Obtaining More Information about Precipitation Biases over East Asia from Hourly-Scale Evaluation of Model Simulation

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ABSTRACT

The hourly summer precipitation simulations over East Asia by the Chinese Academy of Meteorological Science Climate System Model (CAMS-CSM) high-resolution Atmospheric Model Intercomparison Project (AMIP) runs (T255, ~50 km) were evaluated based on the merged hourly precipitation product released by the China Meteorological Administration (CMA). The results show that the simulation biases are closely related to the topography, with the precipitation amount and frequency overestimated (underestimated), and duration of precipitation events being longer (shorter), over the western high-altitude (eastern plain) regions of China. Six regions with large discrepancies were further analyzed. In terms of the frequency–intensity structure, the overestimation of precipitation frequency is mainly due to the excessive simulated weak precipitation over the four regions with positive biases: the southern edge of the Tibetan Plateau (STP), the northeastern edge of the Tibetan Plateau (NETP), the eastern periphery of the Tibetan Plateau (EPTP), and the mountainous area of North China (NCM); while the underestimation of frequency is mainly due to the insufficient precipitation with moderate intensity over the two regions with negative biases: lower reaches of the Yangtze River (LYR) and the South China coast (SCC). Based on the duration–diurnal structure analysis, two kinds of precipitation events with different natures can be distinguished. The long-duration night to early morning precipitation events have a significant contribution to the precipitation amount biases for all the six key regions, and this kind of precipitation mainly affects the precipitation diurnal variation over the mountainous areas or steep terrain. Although the short-duration afternoon precipitation events only have a greater contribution to the precipitation amount biases over the SCC region, this kind of precipitation affects the diurnal variation over the NCM region and the two key regions with negative biases. Such a detailed hourly-scale evaluation is helpful for enriching the understanding of simulation biases and to further improve model performance.

Key words: precipitation simulation, fine-scale evaluation, frequency–intensity structure, diurnal variation, duration

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1. Introduction

As an important tool in climate simulation and climate change research, the climate system model (CSM) has been advancing progressively in recent years (Petoukhov et al., 2000; Blackmon et al., 2001; Collins et al., 2006; Dong et al., 2012; Voldoire et al., 2013). However, biases and uncertainties always exist in climate modeling, due to extreme complexity in the interactions among various components of the climate system (McAvaney et al., 2001; Randall et al., 2007; Flato et al., 2014). The evaluation of model ability in climate simulation, especially that of precipitation, has become an important topic (Olson et al., 1995; Frei et al., 2003; Dai, 2006; Chen and Knutson, 2008; Kendon et al., 2012; Warrach-Sagi et al., 2013; Mehran et al., 2014). Only when the model can reasonably reproduce the comprehensive characteristics of precipitation, including its frequency, intensity, duration, ratio of convective precipitation to stratiform precipitation, as well as diurnal phase and amplitude, will the simulated precipitation be physically reliable (Trenberth et al., 2003; Sun et al., 2006,
2007).

In East Asia, the large-scale precipitation distribution, rainfall movement, and drought and flood disasters are largely controlled by the monsoonal climate. In addition, the influence of small- and medium-scale topography also makes precipitation more complex, with significant regional differences. The unique precipitation distribution makes this region a good test bed for the evaluation of model simulation (Yu et al., 2000; Kang et al., 2002; Zhou et al., 2009; Boo et al., 2011). Relevant assessments indicate that there are some common biases in precipitation among the different models, such as the location bias of the monsoonal rainfall (Chen et al., 2010; Song and Zhou, 2014) and artificial climatic precipitation centers over the eastern margin of the Tibetan Plateau (Zhou and Li, 2002; Kitoh and Kusunoki, 2008). Li et al. (2015) found that the large-positive-bias region over the Tibetan Plateau decreases dramatically with increasing resolution, but the amplitude of the maximum bias still increases. In addition, there are distinct regional differences in the diurnal variation of precipitation over East Asia (Yu et al., 2007a,b; Zhou et al., 2008; Yuan et al., 2010). The abundant diurnal features over East Asia make this area suitable for evaluating the abilities of the model in simulating precipitation diurnal variations (Koo and Hong, 2010; Yuan et al., 2013). Related evaluation results indicate that the models can reproduce the precipitation diurnal cycles with an afternoon peak over the land and a morning peak over the ocean, but the peak time is earlier than that of the observations. These results enrich our understanding of model biases, but to obtain more detailed bias information, a more comprehensive and in-depth evaluation is still needed. Li et al. (2015) suggested that different combinations of hourly rainfall intensity and frequency could lead to similar climatological characteristics. Only when the model correctly reproduces the combination of hourly intensity and frequency, will the simulated precipitation be more reasonable. In addition, the analysis of diurnal cycle in conjunction with the duration characteristics of precipitation events contributes to better understanding of the mechanism of precipitation (Yu et al., 2007a). In a word, hourly-scale assessment has become an indispensable way to understand the nature of precipitation biases.

