Impacts of global warming on Meiyu–Baiu extreme rainfall and associated mid-latitude synoptic-scale systems as inferred from 20km AGCM simulations

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Abstract
The impacts of global warming on Meiyu–Baiu extreme rainfall and the associated mid-latitude synoptic-scale weather systems over the Eastern China (EC) and the Baiu rainband (Bu) regions in East Asia have been examined, based on simulations from the 20-km Meteorological Research Institute atmospheric general circulation model (MRI-AGCM3.2S). This model was demonstrated to give realistic Asian extreme rainfall, when compared with data from the Tropical Rainfall Measuring Mission (TRMM). Here we used a novel wave-selection algorithm based on the 300 hPa wind, in order to identify upper-level propagating wave signals in conjunction with the occurrence of extreme precipitation in either EC or Bu. The same algorithm was applied for both the present (1979–2003) and future (2075–2099) climate simulations from the AGCM, so as to infer the impacts of global warming on the behavior of these systems. Results show robust decrease of intensity of systems influencing both Bu and EC in the future warmer climate. Their corresponding low-to-mid level circulation, as revealed by vertical velocity, temperature advection and sea-level pressure composites, was also found to be weakened. This is likely related to changes in the background circulation in future over the East Asian mid-latitude zone, such as the widespread increment of the seasonal mean static stability at 500 hPa. However, the wave-associated precipitation over these regions was enhanced in the future climate simulations. This can be attributed to more strong intensity rainfall, which increases as the background temperature in these regions warms, largely following the Clausius–Clapeyron relation. Therefore, changes of wave-related extreme precipitation in EC and Bu are mainly controlled by the thermodynamic effect; the latter appears to be much stronger than the potential impacts due to the slight weakening of these weather systems.

1 Introduction
The development of the summer monsoon in East Asia is characterised by large-scale reversal in the low-level winds, together with northward advancement of a monsoon rain belt (see, e.g., Wang and Lin 2002). After rainfall surges over the South China Sea in mid-May, the rain belt undergoes an abrupt northward jump, leading to the initiation of the Meiyu–Baiu season in early to mid-June (Ding and Chan 2005). The latter is also the major rainy season encompassing peaks of precipitation over Yangtze River-Huaihe River basin (Ding et al. 2007) and southwestern Japan (Ninomiya and Akiyama 1992; Ding and Sikka 2006). On the synoptic scale, low-pressure troughs associated with significant horizontal wind shear can bring prolonged heavy rainfall in the vicinity of the rainband. Although Meiyu (over China) and Baiu (over Japan) occur almost concurrently in early summer, they exhibit rather different dynamical features (Ding 1992; Ding et al. 2007; Ninomiya and Shibagaki 2007; Sampe and Xie 2010). For instance, Chen and Chang (1980) showed that while disturbances over the southern East China Sea and southern Japan resemble typical mid-latitude baroclinic frontal systems, those over southeastern China resemble subtropical disturbances.

Observations show that extreme precipitation over most parts of the globe has intensified in the past few decades (Alexander et al. 2006; Donat et al. 2013; Westra et al. 2013; Donat et al. 2016) and is projected to continue in the

