Effects of Horizontal Resolution on Hourly Precipitation in AGCM Simulations

XIANGHUI KONG AND AIHUI WANG

Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

XUNQIANG BI

Climate Change Research Center, and State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

XINGYU LI

Climate Change Research Center, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

HE ZHANG

International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

(Manuscript received 8 July 2019, in final form 7 January 2020)

ABSTRACT

To analyze the effects of horizontal resolution on hourly precipitation, four Atmospheric Model Intercomparison Project simulations are carried out using the Chinese Academy of Sciences Earth System Model (CAS-ESM) and the Community Earth System Model (CESM) during 1998–2016. They include CAS-ESM at resolutions of 1.4° latitude $\times$ 1.4° longitude (CAS-ESM L) and $0.5^\circ \times 0.5^\circ$ (CAS-ESM H), and CESM at resolutions of 1.9° latitude $\times$ 2.5° longitude (CESM L) and $0.47^\circ \times 0.63^\circ$ (CESM H), respectively. We focus on the simulated hourly precipitation frequency and assess the frequency with respect to high-resolution satellite observations and reanalysis. The high-resolution experiments show some improvements of measurable precipitation ($>0.02 \text{ mm h}^{-1}$) frequency. Noticeable improvement of heavy rainfall ($>2 \text{ mm h}^{-1}$) frequency is demonstrated at the high resolutions. The zonal mean, seasonal mean, and area-weighted average frequency support the above results. The high-resolution experiments outperform the low-resolution experiments in reproducing hourly precipitation intensity and amount. The added value is apparent in heavy precipitation intensity from CAS-ESM H and CESM H. Over the monsoon regions and tropical convergence zones, the patterns of probability density functions for precipitation from high-resolution experiments are closer to the observations and reanalysis than those from the low-resolution simulations. The improvement of measurable precipitation frequency is mainly caused by the reductions of the convective rainfall occurrence at high resolutions. The increasing large-scale precipitation and reasonable integrated water vapor flux contribute to the improvements in measurable rainfall intensity and heavy precipitation characteristics. The results of this study support the concept that high-resolution global simulations could produce improved hourly precipitation capabilities, especially for heavy rainfall.

1. Introduction

Precipitation is one of the fundamental elements of the climate system, and the accumulated precipitation amount over a given period greatly impacts local irrigation and farming practices (Trenberth and Zhang 2018). Because rainfall usually occurs at a particular time of day, the accumulated amount is insufficient to describe all features of precipitation, such as frequency and intensity. The rainfall characteristics, including the

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JHM-D-19-0148.s1>.

Corresponding author: Dr. Aihui Wang, wangaihui@mail.iap.ac.cn

frequency, intensity, duration, and type are often used to describe precipitation events (Sun et al. 2006; Pendergrass and Deser 2017). Moreover, as a significant component of the hydrological cycle, a deep understanding of seasonal precipitation features (e.g., Wang and Yang 2017) is critically important for the water resource management and flood risk assessment.

Precipitation frequency (the percentage ratio of time in which precipitation occurs), intensity (the mean precipitation rate during all raining time), and amount (the accumulated precipitation) are commonly used terms in the study of precipitation events. For gauge observations, the precipitation amount is routinely collected and recorded at daily or monthly frequencies (e.g., Zolina 2014). However, the actual precipitation events may last for only a few hours or less. It is really not convenient to use monthly values or daily values to directly investigate the nature of precipitation at subdaily or hourly time scales (Trenberth 1998; Westra et al. 2014). The hourly precipitation characteristics may differ from those of daily records. For instance, Yu et al. (2010) analyzed station rain gauge data over mainland China during 1966–2005 and found that the rainfall intensity in the hourly data decreased in the middle-to-low reaches of the Yangtze River valley, but the intensity based on the daily records increased in the same area. Furthermore, the trends of rainfall events at subdaily time scales have strong impacts on the relationship between extreme precipitation and temperature (e.g., Berg et al. 2013). Therefore, it is necessary to analyze the features of subdaily (or hourly at best) precipitation to understand the realism of physical processes and rainfall occurrence mechanisms.

Over the past decades, there have been a growing number of studies based on subdaily or hourly precipitation from observations and models (e.g., Shaw et al. 2011; Zhang and Zhai 2011; Miao et al. 2016). For example, Miao et al. (2016) found that changes in the precipitation amount mainly resulted from changes in frequency rather than changes in intensity over mainland China based on hourly precipitation from the National Meteorological Information Center (NMIC). Li et al. (2016) analyzed station-measured NMIC hourly precipitation for the 1982–2012 warm season. The researchers observed that southwestern and southeastern China had experienced increasing rainfall frequency and overall increasing rainfall extremes. An analysis indicated a significant increase in rainfall extremes; accumulated precipitation is highly dependent on precipitation frequency (95%), while extremes are related to rainfall intensity (Li et al. 2016). Trenberth et al. (2017) concluded that the observed precipitation events usually persisted for 12–15 h over the oceans in the tropics and

subtropics, while precipitation lasted 20 h from the Community Earth System Model (CESM).

Climate models could provide continuous spatiotemporal hourly precipitation data for investigating its characteristics on a global or regional scale. The precipitation processes in regional climate models (RCMs) and general circulation models (GCMs) are very complex. These processes depend on cloud microphysics, cumulus convection, large-scale circulations, and other processes (Dai 2006). The relatively coarse resolution (typically at several hundred kilometers) of GCMs is one of the obstacles that may hamper the application of GCMs toward the study of precipitation (Schiemann et al. 2018), because those models poorly represent the physical processes evolving on regional and local time scales (Ploshay and Lau 2010). By increasing the spatial resolution of RCMs or GCMs, the details of topography, land use, coastlines, and other mesoscale processes can be resolved.

To this end, researchers have put effort into increasing the horizontal resolution of both RCMs (e.g., Qian and Giorgi 1999; Jacob et al. 2014; Giorgi et al. 2016) and GCMs (e.g., Duffy et al. 2003; Williamson 2013; Zarzycki et al. 2014a; Wu et al. 2017; Rahimi et al. 2019). These studies demonstrated the added value of enhanced resolution in producing the present-day or future climate. According to Giorgi et al. (2016), six RCMs (at a horizontal resolution of approximately 12 km) simulated an increase in summer precipitation over the high Alpine elevations during the twenty-first century, which is not present in the global coarse-scale projections. The increasing horizontal resolution of GCMs could improve the simulations of tropical precipitation (Jung et al. 2012), the land–sea breeze (Boyle and Klein 2010), and the summer monsoon onset over East Asia and West Africa (Zhang et al. 2018). Previous studies also reported that the variable-resolution version of CESM (regionally refined at a 0.125° resolution) exhibited more accurate monthly mean precipitation and heavy precipitation amounts than its uniform 1° counterpart in the Rocky Mountain region and the Tibetan Plateau (Wu et al. 2017; Rahimi et al. 2019). Roberts et al. (2018) found that large-scale circulations in the atmosphere were improved as the horizontal resolution of the GCM was increased, because the model was capable to capture the precipitation accurately in relatively small scales. However, previous studies also found the simulated climate of the high-resolution experiments was not dramatically better than that of their low-resolution counterparts with Community Atmosphere Model versions 4 and 5 (CAM4 and CAM5; Bacmeister et al. 2014). Thus, in terms of the simulated hourly precipitation features,

the effect provided by the enhanced-resolution GCMs remains uncertain.

Few studies have evaluated model-simulated hourly precipitation data with observations because high-resolution GCM results were difficult to obtain owing to computational limitations (Trenberth et al. 2017). In recent years, due to the improvements in model dynamical cores, physical processes and development of the high-performance computers, it is possible to simulate hourly precipitation at high spatial resolutions using GCMs (e.g., Dennis et al. 2012; Zhang et al. 2013). Moreover, advances in satellite observations now provide atmospheric data at high spatiotemporal resolutions, which allows for the closer study of precipitation frequency, intensity, and diurnal cycle (Dai 2006).

In this study, we seek to gain a better understanding of simulated hourly precipitation characteristics, such as its frequency, intensity, and amount, by conducting model experiments at coarse and high spatial resolutions using two GCMs. We assess the model simulated results with both satellite measurements and reanalysis data. Many previous studies (e.g., Stephens et al. 2010; Zarzycki et al. 2014a; Wu et al. 2017; Rahimi et al. 2019) primarily focused on simulated daily, monthly, or seasonal precipitation accuracy. This study reinforces the importance of enhanced horizontal resolution in simulating hourly precipitation, building on previous studies. The results could aid in obtaining a better understanding of the impacts of the model horizontal resolutions on simulated hourly precipitation and overall precipitation systems.

This manuscript is organized as follows. In section 2, the configurations of the two models and the experimental design are described. The dataset for validating the model results and the method used in this study are also presented in section 2. In section 3, comparisons between model-simulated hourly precipitation and observation/reanalysis are presented in terms of frequency, intensity, and amount. To show the detailed comparisons over regional scales, the results from several subregions are also analyzed in section 3. In section 4, the possible specific mechanisms that lead to different precipitation characteristics are discussed. The conclusions are given in section 5.

2. Models, experiments, and data

a. Models and experimental setup

Two models are adopted in this study. One model is the Chinese Academy of Sciences Earth System Model, version 1.0 (CAS-ESM), which was developed by a joint team inside/outside of the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS).

The atmospheric component of the CAS-ESM is the fourth version of the IAP atmospheric general circulation model (AGCM4.1; Zhang et al. 2013). The IAP AGCM4.1 is a global gridpoint model that uses a finite-difference dynamical core with a terrain-following σ coordinate (Phillips 1957). This model has previously been used to investigate the general circulation of the atmosphere as well as summertime precipitation (e.g., Lin and Zeng 1997; Xue et al. 2001; Li et al. 2018) and will be included in the Coupled Model Intercomparison Project phase 6 (CMIP6) model experiments. Yan et al. (2014) found that the meridional displacement of the East Asian subtropical westerly jet has a close relationship with precipitation over East Asia from both observations and IAP AGCM 4.0 simulation results. Xie et al. (2018) implemented cloud microphysical schemes considering the relative dispersion of the cloud droplet size distribution into the IAP AGCM 4.1, and analyses showed that this GCM effectively enhanced the large-scale precipitation.

The other model used in this study is the National Center for Atmospheric Research's Community Earth System Model, version 1.2.2 (CESM). The atmospheric component of the CESM is Community Atmosphere Model, version 5 (CAM5; Neale et al. 2012). CAM5 provides four dynamical cores with different approaches, including finite volume (FV), spectral element (SE), semi-Lagrangian (SLD), and Eulerian (EUL). For this study, we choose the FV dynamical core with hybrid sigma coordinate.

