Comparison of CMIP6 and CMIP5 simulations of precipitation in China and the East Asian summer monsoon

Xiaoge Xin | Tongwen Wu | Jie Zhang | Junchen Yao | Yongjie Fang

Beijing Climate Center, China
Meteorological Administration, Beijing, China

Correspondence
Xiaoge Xin, Beijing Climate Center, China
Meteorological Administration,
46, ZhongGuanCun Nandajie, Haidian District, Beijing 100081, China.
Email: xinxg@cma.gov.cn

Funding information
National Key Research and Development Program of China CERC-WET Project,
Grant/Award Number: 2018YFE0196000;
National Key Research and Development Program of China, Grant/Award Number:
2016YFA0602103

Abstract
We evaluate and compare the simulation of summer precipitation in China and the East Asian summer monsoon (EASM) by eight climate models from Phase 6 of the Coupled Model Intercomparison Project (CMIP6) and the corresponding eight previous models from CMIP5. Skill metrics are calculated to assess the climatology, interannual variation and linear trends during the time period 1961–2005. The CMIP6 multimodel ensemble (MME) is more skillful than the CMIP5 MME in the spatial correlation and standard deviation (SD) of the climatological precipitation over Eastern China. All the CMIP6 models improve the skill scores in the climatological pattern of the EASM relative to the previous models of CMIP5, which is related to their smaller sea surface temperature (SST) biases over the Northwestern Pacific Ocean. The models with a higher capability in reproducing the climatological pattern of the EASM tend to have a better skill in simulating summer precipitation over Eastern China. Most (six of eight) of the CMIP6 models have advantages over the previous CMIP5 models in reproducing the interannual anomalous rainfall pattern over Eastern China related to the EASM. Ten of the 16 models partly reproduce the weakening trend of the EASM during 1961–2005. The high-skill models (GISS-E2-H, GISS-E2-1-H) that simulate a clear weakening trend in the EASM also reasonably simulate the negative correlation between the EASM and the SST over Eastern Indian and the Western Pacific Oceans (EIWP). By contrast, the two models (CESM2 and CESM2-WACCM) that simulate a positive correlation over the EIWP both produce increasing trends in the EASM indices. This indicates the importance of climate models in simulating the relationship between the EASM and the SST over Eastern Indian and the Western Pacific Oceans (EIWP). Among the 16 models, only 2 CMIP6 models (BCC-CSM2-MR and GISS-E2-1-H) partly reproduce the linear trend of precipitation over Eastern China, featured by the pattern of “southern flood and northern drought.”

KEYWORDS
China, climate model, CMIP6, East Asian summer monsoon, precipitation
1 | INTRODUCTION

The East Asian summer monsoon (EASM) is a crucial atmospheric circulation system and dominates the climate in East Asia. Monsoonal rainfall in the summer months accounts for 40–50% of the annual precipitation in South China and 60–70% of the annual precipitation in North China (Lei et al., 2011). The interannual variations in the EASM are associated with droughts and floods in China (Zong and Chen 2000; Zhou et al., 2013; Zhang and Zhou, 2015). Climate models are powerful tools for the prediction of EASM rainfall anomalies. However, it remains challenging for climate models to reasonably simulate the climatology and interannual variability of the EASM as a result of the complex topography of this region and limitations of the models (Huang et al., 2013; Song and Zhou, 2014a). The simulation skills of the EASM and precipitation in the region of the EASM are important metrics in the validation of climate models.

The Coupled Model Intercomparison Project (CMIP), held by the Working Group on Coupled Modelling every few years, provides a large amount of model output, the validation of which reflects the ability of current climate models. Climate models in Phase 5 of the CMIP (CMIP5) showed improvements in the simulation of the Asian summer monsoon relative to the Phase 3 of the CMIP (CMIP3) models (Sperber et al., 2013; Ogata et al., 2014). The ability of models to reproduce the geographical distribution of precipitation over East Asia was also improved from CMIP3 to CMIP5 (Kusunoki and Arakawa, 2015). However, biases still exist in simulations by the CMIP5 models, including the underestimation of rainfall in the Yangtze River valley and a weak Western Pacific subtropical high (Feng et al., 2014; Song and Zhou, 2014a).

The EASM has weakened since the end of the 1970s, which has resulted in a “southern flood and northern drought” (SFND) rainfall pattern over Eastern China (Gong and Ho, 2002; Yu et al., 2004; Yu and Zhou, 2007; Zhou et al., 2009). Some studies have indicated that the intrinsic oscillation of the ocean, mainly the Pacific Decadal Oscillation, is the cause of the decadal change in the EASM (Li et al., 2010; Qian and Zhou, 2014; Dong, 2016). There are also studies suggested that anthropogenic aerosols have contributed to the weakened EASM in recent decades (Menon et al., 2002; Song et al., 2014; Dong et al., 2019). The internal variability of the sea surface temperature (SST) and the uncertainties in aerosols in climate models have led to difficulties in reproducing the decadal change in the EASM. Sun and Ding (2008) examined 19 CMIP3 climate models and