A new climate system model developed at the Chinese Academy of Meteorological Sciences (CAMS-CSM) is planned for participation in the Coupled Model Intercomparison Project Phase 6 (CMIP6). The model’s capability has been evaluated from many perspectives (Rong et al., 2018; Wei et al., 2018; Zhang et al., 2018; Chen et al., 2019; Hua et al., 2019; Qi et al., 2019). This model can capture some climatological mean states of the major climate system and the prominent climate variability modes, such as the Madden–Julian Oscillation (MJO), El Niño–Southern Oscillation (ENSO), and East Asian summer monsoon (EASM; Rong et al., 2018). These evaluations are based on the results of the T106 version (horizontal resolution of approximately 1°) of the model. Currently, a set of high-resolution (T255, ~0.47°) Atmospheric Model Intercomparison Project (AMIP) experiments have been carried out for CAMS-CSM to participate in the High-Resolution Model Intercomparison Project (HighResMIP; Haarsma et al., 2016) of CMIP6. Li J. et al. (2018) first performed a basic assessment of the high-resolution simulation of precipitation climatology before evaluating the model’s ability in simulating extreme precipitation events. However, the precipitation simulation performance over East Asia has not been fully examined and understood. By focusing on the hourly-scale features, the performance and simulation biases in the CAMS-CSM high-resolution AMIP runs for the summer precipitation over East Asia are comprehensively assessed in this study. An additional aim of this study is to gain insight into the common biases in climate models through these assessments and analyses.

The remainder of this paper is organized as follows. In Section 2, a brief description of the model, observational data, and the methods used, is provided. Based on analyses of the climatic precipitation features, the frequency–intensity characteristics of hourly precipitation, and the diurnal cycles with different precipitation durations, the results are presented in Section 3. Major conclusions and related discussion are given in Section 4.

2. Model, data, and methods

2.1 Model

The model used in this study is the atmospheric component of CAMS-CSM (CAMS-CSM-A). This model is based on the Max–Planck Meteorological Institute (MPI-M) ECMWF-HAMburg5 (ECHAM5) (Roeckner et al., 2003), and several modifications have been implemented. The Common Land Model (CoLM) (Dai et al., 2003), the Beijing Climate Center radiative transfer model (BCC_RAD) radiation scheme (Zhang et al., 2006a, b), and the two-step shape preserving scheme (TSPAS: Yu, 1994) have been incorporated to improve the model performance. In this study, the high-resolution version (T255, ~0.47°) of the CAMS-CSM-A is used. It has 31 vertical levels, with the top at 10 hPa. For additional details regarding the CAMS-CSM, readers are referred to
Rong et al. (2018).

Forced by monthly historical sea surface temperature (ERSST v2, Smith and Reynolds, 2004), an experiment from 1999 to 2015 was conducted, and the external forcings including greenhouse gases, aerosols, and ozone, remain unchanged. The outputs of the last 16 years (2000–2015) are used to evaluate the performance of the high-resolution model and to analyze the detailed features of precipitation biases on the hourly timescale.