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future according to model simulations (Sillmann et al. 2013; Donat et al. 2016). It is believed that extreme rainfall scales according to the Clausius–Clapeyron (CC) relation (e.g., Pall et al. 2007), whereas the increase in the mean precipitation is less rapid and constrained by the global energy budget (Allen and Ingram 2002; Sillmann et al. 2013). However, super-CC scaling for changes in rainfall extreme have also been reported based on observations, such as those over Europe (Lenderink and van Meijgaard 2008), which indicates the possibility of influences of other mechanisms such as dynamical effect of weather systems. Over East Asia, a variety of weather systems, such as tropical cyclones (TCs), wintertime extratropical storms that bring extreme precipitation are influenced by global warming (Wang et al. 2006; Ulbrich et al. 2009; Mizuta et al. 2011; Hawcroft et al. 2012; Utsumi et al. 2016; Lui et al. 2018). Geng and Sugi (2002) studied both the wintertime and summertime extratropical cyclones and found that total cyclone density in the northern hemisphere decreases mainly due to the reduced temperature gradient in a warming background. Coumou et al. (2015) focused on summertime synoptic-scale wave activity and its projected change under global warming; they found that total eddy kinetic energy of those synoptic-scale waves decreases mainly due to weakening of the vertical wind shear and zonal-mean flow. On the other hand, Li et al. (2021) studied the East Asian summer monsoon front, and found that the associated regional precipitation intensifies in the future climate. However, few studies have attempted to link changes of the synoptic-scale systems with those associated extreme rainfalls (e.g., Francis and Vavrus 2012; Röthlisberger et al. 2009; Mizuta et al. 2011; Hawcroft et al. 2012; Utsumi et al. 2016; Lui et al. 2018), and their emphasis was more on the global scale.

Motivated by the above results, and following up the recent study of Lui et al. (2018), this study investigates how Meiyu–Baiu extreme rainfall over Eastern China (EC; 25–32 N, 108–120 E) and Baiu rainbow (Bu; 30–35 N, 127–143 E) regions, and their associated mid-latitude synoptic-scale systems change in the future climate, based on projections from the 20-km Meteorological Research Institute (MRI) atmospheric general circulation model (AGCM) (hereinafter referred to as MRI-AGCM3.2S). We will examine changes in mid-latitude synoptic systems and their related rainfall extremes over East Asia, and therefore revealing the relative importance between thermodynamic and dynamical influences in modulating rainfall extremes (see, e.g., Lee 2017). The EC and Bu regions are focused on because of the strong influence of transient eddies during the Meiyu–Baiu rainy season (e.g., Ninomiya and Shibagaki 2007; Sampe and Xie 2010; Cao et al. 2019). Studying these two regions also allows us to examine how synoptic Meiyu and Baiu systems and related rainfall might respond differently to global warming. The remainder of this paper is organized as follows. Section 2 introduces the data and methodology. Section 3 evaluates the performance of the AGCM in capturing extreme precipitation characteristics and projections of early-summer extreme precipitation. Section 4 examines changes in Meiyu–Baiu extreme rainfall and the associated synoptic-scale systems. Discussion and conclusions are given in Sect. 5.

2 Data and methodology

2.1 AGCM experiments

MRI-AGCM3.2S is an improved version of a global model jointly developed by Japan Meteorological Agency (JMA) and Meteorological Research Institute (MRI) (Mizuta et al. 2006; Kito 2009). It is a global, hydrostatic primitive-equation model with a horizontal grid size of about 20 km with unevenly spaced vertical levels reaching 0.01 hPa. Various parameterization schemes, such as Yoshimura cumulus scheme (Yukimoto et al. 2011), the Tiedtke cloud scheme (Tiedtke 1993) and the radiation scheme used in the JMA operational model (JMA 2007), are introduced for improving climate simulations. A comprehensive description and evaluation of the model are given by Mizuta et al. (2012). The present climate (1979–2003) simulation was carried out using monthly-mean sea surface temperature (SST) and sea-ice concentration (SIC) observations from the Met Office Hadley Centre (Rayner et al. 2003). The future climate (2075–2099) was simulated by superimposing SST and SIC with projected changes generated by eighteen different models from the Coupled Model Intercomparison Project phase 3 (CMIP3) (Solomon et al. 2007), under the Special Report on Emissions Scenarios (SRES) A1B scenario, as the prescribed lower boundary conditions (Murakami et al. 2012).