Both CAS-ESM and CESM support various combinations of component sets for different scientific applications. Here, four numerical experiments are carried out, which followed the global Atmospheric Model Intercomparison Project (AMIP) simulations (Gates 1992) with different horizontal resolutions (Table 1). Previous studies have noted that the GCMs with a horizontal resolution of approximately 50 km would improve some smaller-scale processes and substantially improved the precipitation patterns (Gent et al. 2010; Delworth et al. 2012). The increase in horizontal resolution would also better resolve the mesoscale processes (e.g., complex topography, mesoscale circulations, and land use), which will play an important role in precipitation formation (Demory et al. 2014; Roberts et al. 2018). Therefore, our selection on the model horizontal resolution of 50 km is sufficient to investigate the impacts of the model horizontal resolutions on hourly precipitation and it is a reasonable choice in terms of computer resources. The two CAS-ESM experiments are conducted at a relatively coarse horizontal resolution of 1.4° (latitude) $\times$ 1.4° (longitude) (hereinafter referred to as CAS-ESM L) and at a high horizontal

TABLE 1. Summary identification of the four experiments and their resolutions in the atmospheric models.

Experiment	Model/version	Resolution		Time step
		Horizontal (latitude $\times$ longitude)	Vertical (levels)	
CAS-ESM L	CAS-ESM v1.0	$1.4^{\circ} \times 1.4^{\circ}$	L30	20 min
CAS-ESM H		$0.5^{\circ} \times 0.5^{\circ}$		15 min
CESM L	CESM v1.2.2	$1.9^{\circ} \times 2.5^{\circ}$		30 min
CESM H		$0.47^{\circ} \times 0.63^{\circ}$		15 min

resolution of $0.5^{\circ} \times 0.5^{\circ}$ (CAS-ESM H). The two CESM experiments are conducted at a typical coarse horizontal resolution of 1.9° (latitude) $\times$ 2.5° (longitude) (CESM L) and at a high horizontal resolution of $0.47^{\circ} \times 0.63^{\circ}$ (CESM H). Both models have 30 vertical levels, with a top at 2.2 hPa in CAS-ESM and a top at 2.9 hPa in CESM.

All simulations use the CAM5 physical scheme combination (Neale et al. 2012). The components of the CAM5 physical package are given in Table 2. Over land, the lower boundary conditions in CAS-ESM and CESM are represented by the same land surface component, the Community Land Surface Model, version 4.5 (CLM4.5; Oleson et al. 2013). The AMIP simulations use the observed monthly sea surface temperatures (SST) and sea ice as the boundary conditions (Gates 1992). Monthly SST and sea ice from the Hadley Center SST (Rayner et al. 2003), as well as weekly SST data from the National Oceanic and Atmospheric Administration (Reynolds et al. 2002) are merged via the methods in Hurrell et al. (2008) to provide monthly updated SST and sea ice information within the model. Following the AMIP implementation, each simulation spans 21 years from 1 January 1996 to 31 December 2016, with the first two years regarded as model spinup, and the analyses are performed for 1998–2016. In the coarse-resolution experiments, the time steps are the default value, which are 20 and 30 min in CAS-ESM L and CESM L, respectively. The time steps are 15 min in both CAS-ESM H and CESM H.

b. Validation of model-simulated hourly precipitation

The total precipitation can be divided into two types based on different physical processes: convective precipitation and stratiform (large-scale) precipitation

(Houze 1997). Convective rainfall is an intermittent burst of liquid/solid precipitation associated with local upward airflow in an unstable atmosphere, whereas stratiform precipitation is associated with a relatively stable and weak large-scale forced ascent and/or detrainment (Houze 1997). Convective rain is generally of shorter duration and more intense than stratiform precipitation. Convective precipitation usually lasts from minutes to hours, whereas stratiform precipitation could last for many hours or days (Schroeder et al. 2018). The total hourly precipitation consists of convective and large-scale (resolved) precipitation in both models. Convective precipitation is induced by the moist convection, which occurs when there is convective available potential energy for the reversible ascent of an undiluted parcel in the subcloud layer (Zhang and McFarlane 1995). Large-scale precipitation is a proportional function of gridscale saturation, and a higher resolution directly produces more precipitation by an improved ability to resolve convergent and vertical motions (Morrison and Gettelman 2008). Therefore, 1-h temporal resolution from observations, reanalysis, and simulations is appropriate for resolving the features of both convective activity and large-scale ascent-inducing rainfall. Furthermore, simulated and observed subhourly rainfall events are characterized by noise associated with the mode numeric/physics, and observational sampling techniques (Trenberth et al. 2017). Thus, 1 h is also a typical and practicable temporal resolution for interpretation considering the high-frequency precipitation events. Above all, the focus of this study is on hourly precipitation from observations, reanalysis and all model simulations.

TABLE 2. Description of model parameterizations in the CAM5 (version 5.9) physical process scheme combinations.

Physical process	Physical scheme and references
Deep convection	Zhang–McFarlane (Zhang and McFarlane 1995)
Shallow convection	UW Shallow Convection (Park and Bretherton 2009)
Cloud microphysical scheme	Morrison and Gettelman (Morrison and Gettelman 2008)
Cloud macrophysical scheme	Park macrophysics (Neale et al. 2012)
Turbulent boundary layer	UW moist turbulence (Park and Bretherton 2009)
Radiation scheme	Rapid Radiative Transfer Method for GCMs (Iacono et al. 2008)
Chemistry emissions and mechanisms	Liu et al. (2012) (used in CAS-ESM L, CESM L, and CESM H; not used in CAS-ESM H)

To evaluate the model-simulated hourly precipitation, a high frequency and spatially dense observational dataset is necessary. The latest version of the Climate Prediction Center Morphing method (CMORPH v1.0 CRT; Xie et al. 2017) is an intensive hourly observational precipitation dataset on a 0.25° grid. Xie et al. (2017) reprocessed and bias-corrected CMORPH global high-resolution satellite precipitation estimates from January 1998 onward. We also use hourly precipitation reanalysis products at a resolution of $0.625^\circ \times 0.5^\circ$ from the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA2) of the Goddard Earth Observing System-5 (GEOS-5) atmospheric general circulation model (Gelaro et al. 2017). Previous studies (e.g., Wang and Zeng 2012; Reichle et al. 2017) have shown that MERRA/MERRA2 could capture the precipitation spatial pattern, realistic phasing of the diurnal cycle and are reliable at daily/monthly time scales except in polar regions. According to Casanueva et al. (2016), the comparison of the observational and simulated results on the coarse grid could be considered “fair” since different resolutions are able to resolve the analyzed features. Therefore, we interpolated CMORPH, MERRA2 and the simulations from CAS-ESM L, CAS-ESM H, and CESM H onto the grid scale of CESM L ($1.9^\circ \times 2.5^\circ$) using a conservative algorithm. CMORPH covers the region between 60°S and 60°N , and all analyses are carried out over this range.

At each grid box, the rain events are defined as all hours when the hourly precipitation rate exceeds 0.02 mm h^{-1} (hereafter referred to as measurable precipitation) during 1998–2016. In addition, a heavy rate threshold ($>2 \text{ mm h}^{-1}$, considered to be heavy precipitation) is also adopted to classify the precipitation events. In the following analyses, we consider the characteristics of measurable precipitation and heavy precipitation. The mean precipitation frequency (%) is defined as the percentage ratio of the number of hours in which measurable or heavy precipitation occurs to the total hours for the 1998–2016 period. The definition of precipitation intensity (mm h^{-1}) is the rainfall rate averaged over all hours of measurable or heavy precipitation. The mean precipitation amount (mm h^{-1}) is produced by the total accumulated rainfall amount divided by all hours during a certain period. The choice of precipitation thresholds (i.e., 0.02 and 2 mm h^{-1}) are similar to previous studies (Zhou et al. 2008; Trenberth et al. 2017).

To evaluate the performance of convective precipitation and large-scale precipitation from the four simulations, we define three ratios. Rc (Rl) is the percentage ratio of hourly convective precipitation (large-scale precipitation) to hourly total precipitation when measurable or heavy rainfall occurs. Rcl is the percentage

ratio of hourly convective precipitation to hourly large-scale precipitation when measurable or heavy rainfall occurs. The sum of Rc and Rl is equal to 1.

3. Evaluation of model-simulated hourly precipitation

To focus on the effects and added value of horizontal resolution on the simulated hourly precipitation, we compare simulations from both the low-resolution and high-resolution versions of each model in this section. We compute the frequency and intensity of measurable or heavy precipitation, and amount from CMORPH, MERRA2, and the simulations for those precipitation characteristics.

a. Precipitation frequency

Figures 1 and 2 show the geographic distributions of the long-term (1998–2016) annual mean frequency for measurable precipitation and heavy precipitation, respectively. The frequencies are characterized by apparent spatial variability, which are higher over ocean than over land according to CMORPH. CMORPH precipitation frequency presents the lowest value (e.g., $<4\%$ for measurable precipitation) in the subtropical highs over the eastern Pacific and Atlantic Oceans and North Africa. The frequency patterns of CMORPH show two key areas with high precipitation frequencies, which are located in the monsoon ranges (e.g., the East Asian summer monsoon; Wang et al. 2012) and the regions of tropical convergence [e.g., intertropical convergence zone (ITCZ), South Pacific convergence zone (SPCZ), and South Atlantic convergence zone]. Over the extratropical northwestern area of both the Pacific and Atlantic Oceans, CMORPH frequencies vary between 25% and 50% for measurable precipitation (Fig. 1a) and exceed 5% for heavy rain (Fig. 2a), respectively.

For measurable precipitation (Fig. 1), MERRA2 shows similar spatial patterns as CMORPH. On the other hand, Fig. 1 shows that the measurable precipitation frequency of MERRA2 was quite close to the simulation results. According to Gelaro et al. (2017) and Reichle et al. (2017), MERRA2 has ingested a merged satellite-derived precipitation estimates from Tropical Rainfall Measuring Mission (TRMM) and *Nimbus-7*. Previous studies (e.g., Rahimi et al. 2019) also pointed out the uncertainties in the satellite-based CMORPH products, especially over the complex terrain. The comparisons of CMORPH, MERRA2, and simulations might draw a conclusion that the hourly precipitation frequencies from CMORPH may be less than the actual “true” value. At best, CMORPH is a “sophisticated guess” as far as its precipitation frequency estimates.

FIG. 1. Spatial distributions of annual mean precipitation frequency (%) for the hourly measurable precipitation of (a) CMORPH, (b) MERRA2, (c) CAS-ESM L, (d) CAS-ESM H, (e) CESM L, and (f) CESM H during the 1998–2016 period.

A distinct overestimation of hourly precipitation frequency appears in CAS-ESM L and CESM L, although the models reproduce the broad observational patterns over ocean and land. Meanwhile, the high-resolution experiments do show some improvements of measurable precipitation ($>0.02 \text{ mm h}^{-1}$) frequency. Figure 1 shows different results between the low- and high-resolution experiments. In most regions over the ocean, high-resolution experiments decrease the precipitation frequency (Figs. S1a,b in the online supplemental material). The biases of frequency are reduced by about 35% in some parts of the tropical Pacific at high resolutions. Over land, CAS-ESM H outperforms CAS-ESM L by decreasing the rain frequency in parts of eastern Asia, North America, and along the Andes

(Fig. S1a), whereas the CESM H precipitation is more frequent than that of CESM L over land (Fig. S1b). Besides, based on the above estimates and uncertainties of CMORPH, biases of CAS-ESM H (or CESM H) from true measurable precipitation frequency may be smaller than that from CMORPH. Furthermore, the difference between low- and high-resolution experiments reflects the overall added value in the measurable precipitation frequency with enhanced-resolution models over oceans and certain regions over land. The mechanisms for the improvement of measurable precipitation frequency in high-resolution models will be discussed in section 4.