| Institute                                               | Model name | Resolutions | AGCM          | OGCM          |
|---------------------------------------------------------|------------|-------------|---------------|---------------|
| Beijing Climate Center                                  | CMIP5      | BCC-CSM1.1m | 1.125° × 1.12°, L26 | 360 × 232, L40 |
|                                                        | CMIP6      | BCC-CSM2-MR | 1.125° × 1.12°, L46 | 360 × 232, L40 |
| National Center for Climate Research                    | CMIP5      | CESM1-BGC   | 1.25° × 0.9°, L26 | 384 × 320, L60 |
|                                                        | CMIP6      | CESM1-WACCM | 1.25° × 1.9°, L66 | 384 × 320, L60 |
|                                                        | CMIP5      | CESM2       | 1.25° × 0.9°, L32 | 384 × 320, L60 |
|                                                        | CMIP6      | CESM2-WACCM | 1.25° × 0.9°, L70 | 384 × 320, L60 |
| Centre National de Recherches Meteorologiques/         | CMIP5      | CNRM-CM5    | 1.4° × 1.4°, L31 | 362 × 292, L42 |
| Centre Europeen de Recherches et de Formation Avancee   | CMIP6      | CNRM-CM6-1  | 1.4° × 1.4°, L91 | 362 × 292, L75 |
|             en Calcul Scientifique                        |            |             |               |               |
| NASA Goddard Institute for Space Studies                | CMIP5      | GISS-E2-H   | 2.5° × 2°, L29 | 1.25° × 1°, L26 |
|                                                        | CMIP6      | GISS-E2-1-H | 2.5° × 2°, L40 | 1.25° × 1°, L26 |
| Institut Pierre Simon Laplace                           | CMIP5      | IPSL-CM5A-MR| 2.5° × 1.26°, L39 | 149° × 182°, L31 |
|                                                        | CMIP6      | IPSL-CM6A-LR| 2.5° × 1.26°, L79 | 362° × 332°, L75 |
| Atmosphere and Ocean Research Institute, The University  | CMIP5      | MIROC5      | 1.4° × 1.4°, L40 | 256° × 224°, L50 |
| of Tokyo                                                | CMIP6      | MIROC6      | 1.4° × 1.4°, L81 | 360° × 256°, L63 |
| Meteorological Research Institute                       | CMIP5      | MRI-ESM1    | 1.125° × 1.12°, L48 | 360° × 368°, L51 |
|                                                        | CMIP6      | MRI-ESM2    | 1.125° × 1.12°, L80 | 360° × 368°, L61 |
found that only three models captured the decadal variation in precipitation over East Asia in recent decades. Song et al. (2014) showed that the all-forcing runs of CMIP5 climate models partly reproduced the weakening trend of the EASM during the time period 1958–2001, with a primary part played by aerosol forcing.

**FIGURE 1** Climatological mean summer precipitation (mm day$^{-1}$) during 1961–2005 in the (a) CMIP5 MME, (c) CMIP6 MME and (e) observation over China. The difference of precipitation (b) between the CMIP5 MME and the observation, (d) between the CMIP6 MME and the observation, (f) between the CMIP6 MME and CMIP5 MME. CMIP5, Phase 5 of the Coupled Model Intercomparison Project; CMIP6, Phase 6 of the Coupled Model Intercomparison Project; MME, multimodel ensemble.
Modelling groups worldwide have devoted much effort to developing new versions of climate models since CMIP5. CMIP6 is now in progress (Eyring et al., 2016), and some modelling groups have released the 20th historical simulations with the newly developed climate models. The abilities of these models to simulate precipitation in China and the EASM need to be explored, especially in their interannual and decadal variabilities. Validations of the newly released climate models will help to improve the simulation and prediction ability of future models.

The motivation of this study is to compare the CMIP6 climate models with the previous CMIP5 climate models in the simulation of precipitation in China and the EASM in terms of the climatology, interannual variability and long-term changes from 1961 to 2005. The possible influence of the SST on long-term changes in the EASM is also investigated in the climate models.

This article is organized as follows. Section 2 describes the models, data and methods used in this study. Section 3 presents comparison results between the CMIP5 and CMIP6 models with respect to precipitation in China and the EASM, including the climatological states, the interannual pattern associated with the EASM and the linear trend during the time period 1961–2005. A summary is provided in Section 4.

2 MODELS, DATA SETS AND ANALYSIS METHODS

Table 1 gives details of the eight CMIP6 and eight CMIP5 models used in this study, including the horizontal resolution and vertical levels in the atmospheric general circulation model (AGCM) and oceanic general circulation model (OGCM). Each pairs of models are from the same modelling group. Five pairs of models are atmosphere–ocean general circulation models, whereas three pairs are Earth system models. Most of the CMIP6 models have the same horizontal resolution in the AGCM as the corresponding CMIP5 model, except for CESM1-WACCM and CESM2-WACCM. All the CMIP6 models improve the number of vertical layers in the AGCM relative to the corresponding CMIP5 model in the same modelling group. One benefit of the increased number of vertical layers in the AGCM is the improved simulation in the stratosphere. For example, BCC-CSM2-MR is able to reproduce the stratospheric quasi-biennial oscillation with a high vertical resolution, but this oscillation does not exist in BCC-CSM1.1m (Wu et al., 2019). The horizontal and vertical resolutions of the OGCM increase for the models from IPSL-CM5A-MR to IPSL-CM6A-LR and from MIROC5 to MIROC6. The CNRM-CM6-1 and MRI-ESM2 models improve the vertical layers of the OGCM relative to the CMIP5 versions. The other four pairs of models have the same resolutions in the OGCM.

