Projected changes in summer precipitation over East Asia with a high-resolution atmospheric general circulation model during 21st century

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We provide a broad view of East Asian summer monsoon (EASM) precipitation and their changes in the 21st century under the representative concentration pathway RCP4.5 and RCP8.5 scenarios using a high-resolution (at 40 km) atmospheric general circulation model (AGCM). The simulated fields are validated against the multiple observational data sets in the reference period (1979–2008). Validation of seasonal simulated global climatology and EASM precipitation, annual cycle and various circulation fields including 25 individual Coupled Model Intercomparison Project phase 5 (CMIP5) and CMIP5 MME suggests that AGCM can be used to study the future projected characteristics of EASM. An investigation of uncertainty in precipitation shows larger values in the regions of high-precipitation belt and low terrain. Future projections are categorized as near (2010–2039), mid (2040–2069) and far (2070–2100) futures. The model projects an increased summer precipitation of about 3.2% (2.3%) in near future, about 4.5% (4.5%) in mid-future and about 2.4% (2.3%) in far future over East Asia region under RCP4.5 (RCP8.5) scenarios when compared to the reference period. As far as regional landmasses are concerned, model projects a gradual increase in the range of 5–15% over northeast China, coastal regions of southern China, Korea and Japan regions and a decrease of about 5–10% over southeastern and northwest parts of East Asia during the 21st century. The projected increase of EASM can be attributed to an increase in atmospheric moistures (relative humidity) over the east coast of China, Korea and northeast China and north and northwestwards enhancement of eddy geopotential height. Extreme events are examined by using various precipitation indices over EASM regions. Results indicate that the indices of heavy precipitation are projected to increase (both frequency and intensity) over Korea, Japan and northeast China in the range of 5–20%, indicating strong sensitivity of EASM to global warming.

KEYWORDS
AGCM, climate change, EASM, extreme precipitation events, RCP scenarios

1 | INTRODUCTION

The East Asian summer monsoon (EASM) is one of the important subsystems (South Asian summer monsoon and EASM) of the Asian summer monsoon. It has influence on the climate and weather in the East Asian regions. The summer monsoon rainfall accounts for about 70% of the annual precipitation of East Asia and is known as the rainy season or rainband (Mei-yu/Changma/Baiu) for this part of the world. During this season, large variations in precipitation events are found frequently and they often lead the water-related disasters such as heavy rainfall events which cause frequent floods.
Prolonged break in monsoon rainfall leads to severe droughts. Of late, these events have significantly increased due to the recent climate change (Kripalani et al., 2007). Thus, understanding and projection of future climate change is a very important issue for human activities in East Asia.

Previous studies have evaluated the future projections of EASM precipitation and its variability using atmosphere–ocean coupled general circulation models (AOGCMs) from the Intergovernmental Panel on Climate Change (IPCC)’s Coupled Model Intercomparison Project phase 3 (CMIP3; Kitoh and Uchiyama, 2006; Min et al., 2006; Zhou and Yu, 2006; Kripalani et al., 2007; Lu et al., 2007; Lu and Fu, 2010; Min and Jhun, 2010; Kusunoki and Arakawa, 2012; IPCC, 2013; Seo and Ok, 2013). These studies have typically concluded that the anthropogenic global warming would result a more intensified and an increased EASM precipitation than the global-mean precipitation (Min et al., 2006) and projected an increase of about 8% in summer monsoonal rainfall over East Asia towards the end of 21st century (Kripalani et al., 2007; Kusunoki and Arakawa, 2012; Seo and Ok, 2013). This increase is mainly attributed to enhancement in moist southerly flows over East Asia from the tropics (Lu et al., 2007). Using CMIP phase 5 (CMIP5) models (Taylor et al., 2012), future changes of EASM were also examined in the recent studies (Christensen et al., 2013; Seo et al., 2013; Lee and Wang, 2014; Freychet et al., 2015). They have anticipated a significant increase of about 10–15% in summer precipitation towards the end of the 21st century and it is attributed to the enhancement and westwards extension of the North Pacific Subtropical High (NPSH). A significant increase of atmospheric moisture over the East Asian region is expected (Seo et al., 2013; Lee and Wang, 2014). Freychet et al. (2015) have mentioned that the East Asia region would be highly vulnerable to warming and would exhibit more intense and more frequent precipitation. The heavy precipitation events total in the East Asian monsoon region under the warming climate are likely to increase by about 20% on the median estimate of the summer maximum 5-day precipitation (Christensen et al., 2013). Generally, spatial patterns of EASM precipitation and low-level moisture flux in the future climate are more consistent in CMIP5 than CMIP3 models (Seo et al., 2013). It is thought that these improvements may be due to higher horizontal resolution of CMIP5. Even, these AOGCMs have limitations to simulate the complex characteristics of monsoon over EASM regions. Their coarse horizontal resolution still prevents in capturing the local forcings like complex topography and surface heterogeneity which modulate the climate signal at finer time/spatial scales (Giorgi et al., 2009). Many previous studies have emphasized the effect of horizontal resolution dependence for the simulation of EASM (Sperber et al., 1994; Kobayashi and Sugi, 2004; Gao et al., 2006; Kusunoki et al., 2006; Mizuta et al., 2006; Kitoh and Kusunoki, 2008).

To overcome these limitations and improve the details of climate projections, various “regionalization” or “downscaling” techniques have been used to spatially refine the climate simulations of AOGCMs and bridge this spatial scale gap (Giorgi et al., 2001). Among various methods, the regional climate downscaling methods with regional climate models (RCMs) are widely used for climate simulations with the high horizontal resolutions, where lateral boundary conditions are nested from global circulation models (GCMs). Numerous modelling studies for the EASM simulation have confirmed that RCMs with relatively high resolution simulate the regional features of EASM more skilfully than the results of GCMs (Gao et al., 2001; 2011; 2012; 2013; Im et al., 2007; 2015; Yu et al., 2010; Zou and Zhou, 2013; Lee et al., 2014; Oh et al., 2014; Zou et al., 2016; Zou and Zhou, 2016). However, RCMs have to deal with the problem of the lateral boundary conditions because their performance highly depends on the performance of GCMs (Giorgi and Mearns, 2002). The high-resolution global downscaling method has advantage that it can avoid the lateral boundary problems, and that it can represent interactions between global and regional scales explicitly as well as the detailed regional-scale features (Mizuta et al., 2006).