2.2 Data and methods

The hourly merged precipitation analysis product at a resolution of 0.1° × 0.1° from 2008 to 2016 is used in this study (Shen et al., 2014). This dataset combines the quality-controlled hourly precipitation amount measured by more than 30,000 automatic rain gauges with the satellite-retrieved precipitation product from the Climate Prediction Center Morphing Technique (CMORPH; Joyce et al., 2004) using the probability density function–optimal interpolation (PDF–OI) method, hereafter called the CMPA hourly data. Previous studies have shown that the CMPA hourly data can well reflect the major precipitation characteristics over China (Shen et al., 2014; Jiang et al., 2017). For comparison with the model outputs, the CMPA hourly data are interpolated to the model grids by regional average (averaging all observation grids contained in each model grid).

In this study, climatological summer (June–August) precipitation amount is calculated by dividing the cumulative precipitation amount by the number of nonmissing hours in summer during the study period and then multiplying by 24 h to normalize to daily amount (mm day⁻¹). Hourly summer precipitation frequency is defined as the percentage of hours with measurable precipitation (≥ 0.1 mm h⁻¹) versus the total number of nonmissing hours in the summer of the study period. Precipitation intensity is obtained by dividing the cumulative summer precipitation amount by the number of hours with measurable precipitation in the summer. A precipitation event is defined as continuous rainfall without any intermittence. The number of hours between the start and end of an event is defined as the duration time of the rainfall event (Yu et al., 2007a). The precipitation amount of two kinds of events (long-duration night to early morning precipitation events and short-duration afternoon precipitation events) is also normalized to the daily amount by multiplying by 24. The diurnal amplitudes of rainfall are calculated as

\[ A = \frac{R_{\text{max}} - \bar{R}}{\bar{R}} \times 100\% , \]  

where \( R_{\text{max}} \) is the maximum of hourly rainfall in a day, and \( \bar{R} \) is the daily mean rainfall (refer to Yuan et al., 2013).

3. Results

3.1 Hourly frequency, intensity, and duration

The climatological patterns of the summer mean precipitation amount are shown in Fig. 1. As revealed by the observational data, the precipitation amount is quite low (< 1 mm day⁻¹) over the northwestern quarter of Fig. 1a. To the south of this dry region, there is an arc-shaped rain belt over the southern margin of the Tibetan Plateau. The precipitation amount over the Sichuan basin is relatively small, in contrast to the large values over the western, northern and eastern sides of the basin. To the east of the 500-m elevation contour, there are two major rainfall centers. One is located over eastern China (approximately 30°N), and the other is located over southern China (south of 25°N). As shown in Fig. 1b, the model can reproduce the main spatial pattern of summer precipitation. The coefficient of pattern correlation between the observation and simulation is 0.66. The simulated summer precipitation amount averaged over East Asia is 4.31 mm day⁻¹, which is close to the observation (4.09 mm day⁻¹).
but with a slight overestimation. The location of the rain belt over the southern margin of the Tibetan Plateau is similar to the observation. The two largest simulated precipitation grids over the continent are located over the southern slope of the Tibetan Plateau (26.9°N, 96.6°E and 27.4°N, 89.1°E, marked with blue pentacles), which are similar to the observation (25.5°N, 95.6°E and 26.4°N, 89.5°E) but slightly northward and at much higher altitudes. The model also reproduces the low precipitation amount over the Sichuan basin and the relatively large precipitation amount over its surrounding areas. However, the model underestimates the rainfall over eastern China and southern China.

Figure 2a shows the difference in the precipitation amount between the simulation and observation. A conspicuous feature of the discrepancy is the good correspondence with topography. Generally, the elevation descends in three steps from west to east over East Asia. Over the first terrain step (the Tibetan Plateau), the simulated precipitation amount presents large positive biases. The maximum bias, which is as high as 14.10 mm day$^{-1}$, appears on the southern edge of the Tibetan Plateau (STP). To the east of the Tibetan Plateau, the 500-m elevation contour separates the second and third terrain steps. Over the plain areas to the east of the 500-m contour, the simulation presents negative biases. The regional average precipitation amount bias over East Asia is 0.22 mm day$^{-1}$, showing a slightly overestimation overall.