For the heavy rain, the spatial distribution and magnitude of MERRA2's frequency (Fig. 2b) agrees well

FIG. 2. As in Fig. 1, but for the hourly heavy precipitation (%).

with that of CMORPH (Fig. 2a). Both models at low resolutions (Figs. 2c,e) dramatically underestimate the frequency, especially over the tropical oceans. However, the skill in reproducing the spatial pattern and magnitude of heavy precipitation frequencies in the two high-resolution cases (Figs. 2d,f and Figs. S1c,d) is substantially better than those in the two low-resolution cases, especially in ITCZ areas, midlatitude oceans and monsoon regions. The spatial correlation coefficients (SCCs) of heavy rainfall frequency between the simulations and CMORPH are 0.31, 0.46, 0.38, and 0.63 for CAS-ESM L, CAS-ESM H, CESM L, and CESM H, respectively. These results imply the enhanced performance of high-resolution simulations. Although the simulated frequency magnitudes are quite similar to each other, CESM display slightly better performances

than CAS-ESM at both low and high resolutions for heavy precipitation.

Figure 3 shows latitudinal patterns of zonal mean precipitation frequency from CMORPH, MERRA2, and the four simulations averaged over land/ocean. The measurable precipitation frequency (Figs. 3a,c,e) in CMORPH varies with latitude and reaches a maximum of 50% near the equator and near 8°N over land and ocean regions, respectively. Compared to CMORPH, MERRA2 and the two models capture these latitudinal features of the frequencies of measurable rainfall, and an overestimation of simulated results is more severe over oceans than over land. The zonal mean hourly measurable frequencies produced by the high-resolution simulations are closer to those from CMORPH and MERRA2 compared to the corresponding low-resolution simulations,

FIG. 3. Zonal mean, annual average frequency (%) of (left) hourly measurable precipitation and (right) heavy precipitation over the (a),(b) globe, (c),(d) land, and (e),(f) ocean for CMORPH (black), MERRA2 (purple), CAS-ESM L (blue), CAS-ESM H (red), CESM L (orange), and CESM H (green) during the 1998–2016 period. Here, the frequency is a function of latitude.

except for the measurable precipitation frequency in CESM over land. The above zonal characteristics also appear in the heavy precipitation frequency (Figs. 3b,d,f) from CMORPH. MERRA2 has a larger frequency over land and a smaller value over the ocean compared with CMORPH estimates. Although simulated frequencies are slightly lower than those in CMORPH, high-resolution experiments reproduce better latitudinal patterns and peak frequencies in the tropical convection zones. This finding means that the added value of enhanced-resolution is prominent from the zonal curves in the cases of heavy rain used by CAS-ESM and CESM. Moreover, it also seems that there are some potential weaknesses in CMORPH's estimation precipitation frequency by comparisons of the zonal mean curves of CMORPH, MERRA2 and simulated results. Indeed, CMORPH may be low-balling the true measurable precipitation frequency.

To examine the seasonal performance of the precipitation frequency from the model simulations, Table 3 presents the area-weighted average frequency over the globe, land, and ocean in DJF (December–February), MAM (March–May), JJA (June–August), and SON (September–November). The interannual standard deviations of precipitation frequencies during 1998–2016 are also given in Table 3. The precipitation for CMORPH in DJF is less frequent than that in JJA, and the frequency in the transitional seasons (MAM and SON) falls between DJF and JJA over land. For instance, for the case of measurable precipitation, the frequencies over land are 18.48% in DJF, 22.08% in MAM, 25.07% in JJA, and 22.30% in SON. Seasonal variation is less pronounced over oceans than over land. Comparably, MERRA2 produces larger measurable precipitation frequency and heavy rain frequency over land but slightly smaller heavy rainfall over oceans during all seasons. Although the

TABLE 3. The area-weighted average frequency (ave; %) and standard deviations (std) for hourly measurable precipitation and heavy precipitation over globe, land, and ocean for CMORPH, MERRA2, CAS-ESM L, CAS-ESM H, CESM L, and CESM H in DJF, MAM, JJA, and SON during the 1998–2016 period.

		ave $\pm$ std					
		Measurable precipitation			Heavy precipitation		
		Global	Land	Ocean	Global	Land	Ocean
DJF	CMORPH	22.73 $\pm$ 1.28	18.48 $\pm$ 1.23	24.25 $\pm$ 1.34	1.20 $\pm$ 0.08	0.66 $\pm$ 0.08	1.39 $\pm$ 0.10
	MERRA2	49.60 $\pm$ 1.08	37.01 $\pm$ 0.65	54.08 $\pm$ 1.36	0.85 $\pm$ 0.04	0.88 $\pm$ 0.06	0.84 $\pm$ 0.04
	CAS-ESM L	64.13 $\pm$ 0.24	42.63 $\pm$ 0.51	71.79 $\pm$ 0.27	0.08 $\pm$ 0.01	0.03 $\pm$ 0.01	0.10 $\pm$ 0.01
	CAS-ESM H	60.32 $\pm$ 0.27	40.98 $\pm$ 0.47	67.22 $\pm$ 0.29	0.34 $\pm$ 0.02	0.22 $\pm$ 0.03	0.38 $\pm$ 0.02
	CESM L	57.95 $\pm$ 0.37	36.58 $\pm$ 0.71	65.56 $\pm$ 0.34	0.23 $\pm$ 0.03	0.08 $\pm$ 0.01	0.28 $\pm$ 0.04
MAM	CESM H	56.04 $\pm$ 0.23	38.51 $\pm$ 0.52	62.28 $\pm$ 0.28	0.66 $\pm$ 0.03	0.51 $\pm$ 0.03	0.71 $\pm$ 0.04
	CMORPH	23.79 $\pm$ 1.51	22.08 $\pm$ 1.71	24.40 $\pm$ 1.56	1.16 $\pm$ 0.10	0.67 $\pm$ 0.08	1.34 $\pm$ 0.12
	MERRA2	50.16 $\pm$ 1.27	38.29 $\pm$ 1.14	54.39 $\pm$ 1.40	0.82 $\pm$ 0.25	0.95 $\pm$ 0.24	0.77 $\pm$ 0.26
	CAS-ESM L	65.77 $\pm$ 0.43	46.11 $\pm$ 0.83	72.77 $\pm$ 0.39	0.06 $\pm$ 0.01	0.04 $\pm$ 0.01	0.07 $\pm$ 0.01
	CAS-ESM H	62.30 $\pm$ 0.40	44.09 $\pm$ 0.82	68.79 $\pm$ 0.36	0.30 $\pm$ 0.01	0.25 $\pm$ 0.02	0.32 $\pm$ 0.01
JJA	CESM L	59.10 $\pm$ 0.56	36.84 $\pm$ 0.92	67.03 $\pm$ 0.56	0.19 $\pm$ 0.02	0.14 $\pm$ 0.02	0.21 $\pm$ 0.02
	CESM H	57.67 $\pm$ 0.56	40.65 $\pm$ 0.78	63.73 $\pm$ 0.62	0.61 $\pm$ 0.03	0.58 $\pm$ 0.04	0.62 $\pm$ 0.04
	CMORPH	24.49 $\pm$ 1.65	25.07 $\pm$ 2.41	24.28 $\pm$ 1.58	1.15 $\pm$ 0.10	0.76 $\pm$ 0.09	1.28 $\pm$ 0.12
	MERRA2	51.91 $\pm$ 1.32	40.28 $\pm$ 1.19	56.05 $\pm$ 1.54	0.78 $\pm$ 0.03	0.94 $\pm$ 0.07	0.73 $\pm$ 0.04
	CAS-ESM L	65.66 $\pm$ 0.31	45.71 $\pm$ 0.71	72.77 $\pm$ 0.35	0.04 $\pm$ 0.01	0.02 $\pm$ 0.01	0.04 $\pm$ 0.01
SON	CAS-ESM H	62.66 $\pm$ 0.37	44.95 $\pm$ 0.56	68.97 $\pm$ 0.42	0.29 $\pm$ 0.01	0.25 $\pm$ 0.02	0.31 $\pm$ 0.01
	CESM L	59.22 $\pm$ 0.47	35.73 $\pm$ 0.88	67.59 $\pm$ 0.53	0.19 $\pm$ 0.03	0.21 $\pm$ 0.03	0.17 $\pm$ 0.04
	CESM H	58.77 $\pm$ 0.38	41.65 $\pm$ 0.88	64.87 $\pm$ 0.47	0.61 $\pm$ 0.03	0.58 $\pm$ 0.03	0.62 $\pm$ 0.03
	CMORPH	23.85 $\pm$ 1.50	22.30 $\pm$ 1.96	24.41 $\pm$ 1.46	1.14 $\pm$ 0.09	0.67 $\pm$ 0.07	1.31 $\pm$ 0.11
	MERRA2	49.52 $\pm$ 0.99	37.27 $\pm$ 0.85	53.89 $\pm$ 1.18	0.78 $\pm$ 0.02	0.90 $\pm$ 0.06	0.73 $\pm$ 0.02
	CAS-ESM L	63.88 $\pm$ 0.43	44.65 $\pm$ 1.02	70.73 $\pm$ 0.37	0.06 $\pm$ 0.01	0.03 $\pm$ 0.01	0.08 $\pm$ 0.10
	CAS-ESM H	60.52 $\pm$ 0.38	43.29 $\pm$ 1.00	66.67 $\pm$ 0.41	0.31 $\pm$ 0.01	0.22 $\pm$ 0.01	0.34 $\pm$ 0.02
	CESM L	56.87 $\pm$ 0.46	35.48 $\pm$ 0.69	64.49 $\pm$ 0.49	0.19 $\pm$ 0.02	0.12 $\pm$ 0.02	0.22 $\pm$ 0.02
	CESM H	55.77 $\pm$ 0.44	40.06 $\pm$ 0.89	61.37 $\pm$ 0.47	0.60 $\pm$ 0.02	0.55 $\pm$ 0.04	0.62 $\pm$ 0.02

simulations considerably overestimate the frequency of measurable precipitation over land, the seasonal variations are well reproduced by CAS-ESM L, CAS-ESM H, and CESM H; CESM L poorly simulates this seasonal variance. Compared to CAS-ESM L, the frequency of measurable precipitation decreases in CAS-ESM H over both land and oceans in all seasons. For CESM, the precipitation also decreases as the resolution increases over the oceans, but it is the opposite performance over land during all seasons. The measurable rainfall frequency in CAS-ESM H is better than the CESM H over land. This finding indicates that the precipitation frequency is not always improved in the high-resolution experiments. For the heavy precipitation case, three of the simulations (except for CAS-ESM L) represent the seasonal change well over both land and ocean. Furthermore, the high-resolution experiments are improving upon the low-resolution experiments in simulating heavy rainfall frequency over both land and oceans during all seasons. It indicates that the higher-resolution models have a higher skill for the heavy precipitation frequency behaviors during all seasons. From Table 3, the interannual variability in CMORPH is greater than that in MERRA2,

except for the heavy rainfall in MAM. The standard deviations of simulated precipitation frequency by all experiments are smaller than those in CMORPH, indicating a smaller year-to-year variability in the frequencies of the models compared to CMORPH.