With this idea in mind a high-resolution atmospheric general circulation model (AGCM) with 20 and 60 km resolutions has been developed at the Meteorological Research Institute (Mizuta et al., 2006; 2012). This model is used for the future climate projection during partial period with “time-slice method.” This experiment has been extensively applied to climate change studies over East Asia (Kusunoki et al., 2006; 2011; Kitoh and Kusunoki, 2008) as well as for extreme weather phenomena (Kamiguchi et al., 2006; Endo et al., 2012; 2017; Kitoh and Endo, 2016a; 2016b). These studies have indicated that the high-resolution AGCMs perform better in reproducing the spatial distribution of precipitation climatology as well as extremes.

Many studies have projected an increase in EASM precipitation at the end of 21st century over East Asia. They have projected an increase in precipitation amount over the East Asian main landmass (Sun and Ding, 2010). On the other hand, a few studies have postulated a decrease in precipitation over the southeastern portion of the East Asia regions (Li et al., 2006). Likewise, Sun and Ding (2010) projected an increase in the intensity of EASM while Li et al. (2010) have shown that EASM will change its location but not its intensity in response to global warming. Above studies depict that the projected change in EASM during the 21st century remains a controversial issue and emphasizes more focus with a high-resolution AGCM.

The purpose of the present paper is to provide detailed information of future changes in seasonal characteristics of EASM using a high-resolution AGCM with icosahedral-hexagonal grids. In this study, AGCM is continuously integrated from present-day climate to the end of the 21st
century to produce and analyse the projection of EASM changes over East Asia and surrounding oceans. After validation of model performance by comparing the simulated seasonal climatology, annual cycle and circulations with the various observed data sets, we have analysed the future climate change of EASM features in details. The model and simulation details are provided in section 2, while the performance of the model is presented in section 3. Assessment of the projected temperature, precipitation, circulation fields and extreme indices towards the end of the 21st century are described in section 4. Finally, conclusions drawn are summarized in section 5.

2 DESCRIPTION OF GME MODEL, OBSERVED DATA AND SIMULATION DETAILS

2.1 GME model

The atmospheric GCM used here is an operational global numerical weather prediction (NWP) model, GME (Majewski et al., 2002) of German Weather Service. It has been named GME because it replaced the operational global model (GM) and the regional model for the central Europe (EM). It is based on uniform icosahedral-hexagonal grid. Its grid-point approach avoids the disadvantages of spectral techniques as well as the pole problem in latitude-longitude grids and provides a data structure extremely well suited to high efficiency on distributed memory parallel computers. On the icosahedral-hexagonal grids, the time integration was used by a second-order-accurate semi-Lagrangian formulation for the shallow water equations (Baumgardner, 1994). The mass flux convection scheme was used for the cumulus parameterization (Tiedtke, 1989). For long-term simulation, a mass correction was applied in GME (Chaudhari, 2006). In this study, GME has run at a very high resolution \( n_l = 192 \) about 40 km corresponding to \( T_l 511 \) of ECMWF, where \( n_l \) is the number of equal intervals into which each side of the original icosahedral triangles is divided. In \( n_l 192 \) (40 km mesh size), the number of grid points are 368,642 and transform grid uses \( 900 \times 451 \) grid cells. The model has 40 levels in the vertical with the model top at 10 hPa. Detailed descriptions of the present experiment are summarized in Table 1.

Chaudhari (2006) described the model performance in the NWP and the seasonal prediction over East Asia region. The model-simulated precipitation was in good agreement with observation in NWP approach. In particular, the model has been able to capture the extreme weather phenomena such as typhoon, heavy precipitation, etc. over the East Asia coast. In long-term seasonal prediction, the model performance was well noted in the study of seasonally extreme cases, impact of Indian Ocean dipole-zonal mode and El Niño–Southern Oscillation on East and South Asian summer monsoon variability and recommended for long simulations for the study of climate change over Asia. Recently, Woo et al. (2018a; 2018b) tested the performance of GME by evaluating the various statistical measures before projecting future teleconnection between South and East Asian summer monsoon precipitations. Present study suggests that GME can be used for the study of future projection characteristics of South and East Asian monsoon systems.

2.2 Experiment design

We have performed the present-day climate simulation with horizontal resolution of 40 km for 30 years from 1979 to 2008 (considered as a current climate/reference/historical period) with the historical sea surface temperature (SST) and sea ice concentration (SIC) observed data of Atmospheric Model Intercomparison Project (AMIP) by National Center for Atmospheric Research (NCAR) following the procedure as described in Hurrell et al. (2008) (hereafter AMIP-type simulation). For the study of future climate change, the model was integrated from 1979 to 2009 (current climate) and sequentially the future climate simulation from 2010 to 2100 with future SST and SIC boundary data based on the two representative concentration pathway (RCP) scenarios (RCP8.5 and RCP4.5). Based on two RCP scenarios, the projected SST and SIC data from the Centro Euro-Mediterraneo sui Cambiamenti Climatici Climate Model (CMCC-CM) of CMIP5 participating models by IPCC Fifth Assessment Report (AR5) are used as the boundary conditions. The CMCC-CM is a coupled AOGCM, which has been developed and implemented by the Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), composed of ECHAM5 atmosphere, NEMO (OPA8.2) for the ocean, and LIM2 for sea-ice models. The OASIS coupler is used to exchange the relevant fields. The carbon cycle module includes the SILVA terrestrial vegetation model and the PELAGOS marine biogeochemistry model (Scoccimarro et al., 2011). The selection of CMCC-CM from CMIP5 models is due to (a) existence of SST and SIC variables as boundary conditions and (b) longest period of existence of both the RCP scenarios (RCP8.5 and RCP4.5) from CMIP5