Figure 2b shows the percentage of the number of grids categorized by the bias of precipitation frequency and precipitation intensity over East Asia. For the hourly frequency bias (blue line in Fig. 2b), the distribution skews to the positive side, with 61.71% of the grids showing positive biases. In contrast, the numbers of grids with positive and negative intensity biases are comparable (50.39% of the grids show positive intensity biases). The biases at 80.78% of the grids are concentrated between $-0.3$ and $0.3$ mm h$^{-1}$.

The spatial distributions of the frequency and intensity differences between the simulation and observation are shown in Figs. 2c, d, respectively. Consistent with Fig. 2b, the precipitation frequency biases generally
present large overestimations, especially over the Tibetan Plateau. The frequency bias distribution is consistent with that of the precipitation amount, and their pattern correlation coefficient reaches 0.84. The maximum positive bias of precipitation frequency (52.03%) is located on the STP (27.85°N, 90.94°E) and is adjacent to the grid of the maximum precipitation amount bias (27.85°N, 91.41°C). Over the third terrain step, the underestimation of the precipitation frequency presents two centers: the lower reaches of the Yangtze River (LYR) and the South China coast (SCC). As shown in Fig. 2d, the precipitation intensity biases are relatively small over the Tibetan Plateau. Over the central Tibetan Plateau (30°–35°N, 84°–96°E), 85.09% of the grids have intensity biases between −0.1 and 0.1 mm h⁻¹. In general, the precipitation amount biases over the Tibetan Plateau are mostly contributed by the frequency biases.

Based on the patterns shown in Figs. 2a–d, six key regions with large precipitation biases are selected for further analysis (red boxes in Fig. 2a). Four regions present large positive biases in both amount and frequency, which are located at the STP, the northeastern edge of the Tibetan Plateau (NETP), the eastern periphery of the Tibetan Plateau (EPTP), and the mountainous area of North China (NCM). The other two regions with negative biases include the LYR and SCC over the third terrain step.

The frequency–intensity distribution is an important component of climatological rainfall characteristics and is also an important metric for evaluating model capability (Li et al., 2015). Figure 3 shows the precipitation frequency–intensity structure averaged in the six key regions. The logarithmic distribution of precipitation frequency for moderate and high intensity is presented in the subgraph. The bias in the precipitation intensity structure is a common problem in climate models (e.g. Chen et al., 1996; Dai and Trenberth, 2004; Li et al., 2015), manifested as the weak precipitation overestimation and the heavy precipitation underestimation. In CAMS-CSM-A, this problem is more prominent over the mountain areas or places with steep terrain. In all four regions with excessive precipitation amounts (Figs. 3a–d), the simulated hourly frequencies (black line) are higher than the observation (red line) at intensities of less than 6 mm h⁻¹. However, the four regions exhibit different features in stronger intensity bins. For STP, NETP, and EPTP, the simulated frequency presents a negative bias when the intensity exceeds a certain critical value, which is 16, 14, and 9 mm h⁻¹, respectively. Notably, over the NCM region, the simulated line is always above the observation. For the two regions with negative precipitation amount biases (LYR and SCC), the frequency is underestimated in all intensity bins (Figs. 3e, f). Dividing the precipitation intensity into three levels, the precipitation frequency biases in different intensity levels is calculated, and its contribution to the total precipitation frequency biases is expressed by the percentage of the precipitation frequency biases in different intensity levels to the total precipitation frequency biases. Table 1 shows the contributions of frequency biases of weak precipitation (0.1–2.9 mm h⁻¹), moderate precipitation (3.0–9.9 mm h⁻¹), and heavy precipitation (≥ 10.0 mm h⁻¹) to the total frequency biases over the six regions. The overestimation of the weak precipitation frequency contributes the most to the overall bias in the regions with positive biases, while the underestimation of moderate precipitation is more important in regions with negative biases.