2.2 Observations and reanalysis data

The Tropical Rainfall Measuring Mission 3B42 version 7 (TRMM3B42v7) (Huffman et al. 2007) data, produced by combination of satellite-based precipitation estimates with rain gauge-based adjustments, were chosen for comparison with rainfall simulations. TRMM covers the latitude band between 50 N and 50 S since 1998, at relatively fine scales (0.25° × 0.25°, 3 hourly). Zhao and Yatagai (2014) found that the previous version of TRMM3B42 is generally consistent in representing the spacetime rainfall characteristics over China. Although it underestimates (overestimates) light and moderate (heavy) precipitation in western (southeastern) China, the capability of this version in capturing precipitation has been improved (Chen et al. 2013). Best track data from the Joint Typhoon Warning Center (JTWC) were used to distinguish between tropical cyclone (TC) and non-TC rainfall. Upper-air meteorological variables from
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Therefore, a rectangular selection domain was designed with a longitudinal extent of 22°, so that at least half of the wave pattern could be captured. The meridional width of the domain was set to be 10°. In fact, wave spectra of v300', from 60 to 150° E, showed that signals with wavelength of 45° give the greatest variance within the band from 30 to 40° N (figures not shown). Three criteria, as listed below, were then applied to the 6-hourly v300' (v300/hr') data to determine whether an upper-level travelling trough was present within the selection domain:

1) v300/hr' being positive over at least 25%, and negative over at least another 25% of the area of the selection domain, at any synoptic hour (i.e. 00, 06, 12, 18 UTC);
2) The mean longitude of the positive v300/hr' being larger than that of the negative v300/hr' by at least 5.5° at that synoptic hour; and
3) The change in v300/hr' from positive to negative, from 00 to 18 UTC, covering at least 11 (9) % of area of selection domain for EC (Bu) region.

The first criterion requires that there are both negative and positive v300/hr' signals in the domain, consistent with the presence of a pressure trough. For a perfectly sinusoidal wave, positive and negative signals should occupy 50% of the domain; the threshold of 25% is used to accommodate for non-ideal situations. The second criterion ensures that v300/hr' gives a wave-like signal, with a half wavelength of 5.5° or more. Finally, the third criterion examines whether the trough signal is propagating eastward. The threshold value 11 (9) % for EC (Bu) indicates the portion of area where v300/hr' changes sign from positive to negative in one day. The values were based on estimated phase speed of upper-level disturbances 6.5° (5.0°) eastward per day for those affecting EC (Bu); the threshold value is set by considering half of such phase speed, so that the majority of propagating short waves are expected to fulfill this criterion. (We have also explored the use of the relative vorticity; however, this variable is noisier and hence more difficult to use.)

The sensitivity of our results to the relative position between the extreme rainfall location and selection domain was also examined (see Fig. S1). When the selection domain was located to the northwest of the extreme case location, both the fraction of cases satisfying all three criteria, and the domain averaged wave activity were found to be the largest (see Figs. S1b and S1c). Hereafter, extreme rainfall cases, with v300/hr' in the northwestward domain satisfying all three selection criteria, are referred to as “wave-related extreme rainfall cases”. (The remaining extreme rainfall cases are likely to be associated with other weather systems and are not examined here.)

Since the wave-related extreme rainfall days are likely to be serially related, “clusters” of extreme rain days need to...
be identified, to avoid overcounting in subsequent composite analyses. At any geographical location, a cluster is defined as a series of consecutive days during which there were wave-related extreme rainfall cases.

A cluster was further split into two if the average longitude of cases decreases more than 6° (8°) for EC (Bu) region (i.e., half of the longitudinal extent of search region). It was possible to separate the series of days into clusters, each of which corresponds to only one travelling wave. For each cluster, the day with maximum regional mean precipitation is defined as “day 0”; lag composites (from −2 days to +2 days) are computed. We also apply the wave-selection algorithm to observations (TRMM precipitation dataset and JTWC best track data) and ERA-interim reanalysis data. Composite maps for upper-level waves based on model runs and observational/reanalysis datasets are generally consistent with each other (see Figs. 6a, b and S2). The algorithm using the same threshold values and for the northwestward selection box was then applied for the future climate projections, so as to infer the impacts of global warming on the extreme rainfall and the associated wave systems.