| TABLE 1 Detail descriptions of the GME model configuration |
|---------------------------------------------------------|
| Model configuration                                     |
| Horizontal resolution 40 km \( (n_l 192) \)             |
| Grid points 900 × 451                                    |
| Vertical levels 40 (top at 10 hPa)                       |
| Time step 133.33 Sec                                     |
| Convection scheme Tiedtke (1989)                         |
| Cloud microphysics Doms and Schättler (2002)            |
| Radiative transfer of solar and thermal radiation Ritter and Geleyn (1992) |
| Vertical turbulent fluxes Müller (1981)                  |
| Sub-grid-scale orographic effects Lott and Miller (1997) |
| Soil model Heise and Schrodin (2002)                     |
data portal. Moreover, the CMCC-CM has a relatively high resolution (0.75° × 0.75°) in CMIP5 models. The specification of this model is briefly summarized in Table 2. Both monthly observed and projected SST and SIC data are converted into daily data using a linear interpolation technique. We forced the change of CO₂ concentration and other greenhouse gases yearly from the RCP database (reference: http://www.iiasa.ac.at/web-apps/tnt/RcpDb) for future climate simulation.

2.3 Observed data

For the validation of the present-day climate (1979–2008) simulation, we have used the monthly precipitation from CPC Merged Analysis of Precipitation (CMAP) data on a 2.5° lat/lon grid by Xie and Arkin (1997) and Global Precipitation Climatology Project (GPCP) data on a 2.5° lat/lon grid by Adler et al. (2003) and Huffman et al. (2009). To analyse the detailed features of precipitation over East Asia, the daily Asian Precipitation Highly Resolved Observational Data Integration Towards the Evaluation of Water Resources (APHRODITE) Version 1101 data at 0.25° spatial resolution over the monsoon Asia compiled by Yatagai et al. (2009) are also utilized. The APHRODITE is the historical high-resolution daily precipitation based on rain gauge and is available over the landmass only from 1979 to 2007 (29 years). For the other variables (surface air temperature, upper and low-level zonal/meridional winds, etc.), we have used the National Center for Environmental Prediction/Department of Energy (NCEP/DOE) Reanalysis II data (Kanamitsu et al., 2002, hereafter NCEP2) for 1979–2008 with the spatial resolutions of 2.5°.

2.4 Evaluation of CMIP5 models

For the validation of present-day climate simulation with GME, the model output of the AMIP experiments from the CMIP5 data sets are used (Taylor et al., 2012). These models are forced by the observed monthly global SST and sea ice. This AMIP experiments are well documented on the PCMDI website (http://pcmdi9.llnl.gov). We have selected 25 CMIP5 models simulation during 1979–2008 and the first realization (r1i1p1) of each model is used here. Table 3 summarizes the brief description of models (these models are listed in alphabetical order). The horizontal resolution of the CMIP5 models ranged from 3.75 to 0.1875° for the longitudinal grids and all the data sets were bi-linearly interpolated into 0.5 × 0.5° grid to define the multi-model ensemble (MME) mean (CMIP5 MME hereafter) of 25 models with equal weights. Finally, performance of GME is evaluated by comparing the results with the various observed data sets along with CMIP5 individual models and CMIP5 MME.

3 Evaluation of present-day climate simulations

3.1 Global seasonal mean climatology

In this paper, the present-day climate simulation and future climate projection during the 21st century are attempted for the first time using the GME model at 40 km horizontal resolution. Therefore, it is essential to evaluate the performance of GME in reproducing the global-scale climatological mean for present-day climate (1979–2008) conditions prior to the main objectives, that is, future projection of EASM characteristics. With that objective, global distribution of GME-simulated precipitation during summer (June–August; JJA) and winter (December–February; DJF) seasons are validated against the observed data sets and CMIP5 MME during the reference period. Seasonal precipitation patterns produced by CMIP5 MME and 25 individual models for both the seasons are also compared. Comparison reveals that the GME is able to reproduce the general global precipitation patterns over the tropical oceanic zones, major precipitation zones over the extra-tropical Pacific and storm track over the Atlantic sectors, but produced lower precipitation over the tropical ocean and the Asian monsoon regions. The low precipitation of GME can be linked with the appearance of an extra ITCZ (Intertropical Convergence Zone), appears south of the equator and extends from the Indian Ocean to the central Pacific in addition to the observed one north of the equator. This extra ITCZ may have impact on SST through cloud radiative forcing feedback (Zhang and Wang, 2006). It appears a common issue as noticed in many previous studies (Lin et al., 2008; Pascale et al., 2015; Xiang et al., 2017). Seasonal zonal mean precipitation patterns show the seasonal fluctuations with tropical peak, subtropical low and mid-latitude high. These simulated precipitation patterns agree well with the GPCP in both the seasons while an over estimation in mid-latitudes when compared with CMAP. Although GME shows an overestimation around 0°–10°S in JJA and 0–10°N in DJF but it lies within the range of CMIP5 individual models.

3.2 Seasonal summer monsoon precipitation and circulations

Figure 1 shows the spatial distribution of JJA mean precipitation from the GME and CMIP5 MME during the reference periods 1979–2008 based on GPCP and APHRODITE observations. Figure 1a–c depicts the observed JJA mean
precipitation and predominant rain band associated with the Mei-yu/Changma/Baiu front from southeastern part of China through Korea to Japan. The simulated summer precipitation by GME has produced the zones of high precipitation over large portions of Mei-yu/Changma/Baiu front (Korea and Japan regions), however, a low precipitation over the main rain band and stronger tropical precipitation are seen in simulated EASM pattern. These biases can be seen in CMIP5 MME (Figure 1d) also. Comparison (Figure 1d,e) also reveals that the spatial pattern of precipitation biases produced from GME was similar to that from CMIP5 MME but the amplitude is larger in GME even with high resolution. These biases appear a general problem in most of the GMs as mentioned in many previous studies (Sperber et al., 2013; Feng et al., 2014; Song and Zhou, 2014). These studies have pointed out that the CMIP5 and CMIP3 AGCMs have still problem of underestimation in simulating the Mei-yu/Changma/Baiu rainy front though the CMIP5 models showed the enhancement of the rainfall compared to the CMIP3 due to improved horizontal resolution (Ogata et al., 2014). In order to examine whether the biases are significant, the statistical significant tests are applied on the biases (Figure 1d, e). The contour encompassing most of the white patches depicted the statistical significant of biases at 95% significant level. It is noted that the larger negative biases, especially noticed over South Korea, Japan, east coast of south China and adjoining seas are not significant.