An important motivation for conducting high-resolution simulations is to reproduce the regional climate and to capture mesoscale circulations (Bacmeister et al. 2014). To further investigate the regional performances of model simulations in terms of hourly precipitation properties, we divide the global land areas into nine subregions (Trenberth and Zhang 2018). Figure 4 shows the regional average statistics of frequencies over nine subregions from the above datasets. In addition to the heavy rainfall frequencies over Europe and South America, MERRA2's measurable or heavy precipitation frequencies are higher than those of CMORPH in most land subregions. The measurable precipitation frequencies of MERRA2 even exceed all simulated results in Europe and the Maritime Continent. The precipitation frequencies in high-resolution experiments are closer to CMORPH and MERRA2 than those from the low-resolution experiments in all subregions, except the CESM's measurable precipitation frequencies. Compared to CAS-ESM L, CAS-ESM H

FIG. 4. The area-weighted average frequency (%) of hourly measurable precipitation (numbers with gray background) and heavy rainfall (numbers with white background) for over land only for CMORPH (black), MERRA2 (purple), CAS-ESM L (blue), CAS-ESM H (red), CESM L (orange), and CESM H (green) during the 1998–2016 period. The nine subregions in the plot are as follows: Europe: 35°–60°N, 20°W–60°E; Africa: 40°S–35°N, 20°W–40°E; North Asia: 35°–60°N, 60°E–180°; South Asia: 10°–35°N, 60°–150°E; Maritime Continent: 10°S–10°N, 90°–170°E; Australia: 45°–10°S, 110°–160°E; North America: 25°–60°N, 130°–50°W; Central America: 0°–25°N, 120°–40°W; and South America: 60°S–0°, 100°–30°W.

exhibits lower frequencies of measurable rainfall and higher intense precipitation frequencies. The measurable or heavy precipitation frequencies are higher in CESM H than CESM L in all subregions. This result implies that the effect of the horizontal resolution for measurable precipitation depends on the model, but the enhanced-resolution has a consistent added value to heavy rainfall over different regions. Taking North Asia as an example, the heavy precipitation frequencies are 0.20% and 0.24% from CMORPH and MERRA2, respectively. The precipitation frequencies of heavy rain increase from 0.05% to 0.19% in CAS-ESM and from 0.19% to 0.25% in CESM over North Asia. CESM H's heavy rain results are relatively closer to those of CMORPH than the other three AMIP simulations in all subregions. Similar results are found in the other eight subregions.

b. Precipitation intensity and amount

Figures 5 and 6 illustrate the spatial distributions of the annual mean intensity for hourly measurable precipitation

and heavy rainfall, respectively. For measurable precipitation, CMORPH shows a maximum intensity of 0.7–1.5 mm h^{−1} over the monsoon areas (e.g., India Peninsula, East Asia, east coast of North America, and South America), the tropical convection zones and midlatitude oceans (Fig. 5a), which are consistent with the previous studies (e.g., Dai 2006). The measurable precipitation intensity in MERRA2 (Fig. 5b) resembles to CMORPH with the lower magnitude. Comparably, the general intensity patterns in the hourly measurable precipitation are well reproduced by CAS-ESM and CESM. However, both models underestimate the measurable precipitation intensity compared to CMORPH and MERRA2. High-intensity bands in the tropics are too narrow in the simulation results (e.g., hourly precipitation > 0.5 mm h^{−1} in Fig. 5), with larger biases in the simulations at low resolutions than at high resolutions. Previous studies have shown similar simulated results. In these previous studies, the GCMs reproduced a more frequent measurable precipitation than the observed,

FIG. 5. Spatial distributions of the annual mean precipitation intensity (mm h^{-1}) for hourly measurable precipitation for (a) CMORPH, (b) MERRA2, (c) CAS-ESM L, (d) CAS-ESM H, (e) CESM L, and (f) CESM H during the 1998–2016 period.

which led to a simulated rainfall intensity that was far too small over most of the low latitudes (e.g., Dai 2006; Stephens et al. 2010). Averaged globally, the mean annual measurable precipitation intensities are 0.42 and 0.25 mm h^{-1} from CMORPH and MERRA2, respectively. The simulation counterparts are 0.18, 0.22, 0.21, and 0.24 mm h^{-1} for CAS-ESM L, CAS-ESM H, CESM L, and CESM H, respectively, which further emphasizes the intensity improvements from the high-resolution simulations.

Heavy rainfall is relatively abundant in the tropical convection zones, west of the midlatitude oceans and the monsoon regions over land ($>3 \text{ mm h}^{-1}$) from CMORPH (Fig. 6a). By analyzing Figs. 2a and 6a together, the regions with high precipitation intensities are

also the areas with relatively high heavy precipitation frequencies. This finding may indicate that the frequency of hourly precipitation is partly related to the intensity. The MERRA2 counterpart, with a relatively strong value in equatorial regions (Fig. 6b), is not much different from CMORPH. The global mean heavy precipitation intensities are 3.05 and 2.93 mm h^{-1} from CMORPH and MERRA2, respectively. As shown in Fig. 6, both CAS-ESM L and CESM L suffer from a weak intensity of heavy precipitation. CAS-ESM H and CESM H exhibit improvement over their low-resolution counterparts in monsoon areas, over land and across tropical convection zones, but CESM H's intensity (Fig. 6f) is too strong over most tropical oceans. The global area-weighted averages are 1.42, 2.34, 1.30, and

FIG. 6. As in Fig. 5, but for hourly heavy rainfall (mm h^{-1}).

2.69 mm h^{-1} for CAS-ESM L, CAS-ESM H, CESM L, and CESM H, respectively.

From the above analyses, both CAS-ESM and CESM overestimate the frequency of hourly measurable rainfall (Fig. 1) but underestimate the intensity of hourly precipitation (Fig. 5). As a result, the broad spatial pattern of the annual amount from the simulated hourly precipitation is generally similar to that of CMORPH and MERRA2 (Fig. 7). Quantitative comparisons of amount [including global area-weighted average, the root-mean-square error (RMSE) and SCC] are shown in Fig. 8. MERRA2 and simulated precipitation amounts are larger than CMORPH, especially in parts of the western Pacific Ocean, Indian Ocean, Atlantic Ocean, and along the southern part of the Tibetan Plateau (Fig. 8a and Fig. S2). Simulated precipitation amount

noticeably changes with grid spacing. For the two low-resolution simulations, dry biases are present across the eastern portions of the Indian Ocean, which are partly reduced in CAS-ESM H and CESM H. The amount in the eastern Pacific Ocean also becomes more abundant in the high-resolution cases than in the low-resolution cases. Over land, the negative bias in South America is noticeably reduced in CAS-ESM H (CESM H) compared to CAS-ESM L (CESM L). Furthermore, the increasing resolution has an enhanced effect of rainfall (Fig. 8a), which is probably caused by the increasing intensity (Figs. 5, 6). MERRA2 has the highest RMSE values (Fig. 8b) over both land (0.15 mm h^{-1}) and ocean (0.10 mm h^{-1}). High-resolution simulations show increased RMSE and SCC compared to the low-resolution simulations. CAS-ESM H not only reproduces the closest

FIG. 7. Spatial distributions of annual mean precipitation amount (mm h^{-1}) for (a) CMORPH, (b) MERRA2, (c) CAS-ESM L, (d) CAS-ESM H, (e) CESM L, and (f) CESM H during the 1998–2016 period.

RMSE to that of CMORPH globally and over the ocean but also has the largest SCC values globally and over land. The improvements in the high-resolution experiments compared to the low-resolution experiments are attributed by changes in both convective and large-scale rainfall (section 4).

The term “monsoon” is generally applied to tropical and subtropical seasonal reversals in precipitation, and global/regional monsoon precipitation domains were defined in previous studies (Trenberth et al. 2000; Wang et al. 2012). On the other hand, the tropical precipitation maximum regions are located in the ITCZ and SPCZ positions (e.g., Donohoe et al. 2013). GCMs with coarse resolutions have difficulty in accurately simulating mean precipitation and heavy rain over monsoon domains and

much of the tropics (e.g., Sperber et al. 2013; Lin et al. 2014). To validate the effect of horizontal resolution on hourly precipitation in monsoon regions and tropical convergence zones, Fig. 9 shows a comparison of the probability density functions (PDFs; the frequency versus hourly precipitation amount) of precipitation from all simulations and the corresponding CMORPH and MERRA2 values (note that it is the logarithmic scale in the y coordinate). We adopt all the summer (i.e., JJA for the Northern Hemisphere, DJF for the Southern Hemisphere) hourly precipitation data at all grid cells in eight subregions (including six monsoon regions over land and two convergence zones over the oceans) during 1998–2016. Note the six regional monsoon regions (Wang et al. 2012) in Fig. 9

FIG. 8. Area-weighted (a) average amount and (b) RMSE for CMORPH, MERRA2, CAS-ESM L, CAS-ESM H, CESM L and CESM H during the 1998–2016 period (mm h^{-1}), and (c) the SCCs between MERRA2 or the simulations and CMORPH.

are as follows: the North African monsoon region (NAF), the South African monsoon region (SAF), the East Asian/Indian/western North Pacific monsoon region (EAS+IND+WNP), the Australian monsoon (AUS), the North American monsoon (NAM), and the South American monsoon (SAM).

A distinct exponential decay with an increasing precipitation rate is presented in each subregion from CMORPH. MERRA2's PDF distributions nearly coincide with CMORPH in all subregions. Both CAS-ESM and CESM could reproduce the exponential decay distributions of the frequency, with an overestimation of the relatively light rainfall magnitude ($<1 \text{ mm h}^{-1}$). Obviously, the patterns of CAS-ESM L (CESM L) significantly underestimate the heavy rainfall frequency and decay faster than those of CAS-ESM H (CESM H). For instance, CAS-ESM L and CESM L can only reproduce heavy events of up to approximately 2 and 9 mm h^{-1} in the NAF (Fig. 9a), which clearly does not coincide with the results of CMORPH and MERRA2. On the other hand, both CAS-ESM H and CESM H substantially improve the PDF metrics compared to CAS-ESM L and CESM L. In particular, the high-resolution simulations could reproduce the extreme heavy rainfall events observed in CMORPH, and the range of high-resolution simulations nearly encompasses the CMORPH in each monsoon region and convergence zone. Notably, CESM L outperforms CAS-ESM L

with respect to the PDF metrics, which may result from the different dynamical cores, horizontal resolutions and time steps. In contrast to CAS-ESM H, CESM H shows higher heavy rainfall frequencies, even higher than CMORPH and MERRA2 in the NAM (Fig. 9e) and ITCZ (Fig. 9g).