We used historical simulations from 1961 to 2005. The first member is chosen, although all the models provided several ensemble members. The models in the historical simulation of CMIP5 and CMIP6 are driven by external forcings covering greenhouse gases, aerosols, ozone, solar activity, volcanoes and land use. These external forcing data were updated from CMIP5 to CMIP6 with the purpose of reducing the uncertainty. Detailed information about these input data is provided at https://esgf-node.llnl.gov/projects/input4mips/.

The Japanese 55-year reanalysis (JRA-55) data set with a horizontal resolution of 1.25° in both longitude and latitude is used to verify the simulated large-scale atmospheric circulation (Kobayashi et al., 2015; Harada et al., 2016). The observed precipitation data are from the gridded monthly data set of CN05.1 (Wu and Gao, 2013). The spatial resolution of this data set is 0.25° × 0.25° based on 2,416 station observations in China. This observed precipitation dataset, as well as the simulated precipitation and atmospheric circulation of all climate models are interpolated to a 1.25° × 1.25° common grid by bilinear interpolation. The Hadley Centre Sea Ice and Sea SST data set (HadISST) is used in the validation of the SST (Rayner et al., 2003). The modelled SST data are interpolated onto the grid points (360 × 180) of HadISST.

A number of previous studies have defined the EASM index. Here, we choose EASM index defined as the
normalized zonal wind \((u)\) shear between 850 and 200 hPa averaged over \((20^\circ-40^\circN, 110^\circ-140^\circE)\) (Han and Wang, 2007). This index is similar to that defined by Webster and Yang (1992), but focused on the region of East Asia. This index provides a first-order approximation of the strength of the strongest baroclinic mode that has a dominant effect on the EASM (Wang and Fan, 1999).
To quantitatively compare the performance of the CMIP6 models with that of the CMIP5 models, we calculate the skill score of the EASM in the simulation of the climatology and interannual EASM pattern over East Asia, as proposed by Chen et al. (2010). This has been used to verify the model performance of the EASM in previous studies (He and Zhou, 2014; Song and Zhou, 2014a):

\[
\text{Skill} = \frac{(1+R)^2}{(\text{SDR} + |1/\text{SDR}|)^2},
\]

where \( R \) represents the pattern correlation between the model and observations and \( \text{SDR} \) is the ratio of the spatial standard deviation (SD) of the model against that of the observations. As in earlier studies, we convert the zonal and meridional winds into a one-dimensional array to compute the skill of the wind field (He and Zhou, 2014; Song and Zhou, 2014a).

3 | RESULTS

3.1 | Climatology of precipitation in China

Figure 1 compares the precipitation climatology over China in summer during the time period of 1961–2005 simulated by the CMIP5 and CMIP6 multimodel ensembles (MMEs) with the observation. The observed rainfall amount is largest over Southern China and decreased from the southeast to northwest (Figure 1e). This feature can be reasonably reproduced by both the CMIP5 and CMIP6 MMEs (Figure 1a, c). The biases of CMIP5 and CMIP6 MMEs are similar, with deficient rainfall in the Yangtze River valley and northwestern Xinjiang Province, and excess rainfall in North China, Northwestern China and the Tibetan Plateau (Figure 1b,d). The largest rainfall bias in both the CMIP5 and the CMIP6 MMEs appear on the southwestern flank of the Tibetan Plateau, indicating that the effect of the high topography on precipitation is still a challenge for these models. The difference between the CMIP5 MME indicates that CMIP6 MME shows an improvement in reducing the rainfall bias in the Yangtze River valley and part of North China (Figure 1f).

Figure 2 shows the Taylor diagram of the precipitation over Eastern China (to the east of 105°E) simulated by the CMIP5 and CMIP6 models relative to the observations. Most (five of eight) of the CMIP5 models simulated smaller SDs of the precipitation than the observation, whereas most (seven of eight) of the models of CMIP6 simulated a similar or larger SD of precipitation relative to the observation. The CMIP6 MME shows a SD equivalent to the observations, whereas the CMIP5 MME underestimates it.

In terms of spatial correlation, all the CMIP6 models, except for GISS-E2-1-H, simulate a larger correlation coefficient than the corresponding previous CMIP5 models. The correlation coefficient between the CMIP6 MME and the observation is 0.89, which is slightly larger than that
between the CMIP5 MME and the observation (0.88). The MME outperforms individual models for both the CMIP5 and CMIP6 models. This is consistent with previous studies (Lambert and Boer, 2001; Gleckler et al., 2008; Reichler and Kim, 2008). It is noted that MIROC5 overestimates the SD of precipitation in Eastern China by about one time. Kusunoki and Arakawa (2015) also found that the MIROC5 shows a considerably larger positive bias in the June precipitation than other CMIP5 models.