To consider the high-resolution simulated precipitation features, JJA precipitation and biases in GME and CMIP5 MME against the APHRODITE over East Asia landmass have been shown in Figure 1f–h. As the APHRODITE is available from 1979 to 2007 (only 29 years), hence the GME and CMIP5 model results are considered for the same period. Compared to APHRODITE, the GME has shown the negative biases over the southern parts (e.g., Mei-yu/Changma/Baiu rainy front) of East Asia, which is already discussed in Figure 1e. On the contrary, positive biases can be seen from west to east (120°–130°E) in the northern parts of north East Asia region which are commonly indicated in GME and CMIP5 MME both mainly over North Korea and

| Model name       | Modelling group                                                                 | Horizontal resolution (lon. × lat.) |
|------------------|---------------------------------------------------------------------------------|-----------------------------------|
| ACCESS1.0        | Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology, Australia | 1.875 × 1.25°                     |
| ACCESS1.3        |                                                                                 | 1.875 × 1.25°                     |
| BCC-CSM1.1       | Beijing Climate Center, China                                                   | 2.8 × 2.8°                        |
| BNU-ESM          | Beijing Normal University, China                                                | 2.8 × 2.8°                        |
| CanAM4           | Canadian Centre for Climate Modelling and Analysis, Canada                      | 2.8 × 2.8°                        |
| CCSM4            | National Center for Atmospheric Research, United States                        | 1.25 × 0.94°                      |
| CMCC-CM          | Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy                      | 0.75 × 0.75°                      |
| CNRM-CM5         | Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France | 1.4 × 1.4°                        |
| EC-EARTH         | EC-EARTH consortium published at Irish Centre for High-end Computing, Netherlands/Ireland | 1.125 × 1.125°                    |
| FGOALS-s2        | Institute of Atmospheric Physics, Chinese Academy of Sciences, China          | 2.8 × 3.0°                        |
| FGOALS-s2        |                                                                                 | 2.8 × 1.667°                      |
| GFDL-CM3         | Geophysical Fluid Dynamics Laboratory, United States                           | 2.5 × 2.0°                        |
| GFDL-HIRAM-C180  |                                                                                 | 0.625 × 0.5°                      |
| GFDL-HIRAM-C360  |                                                                                 | 0.3125 × 0.25°                    |
| GISS-E2-R        | NASA/GISS (Goddard Institute for Space Studies), United States                  | 2.5 × 2.0°                        |
| HadGEM2-A        | Met Office Hadley Centre, UK                                                    | 1.875 × 1.25°                     |
| INM-CM4          | Institute for Numerical Mathematics, Russia                                    | 2.0 × 1.5°                        |
| IPSL-CM5A-LR     | Institut Pierre Simon Laplace, France                                           | 3.75 × 1.875°                     |
| IPSL-CM5A-MR     |                                                                                 | 2.5 × 1.25°                       |
| IPSL-CM5B-LR     |                                                                                 | 3.75 × 1.875°                     |
| MIROC5           | Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan | 1.4 × 1.4°                        |
| MPI-ESM-LR       | Max Planck Institute for Meteorology, Germany                                   | 1.875 × 1.875°                    |
| MPI-ESM-MR       |                                                                                 | 1.875 × 1.875°                    |
| MRI-AGCM3.2H     | Meteorological Research Institute, Japan                                        | 0.5625 × 0.5625°                  |
| MRI-AGCM3.2S     |                                                                                 | 0.1875 × 0.1875°                  |

TABLE 3 Detail descriptions of the 25 CMIP5/AGCMs models used in this study
While over south China, large biases can be seen in GME, although it is insignificant. Nevertheless, the geographical distribution of precipitation in GME is improved in the central China, west Korea, and Japan with white patches which are significant at 95% significance level. Figure 1 also reveals that the GME (Figure 1b) and APHRODITE (Figure 1f) provide more regional details of seasonal precipitation as compared to the CMIP5 MME (Figure 1a) and GPCP (Figure 1c).

In order to understand the high amplitude of precipitation biases in GME, we have examined the biases for two cases; (a) topography above than 500 m and (b) topography less than 500 m. For case (a), Figure 2a–d shows that the precipitation biases over Korea-Japan regions, and large parts of east coast of south China and north China are closer to the observations in GME and CMIP5 MME. While over northwest China, CMIP5 model overestimated compared to GME over larger portions. While for case (b), both the models have overestimated mainly over north China and underestimated over South Korea and east coast of south China. Overall, negative biases are stronger in the regions of low terrain areas.

It is useful to identify the uncertainty over EASM regions where GME and CMIP5 MME perform better/and or worse, which may be useful for reliable assessment of climate change and to suggest for further improvement in GCM (GME) models. In this paper, we use the root-mean-square error to examine the uncertainty in CMIP5 MME and GME. The analysis is performed for summer precipitation. Analysis indicates that the uncertainty is larger in the regions that received high precipitation and in coastal areas, suggesting that the GCM not accurately represent these features. Over land areas (east coast of south China, Korea, and Japan regions) uncertainty ranges between 2–5 and 5–10 mm/day over the adjoining oceanic regions. Finally, the identification of specific regions where model perform better/and or worse as found in the present study, may provide fruitful information for scientists to improve the GME model.