4. Possible mechanisms of the differences

a. Convective precipitation, large-scale precipitation, and vapor flux

Compared to the low-resolution cases, two high-resolution experiments have lower frequencies over the oceans and stronger rain intensities of hourly measurable precipitation. Interestingly, CAS-ESM H (CESM H) simulates a higher frequency and stronger intensity of hourly heavy precipitation than that of CAS-ESM L (CESM L). To understand what causes the results, Fig. 10 presents the regional area-weighted average convective and large-scale precipitation over the eight subregions (the selected regions same as shown in Fig. 9) from MERRA2 and all simulations in JJA and DJF. Overall, two models produce stronger convective precipitation than MERRA2, whereas they simulate less large-scale precipitation (see also Fig. S3) over land, especially in the summer season over the NAM, EAS+IND+WNP, and AUS. It indicates that

FIG. 9. Hourly precipitation rate empirical PDFs (frequency vs hourly precipitation amount) for CMORPH (black), MERRA2 (purple), CAS-ESM L (blue), CAS-ESM H (red), CESM L (orange), and CESM H (green) in different monsoon regions and the ITCZ and SPCZ in summer (JJA in the Northern Hemisphere, DJF in the Southern Hemisphere). (a)–(f) Only the data over land were used, and (g)–(h) only the data over oceans were used. Note that the scale is logarithmic. The different monsoon regions are defined in Wang et al. (2012), ITCZ: 0°–15°N, 125°E–85°W; and SPCZ: 30°S–0°, 140°E–110°W.

the reason for more precipitation amount in simulations (Fig. 8a) than CMORPH is that both models reproduce too much convective precipitation.

Figure 11 shows the time-averaged difference of convective and large-scale precipitation for CAS-ESM H (CESM H) minus CAS-ESM L (CESM L) in JJA and DJF. Generally, high-resolution experiments simulate less convective precipitation than the low-resolution ones (Fig. 11, left-hand side), which thus were closer to MERRA2. CAS-ESM H (CESM H) produces stronger convective rainfall than CAS-ESM L (CESM L) over some tropical regions. The reason is mainly related to the deep convection scheme (Fig. S4) since it contributes to a majority of the rainfall in tropics. The other part of

rainfall in the tropics is related to the shallow cumulus scheme (not shown). Meanwhile, high-resolution experiments obviously simulate stronger large-scale precipitation than the low-resolution experiment, especially over tropical and midlatitude oceans and monsoon regions (Fig. 11, right-hand side). The results are consistent in different subregions (Fig. 10). Therefore, the decreased measurable precipitation frequency is likely to be the result of biases in the convective schemes, especially the deep convective schemes. The improvement of measurable precipitation intensity and heavy characteristics are possibly related to the large-scale precipitation. As horizontal resolution is enhanced, the tropics (extratropics) in CAS-ESM H becomes wetter (drier) for both DJF and

FIG. 10. Hourly convective precipitation (red) and large-scale precipitation (blue) for MERRA2, CAS-ESM L, CAS-ESM H, CESM L, and CESM H in different monsoon regions and the ITCZ and SPCZ in JJA and DJF. In monsoon regions, only the data over land were used. In ITCZ and SPCZ, only the data over oceans were used. The different subregions are the same used in Fig. 9.

JJA (Figs. 11a,e). The possible reason is that CAS-ESM H may be more capable of capturing the general circulation of the atmosphere through enhancing (depressing) tropical (extratropical) convection. Meanwhile, CESM H generally exhibits drying signals in the tropics, which is less pronounced in the extratropics (Figs. 11c,g). This implies CESM H may be more skillful in producing atmosphere general circulation via depressing tropical convective activities.

Furthermore, convective and large-scale cloud systems employ different treatments of microphysics (Morrison and Gettelman 2008), which also affect the total precipitation. Figures 12 and 13 illustrates the simulated in-cloud ice number concentration (cm^{-3}) and in-precipitation snow number concentration (L^{-1}) in JJA, respectively (similar results in other seasons, not shown). Both ice and snow numbers are high near the tropical tropopause, which is in close relationship with strong convection. Obviously, two models produce less ice/snow number concentration at high resolutions. The high-resolution experiments require

less adjustment from the convective schemes due to increased large-scale resolved updrafts (Zarzycki et al. 2014b). The experiments simulate less number concentration, then the occurrences of cloud ice and snow also need more time. The frequency of convective precipitation falling to ground is delayed. It indicates that the weaker convective precipitation (Figs. 10, 11) is mainly caused by less frequency. As a result, total measurable precipitation frequency would be reduced in the high-resolution experiments. On the other hand, CAS-ESM H has larger cloud ice effective radius and in-precipitation snow mixing ratio in the tropopause, which is opposite to the result in CESM H (not shown). It implies that high-level cloud fractions (Fig. S5) are different in two models, which likely relate to the various performance of convective rainfall in the tropical latitudes.

Figure 14 illustrates the simulated column (i.e., vertically integrated) cloud droplet concentration in JJA. Simulated cloud droplet numbers are high in storm track regions, in particular, over East Asia,

FIG. 11. Spatial pattern of different (left) convective and (right) large-scale precipitation from CAS-ESM H minus CAS-ESM L, and CESM H minus CESM L in JJA and DJF during the 1998–2016 period.

Africa, and North America. Cloud droplet numbers are low over tropical oceans and subtropical land regions, which are consistent with results in Morrison and Gettelman (2008). High-resolution experiments produce more cloud droplet numbers over oceans and

monsoon regions. Meanwhile, CAS-ESM H (CESM H) simulates larger cloud droplet effective radius, cloud droplet numbers, in-precipitation rain mixing ratio, and rain number concentration (figures not shown), as well as more low cloud fraction (full of liquid cloud; Fig. S5)

FIG. 12. Zonal-mean in-cloud ice number concentration (cm^{-3}) as a function of latitude and pressure for (a) CAS-ESM L, (b) CAS-ESM H, (c) CESM L, and (d) CESM H in JJA during the 1998–2016 period.

than those of CAS-ESM L (CESM L). Those changes lead to enhancement of large-scale precipitation, which is also in agreement with the improvement of precipitation intensity and amount. It also indicates the decreased convective frequency is faster than the increased large-scale precipitation frequency, since total measurable precipitation frequency decreased. Besides, the higher measurable frequency possibly relates to the more frequent large-scale precipitation in CESM H.

Figure 15 shows the time-averaged distributions of simulated Rc and RI of heavy rainfall in JJA during 1998–2016. CAS-ESM L shows convective (Fig. 15a) and large-scale precipitation (Fig. 15b) over only small parts of the middle and high-latitudes. However, CAS-ESM H (Figs. 15c,d) can reproduce convective and large-scale precipitation in both the tropics and monsoon regions,

which fits well with the frequency distribution of heavy rainfall (Fig. 2d). The improved representation of convective and large-scale precipitation in CAS-ESM H makes the model more likely to produce heavy rainfall than CAS-ESM L. The CESM result is different from that of CAS-ESM. CESM L has a greater Rc than RI in the tropics and subtropics, while the opposite occurs in the mid- and high latitudes (Figs. 15e,f). The convective ratio decreases and the large-scale ratio increases over the tropical convergence zones and monsoon regions in CESM H (Figs. 15g,h). The results clearly suggest that the increases in heavy rainfall frequency and intensity are due to the physical parameterization of large-scale precipitation and not the CESM convective precipitation. This finding is consistent with the results of O'Brien et al. (2016).

FIG. 13. As in Fig. 12, but for in-precipitation snow number concentration (L^{-1}).

Water vapor transport is necessary for producing precipitation, especially heavy rainfall. Figure 16 shows the time-averaged difference of zonal and meridional vertical integrated vapor flux for CAS-ESM and CESM in JJA and DJF. The westward water vapor transport associated with tropical easterlies is pronounced in the tropics and subtropics in JJA (Fig. S6). The eastward zonal and northward meridional vapor transports are also evident in the Indian monsoon region and its surrounding areas. The zonal integrated water vapor transport is stronger in CAS-ESM H (CESM H) than in CAS-ESM L (CESM L) over the Indian monsoon region or East Asia (Figs. 16a,c), which leads to the increasing PDFs of heavy rainfall over the regions (Fig. 9c). Compared to CESM L, the westward vapor transport increases in the eastern tropical Pacific and Atlantic Ocean and midlatitude East Asia but decreases

in the northern Indian Ocean. When horizontal resolution is enhanced, the westward water vapor increases in the eastern part of the Pacific and decreases in the northern Indian Ocean in CESM (Fig. 16c). The patterns lead to a vapor flux convergence along the tropical Pacific, which is in favor of increasing heavy rainfall. In DJF, CAS-ESM H produces stronger westward and northward water vapor fluxes (Figs. 16e,f) than CAS-ESM L over the tropical Pacific, which contributes to the heavy rainfall in AUS, ITCZ, and SPCZ. The above convergence also appears in SPCZ and the tropical eastern parts of the Pacific in CESM for DJF (Fig. 16g). In addition, the different meridional vapor transports also contribute to the rainfall frequency and intensity. For example, compared to CAS-ESM L (CESM L), the northward vapor transport over EAS+IND+WNP region in JJA (Figs. 16b,d) the southeastern tropical

FIG. 14. The column (vertically integrated) cloud droplet number concentration (10^6 cm^{-2} or 10^{10} m^{-2}) from (a) CAS-ESM L, (b) CAS-ESM H, (c) CESM L, (d) CESM H, (e) CAS-ESM H minus CAS-ESM L, and (f) CESM H minus CESM L in JJA during the 1998–2016 period.

Pacific in DJF (Figs. 16f,h) is increased in CAS-ESM H (CESM H), which results in more frequent rainfall and a stronger intensity in those regions. High-resolution experiments (Figs. 16f,h) also have a stronger southward vapor transport than low-resolution experiments along the Andes Mountain, which are in accordance with the heavy rainfall intensity along this mountain.

b. Topography

In our simulations, the major difference between CAS-ESM L (CESM L) and CAS-ESM H (CESM H) is terrain. When horizontal resolutions are enhanced, both models increase consistently in their heavy precipitation

frequencies. The main reason for the increase may be that the topography is better described in CAS-ESM H and CESM H. The Tibetan Plateau and Andes Mountains have a significant influence on large-scale or regional-scale atmospheric circulation by modifying stationary wave patterns (e.g., Insel et al. 2010). To understand the effect of the resolution on the heavy precipitation frequency in complex terrain, Fig. 17 illustrates the different frequencies of heavy rainfall over East Asia (JJA) and South America (DJF) from CAS-ESM H (CESM H) minus CAS-ESM L (CESM L). Figure 17 also shows the meridional (Fig. 17e) and zonal (Fig. 17f) mean heavy precipitation frequencies along the original topography

FIG. 15. Spatial distributions of (left) Rc and (right) RI (%) for heavy precipitation for (a),(b) CAS-ESM L, (c),(d) CAS-ESM H, (e),(f) CESM L, and (g),(h) CESM H in JJA during the 1998–2016 period.