3.2 | Climatology of the EASM

Figure 3 shows the climatological distribution of the summer 850 hPa winds and wind speed in CMIP5 and CMIP6 MMEs and their biases relative to the JRA-55. Both the CMIP5 and the CMIP6 MMEs capture the main feature of the EASM, with southwesterly winds originating from the Bay of Bengal, the South China Sea and the western flank of the tropical Western Pacific high (Figure 3a, c). The bias of the horizontal winds in the Western Pacific in the CMIP5 MME is characterized by a cyclone, indicating a weakened tropical Western Pacific high (Figure 3b). This is consistent with the results of previous studies (Song and Zhou, 2014a; Kusunoki and Arakawa, 2015). The biases of the wind over the Western Pacific in the CMIP6 MME are much smaller than in the CMIP5 MME, indicating that the bias of the subtropical Western Pacific high is reduced in the CMIP6 MME (Figure 3d). By contrast, the bias in the southerly wind of the CMIP6 MME is larger than that of the CMIP5 MME over Southern China and the Bay of Bengal, indicating a stronger EASM over this region in the CMIP6 MME than in the CMIP5 MME. This is clearly shown in the difference between the CMIP6 and CMIP5 MMEs (Figure 3f).

We calculate the skill scores of the models in reproducing the climatological EASM over the region (0°–50°N, 100°–160°E) using Equation (1). This region is the same as that adopted in the study of Song and Zhou (2014a). Figure 4 shows that the skill scores of the EASM of all the CMIP6 models are above 0.8 and most are higher than the skill scores of the corresponding previous CMIP5 model. The distinct improvement in the models includes BCC-CSM2-MR (0.89) and MRI-ESM2.0 (0.86) relative to BCC-CSM1.1m (0.49) and MRI-ESM1 (0.56), respectively. Among the CMIP6 models, CESM2 performs best in the EASM with a skill score of 0.89. The skill score of the CMIP6 MME is 0.94, which is larger than the CMIP5 MME (0.89), indicating the advantages of the CMIP6 MME over the CMIP5 MME in the climatological EASM.

The improved skill scores of the EASM from CMIP5 to CMIP6 are consistent with those of precipitation in Eastern China from CMIP5 to CMIP6. As shown in Figure 5a, both the skill scores of the East Asian 850 hPa wind and precipitation in Eastern China in the CMIP6
models are higher than those of the CMIP5 models and that the discrepancy in the skill score of different models is smaller than that in the CMIP5 models. There is a positive linear relationship between the skill score of the East Asian 850 hPa wind and precipitation in Eastern China among both the CMIP5 and CMIP6 models. This indicates that a good reproduction of the climatological pattern of the EASM favours a reasonable simulation of the climatological distribution of precipitation over Eastern China.

Previous study indicated that the SST bias in the Northwestern Pacific Ocean (NWP) is closely related to the bias Western North Pacific subtropical high (Song and Zhou, 2014a). We further explore the relationship between the Northwestern Pacific (10°–30°N, 110°–160°E) SST bias and East Asian 850 hPa wind skill in CMIP5 and CMIP6 models (Figure 5b). It is shown that CMIP6 MME has less NWP SST bias than the CMIP5 MME. The model spread of NWP SST bias is much less than that in the CMIP5 models. In addition,
there is a linear relationship between the NWP SST bias and the EASM wind skill in the CMIP6 models. The model with small NWP SST bias corresponds to a higher EASM skill in CMIP6.

### 3.3 Interannual pattern of the EASM and precipitation in Eastern China

Figures 6 and 7 show the regressed patterns of the 850 hPa winds and precipitation on the EASM index of each CMIP5 and CMIP6 models and the MMEs, respectively. Most of the models reproduce the anticyclone over the Western Pacific Ocean with a southwesterly flow over Southeast China, but the locations of the anticyclone are different among the models. The models from Beijing Climate Center (BCC-CSM1.1m, BCC-CSM2-MR), Centre National de Recherches Meteorologiques (CNRM-CM5, CNRM-CM6-1) and NASA Goddard Institute for Space Studies (GISS-E2-H, GISS-E2-1-H) are consistent with the observation with an area about 35°N. These models perform well in reproducing the rainfall pattern of the SFND rainfall pattern associated with the negative EASM index, with spatial correlation coefficients above 0.3 between the simulations and the observations over Eastern China. BCC-CSM2-MR shows the best performance in reproducing the anomalous rainfall pattern over Eastern China with the highest spatial correlation of 0.59. This suggests that the rainfall anomalies over Eastern China can be realistically simulated by this model if the EASM index is reasonably reproduced.

**FIGURE 7** Horizontal distribution of summer precipitation (shaded; mm day$^{-1}$) and 850 hPa wind (vectors; m s$^{-1}$) regressed on the EASM index during the time period 1961–2005 in (a–h) each CMIP6 model, (i) the CMIP6 MME. The number in the upper right-hand corner of the figure denotes the spatial correlation coefficient of the regressed precipitation pattern over Eastern China (to the east of 105°E) between the simulation and the observation. CMIP5, Phase 5 of the Coupled Model Intercomparison Project; CMIP6, Phase 6 of the Coupled Model Intercomparison Project; EASM, East Asian summer monsoon; MME, multimodel ensemble.
In the CESM1-BGC, CESM1-WACCM, CESM2, CESM2-WACCM and MIROC6 models, the anomalous anticyclones are located to the south of the observations and are associated with drought over South China instead of the Yangtze River valley. Two CMIP5 models (IPSL-CM5A-MR, MRI-ESM1) and two CMIP6 models (IPSL-CMN6A-LR, MRI-ESM2) simulate an anticyclone to the north of the observation. In these models, there is more rainfall over most of Eastern China associated with a positive EASM index. The MMEs outperform individual models for both CMIP5 and CMIP6 in the simulation of interannual pattern of rainfall and 850 hPa wind associated with the EASM (Figures 6i and 7i). The EASM index defined by Wang and Fan (1999) was often used in studies of interannual variabilities of the EASM (Song and Zhou, 2014a, 2014b). We also use the EASM index of Wang and Fan (1999) to explore interannual patterns of the EASM in our study and get similar results.