3 Present climate simulations and projected changes in extreme precipitation

To examine the capability of the AGCM in reproducing realistic extreme precipitation over the East Asian monsoon region, its characteristics based on the present climate simulations are first evaluated. Figures 2 and 3 show the climatological decad-mean precipitation and probability of occurrence of extreme cases from the 13th (1 May–10 May) to 21st decad (20 Jul–29 Jul), based on TRMM and model simulations, respectively. Here the decad-mean probability is computed by dividing the count of extreme cases by the total number of days for each decad. From Fig. 2, it can be seen that extreme cases become more frequent from the 15th (21 May–30 May) to 17th decad (10 Jun–19 Jun) over southeastern China to

Fig. 2 Climatological decad-mean probability of occurrence of extreme cases from the 13th to 21st decad based on TRMM3B42v7. Orange contours (in intervals of 5 mm day⁻¹, for values greater than 10 mm day⁻¹ only) represent climatological decad-mean precipitation rate. See text for details

In the first half analysis of Sect. 3, all extreme cases are defined using R95p values based on whole analysis period of respective datasets; hereafter, as inferred from the context, all extreme rainfall indices and cases are re-defined using data within period of June 1 to July 15 only.

Decad is defined as ten-day period.
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southern Japan due to frontal activity. An abrupt increase of occurrences is seen over the northern South China Sea in the 14th decad (11 May–20 May), followed by the formation and northward movement of a band-shaped region comprising strong activity, from eastern China to south of Japan. The AGCM also gives a similar northward moving cluster of extreme rainfall events, although the activity over eastern China and Japan appear to be disjoined (see Fig. 3). The strong activity band associated with the Baiu front starts to influence southern Japan and the nearby seas since the 17th decad, but the zone of major activity from simulations is mainly confined to the land of Japan. Such an activity band reaches its northern-most position around the 19th and 20th decad (30 Jun–9 Jul and 10 Jul–19 Jul); this is also captured by the model (Fig. 3). From the 20th decad, rare extreme cases are found in either TRMM or model data over this region. Finally, the commencement, northward movement and the end of Meiyu–Baiu precipitation corresponds well with the evolution of extremes (Fig. 2). This is also captured by the AGCM, although the simulated total precipitation over eastern China before the 17th decad and the simulated extreme activity over central to northern Japan from the 17th to 19th decad are both overestimated. In general, the Meiyu–Baiu rainband evolution, together with the accompanying heavy rainfall for the EC and Bu regions, are broadly reproduced in the model environment.

Figure 4 shows the deviation of probability of occurrence of extreme rainfall cases from the annual mean, averaged over the two regions. Based on TRMM data, there is high probability of occurrence over EC from the 11th to 21st decad, with a maximum in the 17th and 18th decad (Fig. 4a). Model simulated extremes tend to occur from the 7th to 18th decad, with a relatively broad peak from the 10th to 16th decad (Fig. 4c). This might be related to overestimated springtime rainfall in the EC region. For Bu, both observations and model simulations show the highest probability from the 16th to 19th decad, followed by a secondary peak around the 25th to 28th decad (Figs. 4b and 4d). The above indicates that the heaviest precipitation in these regions is associated with the northward passage of the Meiyu–Baiu rainband from June to mid-July. Hereinafter, we will focus on rainfall extremes re-defined using data within period of June 1 to July 15, which will be referred to as the Meiyu–Baiu season.

Before inspecting the associated synoptic-scale systems, projected changes in Asia/western north Pacific extreme rainfall, according to various metrics, are briefly examined. Figure 5 shows changes in the Simple Daily Intensity Index (SDII; defined as accumulated rainfall averaged over wet

Fig. 3 As in Fig. 2, except for MRI-AGCM3.2S simulations

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days only) and R95p during the Meiuy–Baiu season, in the future compared to the present climate. Over the latitude band of about 20–35 N (from 90 to 150 E), the amplitudes of strongest signals are significantly enhanced. This is sandwiched by two broad regions with suppressed signals, with one extending from northern China, Korea and around the northern Japan, and the other of from northern part of the South China Sea to east of the Philippines. Such region of enhanced rainfall is generally consistent with the summertime rainfall change projected by Oh et al. (2014), although there still exists large uncertainties of the position of enhanced precipitation among different models. Since
the longitudinal extent of westerlies and subtropical high-pressure belt is generally much larger than their meridional width, such sandwiched patterns of signals may be related to projected changes in those large-scale circulation systems. It is noteworthy that both SDII and R95p are found to increase significantly over both EC and Bu regions. The projected changes in the regional average of SDII and R95p indices are, respectively, $+1.6$ (+4.9) and $+2.0$ (+9.5) mm day$^{-1}$, with percentage changes between 15 to 17%, over the EC (Bu) region.