(no interpolation), averaged from 85° to 87.5°E in JJA (a belt region in the Tibetan Plateau, hereinafter referred to as TP, the black box in Figs. 17a,b) and from 19.89° to 21.79°S in DJF (a small area in the Andes Mountains, hereinafter referred to as AM, the black box in Figs. 17c,d), respectively. Except in some regions of East Asia from

CESM H, the high-resolution experiments produce stronger frequencies of heavy rainfall than the low-resolution experiments in southern parts of the Tibetan Plateau and eastern sides of the Andes Mountains. The maximal frequencies in MERRA2, CAS-ESM H and CESM H appear at the same latitude (longitude) in TP

FIG. 16. Spatial pattern of different (left) zonal and (right) meridional average integrated water vapor flux for (a),(b) CAS-ESM H minus CAS-ESM L and (c),(d) CESM H minus CESM L in JJA, and (e),(f) CAS-ESM H minus CAS-ESM L and (g),(h) CESM H minus CESM L in DJF during the 1998–2016 period.

(AM) from the curves. Both CAS-ESM H and CESM H agree with MERRA2 better than CAS-ESM L and CESM L in TP and AM (Figs. 17e,f). This finding indicates the improvement in the high-resolution

experiments, considering that the reanalysis products are more reliable than the observational data over complex regions (e.g., Winiger et al. 2005; Palazzi et al. 2013).

FIG. 17. Spatial distributions of different frequencies (%) for hourly heavy rainfall for (a),(c) CAS-ESM H minus CAS-ESM L and (b),(d) CESM H minus CESM L in JJA in (a) and (b) and DJF in (c) and (d) during the 1998–2016 period; the meridional and zonal distribution of the topography (top dashed curves; km) and heavy precipitation frequency (bottom solid curves) are averaged zonally (e) from 85° to 87.5°E and (f) from 19.89° to 21.79°S and calculated from the black boxes in (a)–(d) in summer during the 1998–2016 period. The terrain is the original data in each simulation.

Compared to CMORPH, MERRA2 and all experiments nearly reproduce lower heavy rainfall frequencies in the area south of 25.58°N, but higher values in the area north of 25.58°N in the TP (Fig. 17e). CAS-ESM H could reproduce the heavy rainfall frequency, whereas CAS-ESM L can hardly simulate the results. The heavy rainfall of CESM L is more frequent than that of CESM H between 25.58° and 31.26°N. In AM, both CMORPH and CESM L show the maximum located at 62.5°W, but MERRA2, CAS-ESM H and CESM H exhibit the maximum at 65°W (Fig. 17f). What contributes to the difference between CAS-ESM L (CESM L) and

CAS-ESM H (CESM H) includes various terrain heights, along with the different gradient in height from 26° to 32°N and time steps. From the physical explanations via Rahimi et al. (2019), the high-resolution experiments better represent the topographic variance and gradient, more accurately simulate moisture convergence, and the heavy precipitation frequency is well captured in the high-resolution simulations.

This mechanism is true for CAS-ESM, whereas it does not apply to CESM in the simulations, since the different performances of convective physical parameterization in the two models. Obviously, the topography in CESM H

is better resolved than that in CESM L, but the heavy precipitation frequency is stronger in CESM L than in CESM H between 25.58° and 31.26°N. From Figs. 12 and 13, the decreasing rate of ice numbers and snow numbers are faster in CESM than in CAS-ESM as resolution is enhanced. In the TP, CAS-ESM H simulates more convective precipitation amount (Fig. 11a) and larger Rc (Fig. 15c) than CAS-ESM L. CESM H produces less convective rainfall (Fig. 11c) and smaller Rc (Fig. 15g) than CESM L. It implies that the convective heavy rainfall frequency decreases too much, which causes the decrease in lower heavy precipitation frequency in the TP for CESM H. Further analysis shows that CAS-ESM H has heavier low clouds, larger relative humidity in the low layers, and a more consistent upward vertical velocity than CAS-ESM L in the southern TP (Fig. S7). Compared to CESM L, CESM H has fewer clouds, lower relative humidity, and weaker upward vertical velocity from the bottom layer to the top layer in the south part of the TP (Fig. S7), also suggesting a lower heavy precipitation frequency in CESM H.

The Andes Mountains profoundly influence the moisture transport, deep convective processes, and precipitation through a mechanical forcing of the low-level jet and topographic blocking of the westerly flow over South America (Insel et al. 2010). The distinct appearance of heavy rainfall frequency in eastern parts of AM is due to effectively capturing the variation in the terrain in CAS-ESM H and CESM H. In addition, the upward velocity is stronger in CAS-ESM H (CESM H) than in CAS-ESM L (CESM L) at approximately 65°W (Fig. S8), which leads to higher heavy precipitation. As horizontal resolution is enhanced, it will push closer to the limit of hydrostatic approximation. In such cases, the vertical acceleration is not relatively small and cannot be negligible (Markowski and Richardson 2010). The pressure perturbation gradient force cannot be deduced accurately using an integrated form of the hydrostatic equation (Markowski and Richardson 2010) as that used in both IAP AGCM4 and CAM5, which may cause the increase in the upward velocity in the high-resolution experiments.

The horizontal resolution increases, the time step will decrease in experiments. Based on previous studies (e.g., Williamson and Olson 2003; Williamson 2013; Wan et al. 2015; Rahimi et al. 2019), both time step and horizontal resolution could make difference to the characteristics of hourly precipitation. In CESM, the time steps are 30 and 15 min in CESM L and CESM H. The time steps are relatively close to each other in CAS-ESM (20 and 15 min in CAS-ESM L and CESM H, respectively). Compared to CAS-ESM L, the main improvements in the CAS-ESM H were very likely brought about by increased horizontal resolution

rather than physics time step reductions. It seems that the frequency, intensity and amount are more sensitive to changes in the model horizontal resolutions than reduction of time steps. To quantitatively identify which plays a more important role, we will run CAS-ESM/CESM with the same physics time steps as in the high-resolution experiments to study this time-step issue in future work.

Furthermore, CAS-ESM H has a weaker upward vertical velocity (ω , negative means upward air-flow) than CESM H along the southern side of the TP (Fig. S7f,l), but the opposite is true along the eastern side of the Andes (Figs. S8f,l). As the terrain curves nearly coincide, the physical schemes and time steps are the same, the different values in the precipitation frequency peak between CAS-ESM H and CESM H may result from the different model dynamical cores and coupling of the dynamical cores and physical parameterization. If the same atmospheric governing equations are formulated differently, the discretization methods can make them different. As mentioned in section 2a, the traditional finite-difference scheme with a terrain-following σ coordinate is used in IAP AGCM4. Other details about the dynamical core are shown in Zhang et al. (2013). The FV dynamical core is selected in CAM5 for our simulations. The quasi-uniform polygonal mesh is used for the finite-volume method. In physical space, a conservative “flux-form semi-Lagrangian” scheme is applied in the horizontal discretization, and a conservative remapping (makes it quasi-Lagrangian) is used in the vertical discretization (Neale et al. 2012). The main differences between the two dynamical cores are as follows: 1) conservation of available potential energy in the IAP core versus conservation of total energy by an energy fixer in CAM5; 2) in IAP AGCM, u is a function of longitude and v is a function of latitude in the one-half grid, whereas the location is the opposite in CAM5; and 3) subtraction of standard stratification is only used in the IAP model. The issue of how interactive physical processes, especially clouds and relative humidity, change the behavior of the two dynamical cores is complex. The knowledge of isolated and fully physical dynamical cores is not the subject of this study.

5. Conclusions and discussion

In this study, the effects of horizontal resolution on the characteristics of hourly precipitation from four AMIP style simulations were investigated using two state-of-the-art models (i.e., CAS-ESM and CESM). The simulations were carried out at typical coarse resolutions of $1.4^\circ \times 1.4^\circ$ in CAS-ESM (CAS-ESM L) and $1.9^\circ \times 2.5^\circ$ in CESM (CESM L) and at high resolutions

of $0.5^\circ \times 0.5^\circ$ in CAS-ESM (CAS-ESM H) and $0.47^\circ \times 0.63^\circ$ in CESM (CESM H). Driven by the same observed SST forcing, all experiments were run from 1 January 1996 through 31 December 2016 (Table 1). The simulated hourly precipitation during 1998–2016 was validated against high-resolution, high-quality satellite observations [CMORPH, bias-corrected by Xie et al. (2017)] and the MERRA2 reanalysis dataset (Gelaro et al. 2017).

The intercomparison among CMORPH, MERRA2, and simulations were mainly performed on the CESM L grid (the lowest horizontal resolution of all experiments). Our analyses focused on the different metrics related to the spatial patterns and statistics of mean frequency, intensity, and amount of hourly measurable precipitation ($>0.02 \text{ mm h}^{-1}$) and heavy precipitation ($>2 \text{ mm h}^{-1}$) in the annual mean and different seasons covering 60°S – 60°N , within which the satellite observation dataset is available. The main results of this manuscript are as follows:

- 1) The measurable precipitation frequencies for high-resolution experiments perform better than low-resolution counterparts over oceans and some regions over land. The performance of heavy rainfall characteristics obviously exhibited improvement in high resolution simulations. The zonal mean, seasonal mean, and area-weighted average hourly rainfall frequency also supported the above results. Moreover, the high-resolution simulations reproduced the seasonal variations in average seasonal precipitation frequency over land. CESM H did not outperform CESM L in measurable precipitation frequency over land.
- 2) CAS-ESM L and CESM L overpredicted measurable precipitation frequency, and they underestimated the intensity of hourly measurable or heavy rainfall. However, the metrics of the simulated measurable or heavy precipitation intensity notably improved in both CAS-ESM H and CESM H.
- 3) The precipitation amount was also affected by the horizontal resolution, with relatively abundant precipitation, RMSE, and SCC in CAS-ESM H and CESM H. For regional and local scales, the precipitation apparently improved in the high-resolution simulations in South America and eastern parts of the tropical Pacific. The PDFs of the hourly precipitation in different monsoon regions, ITCZ and SPCZ, were significantly affected by the increased resolution. In particular, CAS-ESM H and CESM H successfully simulated the observed heavy-magnitude events. This finding highlights the importance of using high-resolution models to treat the characteristics of hourly heavy precipitation over

regions characterized by complex topography and convergence zones.

- 4) In general, the improvement of measurable precipitation frequency was related to the less in-cloud ice and in-precipitation snow number concentrations in convective schemes at high resolutions. The enhanced large-scale precipitation improved the precipitation intensity. For heavy rainfall, both convective and large-scale schemes contributed to the improvement of the characteristics in CAS-ESM. While the improvement of heavy rainfall is mainly caused by the enhanced of large-scale precipitation in CESM. Other reasons included reasonable integrated water vapor flux and a more realistic terrain gradient in the enhanced-resolution experiments.

The meteorological elements associated with different resolutions, dynamical cores, and coupling between the dynamical cores and physical schemes also affected the simulated frequency, intensity, and amount of hourly precipitation. Individual rain events become more concentrated for the more intense rates (Bacmeister et al. 2014), which led to a better skill in the high-resolution simulations with respect to the counterparts at coarse-resolutions. The common biases in precipitation frequency (i.e., the overestimation of measurable precipitation with respect to CMORPH) may be attributed to a lack of complexity in the simulated cloud microphysical processes related to heavy precipitation (Kang et al. 2015). Meanwhile, taking into account the estimates and uncertainties of CMORPH, we wanted to reemphasize the weaknesses of measurable precipitation frequency of CMORPH. The actual true measurable precipitation frequencies may be larger than what is derived from CMORPH. We might draw a conclusion that both MERRA2 and models are not necessarily “wetter” than reality.