Equation (1) is applied to evaluate the anomalous precipitation and 850 hPa wind pattern associated with the EASM index over the region (15°–55°N, 105°–140°E), where the rainfall and wind anomalies dominate. The skill scores are shown in Figure 8. Six CMIP6 models improve the skill scores in the precipitation, whereas three models improve the skill scores in the 850 hPa winds compared with the corresponding previous CMIP5 models. The CMIP6 MME achieves higher skill scores for precipitation in Eastern China (0.2) and the 850 hPa winds (0.39) than the CMIP5 MME (0.04 and 0.25, respectively). From CMIP5 to CMIP6, the precipitation skill of the BCC model improved from 0.48 to 0.62. Both the skills of precipitation and the 850 hPa winds improve from MRI-ESM1.0 to MRI-ESM2.0. CESM1-BGC and CESM1-WACCM show high scores in the simulation of precipitation, but they have low skills in the 850 hPa winds.
3.4 | Linear trend from 1961 to 2005

The observed EASM shows a prominent weakening trend from 1961 to 2005. As shown in Figure 9, six of the eight CMIP5 models reproduce the negative linear trend in the EASM. But only GISS-E2-1-H simulates the negative trend of EASM index significant at the 5% level, indicating that the long-term change of EASM is still challenges for the current climate models.

Although there is some controversy about the mechanism leading to the weakening tendency in the EASM, the role of the oceans in the change in the EASM is not negligible. Lin et al. (2016), through conducting a simulation with assimilated ocean data in a coupled model, suggested that the variation in the oceanic fields is the dominant factor responsible for the decadal transitions in the EASM. We therefore explored the ability of each model to simulate the correlation between the SST and the EASM index.

Figure 10 shows that all models reproduce the negative correlation over the eastern tropical Pacific Ocean and the positive correlation in the midlatitudes of the Pacific. However, the models show discrepancies in simulating the correlation in the Eastern Indian and Western Pacific Oceans (EIWP) (10°S–20°N, 80°–140°E). The CESM1-WACCM, IPSL-CM5A-MR, CESM2 and CESM2-WACCM models all produce positive correlations in this region that are at odds with the observations. Correspondingly, these models all simulate increasing trends in the EASM index. Three models (GISS-E2-H, MRI-ESM1, GISS-E2-1-H) that reasonably simulate the negative correlation over the EIWP reproduce the weakening trend of the EASM index well. It has been suggested that the changes in the SST and convective activity over the tropical Indian Ocean and far Western Pacific Ocean may induce the decadal westward extension of the western Pacific subtropical high (WPSH) (Hu, 1997; Gong and Ho, 2002). This may partly explain why the warmer SSTs over the EIWP are associated with a weakened EASM index.

Wang et al. (2005) reported that air–sea coupling is important in simulations of the EASM because atmospheric feedback on the SST is crucial over the tropical Indo-Pacific Oceans. Song and Zhou (2014a, 2014b) proposed that the Indian Ocean–Western Pacific anticyclone teleconnection is important in the simulation of the EASM in CMIP5 models. In CMIP6 models, the teleconnection is still important for the interannual variability of the EASM. The models that can well reproduce the negative correlation over the tropical Eastern Indian Ocean including CNRM-CM6-1, GISS-E2-1-H and IPSL-CM6A-LR all have high skill scores of 850 hPa wind over East Asia (Figure 8). The two models (CESM2 and CESM2-WACCM) simulate positive correlation over the tropical Eastern Indian Ocean are the low-skill models in simulating 850 hPa wind over East Asia (Figure 8). The

![Figure 9](image-url)
simulation of tropical Indian SST could be rooted in El Niño-Southern Oscillation (ENSO) of the preceding year, as mentioned in Song and Zhou (2014a). CESM2 and CESM2-WACCM are also the models that could not well simulate the relationship between EASM and ENSO in the preceding winter (figure not shown).

We choose four models (CESM2, CESM2-WACCM, GISS-E2-H and GISS-E2-1-H) to further explore the time series of the EASM indices and the SST averaged over the EIWP. As shown in Figure 11, the EASM indices simulated by CESM2 and CESM2-WACCM showed coherent variations in the SST time series, with correlation coefficients of .59 and .39, respectively (Figure 11a,c). The EASM indices show positive linear trends with the increasing trend of the EIWP SST time series from 1961 to 2005. However, the EASM indices in the GISS-E2-H and GISS-E2-1-H models show out-of-phase relationships with the EIWP SST time series, with correlation coefficients of −0.39 and −0.4, respectively (Figure 11b,d). The EASM indices show a decreasing trend in the two GISS models as the EIWP SST time series increases from 1961 to 2005. This is consistent with the observation (Figure 11c). It is inferred the simulation ability of the relationship between the EASM and the SST over the EIWP may influence the long-term changes in the EASM in climate models.