Figure 3 shows the climatological wind fields at lower (850 hPa) and upper (200 hPa) levels simulated by GME.
and CMIP5 MME against the NCEP2. Figure 3a shows two dominant flows, one is southwesterly originated from South Asia region and another is anticyclonic circulation around 30°N over the West Pacific by western North Pacific Sub-tropical High (WNPSH), influenced the eastern China, Korea to Japan regions. The strength of these two merged flows (southwesterly from tropical region and southeasterly from West Pacific) is the key factors to influence the precipitation of Mei-yu/Changma/Baiu frontal regions. The CMIP5 MME and GME also reproduced the two apparent flows (Figure 3b,c), but slight north shifted patterns in WNPSH. While GME (CMIP5 MME) shows the weaker (stronger) southwesterly winds over the Southeast Asia regions can be attributed with lower precipitation of GME in JJA over East Asia region. Similar biases of weakened/strengthen southwesterly flows and anticyclonic circulations

**FIGURE 2** Seasonal biases (in %) from CMIP5 MME and GME with GPCP (APHRODITE) in JJA for topography above than 500 m (a–d) and for topography less than 500 m (e–h). The contours represent the topography at the 500 m [Colour figure can be viewed at wileyonlinelibrary.com]
due to the slanted northwards/southwards WNPSH (not shown) are also noted for the CMIP5 individual models. For the validation of simulated WNPSH, the closed contours of 1,530 m in geopotential height (GH) at 850 hPa, which describes the climatological position and intensity of WNPSH, are also examined from NCEP2 observation. The position of WNPSH simulated in GME, CMIP5 MME and its individual models are studied. Analysis indicates that most of the models including GME and CMIP5 MME show a northwards shift in the latitudinal position of WNPSH by

![850hPa Wind](image)

![200hPa Wind](image)

**FIGURE 3** JJA mean wind (m/s) fields at 850 and 200 hPa during reference periods (1979–2008) in (a, f) NCEP/NCAR Reanalysis II, (b, g) CMIP5 MME, (c, h) GME and (d, e, i, j) seasonal biases in CMIP5 MME and GME. The contours and shading show u-wind and v-wind components at the 95% confidence level based on Student’s t test [Colour figure can be viewed at wileyonlinelibrary.com]

![Climatological annual cycle of precipitation](image)

**FIGURE 4** Climatological annual cycle of precipitation during reference periods (1979–2008) over (a) East Asia (100°–150°E, 20°–50°N) and three main regions; (b) southern China (100°–120°E, 20°–40°N), (c) Korea (120°–130°E, 30°–45°N) and (d) Japan (130°–150°E, 30°–40°N) [Colour figure can be viewed at wileyonlinelibrary.com]
~5°N in comparison to the observation (around 35°N). However, the WNPSH from GME shows a more stretched westwards along with several CMIP5 individual models, while its intensity compared to the CMIP5 MME is relatively weak. The wind fields at 200 hPa (Figure 3f–j), which is related to the activity of upper-level jet, the GME simulates the stronger westerlies over the northeastern China, Korea, and Japan compared to the observation. Here also, a northwards shift in the westerly jet can be seen in CMIP5 individual models and GME which could not stretch the westerly jet around 40°N as it has noticed in the observation. Overall, GME is able to simulate the seasonal precipitation and circulation fields within the range of CMIP5 models.

### 3.3 Annual cycle in precipitation

Based on validation from spatial distribution of climatological precipitation and circulations fields, the monthly march of EASM precipitation are investigated to understand how GME reflects the generation of monthly rain. To validate the detailed annual cycle of precipitation for three main regions of EASM, simulated area-averaged monthly precipitations over East Asia (100°–150°E, 20°–50°N), southern China (100°–120°E, 20°–40°N), Korea (120°–130°E, 30°–45°N), and Japan (130°–150°E, 30°–50°N) are presented separately in Figure 4. For comparison, same observations, as well as CMIP5 MME including CMIP5 individual models, are used and monthly precipitation over landmass area is considered. On comparing the annual cycle, Figure 4a shows that the GME well captured the annual cycle of precipitation over East Asia compared to the CMIP5 individual models. It is interesting to note that the precipitation amounts in the rainy season are well simulated in GME, although it is underestimated in the face of Mei-yu/Changma/Baiu front as discussed in section 3.2 previously. Most of the CMIP5 models (GME also) overestimated precipitation after monsoon season. GME shows slightly less precipitation in July over southern China (Figure 4b) whereas the high precipitations are indicated from May to June over Korea and Japan (Figure 4c,d). On the whole, GME presents a better annual precipitation cycle better over the specific regions of East Asia compared to CMIP5 MME as well as the CMIP5 individual models.

These comparative studies of climatological precipitation, circulations, and annual cycle of EASM lead to believe that the GME can be used for the projection of future EASM characteristics.
4 | PROJECTION OF FUTURE CLIMATE CHANGE AND EXTREME EVENTS

4.1 | Projected annual temperature and JJA precipitation

Figure 5 presents the GME projected annual temperature and precipitation relative to the current climate (1979–2008) based on two RCP scenarios over East Asia region for the period 2010–2100. Figure 5 shows that the model projected annual temperature under RCP8.5 is increasing at faster rate after 2060 as compared to the RCP4.5 but the rate of increase is always higher in RCP8.5 during the study period. The years 2100 (5.95 °C) and 2098 (3.0 °C) are found to be the warmest years under RCP8.5 and RCP4.5, respectively, over East Asia region. It may be worth to project the number of warm years also during the period of study. Categorizing the number of projected warm years (cases) over East Asia during the 21st century having an increase of annual temperature above than 2 and 3 °C, present study found 56 (41) cases of above 2 °C and 41 (1) cases of above 3 °C under RCP8.5 (RCP4.5). Analysis also noticed 24 and 9 cases of above 4 and 5 °C under RCP8.5 over East Asia towards the end of 21st century. But there is not a single case of the same warming under RCP4.5 over the same region. Present study has also examined the common cases of projected warm years within the both scenarios. Results indicate a list of 41 common cases of above 2 °C and only one case of above 3 °C over East Asia region. It is worth noting that the maximum common warm cases under both the scenarios are after 2070. It implies that there is a strong possibility of warming of above 2 °C after 2070 compared to the reference period. For detail examination of future projection, total projection period are categorized into three time slices as each of 30 years length, that is, 2010–2039 (near future), 2040–2069 (mid-future) and 2070–2099 (far future). Different time slices indicate that the mean surface air temperature over the East Asia region could be raised by 0.74 °C (0.86 °C) during 2010–2039, 1.68 °C (2.29 °C) during 2040–2069 and 2.25 °C (4.02 °C) towards the end of 21st century under RCP4.5 (RCP8.5) scenarios.