Precipitation duration is an important metric for distinguishing precipitation events with different mechanisms (Yu et al., 2007a). The mean duration of all summer precipitation events is calculated, and the spatial distribution is shown in Fig. 4. For the observation (Fig. 4a), the large value of the precipitation duration is distributed along the Yangtze River Valley (YRV; approximately 30°N), with an average duration of approximately five hours. This feature corresponds well with the conclusion of Yu et al. (2007a), which is that the long-lasting precipitation contributes more to the total precipitation in the warm season along the YRV. There is also a long-duration zone over the STP, while the duration over the northwestern plateau is relatively short (mainly less than three hours). Figure 4b shows the spatial distribution of the simulated duration, which is quite different from the observation, and the spatial correlation is only −0.26. The East Asian average duration of simulated precipitation events is 4.91 h, which is longer than that of the observation (4.21 h). Over the high-altitude regions, such as the Tibetan Plateau and the second terrain step, the duration is significantly overestimated, which indicates that the model is prone to continuously produce precipitation over the mountain areas or places with steep terrain. In contrast, the model cannot reproduce the long-duration zone along the YRV and underestimates the duration in southern China. Overall, the relationship between the duration and topography is exaggerated. Along 30°N, from the Tibetan Plateau to eastern China and to the oceanic area, the simulated and observed durations present contrary gradients.

3.2 Diurnal variation

The diurnal variation in summer precipitation over East Asia has distinct regional characteristics and is
closely related to the regional and large-scale dynamic and thermodynamic conditions (Yu et al., 2014). The most prominent feature is the eastward-delayed signal of the precipitation diurnal peak phase along the YRV (Yu et al., 2007b). Figure 5 shows the time–longitude distributions of normalized diurnal rainfall averaged between 28° and 35°N to analyze whether the model can reproduce this feature. For the observation (Fig. 5a), the propagating eastward feature of the precipitation diurnal peaks appears over the western plain (approximately 102°–108°E), with a midnight peak over the upper valley and an early morning peak over the middle valley. Another major feature of the observation is the double peaks in the diurnal variations over the eastern plain (approximately 108°–120°E), and the diurnal peaks occur in the early morning and late afternoon. The model not only depicts the large amount of precipitation over the plateau at night but also the characteristics of the diurnal phase frequency over the YRV.

Table 1. Contribution of precipitation frequency bias at different intensity levels to total precipitation frequency bias (%) over the six regions

| Intensity level | STP  | NETP  | EPTP  | NCM  | LYR  | SCC  |
|----------------|------|-------|-------|------|------|------|
| Weak (0.1–2.9 mm h⁻¹) | 77.84 | 79.17 | 82.99 | 62.32 | 26.38 | 34.12 |
| Moderate (3.0–9.9 mm h⁻¹) | 21.95 | 20.79 | 18.18 | 32.92 | 52.05 | 48.75 |
| Heavy (≥ 10 mm h⁻¹) | 0.21  | 0.04  | −1.17 | 4.76  | 21.57 | 17.13 |
shift near the coastline. More importantly, the model can capture the eastward-delayed diurnal features over the western plain. However, the model is unable to reproduce the double-peak phenomenon over the eastern plain, and it shows a single noon peak.

Figure 6 shows the spatial distribution of the diurnal peaks and the diurnal amplitude in the summer precipitation amount. The observed precipitation over the Tibetan Plateau is mainly dominated by peaks from late afternoon to night (1700–0200 BJT; Fig. 6a), while the simulated precipitation peaks several hours later at night (2000–0500 BJT; Fig. 6c). The diurnal amplitude generally exceeds 60% over the Tibetan Plateau both in observation and simulation (Figs. 6b, d). Over the STP, the model can reproduce the early morning peak, but the simulated morning-peak zone is located at a much higher altitude compared with the observation. The model fails to reproduce the nocturnal rainfall over the second terrain step between 25° and 35°N, but it captures the large value of diurnal amplitude over the Sichuan basin. Over the third terrain step, both the model simulation and observation show dominant daytime peaks, but the simulated peak is earlier than that of the observation. It is worth noting that the diurnal amplitude increases from the lower reaches of the YRV to the NCM in the observation, while the model presents contrary results.