Regressions of zonal wind at 200 hPa and the horizontal winds at 850 hPa on the EIWP SST index simulated by the four models are shown in Figure 12. The anticyclone in the low troposphere over East Asia can be reproduced by CESM2, CESM2-WACCM and GISS-E2-H. Obvious differences are found in the regressions patterns of zonal wind at 200 hPa between the two pairs of models. In GISS-E2-H and GISS-E2-1-H, the zonal wind at 200 hPa increases (decreases) to the south (north) of 40°N, which is consistent with the observation. This indicates that the westerly is enhanced south of the 200-hPa jet axis over East Asia with the warming SST in the EIWP Ocean. Such change of the East Asian jet stream is corresponding to the weakened EASM (Yu and Zhou, 2007). This partly explains why the two models could reproduce the weakening trend of the simulated EASM indices. However, CESM2 and CESM2-WACCM simulate an opposite variation of the East Asian jet stream associated

---

**FIGURE 10** Correlation between summer SST and the EASM index during the time period 1961–2005 for (a1–a8) each CMIP5 model, (b1–b8) each CMIP6 model, and (c1) the observation. The black dots indicate the correlation coefficients are above the 5% significant level.

CMIP5, Phase 5 of the Coupled Model Intercomparison Project; CMIP6, Phase 6 of the Coupled Model Intercomparison Project; EASM, East Asian summer monsoon; SST, sea surface temperature
with the warming SST in the EIWP Ocean, and consequently the increasing trend of the EASM index. Further improvements need to be made in the air–sea interaction over the EIWP region in these climate models.

The linear trend of precipitation in China is further explored during the time period 1961–2005 for simulations by the CMIP5 and CMIP6 models (Figure 13). Only two models (BCC-CSM2-MR and GISS-E2-1-H) from the CMIP6 partly reproduce the SFND rainfall pattern over Eastern China with a spatial correlation coefficient above 0.25, although 10 models simulate a decreasing trend in the EASM index. None model from CMIP5 can reproduce the SFND feature. The long-term change in precipitation in China is therefore even harder to reproduce in climate models than the EASM. This is also consistent with Song et al. (2014), which found that SFND pattern could not be reproduced by the CMIP5 models, although the weakening of EASM circulation was partly reproduced under all-forcing runs. The models simulating a positive trend in the EASM index (including CESM1-WACCM, CESM2 and CESM2-WACCM) all produce the opposite pattern of precipitation, with floods in North China and drought in the Yangtze River valley. The CMIP5 and CMIP6 MMEs both have little skill in the simulation of precipitation change over Eastern China.

4 | SUMMARY

We compare the ability of eight CMIP6 climate models and the corresponding eight previous models of CMIP5 to simulate summer precipitation in China
and the EASM during the time period 1961–2005, including the climatological states, the interannual pattern associated with the EASM and the long-term trend in recent decades. The results are summarized as follows:

1. The CMIP6 MME is more skillful than the CMIP5 MME in both the spatial correlation and SD of the climatological precipitation over Eastern China. Most (seven of eight) of the CMIP6 models show an improvement in simulating the distribution of the climatological precipitation relative to the previous CMIP5 models, with improved scores of the spatial correlations over Eastern China.

2. All the CMIP6 models improve their ability to simulate the climatological pattern of the EASM compared with the previous CMIP5 models. The MME of CMIP6 (0.94) has a higher skill score than the CMIP5 MME (0.89) in the climatological EASM. This is related to the less NWP SST biases in the CMIP6 models than the CMIP5 models. The models with a higher capability in simulating the EASM tend to have a higher ability in reproducing the climatological precipitation in Eastern China.

3. The models with a reasonable simulation of the anticyclonic anomalies over the Western Pacific also have a higher ability in the reproduction of the anomalous rainfall pattern in Eastern China associated with the EASM index. From CMIP5 MME to CMIP6 MME, the skill scores related to the EASM index improve from 0.04 to 0.2 for precipitation in Eastern China and from 0.25 to 0.39 for the 850 hPa winds over East Asia.

4. Six of the eight models from CMIP5 and four of the eight CMIP6 models simulate a weakening trend of
the EASM during the time period 1961–2005. The models reproducing the weakening trend of the EASM (GISS-E2-H and GISS-E2-1-H) can also capture the negative correlation between the EASM and the SST over the EIWP, indicating the importance in the simulation of the relationship between the EASM and the SST over the EIWP in climate models.

5. Two models (BCC_CSM2-MR and GISS-E2-1-H) from CMIP6 partly reproduce the linear trend in precipitation with SFND rainfall pattern in Eastern China during the time period 1961–2005, while no
model from CMIP5 could realistically produce this feature.

ACKNOWLEDGEMENTS
This work was jointly supported by the National Key Research and Development Program of China under Grant No. 2016YFA0602103 and the National Key Research and Development Program of China CERC-WET Project under Grant No. 2018YFE0196000.