Figure 5b–e depicts the multi-decadal climate variability in JJA precipitation for current (1979–2009) and future (2010–2100) climates over East Asia and its three subregional landmasses based on above mentioned scenarios. Figure 5b–e presents the prominent multi-decadal variability: thus epochal trends are modulated by the phase of the
multi-decadal variability. Figure 5b–e shows positive phase of variability after 2030 over Korea and Japan regions whereas over South China, most of the time, it is in negative phase of slow time variability in RCP8.5. While RCP4.5 shows both positive and negative phases in all three subregions but a longer positive phase can be seen over Korea and Japan. After investigating the projected multi-decadal variability, it may be interesting to project the flood and drought years (cases) during the 21st century. Categorizing the model projected floods (based on precipitation \( \geq 1.5\sigma \)) and droughts (precipitation \( \leq -1.5\sigma \)) cases under both the scenarios, present analysis found 6 (7) floods and 9 (11) droughts under RCP4.5 (RCP8.5) over East Asia region, while 8 (5) floods and 12 (7) droughts over Korea, 10 (5) floods and 11 (4) droughts over Japan, and 8 (9) floods and 7 (11) droughts over South China under RCP4.5 (RCP8.5). Above analysis indicates that the projected numbers of flood cases are higher compared to drought cases especially over the Korea and Japan region under both the scenarios. Considering East Asia as a whole, the numbers of drought cases are recorded higher compared to flood cases during the same period and same scenarios, while over southern China; projected drought cases is likely to be higher compared to flood cases in RCP8.5 during the study period. For listing the common cases of projected floods (droughts) within both scenarios, analysis found a list of 1 (5) for East Asia; 4 (2) for Korea; 1 (2) for Japan and 1 (4) for the southern China.

4.2 | Projected seasonal summer monsoon precipitation and circulations

In this section, the model projected change in JJA precipitation and circulations at 850 hPa over East Asia under both scenarios have been investigated in detail. As mentioned earlier, we have analysed JJA mean precipitation in three time slices in future, that is, 2010–2039 (near future), 2040–2069 (mid-future) and 2070–2099 (far future). Here, the period 1979–2008 is used as historical (reference) period. The future projected changes for the 21st century are obtained by taking the difference between future and the reference periods. The distribution of JJA precipitation and circulations for the reference and in the near, mid and far futures as simulated by the model and the projected change in three time slices are presented in Figure 6 for RCP4.5 and Figure 7 for RCP8.5, respectively. The spatial characteristics of projected precipitations show a general increase over east coast of China, Korea and Japan and a major decrease over northwest China under both scenarios. Similar enhancement in seasonal precipitation over East Asia is also reported in many previous studies during the 21st century (Christensen et al., 2013; Lee and Wang, 2014). Analysis of Figure 6e–g.
shows an increase of about 5–15% in precipitation over northeast China and near the coastal regions of southern China from near to mid future but a decrease of about 5–15% over southeastern and northwest parts of East Asia (above 40°N and west of 110°E) in far future. Previous study (Li et al., 2006) has also postulated a similar decrease in precipitation over the southeastern East Asia region. Over Korea and Japan sectors, model projected a slight decrease in precipitation over the Korean peninsula (5–10%) during near future but an increase (revival of monsoon) can be seen during the mid-future over both the sectors (5–20%); while for far future, there is an indication of large increase in precipitation (10–25%) over northeast China and north Japan in RCP8.5. While RCP4.5 shows an increase during far future but the rate of increase is lower than the RCP8.5. Figure 6e–g also shows a steady increase over the West Pacific in the range of 10–20% from near to far future in RCP8.5 but over the East Sea, there is an indication of an increase in precipitation in near future and a decrease from mid to far future (except for RCP8.5 during mid-future). The regions of positive precipitation over the East Asia domain coincide with the lower tropospheric cyclonic circulation centred on 25°N and 115°E. Furthermore, dry northerly/northeasterly flow close to the north of 30°N between 105° and 115°E may be one of the possible causes for low precipitation over the southern parts of China (high precipitation patches can be seen close to the east coast only) which suppressed the tropical southerly/southwesterly under both the scenarios. The difference in the wind fields exhibited a large-scale anticyclonic perturbation over the subtropical East Asian continent (close to the north of 35°N and 130°E). This perturbation induces strong northerly/northeasterly anomalies along the East Asian coast, causing influx of moistures from the West Pacific and leads to high seasonal summer precipitation over northeast China, Korea and Japan regions.

Figure 7 is similar to the Figure 6, but for the simulated precipitation change under RCP8.5 scenario. Comparison of precipitation change between RCP4.5 and RCP8.5 shows similar patterns as in RCP4.5. The remarkable difference can be noticed over the East Sea of Japan where precipitation patterns are completely different in the near and mid-future (in RCP8.5). Another remarkable difference can be noted over the northwest China and south of Japan, where RCP8.5 projected a significant decrease in precipitation of about 5–25% (RCP4.5 shows a significant decrease over northwest China only in far future). The computation of percentage change in JJA precipitation over East Asia as a whole, the model projects an increase of about 3.2% (2.3%) in near
future, about 4.5% (4.5%) in mid-future and about 2.4% (2.3%) in far future compared to the reference period under RCP4.5 (RCP8.5) scenarios.