4 Projected changes in Meiyu–Baiu extreme rainfall and associated synoptic-scale systems

We now examine the upper-level synoptic-scale systems associated with EC and Bu extreme rainfall, in the present and future climate. Here composite maps of $v_{300'}$ for day 0 in the present and future climate simulations are computed. From Fig. 6, it can be clearly seen that there exists a wave train (within 30–45 N) with wavelength of about 45° to 50° affecting the search regions. Such a wave train is positioned in a way that, a significantly positive $v_{300'}$ signal is influencing just up-stream of the search region, while negative signals are located to its east and west. The mean wave amplitude and anomalous streamfunction at 300 hPa ($\Psi_{300'}$) shown in composite maps can also be used to estimate the magnitude of these waves. Results show that while there is no obvious change for those affecting EC, the mean

Fig. 6 Day 0 composite 300 hPa $v$-wind (shading; units: m s$^{-1}$) and streamfunction anomalies (contours in intervals of $2 \times 10^6$ m$^2$ s$^{-1}$; dashed and solid contours representing negative and positive values, with zero contours omitted) for a, c Eastern China (25–32 N, 108–120 E) and b, d Baiu rainband (30–35 N, 127–143 E) extreme rainfall events identified in the June-to-mid-July season, for a, b present and c, d future climate MRI-AGCM3.2S simulations. Cross-hatches indicate $v$-wind anomalies passing the 90% significance level.
The amplitude of waves influencing the Bu region exhibits weakening in the future climate. 

$\nu_{300}'$ composites from lag = −2 to 2 days (Fig. S3) are also computed, so as to better visualize the eastward propagation of wave signals. The strongest positive $\nu_{300}'_{\text{max}}$ signal of the synoptic-scale wave passes through the search region (on day 0) with almost the same phase speed in the present as well as the future climate simulations. Based on two-sided Monte Carlo permutation tests of the phase speed estimated by best fitting maximum signal positions, there is no significant change in the phase speed of waves influencing these two regions. On the other hand, the background subtropical jet stream is projected to be displaced slightly southward over East Asia (see Fig. S3); projected changes in the low-to-mid level and large-scale circulations will be further examined.

We have also examined the probability distribution of the amplitude of waves affecting the EC and Bu regions. By taking the northernmost and southernmost boundaries of rectangular selection domains (see Sect. 2) and the longitudinal positions of the $v_{300}'$ trough signal, the wave amplitude is computed as the half of the mean difference between the maximum 5% of the positive $v_{300}'$ and minimum 5% of the negative $v_{300}'$ within such a rectangular domain. The probability density functions of wave amplitudes for day 0 are shown in Fig. 7. Upper-level waves affecting both regions are projected to decrease in amplitude by about 6% [or 0.8 (1.0) ms$^{-1}$ for EC (Bu), passing the 95% significance level based on one-sided Monte Carlo permutation tests] in the future climate. For both regions, waves with weak-to-intermediate amplitude become more likely to occur, while the stronger waves generally become less likely in the future climate.