ORCID
Xiaoge Xin https://orcid.org/0000-0001-9712-5368
Yongjie Fang https://orcid.org/0000-0002-2328-6043

REFERENCES
Chen, H., Zhou, T., Neale, R.B., Wu, X. and Zhang, G.J. (2010) Performance of the new NCAR CAM3.5 in East Asian summer monsoon simulations: sensitivity to modifications of the convection scheme. *Journal of Climate*, 23(13), 3657–3675. https://doi.org/10.1175/2010JCLI3022.1.
Dong, B., Wilcox, L.J., Highwood, E.J. and Sutton, R.T. (2019) Impacts of recent decadal changes in Asian aerosols on the East Asian summer monsoon: roles of aerosol–radiation and aerosol–cloud interactions. *Climate Dynamics*, 53, 3235–3256. https://doi.org/10.1007/s00382-019-04698-0.
Dong, X. (2016) Influences of the Pacific Decadal Oscillation on the East Asian Summer Monsoon in non-ENSO years. *Atmospheric Science Letters*, 17, 115–120.
Eyring, V., Bony, S., Meehl, G.A., Senior, G.A., Stevens, B., Stouffer, R.J. and Taylor, K.E. (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development, 9, 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016.

Feng, J., Wei, T., Dong, W., Wu, Q. and Wang, Y. (2014) CMIP5/AMIP GCM simulations of east Asian summer monsoon. Advances in Atmospheric Sciences, 31, 836–850. https://doi.org/10.1007/s00376-013-3131-y.

Gleckler, P.J., Taylor, K.E. and Doutriaux, C. (2008) Performance metrics for climate models. Journal of Geophysical Research, 113, D06104. https://doi.org/10.1029/2007JD008972.

Gong, D. and Ho, C. (2002) Shift in the summer rainfall over the Yangtze River valley in the late 1970s. Geophysical Research Letters, 29, 78–1–78-4. https://doi.org/10.1029/2001GL014523.

Han, J. and Wang, H. (2007) Interdecadal variability of the East Asian summer monsoon in an AGCM. Advances in Atmospheric Sciences, 24, 808–818. https://doi.org/10.1007/s00376-007-0808-0.

Harada, Y., Kamahori, H., Kobayashi, C., Endo, H., Kobayashi, S., Ota, Y., Onoda, H., Onogi, K., Miyaoka, K. and Takahashi, K. (2016) The JRA-55 reanalysis: representation of atmospheric circulation and climate variability. The Journal of the Meteorological Society of Japan, 94, 269–302. https://doi.org/10.2151/jmsj.2016-015.

He, C. and Zhou, T. (2014) The two interannual variability modes of the western North Pacific subtropical high simulated by 28 CMIP5–AMIP models. Climate Dynamics, 43, 2455–2469. https://doi.org/10.1007/s00382-014-2068-x.

Hu, Z.Z. (1997) Interdecadal variability of summer climate over East Asia and its association with 500-hPa height and global sea surface temperature. Journal of Geophysical Research, 102(D16), 19403–19412. https://doi.org/10.1029/97JD01052.

Huang, D.Q., Zhu, J., Zhang, Y.C. and Huang, A.N. (2013) Uncertainties on the simulated summer precipitation over Eastern China from the CMIP5 models. Journal of Geophysical Research: Atmospheres, 118, 9035–9047. https://doi.org/10.1002/2012JD020695.

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoka, K. and Takahashi, K. (2015) The JRA-55 reanalysis: general specifications and basic characteristics. Journal of the Meteorological Society of Japan, 93, 5–48. https://doi.org/10.2151/jmsj.2015-001.

Kusunoki, S. and Arakawa, O. (2015) Are CMIP5 models better than CMIP3 models in simulating precipitation over East Asia? Journal of Climate, 28, 5601–5621. https://doi.org/10.1175/JCLI-D-14-00585.1.

Lambert, S.J. and Boer, G.J. (2001) CMIP1 evaluation and intercomparison of coupled climate models. Climate Dynamics, 17, 83–106. https://doi.org/10.1007/PL00013736.

Lei, Y., Hoskins, B. and Slingo, J. (2011) Exploring the interplay between natural decadal variability and anthropogenic climate change in summer rainfall over China. Part I: observational evidence. Journal of Climate, 24, 4584–4599. https://doi.org/10.1175/2010JCLI3794.1.

Li, H., Dai, A., Zhou, T. and Lu, J. (2010) Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950–2000. Climate Dynamics, 34, 501–514. https://doi.org/10.1007/s00382-008-0482-7.

Lin, R., Zhu, J. and Zheng, F. (2016) Decadal shifts of East Asian summer monsoon in a climate model free of explicit GHGs and aerosols. Scientific Reports, 6, 38546. https://doi.org/10.1038/srep38546.

Momen, S., Hansen, J., Nazarenko, L. and Luo, Y.-F. (2002) Climate effects of black carbon aerosols in China and India. Science, 297, 2250–2253. https://doi.org/10.1126/science.1075159.