4.3 Projected annual cycle

Figure 8 presents the mean monthly change in regionally averaged precipitation over the East Asia, Korea and Japan sectors from near to far future relative to the current climate (1979–2008) for both scenarios. It shows a large increase in monthly precipitation from January to March during 21st century under both the scenarios. This increase is of the order 3–49% over East Asia, 5–80% over Korea and 1–49% over Japan from near to far future. From April to May, there is a marginal change in precipitation over all the regions except over the Korean Peninsula, especially in April. Over the Korean Peninsula, there is a decrease of more than 8% from near to mid-future under RCP4.5, while an increase of around 8% is noted during far future. However, RCP8.5 shows initially a decrease (4.5%) then an increase of about 17% from mid to far future over the same domain. In June, precipitation decreases slightly mainly over East Asia from near to mid-future under both the scenarios indicating a late onset of monsoon as reported in other studies (Kitoh and Uchiyama, 2006) also. Figure 8 shows a high precipitation over Korea and Japan in July from mid to far future under both the scenarios. A large increase in July precipitation is noted over East Asia and Japan from mid to far future. The model projected high precipitation intensity from June to August mainly over Korea and Japan sectors during far future. In the month of September, there is a large decrease in precipitation over all the regions. While a large increase in precipitation is projected from October to December, indicating an enhancement in the period of EASM withdrawal (shifting of summer monsoon period). In other words, monsoon retreat date will be delayed, while onset date will either advance or show no change, resulting lengthening of the actual monsoon period.
An increase is projected in precipitation from December to March over the East Asia, Korea, and Japan during the 21st century under both scenarios. It is also worth mentioning that there is a large increase in precipitation during August over East Asia and Japan. A decrease in precipitation can be seen over all the sectors of East Asia in September under both the scenarios.

4.4 Projected seasonal summer monsoon relative humidity

Relative humidity (RH), especially at lower level, can be considered as an essential climate variable in both the energy and hydrological cycles of the climate system (Bojinski et al., 2014). Hence, proper investigation of its future behaviour is important for providing robust future projection of EASM. There are number of ways of representing the amount of water vapour present in the air (Willett et al., 2014) but here, we shall focus on RH. RH is defined as the amount of water vapour in the air relative to the maximum amount of water vapour that the air can hold at the same temperature without condensing it (expressed in percentage).

Figures 9 and 10 exhibit an increasing RH over the oceanic sectors, southeast China coast, northeast China, Korea and Japan and a low RH over large parts of the northwest China from near to far future under both the scenarios. These figures also show the percentage change in RH during near, mid and far future climates under RCP4.5 and RCP8.5, respectively. Figure 9e–g shows a high RH spreads over the southeast coast of China, south of Korean Peninsula and a large parts of northeast China while a low RH is seen over the west parts of the south and north China from near to far future (these are the pockets of projected low precipitation as mentioned in section 4.2). Similar patterns, that is, the positive (high RH) and negative (low RH) patterns of RH are seen under RCP8.5 (Figure 10e–g) as well as in RCP4.5. Major differences can be noted during far future where high and low RH intensified and spread over the larger areas. The projected RH indicates that the large parts of northwest and some parts of southwest China would be more arid (about 5%) whereas the eastern coast of China, Korea and northeast China would be more humid (5–20%) during the end of the 21st century. The wet and dry regions (as discussed in section 4.2) over the East Asian domain matched with the
The largest increase in RH is projected over the Korean peninsula in the range of 0.5–2% under RCP4.5 and 0.5–3% under RCP8.5 from near to far future. The largest decrease in RH is projected over parts of northwest and south China during mid-future in the range of −0.39% (−0.72%) and −0.64% (−1.11%) under RCP4.5 (RCP8.5). Although these values appear small in magnitudes, these projections indicate a decline RH in locations associated with large landmasses (pockets of projected low precipitation) such as west parts of north China. This is probably due to fact that there is a limited supply of water vapour from the surrounding ocean over the vast expanses of land, meaning the actual amount of water vapour in the air cannot increase at the same rate as the water vapour holding capacity of the atmosphere. Therefore, enhanced RH contributes to the increase in seasonal precipitation over the EASM regions.

4.5 | Projected seasonal summer monsoon eddy geopotential height

One of the major factors influencing the EASM characteristics is the NPSH and its westwards extension over the western North Pacific region is called the WNPSH. Yim et al. (2008) mentioned that the western North Pacific convective heating generates meridional teleconnection patterns, and this induces height anomalies. Such atmospheric circulation anomalies then affect the precipitation anomalies over East Asia region. The GH is widely used for depicting the WNPSH. But recent study by He et al. (2018) has suggested
for adopting the eddy geopotential height (EdGPH) for measuring WNPSH instead of geopotential height (GPH) under global warming scenario. A comparison between GPH and EdGPH, by using hypsometric equation, suggests that GPH metric perform extremely well in measuring the WNPSH in an unchanged climate rather than warming climate. Detail descriptions of the major advantage of using EdGPH and its computational procedure are nicely described in He et al. (2018). Therefore, present study also uses the EdGPH in measuring the WNPSH instead of GPH.