Figure 7 shows the diurnal variation over the six large-bias regions. In general, the simulated diurnal variation curves are similar to the observations, and the maximum temporal correlation coefficient over the six regions reaches 0.96. The observed diurnal curve over the STP (Fig. 7a) shows a single peak at 0500 BJT in the early morning. The model captures the early morning peak one hour earlier than the observation. In addition, the simulated precipitation is also relatively high during 1700–2000 BJT. For the NETP (Fig. 7b), the model reproduces the same afternoon peak (1900 BJT) as that of
the observation, but the simulated diurnal amplitude is much smaller. The model can also well simulate the diurnal variation in precipitation over the EPTP (Fig. 7c), with the maximum (minimum) precipitation around midnight (noon). For the NCM (Fig. 7d), even though both the simulation and observation exhibit a single-wave pattern, they have quite different diurnal curves. In contrast to the concentrated and narrow single peak in the observation, the model has too much precipitation in the late night and early morning, which leads to a broad high-value period with the diurnal amplitude (12.65%) quite smaller than the observation (59.06%), corresponding to the Figs. 7c, d. In addition, the maximum and minimum values of the simulation appear three hours earlier than the observation.

Figure 8 shows the observed and simulated duration-diurnal structures, which are presented by the distribution of the accumulated summer precipitation amount against the diurnal phase and duration of each event. Although the observed diurnal variation over the STP region presents a single early morning peak (Fig. 7a), there are two large-value regimes in Fig. 8a: one with a short duration in the late afternoon (centered at 1800 BJT), and the other with a long duration in the early morning. The simulated precipitation also presents two large-value centers, and the short-duration precipitation center in the late afternoon is similar to that of the observation. Although the peak time of early morning precipitation coincides with the obser-
vation, its duration is much longer. In addition, the value of the long-duration precipitation center is comparable to that of the short-duration center, which leads to the secondary peak in the black line in Fig. 7a. In general, the biases over the STP are mostly due to unrealistic long-duration events. For the NETP region (Fig. 8b), the observation presents a short-duration center in the afternoon. The model can capture this kind of precipitation events. However, compared with the observation, the proportion of long-duration precipitation events is significantly overestimated. As shown in Fig. 8c, the overall feature of the simulated duration-diurnal structure is similar to the observation over the EPTP. However, the simulated results extend much further to the long-duration side. For the NCM region (Fig. 8d), the model can reproduce the short-duration afternoon precipitation center, but with a lower precipitation amount. Simultaneously, the model overestimates the morning precipitation with a duration of approximately 6–15 h. As illustrated in Fig. 8e, the most prominent feature of the observation is the short-duration precipitation center in the afternoon. The model can capture this type of precipitation events, but with shorter durations and earlier peaks. In addition, the model underestimates both the duration and accumulated rainfall amount in the morning period. For the SCC region (Fig. 8f), the observation presents a large afternoon center. Similar to the LYR region, the simulation biases for the SCC region are also shorter in duration and earlier in peak time.

Based on the above analysis, the short-duration (duration ≤ 6 h) afternoon (1400–2000 BJT) precipitation and the long-duration (duration > 6 h) night to early morning (2200–0000 BJT) precipitation are selected, and Fig. 9 shows the spatial distribution of the precipitation amount difference between CAMS-CSM-A and CMPA for the two kinds of precipitation. As shown in Fig. 9a, the un-
derestimation of short-afternoon precipitation is located in the central Tibetan Plateau and the coastal region of China. Over the lowlands south of the Tibetan Plateau and over the northern Indochina Peninsula, the short-afternoon precipitation is overestimated. For the four positive bias regions (STP, NETP, EPTP, and NCM), the simulated short-duration afternoon precipitation is close to that of the observations and even smaller than that of the
observations (over the NCM region with $-0.53$ mm day$^{-1}$ underestimation amount). There is also no significant bias in the short-duration afternoon precipitation over the LYR region. However, a considerable negative bias is found over the SCC region, which accounts for $26.07\%$ of the underestimation of the total precipitation amount. Figure 9b shows the biases of long-duration night to early morning precipitation, which generally presents a contrary spatial pattern to that shown in Fig. 9a. The largest positive bias is located at the STP. All four large-positive-bias regions largely overestimate this kind of precipitation. In contrast, negative biases are found over the lower lands surrounding the Tibetan Plateau and over the third terrain step. The LYR and SCC regions are two local centers of underestimation. This kind of bias contributes most to the total negative bias over the two regions.

4. Summary and discussion

Focusing on the detailed precipitation features at the hourly scale, the performance of the high-resolution CAMS-CSM-A in simulating summer precipitation over East Asia is evaluated. The major conclusions are summarized below.