Ogata, T., Ueda, H., Inoue, T., Hayasaka, M., Yoshida, A., Watanabe, S., Kira, M., Ooshiro, M. and Kumai, A. (2014) Projected future changes in the Asian monsoon: a comparison of CMIP3 and CMIP5 model results. Journal of the Meteorological Society of Japan, 92, 207–225. https://doi.org/10.2151/jmsj.2014-302.

Qian, C. and Zhou, T. (2014) Multidecadal variability of North China aridity and its relationship to PDO during 1900–2010. Journal of Climate, 27, 1210–1222. https://doi.org/10.1175/JCLI-D-13-00235.1.

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C. and Kaplan, A. (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. Journal of Geophysical Research, 108(D14), 4407. https://doi.org/10.1029/2002JD002670.

Reichler, T. and Kim, J. (2008) How well do coupled models simulate today’s climate? Bulletin of the American Meteorological Society, 89, 303–311. https://doi.org/10.1175/BAMS-89-3-303.

Song, F. and Zhou, T. (2014a) The climatology and interannual variability of East Asian summer monsoon in CMIP5 coupled models: does air–sea coupling improve the simulations? Journal of Climate, 27, 8761–8777. https://doi.org/10.1175/JCLI-D-14-00396.1.

Song, F. and Zhou, T. (2014b) Interannual variability of East Asian summer monsoon simulated by CMIP3 and CMIP5 AGCMs: skill dependence on Indian Ocean–Western Pacific anticyclone teleconnection. Journal of Climate, 27, 1679–1697. https://doi.org/10.1175/JCLI-D-13-00248.1.

Song, F., Zhou, T. and Qian, Y. (2014) Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. Geophysical Research Letters, 41, 596–603. https://doi.org/10.1002/2013GL058705.

Sperber, K.R., Annamalai, H., Kang, I.-S., Kitoh, A., Moise, A., Turner, A.G., Wang, B. and Zhou, T. (2013) The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Climate Dynamics, 41, 2711–2744. https://doi.org/10.1007/s00382-012-1607-6.

Sun, Y. and Ding, Y.H. (2008) An assessment on the performance of IPCC AR4 climate models in simulating interdecadal variations of the East Asian summer monsoon. Acta Meteorologica Sinica, 22, 472–488.

Wang, B., Ding, Q.H., Fu, X.H., Kang, I.S., Jin, K., Shukla, J. and Doblas-Reyes, F. (2005) Fundamental challenge in simulation and prediction of summer monsoon rainfall. Geophysical Research Letters, 32, L15711. https://doi.org/10.1029/2005GL022734.

Wang, B. and Fan, Z. (1999) Choice of south Asian summer monsoon indices. Bulletin of the American Meteorological Society, 80,
Webster, P. and Yang, S. (1992) Monsoon and ENSO: selectively interactive systems. *Quarterly Journal of the Royal Meteorological Society*, 118, 877–926. https://doi.org/10.1002/qj.49711850705.

Wu, J. and Gao, X. (2013) A gridded daily observation dataset over China region and comparison with the other datasets. *Chinese Journal of Geophysics*, 56, 1102–1111 (in Chinese).

Wu, T., Lu, Y., Fang, Y., Xin, X., Li, L., Li, W., Jie, W., Zhang, J., Liu, Y., Zhang, L., Zhang, F., Zhang, Y., Wu, F., Li, J., Chu, M., Wang, Z., Shi, X., Liu, X., Wei, M., Huang, A., Zhang, Y. and Liu, X. (2019) The Beijing Climate Center Climate System Model (BCC-CSM): Main Progress from CMIP5 to CMIP6. *Geoscientific Model Development*, 12, 1573–1600. https://doi.org/10.5194/gmd-12-1573-2019.

Yu, R., Wang, B. and Zhou, T. (2004) Tropospheric cooling and summer monsoon weakening trend over East Asia. *Geophysical Research Letters*, 31, L22212. https://doi.org/10.1029/2004GL021270.

Yu, R. and Zhou, T. (2007) Seasonality and three-dimensional structure of the interdecadal change in East Asian monsoon. *Journal of Climate*, 20, 5344–5355. https://doi.org/10.1175/2007JCLI1559.1.

Zhang, L. and Zhou, T. (2015) Drought over East Asia: a review. *Journal of Climate*, 28, 3375–3399. https://doi.org/10.1175/JCLI-D-14-00259.1.

Zhou, T., Gong, D., Li, J. and Li, B. (2009) Detecting and understanding the multi-decadal variability of the East Asian summer monsoon: recent progress and state of affairs. *Meteorologische Zeitschrift*, 18, 455–467. https://doi.org/10.1127/0941-2948/2009/0396.

Zhou, T., Song, F., Lin, R., Chen, X. and Chen, X. (2013) The 2012 North China floods: explaining an extreme rainfall event in the context of a longer-term drying tendency. *Bulletin of the American Meteorological Society*, 94, S49–S51.

Zong, Y. and Chen, X. (2000) The 1998 flood on Yangtze, China. *Natural Hazards*, 22, 165–184. https://doi.org/10.1023/A:1008119805106.

How to cite this article: Xin X, Wu T, Zhang J, Yao J, Fang Y. Comparison of CMIP6 and CMIP5 simulations of precipitation in China and the East Asian summer monsoon. *Int J Climatol.*, 2020;40:6423–6440. https://doi.org/10.1002/joc.6590