With the development of the dynamic cores of the GCMs and high-performance computers, high-resolution simulation of GCMs provide finescale climate simulations, which are critical to assess the societal and economic impacts on weather and climate extremes. However, it should be noted that increasing only the horizontal resolution will not always improve the climate simulations of the intermittencies of hourly precipitation, such as the frequency of measurable precipitation in CESM H. In addition to the cloud and convection physical schemes discussed above, the schemes were dependent upon understanding the model integration time steps in detail because the time steps are often reduced at high resolutions (Williamson and Olson 2003; Williamson 2013; Wan et al. 2015; Rahimi et al. 2019). We will study this time-step issue in future work. Besides increasing

the horizontal resolution, the modification and development of the physical schemes controlling the precipitation will be a critical factor for improving model performance.

Acknowledgments. This work was supported by the National Natural Science Foundation of China (Grant 41875106) and the National Natural Science Foundation of China (Grant 41575089). Dr. Baohuang Su (IAP, Beijing, China), Dr. Jing Ming (IAP, Beijing, China), and Dr. Qin Hu (CUIT, Chengdu, China) are appreciated for their helpful discussions. Three anonymous reviewers are thanked for their suggestions and insightful comments. The CMORPH data were obtained online (ftp://ftp.cpc.ncep.noaa.gov/precip/global_CMORPH/). The MERRA2 data were obtained from the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC). We are grateful for the datasets and data archiving centers that supported this work.

REFERENCES

- Baumeister, J. T., M. F. Wehner, R. B. Neale, A. Gettelman, C. Hannay, P. H. Lauritzen, J. M. Caron, and J. E. Truesdale, 2014: Exploratory high-resolution climate simulations using the Community Atmosphere Model (CAM). *J. Climate*, **27**, 3073–3099, <https://doi.org/10.1175/JCLI-D-13-00387.1>.
- Berg, P., C. Moseley, and J. O. Haerter, 2013: Strong increase in convective precipitation in response to higher temperatures. *Nat. Geosci.*, **6**, 181–185, <https://doi.org/10.1038/ngeo1731>.
- Boyle, J., and S. A. Klein, 2010: Impact of horizontal resolution on climate model forecasts of tropical precipitation and diabatic heating for the TWP-ICE period. *J. Geophys. Res.*, **115**, D23113, <https://doi.org/10.1029/2010JD014262>.
- Casanueva, A., and Coauthors, 2016: Daily precipitation statistics in a EURO-CORDEX RCM ensemble: Added value of raw and bias-corrected high-resolution simulations. *Climate Dyn.*, **47**, 719–737, <https://doi.org/10.1007/s00382-015-2865-X>.
- Dai, A., 2006: Precipitation characteristics in eighteen coupled climate models. *J. Climate*, **19**, 4605–4630, <https://doi.org/10.1175/JCLI3884.1>.
- Delworth, T. L., and Coauthors, 2012: Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model. *J. Climate*, **25**, 2755–2781, <https://doi.org/10.1175/JCLI-D-11-00316.1>.
- Demory, M.-E., P. L. Vidale, M. J. Roberts, P. Berrisford, J. Strachan, R. Schiemann, and M. S. Mizielski, 2014: The role of horizontal resolution in simulating drivers of the global hydrological cycle. *Climate Dyn.*, **42**, 2201–2225, <https://doi.org/10.1007/s00382-013-1924-4>.
- Dennis, J., and Coauthors, 2012: CAM-SE: A scalable spectral element dynamical core for the Community Atmosphere Model. *Int. J. High Perform. Comput. Appl.*, **26**, 74–89, <https://doi.org/10.1177/1094342011428142>.
- Donohoe, A., J. Marshall, D. Ferreira, and D. Mcgee, 2013: The relationship between ITCZ location and cross-equatorial atmospheric heat transport: From the seasonal cycle to the Last Glacial Maximum. *J. Climate*, **26**, 3597–3618, <https://doi.org/10.1175/JCLI-D-12-00467.1>.
- Duffy, P. B., B. Govindasamy, J. P. Iorio, J. Milovich, K. R. Sperber, K. E. Taylor, M. F. Wehner, and S. L. Thompson, 2003: High-resolution simulations of global climate, part I: Present climate. *Climate Dyn.*, **21**, 371–390, <https://doi.org/10.1007/s00382-003-0339-z>.
- Gates, W. L., 1992: AMIP: The Atmospheric Model Intercomparison Project. *Bull. Amer. Meteor. Soc.*, **73**, 1962–1970, [https://doi.org/10.1175/1520-0477\(1992\)073<1962:ATAMIP>2.0.CO;2](https://doi.org/10.1175/1520-0477(1992)073<1962:ATAMIP>2.0.CO;2).
- Gelaro, R., and Coauthors, 2017: The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). *J. Climate*, **30**, 5419–5454, <https://doi.org/10.1175/JCLI-D-16-0758.1>.
- Gent, P. R., S. G. Yeager, R. B. Neale, S. Levis, and D. A. Bailey, 2010: Improvements in a half degree atmosphere/land version of the CCSM. *Climate Dyn.*, **34**, 819–833, <https://doi.org/10.1007/s00382-009-0614-8>.
- Giorgi, F., C. Torma, E. Coppola, N. Ban, C. Schär, and S. Somot, 2016: Enhanced summer convective rainfall at Alpine high elevations in response to climate warming. *Nat. Geosci.*, **9**, 584–589, <https://doi.org/10.1038/ngeo2761>.
- Houze, R. A., 1997: Stratiform precipitation in regions of convection: A meteorological paradox? *Bull. Amer. Meteor. Soc.*, **78**, 2179–2196, [https://doi.org/10.1175/1520-0477\(1997\)078<2179:SPIROC>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<2179:SPIROC>2.0.CO;2).
- Hurrell, J. W., J. J. Hack, D. Shea, J. M. Caron, and J. Rosinski, 2008: A new sea surface temperature and sea ice boundary dataset for the Community Atmosphere Model. *J. Climate*, **21**, 5145–5153, <https://doi.org/10.1175/2008JCLI2292.1>.
- Iacono, M. J., J. S. Delamere, E. J. Mlawer, M. W. Shephard, S. A. Clough, and W. D. Collins, 2008: Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models. *J. Geophys. Res.*, **113**, D13103, <https://doi.org/10.1029/2008JD009944>.
- Insel, N., C. J. Poulsen, and T. A. Ehlers, 2010: Influence of the Andes Mountains on South American moisture transport, convection, and precipitation. *Climate Dyn.*, **35**, 1477–1492, <https://doi.org/10.1007/s00382-009-0637-1>.
- Jacob, D., and Coauthors, 2014: EURO-CORDEX: New high-resolution climate change projections for European impact research. *Reg. Environ. Change*, **14**, 563–578, <https://doi.org/10.1007/s10113-013-0499-2>.
- Jung, T., and Coauthors, 2012: High-resolution global climate simulations with the ECMWF model in Project Athena: Experimental design, model climate and seasonal forecast skill. *J. Climate*, **25**, 3155–3172, <https://doi.org/10.1175/JCLI-D-11-00265.1>.
- Kang, I. S., Y. Yang, and W. Tao, 2015: GCMs with implicit and explicit representation of cloud microphysics for simulation of extreme precipitation frequency. *Climate Dyn.*, **45**, 325–335, <https://doi.org/10.1007/s00382-014-2376-1>.
- Li, D., J. Sun, S. Fu, J. Wei, S. Wang, and F. Tian, 2016: Spatiotemporal characteristics of hourly precipitation over central eastern China during the warm season of 1982–2012. *Int. J. Climatol.*, **36**, 3148–3160, <https://doi.org/10.1002/joc.4543>.
- Li, X., X. Bi, and H. Zhang, 2018: Evaluation of NCAR CESM and CAS ESM models for the simulation of boreal summer climate over eastern Asia: Climatological mean and diurnal cycle of precipitation (in Chinese). *Climatic Environ. Res.*, **23**, 645–656.
- Lin, R., T. Zhou, and Y. Qian, 2014: Evaluation of global monsoon precipitation changes based on five reanalysis datasets. *J. Climate*, **27**, 1271–1289, <https://doi.org/10.1175/JCLI-D-13-00215.1>.