Projected changes in the low-to-mid level circulations as well as the related precipitation are also analyzed. The anomalous 500 hPa pressure velocity and 700 hPa temperature advection are both modulated under the weakening of the upper-level waves in both EC and Bu regions (see Fig. S4), as expected from the quasi-geostrophic analysis (Holton and Hakim 2012). It is consistent with the projected weakening of the surface low-pressure system and 10 m wind anomalies. Nonetheless, both the anomalous precipitation ($pp'$) and its contribution due to extreme precipitation ($\text{extcont}$) over both regions are found to intensify due to global warming (see Fig. S5). The area-averaged values of aforementioned precipitation quantities are listed in Table 1. Extreme precipitation contribution increases from 4.56 to 4.82 (6.84 to 7.93) mm day$^{-1}$ for EC (Bu) in the future climate simulations. Its percentage in the regional average $pp'$, which is greater than 90% (80%) over EC (Bu) region in the present climate, is also found to increase under global warming.

Projected changes in the basic state of the atmospheric general circulation from the AGCM are now examined. Figure 8 shows the difference of various circulation variables between the future and the present climate simulations. Widespread increment of static stability (N) at 700 hPa is
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found over northern to northeastern Asia, southern Asia and western North Pacific, while its decrement is found over the central of Asia and central-north of China (Fig. 8a). It’s probably due to the intense upper-level warming to the south of 30 N and to the north of 45 N, and also the intense low-level warming near the northern Tibetan Plateau (figure not shown). Static stability becomes stronger especially to the northwest of Bu region, which is generally consistent with more significant weakening of waves affecting the Bu region (Fig. 7). Here, change in baroclinity is further examined by using the Eady growth rate:

\[
\sigma_E = 0.3098 \cdot \left| \frac{f}{N} \right| \frac{|\partial u|}{\partial x}
\]

(Vallis 2006; Simmonds and Lim 2009), where \( f \) is the Coriolis parameter, \( u \) is the zonal wind speed and \( N \) is the Brunt-Väisälä frequency. \( \sigma_E \) is commonly used to reflect the baroclinicity by combining the horizontal temperature gradient and the static stability. Although it is still unclear that which level would be more informative (see, e.g., Lim and Simmonds 2007), \( \sigma_E \) at 500 hPa will be considered here since its projected changes are similar to but smoother than those at 700 hPa. From Fig. 8b, the seasonal mean \( \sigma_E \) is projected to decrease over most of the East Asian mid-latitude regions, with the exception of the increment along a zonal belt near 30 N and the slight increase around Mongolia (probably due to warming over the Tibetan Plateau). It is noteworthy that upper-level wave trains influencing both regions (as shown in Fig. 6) generally pass through the regions of reduced \( \sigma_E \), thus consistent with the weakening of baroclinic systems influencing both EC and Bu. To have a broader view of those mid-latitude synoptic-scale systems, Fig. 8c shows the projected changes in the variance of eastward-propagating \( v300' \) signals. The \( v300' \) variance, which reflects the wave amplitudes, is found to decrease in mid-latitude East Asia in the future climate. Such decrease

![Fig. 8](https://via.placeholder.com/150)
of variance is particularly strong around 45-55 N, but otherwise weak in the central and north of China. Such patterns of reduced variance match those showing an increase of N (Fig. 8a), suggesting that the increment of static stability is the main reason of weakening of those synoptic-scale waves.

After examining changes in the basic state, how global warming might affect the EC and Bu extreme rainfall associated with the synoptic-scale disturbances is now studied. Figure 9 shows the probability density function of percentage changes in time mean precipitation rates (blue), SDII (red) and averaged precipitation rates for extreme cases (violet) per °C of warming in the lower-to-mid troposphere, computed for a, b June-to-mid-July season, and c, d extreme rain days associated with synoptic-scale waves only, over a, c Eastern China (25–32 N, 108–120 E) and b, d Baiu rainband (30–35 N, 127–143 E). Also shown are changes in R95p (orange) for the June-to-mid-July period. The vertical dashed line represents the change of 7%/°C expected from the CC-relation. See text for details.