1. Compared to the observation, the CAMS-CSM-A presents some differences in the distribution of climatological summer precipitation over East Asia. The biases are closely related to the topography. Over the Tibetan Plateau, the simulated precipitation amount is significantly larger than that of the observation, and this amount bias is mostly contributed by the overestimated precipitation frequency. Over the third terrain step, the simulation presents an underestimation of precipitation amount, frequency, and intensity. In addition, the simulated precipitation presents a longer (shorter) duration over the Tibetan Plateau (the third terrain step).

2. In terms of the frequency–intensity structure, the biases with weak (heavy) precipitation overestimation (underestimation) are more prominent over the mountain areas or places with steep terrain. The precipitation frequency biases at different intensity levels contribute differently to the total biases. The overestimation of frequency over the large-positive-bias regions is mainly due to the excessive simulated weak precipitation, while the underestimation of frequency over the large-negative-bias regions is mainly due to the negative frequency biases of moderate precipitation.

3. Although the model can reasonably reproduce the eastward-delayed diurnal feature over the upper and middle reaches of the Yangtze River, it cannot reproduce the double-peak phenomenon over the western plain (approximately $102^\circ$–$108^\circ$E), and it presents a single peak at noon. Correspondingly, the simulated diurnal amplitude is significantly larger than the observation over the LYR region. The model simulates more early morning precipitation over the NCM region, which makes the diurnal amplitude quite smaller than the observation.

4. For the regions around the Tibetan Plateau, the differences in diurnal variation are mainly concentrated on the long-duration precipitation events. In addition to the long-duration morning precipitation, the short-duration afternoon precipitation may also affect the diurnal variation simulation over the NCM region. The simulated short-duration afternoon precipitation also peaks earlier than the observations over the LYR and SCC regions, and the duration of this kind of precipitation is much shorter. Generally, the long-duration night to early morning precipitation biases contribute more to the total biases in the precipitation amount. The underestimation of short-duration afternoon precipitation also contributes to the total negative biases over the SCC region.

The hourly-scale evaluation is helpful for understanding the biases of simulated precipitation in climate mod-
els. These biases are mainly related to two kinds of events: short-duration afternoon precipitation and long-duration night to early morning precipitation. Taking the short-duration afternoon precipitation as an example, the third step terrain, especially that over the SCC, has some impact on the biases in this kind of precipitation. This kind of precipitation is more likely to be convective precipitation under the influence of local thermal conditions and unstable energy, and it is closely related to the convection parameterization in the model (Dai et al., 1999; Betts and Jakob, 2002; Liang et al., 2004, Zhang and Chen, 2016). The main bias of the short-duration afternoon precipitation over land lies in the earlier simulated diurnal peak. Adjusting the parameterization scheme can improve the simulation of the diurnal cycle of precipitation (Zhang, 2003; Bechtold et al., 2004; Wang et al., 2007; Lee et al., 2008). In addition, using the cloud-resolving model (CRM) is also an effective means for improving the simulation of diurnal variation (Sato et al., 2009; Ban et al., 2014; Liu et al., 2017), and the diurnal cycle improvement can be also found over East Asia using CRM (Li P. X. et al., 2018). Considering the frequency–intensity structure, it is found that the contribution of precipitation at different intensity levels to the total precipitation amount biases varies in different regions. Huang et al. (2013, 2018) analyzed the climate model uncertainty on the simulated summer precipitation, and they indicated that the model biases are concentrated on heavy precipitation and the large uncertainties may be related to the partitioning of stratiform and convective precipitation and horizontal resolutions differences. In addition, the influence of dynamic processes in the model cannot be ignored. For example, the excessive precipitation around the Tibetan Plateau in the model is related to moisture transport and divergence (Yu et al., 2015; Zhang and Li, 2016). The specific causes of the biases require further study using sensitivity tests based on different kinds of precipitation events. In addition, the transpose-AMIP test can be used to control the biases associated with synoptic-scale circulation, and the evolution process of precipitation event biases can be analyzed to better understand the internal physical processes that produce biases.

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