- Lin, Z., and Q. Zeng, 1997: Simulation of East Asian summer monsoon by using an improved AGCM. *Adv. Atmos. Sci.*, **14**, 513–526, <https://doi.org/10.1007/s00376-997-0069-y>.
- Liu, X., and Coauthors, 2012: Toward a minimal representation of aerosols in climate models: Description and evaluation in the Community Atmosphere Model CAM5. *Geosci. Model Dev.*, **5**, 709–739, <https://doi.org/10.5194/gmd-5-709-2012>.
- Markowski, P., and Y. Richardson, 2010: *Mesoscale Meteorology in Midlatitudes*. Wiley-Blackwell, 430 pp.
- Miao, C., Q. Sun, A. G. Borthwick, and Q. Duan, 2016: Linkage between hourly precipitation events and atmospheric temperature changes over China during the warm season. *Sci. Rep.*, **6**, 22543, <https://doi.org/10.1038/srep22543>.
- Morrison, H., and A. Gettelman, 2008: A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (CAM3). Part I: Description and numerical tests. *J. Climate*, **21**, 3642–3659, <https://doi.org/10.1175/2008JCLI2105.1>.
- Neale, R. B., and Coauthors, 2012: Description of the NCAR Community Atmosphere Model (CAM 5.0). NCAR Tech. Note NCAR/TN-486+STR, 274 pp., www.cesm.ucar.edu/models/cesm1.0/cam/docs/description/cam5_desc.pdf.
- Oleson, K. W., and Coauthors, 2013: Technical description of version 4.5 of the Community Land Model (CLM). NCAR Tech. Note NCAR/TN-503+STR, 420 pp., <https://doi.org/10.5065/D6RR1W7M>.
- O'Brien, T. A., W. D. Collins, K. Kashinath, O. Rübél, S. Byna, J. Gu, H. Krishnan, and P. A. Ullrich, 2016: Resolution dependence of precipitation statistical fidelity in hindcast simulations. *J. Adv. Model. Earth Syst.*, **8**, 976–990, <https://doi.org/10.1002/2016MS000671>.
- Palazzi, E., J. von Hardenbert, and A. Provenzale, 2013: Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios. *J. Geophys. Res. Atmos.*, **118**, 85–100, <https://doi.org/10.1029/2012JD018697>.
- Park, S., and C. S. Bretherton, 2009: The University of Washington shallow convection and moist turbulence schemes and their impact on climate simulations with the community atmosphere model. *J. Climate*, **22**, 3449–3469, <https://doi.org/10.1175/2008JCLI2557.1>.
- Pendergrass, A., and C. Deser, 2017: Climatological characteristics of typical daily precipitation. *J. Climate*, **30**, 5985–6003, <https://doi.org/10.1175/JCLI-D-16-0684.1>.
- Phillips, N. A., 1957: A coordinate system having some special advantages for numerical forecasting. *J. Meteor.*, **14**, 184–185, [https://doi.org/10.1175/1520-0469\(1957\)014<0184:ACSHSS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1957)014<0184:ACSHSS>2.0.CO;2).
- Ploshay, J. J., and N. C. Lau, 2010: Simulation of the diurnal cycle in tropical rainfall and circulation during boreal summer with a high-resolution GCM. *Mon. Wea. Rev.*, **138**, 3434–3453, <https://doi.org/10.1175/2010MWR3291.1>.
- Qian, Y., and F. Giorgi, 1999: Interactive coupling of regional climate and sulfate aerosol models over eastern Asia. *J. Geophys. Res.*, **104**, 6477–6499, <https://doi.org/10.1029/98JD02347>.
- Rahimi, S., X. Liu, C. Wu, and H. Brown, 2019: Exploring a variable-resolution approach for simulating regional climate over the Tibetan Plateau using VRCESM. *J. Geophys. Res. Atmos.*, **124**, 4490–4513, <https://doi.org/10.1029/2018JD028925>.
- Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of seas surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108**, 4407, <https://doi.org/10.1029/2002JD002670>.
- Reichle, R. H., Q. Liu, R. D. Koster, C. S. Draper, S. P. P. Mahanama, and G. S. Partyka, 2017: Land surface precipitation in MERRA-2. *J. Climate*, **30**, 1643–1664, <https://doi.org/10.1175/JCLI-D-16-0570.1>.
- Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. *J. Climate*, **15**, 1609–1625, [https://doi.org/10.1175/1520-0442\(2002\)015<1609:AHSAS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<1609:AHSAS>2.0.CO;2).
- Roberts, M. J., and Coauthors, 2018: The benefits of global high resolution for climate simulation: Process understanding and the enabling of stakeholder decisions at the regional scale. *Bull. Amer. Meteor. Soc.*, **99**, 2341–2359, <https://doi.org/10.1175/BAMS-D-15-00320.1>.
- Schiemann, R., P. L. Vidale, L. C. Shaffrey, S. J. Johnson, M. J. Roberts, M.-E. Demory, M. S. Mizieliński, and J. Strachan, 2018: Mean and extreme precipitation over European river basins better simulated in a 25 km AGCM. *Hydrol. Earth Syst. Sci.*, **22**, 3933–3950, <https://doi.org/10.5194/hess-22-3933-2018>.
- Schroeder, K., G. Kirchengast, and O. Sungmin, 2018: Strong dependence of extreme convective precipitation intensities on gauge network density. *Geophys. Res. Lett.*, **45**, 8253–8263, <https://doi.org/10.1029/2018GL077994>.
- Shaw, S. B., A. A. Royem, and S. J. Riha, 2011: The relationship between extreme hourly precipitation and surface temperature in different hydroclimatic regions of the United States. *J. Hydrometeor.*, **12**, 319–325, <https://doi.org/10.1175/2011JHM1364.1>.
- Sperber, K. R., H. Annamalai, I.-S. Kang, A. Kitoh, A. Moise, A. Turner, B. Wang, and T. Zhou, 2013: The Asian summer monsoon: An intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. *Climate Dyn.*, **41**, 2711–2744, <https://doi.org/10.1007/s00382-012-1607-6>.
- Stephens, G., and Coauthors, 2010: Dreary state of precipitation in global models. *J. Geophys. Res.*, **115**, D24211, <https://doi.org/10.1029/2010JD014532>.
- Sun, Y., S. Solomon, A. Dai, and R. W. Portmann, 2006: How often does it rain? *J. Climate*, **19**, 916–934, <https://doi.org/10.1175/JCLI3672.1>.
- Trenberth, K., 1998: Atmospheric moisture residence times and cycling: Implications for rainfall rates with climate change. *Climatic Change*, **39**, 667–694, <https://doi.org/10.1023/A:1005319109110>.
- , and Y. Zhang, 2018: How often does it really rain? *Bull. Amer. Meteor. Soc.*, **99**, 289–298, <https://doi.org/10.1175/BAMS-D-17-0107.1>.
- , D. P. Stepaniak, and J. M. Caron, 2000: The global monsoon as seen through the divergent atmospheric circulation. *J. Climate*, **13**, 3969–3993, [https://doi.org/10.1175/1520-0442\(2000\)013<3969:TGMASST>2.0.CO;2](https://doi.org/10.1175/1520-0442(2000)013<3969:TGMASST>2.0.CO;2).
- , Y. Zhang, and M. Gehne, 2017: Intermittency in precipitation: Duration, frequency, intensity, and amounts using hourly data. *J. Hydrometeor.*, **18**, 1393–1412, <https://doi.org/10.1175/JHM-D-16-0263.1>.
- Wan, H., P. J. Rasch, M. A. Taylor, and C. Jablonowski, 2015: Short-term time step convergence in a climate model. *J. Adv. Model. Earth Syst.*, **7**, 215–225, <https://doi.org/10.1002/2014MS000368>.
- Wang, A., and X. Zeng, 2012: Evaluation of multireanalysis products with in situ observations over the Tibetan Plateau. *J. Geophys. Res.*, **117**, D05102, <https://doi.org/10.1029/2011JD016553>.
- Wang, B., J. Liu, H. J. Kim, P. J. Webster, and S. Y. Yim, 2012: Recent change of the global monsoon precipitation (1979–2008).

- Climate Dyn.*, **39**, 1123–1135, <https://doi.org/10.1007/s00382-011-1266-z>.
- Wang, F., and S. Yang, 2017: Regional characteristics of long-term changes in total and extreme precipitations over China and their links to atmospheric-oceanic features. *Int. J. Climatol.*, **37**, 751–769, <https://doi.org/10.1002/joc.4737>.
- Westra, S., and Coauthors, 2014: Future changes to the intensity and frequency of short-duration extreme rainfall. *Rev. Geophys.*, **52**, 522–555, <https://doi.org/10.1002/2014RG000464>.
- Williamson, D. L., and J. G. Olson, 2003: Dependence of aquaplanet simulations on time step. *Quart. J. Roy. Meteor. Soc.*, **129**, 2049–2064, <https://doi.org/10.1256/qj.02.62>.
- Williamson, L., 2013: The effect of time steps and time-scales on parameterization suites. *Quart. J. Roy. Meteor. Soc.*, **139**, 548–560, <https://doi.org/10.1002/qj.1992>.
- Winiger, M., M. Gumpert, and H. Yamout, 2005: Karakorum-Hindukush-western Himalaya: Assessing high-altitude water resources. *Hydrol. Processes*, **19**, 2329–2338, <https://doi.org/10.1002/hyp.5887>.
- Wu, C., X. Liu, Z. Lin, A. M. Rhoades, P. A. Ullrich, C. M. Zarzycki, Z. Lu, and S. R. Rahimi-Esfarjani, 2017: Exploring a variable-resolution approach for simulating regional climate in the Rocky Mountain Region using the VR-CESM. *J. Geophys. Res. Atmos.*, **122**, 10 939–10 965, <https://doi.org/10.1002/2017JD027008>.
- Xie, P., R. Joyce, S. Wu, S.-H. Yoo, Y. Yarosh, F. Sun, and R. Lin, 2017: Reprocessed, bias-corrected CMORPH global high-resolution precipitation estimates. *J. Hydrometeorol.*, **18**, 1617–1641, <https://doi.org/10.1175/JHM-D-16-0168.1>.
- Xie, X. N., H. Zhang, X. Liu, Y. Peng, and Y. Liu, 2018: Role of microphysical parameterizations with droplet relative dispersion in IAP AGCM4.1. *Adv. Atmos. Sci.*, **35**, 248–259, <https://doi.org/10.1007/s00376-017-7083-5>.
- Xue, F., X. Bi, and Y. Lin, 2001: Modelling the global monsoon system by IAP 9L AGCM. *Adv. Atmos. Sci.*, **18**, 404–412, <https://doi.org/10.1007/BF02919319>.
- Yan, Z., Z. Lin, and H. Zhang, 2014: The relationship between the East Asian subtropical westerly jet and summer precipitation over East Asia as simulated by the IAP AGCM4.0. *Atmos. Ocean. Sci. Lett.*, **7**, 487–492, <https://doi.org/10.1080/16742834.2014.11447212>.
- Yu, R., J. Li, W. Yuan, and H. Chen, 2010: Changes in characteristics of late-summer precipitation over eastern China in the past 40 years revealed by hourly precipitation data. *J. Climate*, **23**, 3390–3396, <https://doi.org/10.1175/2010JCLI3454.1>.
- Zarzycki, C. M., C. Jablonowski, and M. A. Taylor, 2014a: Using variable-resolution meshes to model tropical cyclones in the community atmosphere model. *Mon. Wea. Rev.*, **142**, 1221–1239, <https://doi.org/10.1175/MWR-D-13-00179.1>.
- , M. N. Levy, C. Jablonowski, J. R. Overfelt, M. A. Taylor, and P. A. Ullrich, 2014b: Aquaplanet experiments using CAM's variable-resolution dynamical core. *J. Climate*, **27**, 5481–5503, <https://doi.org/10.1175/JCLI-D-14-00004.1>.
- Zhang, G., and N. A. McFarlane, 1995: Sensitivity of climate simulations to the parameterization of cumulus convection in the Canadian climate centre general circulation model. *Atmos.–Ocean*, **33**, 407–446, <https://doi.org/10.1080/07055900.1995.9649539>.
- Zhang, H., and P. Zhai, 2011: Temporal and spatial characteristics of extreme hourly precipitation over eastern China in the warm season. *Adv. Atmos. Sci.*, **28**, 1177–1183, <https://doi.org/10.1007/s00376-011-0020-0>.
- Zhang, H., M. Zhang, and Q. Zeng, 2013: Sensitivity of simulated climate to two atmospheric models: Interpretation of differences between dry models and moist models. *Mon. Wea. Rev.*, **141**, 1558–1576, <https://doi.org/10.1175/MWR-D-11-00367.1>.
- Zhang, L., T. Zhou, N. P. Klingaman, P. Wu, and M. Roberts, 2018: Effect of horizontal resolution on the representation of the global monsoon annual cycle in AGCMs. *Adv. Atmos. Sci.*, **35**, 1003–1020, <https://doi.org/10.1007/s00376-018-7273-9>.
- Zhou, T., R. Yu, H. Chen, A. Dai, and Y. Pan, 2008: Summer precipitation frequency, intensity, and diurnal cycle over China: A comparison of satellite data with rain gauge observations. *J. Climate*, **21**, 3997–4010, <https://doi.org/10.1175/2008JCLI2028.1>.
- Zolina, O., 2014: Multidecadal trends in the duration of wet spells and associated intensity of precipitation as revealed by a very dense observational German network. *Environ. Res. Lett.*, **9**, 025003, <https://doi.org/10.1088/1748-9326/9/2/025003>.