Fig. 9 Probability distribution of percentage changes in time mean precipitation rates (blue), SDII (red) and averaged precipitation rates for extreme cases (violet) per °C of warming in the lower-to-mid troposphere, computed for a, b June-to-mid-July season, and c, d extreme rain days associated with synoptic-scale waves only, over a, c Eastern China (25–32 N, 108–120 E) and b, d Baiu rainband (30–35 N, 127–143 E). Also shown are changes in R95p (orange) for the June-to-mid-July period. The vertical dashed line represents the change of 7%/°C expected from the CC-relation. See text for details.
first two statistics over Bu become larger for wave-related days only, which highlights the importance of extremes in contributing to the mean precipitation in Bu. Except for mean rainfall and SDII for the EC region, changes in all extreme indices and mean rainfall for both regions seem to show consistency with the CC-relation for wave-related days only. It suggests that weakening of the synoptic-scale systems due to global warming is too modest to modulate the thermodynamic impacts on extreme precipitation.

5 Discussions and conclusions

In this study, we examined the projected changes in Meiyu–Baiu extreme precipitation and the associated mid-latitude synopt-ic-scale weather systems over the EC and Bu regions, based on simulations from the 20-km MRI-AGCM3.2S. The model can capture well the seasonal evolution of extreme rainfall activity associated with the Meiyu–Baiu rainband, albeit with their occurrence overestimated during spring for the EC region and the Meiyu–Baiu season for central to northern Japan. Furthermore, the AGCM can reproduce the relation between wave-like upper-level v-wind/streamfunction signals and the regional precipitation as seen in observations, in the June-to-mid-July season. A novel wave-selection algorithm was developed to identify upper-level propagating v-wind wave signals associated with extreme rainfall. This algorithm was then applied to both the present and future climate simulations by the MRI model, so as to infer impacts of global warming on the behavior of these circulation systems.

Results show that the intensity of those upper-level waves influencing both EC and Bu regions reduces by about 6% in the future climate. The corresponding low-to-mid level circulations, as indicated by vertical velocity, temperature advection and sea-level pressure anomalies, are also weakened for both regions. Indeed, the amplitude of eastward-propagating v300° signals in mid latitudes is projected to be reduced in the model simulations, consistent with the increment of static stability and the decrement of Eady growth rate over the Eurasian mid-to-high latitude locations. However, extreme rainfall for both regions as well as mean rainfall for Bu are projected to increase in the future climate simulations. The extreme rainfall will become increasingly important to the EC and Bu rainfall variability; the former will contribute even more to the rainfall amount expected from these wave-like systems. The intensification of Meiyu–Baiu extreme rainfall was likely due to the warmer low-to-mid level background temperature, with scaling broadly consistent with the CC-relation. In summary, the thermodynamic effect seems to play a dominant role in governing changes of EC and Bu extreme precipitation; even though the synoptic-scale disturbances will become weaker in the future climate, the related extreme rainfall still scales with background temperature according to the CC-relation.

It is noticed that MRI-AGCM tends to underestimate early-summer southwesterlies and overestimate springtime precipitation over southeastern China; the model-simulated proportion of wet days during the Meiyu–Baiu season is also greater than that according to TRMM. These biases might be related to the sensitivity of the monsoon rainband evolution to the cumulus parameterization scheme used (e.g., Lee et al. 2008; Kusunoki 2018). One possible way to reduce such systematic bias is to implement multi-physics or multi-model ensemble simulations. Whether the resolution adopted by this AGCM is good enough to capture the projected changes in extreme precipitation characteristics might also need to be further investigated. Gao et al. (2006) found that model resolutions of 60 km or higher are needed for accurate simulation of East Asian precipitation; however, Shi et al. (2018) found that fine resolution is critical only for spatial variability of the general circulation features themselves, but not the response due to climate forcing. Finally, since the AGCM is an atmosphere-only model, particular attention should be paid to examine how the absence of air-sea interaction might impact on the simulated monsoon rainfall (see, e.g., Wang et al. 2005).

Using projections by the same AGCM, Chen et al. (2021) found that rainfall associated with each TC system tends to intensify; these systems also tend to move further inland over Asia in the future climate. On the other hand, the same model also projected a reduction of TC frequency south of Japan (see Lui et al. (2018)). Further investigation should be conducted to see how TC-related extreme precipitation over Bu might be modulated in future, in view of these competing effects under global warming.

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