar to Figure 2d, we calculated future change in onset date by all the simulations (Figure S8). All the simulations generally project earlier onset in most part of East Asia, while onset tends to delay in some part over Japan. Geographical distributions of future change in onset are somewhat different among simulations, but changes are relatively not sensitive to cumulus convection scheme as compared with SST distributions. For further details, see Text S4.

We finally synthesized all the 16 future changes projected by the 20-km and 60-km models (Figure S8a–d, f–i, k–n, p–s) into Figure 3. The number of available data at each grid point ranges from 0 to 12. We averaged onset changes using available data only. Since the number of simulation by the 60-km is three times larger than the 20-km model, it is not fair to make simple average. Therefore, we gave three times larger weighting factor to the 20-km model simulations. This kind of weighted averaging was also introduced by previous study of Kusunoki (2017). Moreover, we proposed two kinds of measures on the reliability of future change. One is the existence rate of data ranging from 0 to 100%. For example, if the average of future change is positive at a certain grid point, we counted the number of simulations with positive change at the grid point and then calculated the ratio to total ensemble size. In the calculation of two measures on reliability, we also gave three time larger weight for the 20-km model than for the 60-km model. Figure 3a illustrates the future change in onset using all the 16 future simulations. The two measures on reliability are also plotted in the same panel by vertical and horizontal hatches. Onset will become earlier in most part in East Asia, but delay in some area in the western part of Japan and to its south. The reliability of changes is relatively high over the sea to the south of 20°N. In contrast, the robustness of changes is low in the East China Sea.

Earlier onset in East Asia is partly consistent with enhanced water vapor transport in May and June (Figure S11a and b) which is caused by the southward displacement of subtropical high especially in June (Figure 4a). The delay of onset in some area in western Japan is partly consistent with the result by Kusunoki (2017). The future change in retreat is summarized in Figure 3b using all the future simulations (Figure S9). Retreat will tend to become earlier over the sea to the south of Japan, but the
spatial pattern is rather noisy and reliability is low. In contrast, retreat will delay over China and Korea. This is consistent with enhanced water vapor transport over these regions in July and August (Figure S11c and d).

Figure 3c depicts future change in duration of rainy season using all the future simulations (Figure S10). Duration will increase in most part of East Asia, especially over China and Korea, while it will decrease in western Japan. Longer rainy season over East Asia may be attributed to enhanced water transport from tropics to East Asia from May to August (Figure S11). Shorter rainy season in western Japan is consistent with Kusunoki (2017) who indicated the delay of onset without any change in retreat. In June, the southward shift of the subtropical high (Figure 4a) produces the southward shift of clockwise water vapor flow which causes divergence of moisture over western Japan (Figure 4b). This leads to the decrease of precipitation in June over western Japan (Figure 4c) and the delay of onset.

Climatological precipitation in summer over western side of the subtropical high is relatively larger compared to other regions in the Pacific. Figure 4c indicates the increase of precipitation over the subtropical western Pacific. This is consistent with the so-called “a wet-get-wetter” type of response in a warmer future climate (Held and Soden, 2006; Collins et al., 2013). Since the present study introduces fixed threshold to define rainy season, the increase of precipitation directly leads to earlier onset and delayed retreat, resulting in the increase of duration as shown in Figure 3(c). An example of time evolutions for a single present-day simulation and a single future simulation at certain grid point over the subtropical high is illustrated in Figure S12 which indicates the increased duration of rainy season.

### CONCLUSIONS AND DISCUSSION

1. The onset of rainy season becomes earlier in most regions over East Asia, but delays in some area in western Japan.
2. Retreat delays over China and Korea.
3. Duration increases in most part of East Asia especially over China and Korea, but decreases in western Japan.
4. The southward shift of clockwise water vapor flow over the subtropical high is responsible for the delay of onset in western Japan.

The observational study by Zhan et al. (2016) indicated that the onset of Japanese rainy season tends to become late from 1951 to 2009. It is interesting to note that our result of future delay in onset is in line with their finding. Kitoh and Uchiyama (2006) revealed that retreat will delay over the southern part of Japan. Our results are different from theirs because of differences in models and emission scenarios as well as definition of onset and retreat. The performance and horizontal resolution of models in our studies is much higher than those in the study by Kitoh and Uchiyama (2006). Moreover, we proposed two kinds of reliability information on future change, while they showed only one measure. We convince that our results will be useful for impact, adaptation and mitigation studies of river flow, agriculture and irrigation, because the change in rainy season will require us change in water resource management.
FIGURE 4 Future changes in three variables for June. The ensemble averages of all simulations are illustrated. All the simulation was averaged giving three time larger weight to the 20-km model. (a) Mean sea level pressure (hPa). Hatched regions show changes above the 95% significance level. (b) The vertically integrated water vapor flux (arrow; kg [m s] $^{-1}$) and its convergence (shading; mm/day). The unit of convergence is converted to mm/day assuming the density of liquid water as 1 g cm$^{-3}$. Arrow is plotted only if change is above the 95% significance level. (c) Precipitation. Hatched regions show changes above the 95% significance level.

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