We have presented the seasonal EdGPH at 850 and 500 hPa under both the RCP scenarios to measure the WNPSH that influences the Mei-yu/Changma/Baiu rain band over East Asian domain. The seasonal changes in EdGPH at 850 and 500 hPa during near, mid and far future relative to the current climate are presented in Figure 11. Figure 11 shows major changes in EdGPH from mid to far future under both scenarios at 850 hPa. A smaller change in EdGPH is noticed in near future also (Figure 11a,b). A large increase in EdGPH (in the range of 9–15 m) can be seen in far future (Figure 11e,h). This increase is noticed in northwest direction covering large area of East Asian land masses. The increase in EdGPH is consistent up to 500 hPa especially during far future under both the scenarios (Figure 11k, l). Figure 11 also shows a decrease in EdGPH over western Pacific from near to far future mainly under RCP8.5 (Figure 11b,d,f). The maximum decrease of 3–6 m in EdGPH can be seen during far future under RCP8.5 (Figure 11f). Over the oceanic sector, North Pacific shows an increase and south portion of the ocean shows a decrease in EdGPH, which indicates convective heating over that areas. This meridional change in pattern of EdGPH can be linked with the East Asian monsoon teleconnection (an increase in precipitation).
Projected seasonal summer monsoon extreme precipitation events

The GME is used here also to project the change in extreme precipitation intensity in JJA under both scenarios during the 21st century. We have used three precipitation indices as described in Klein Tank et al. (2009) and Zhang et al. (2011). These indices are WDAY (the number of days having precipitation ≥1 mm/day), R20D (number of days having precipitation ≥20 mm/day), SDII (simply daily intensity index; total precipitation divided by the number of days with precipitation greater than or equal to 1 mm). Figure 12a–f shows the spatial distribution of future changes (in %) in extreme precipitation indices such as WDAY, R20D and SDII in near future (2010–2039), mid-future (2040–2069) and far future (2070–2099) relative to the current climate over East Asia.

Figure 12a–f shows an increase in WDAY by 5–15% over the southeast coast of China and northeast China and a decrease over northwest China in the range of 10–20% under RCP4.5 in near future. RCP8.5 shows a similar change in WDAY as in RCP4.5 except for a slight decrease over the Korean Peninsula during the same period (Figure 12a,b). For
mid-future, the WDAY shows similar patterns as in near future except an increase (by 5–10%) over Korea and Japan sectors (Figure 12d) and a decreased intensity compared to the near future under both the scenarios (Figure 12c,d). During far future, a large increase is noticed over the Korean Peninsula under RCP8.5 (Figure 12f) and the other changes are almost similar to that in RCP4.5. The RCP8.5 projected a larger decrease in WDAY over northwest China from near to far future as compared to RCP4.5.

Analysis of Figure 12g–l shows future change in R20D (heavier precipitation events) over East Asia for the above mentioned periods and scenarios. Figure 12g–l shows an increase of about 10–20% in R20D over large parts of the southeast coast of China, north China and over the Japan by 10–20% under RCP4.5 in near future while RCP8.5 shows a similar pattern as in RCP4.5 except a slightly larger increase (>20%) over Japan and a decrease (10–20%) over North Korea. For mid-future, the model projected an increase similar to that in near future but a large increase is projected over South Korea and Japan (10–30%) sectors under both the scenarios (Figure 12i,j). During far future, there is a similar pattern of increase over East Asia as in mid-period but the rate of increase in R20D is lower than that in the mid-future under both the scenarios. The largest changes in R20D are projected over the coastal south China, northeast China, parts of northwest China (close to 40°N and 105°E), Japan and Korea. The obvious increase of precipitation events over the above-mentioned regions have been also reported by previous studies (Ho et al., 2003; Kim et al., 2006; Yun et al., 2008; Min and Jhun, 2010; Christensen et al., 2013).
As far as SDII is concerned, Figure 12m–r shows an increasing pattern of SDII over large parts of the inland areas of East Asia under RCP4.5 and a similar pattern is also noticed in RCP8.5 except a significant increase (5–20%) over the northeast China during near future (Figure 12m,n). For mid to far futures, Figure 12o–r shows a larger increase under both the scenarios compared to the near future. The SDII shows an increase from near to far future and this increase is higher and significant during far future under both the scenarios. A high changes in SDII can be seen over Japan, coastal regions of China, northeast China and parts of the Korean Peninsula. Thus, we can anticipate that the above mentioned regions of the East Asia may experience more frequent extreme precipitation events even though low precipitation is simulated by GME compared to the observation (shown in section 4.2).

Overall, heavy precipitation events are projected to be increased over large parts of the East Asian during the 21st century.

5 | SUMMARY AND CONCLUSIONS

Present study examines the potential impacts of climate change over East Asia region. For this study, an atmospheric general circulation model (GME) at 40 km horizontal resolution is used first time to project the future climate change from near to far future periods under the RCP4.5 and
RCP8.5 scenarios. The model performance in simulating the seasonal summer circulations and precipitation was first validated over the reference period 1979–2008 using the observed precipitation from GPCP, APHRODITE and simulations from the NCEP2 as well as CMIP5 individual model and CMIP5 MME. The evaluation of GME performance for seasonal climatological global precipitation reveals that the GME is able to reproduce the seasonal precipitation patterns over major zones of tropical and extra-tropical regions. While over East Asia region, model in general captured the main characteristics of the EASM precipitation, annual cycle and circulations. GME shows large negative amplitude of precipitation biases in low terrain. The analysis of uncertainty in model produced precipitation biases depicts that the uncertainty is higher in the zone of high precipitation belts and mountainous coastal areas.

The GME-simulated annual temperature indicates a warming from near to far future periods under both the scenarios and a fast rising in annual temperatures (above 2 °C) are likely to be occurred after 2069 (in RCP4.5) and after 2051 (in RCP8.5) over East Asia. The rate of warming under RCP8.5 is higher than that under RCP4.5. The events of flood are also projected to be increased over Korea and Japan regions compared to southern China and East Asia as a whole in both the scenarios. The GME also projected an increase in JJA precipitation of 3.2% (2.3%) in near future, 4.5% (4.5%) in mid-future and 2.4% (2.3%) in far future compared to the reference period under RCP4.5 (RCP8.5) scenarios.

A peculiar feature in the projected EASM is the strengthening of WNPSh towards north and northwestwards from 850 to 500 hPa under both the scenarios. Therefore, along the northern and northwestern flanks, the strengthened WNPSh leads to an increase in moisture convergence (as discussed in the wind, RH and EdGPH analysis), enhancing the precipitation particularly over the east coast of Japan, Korea and northeast China. Heavy precipitation events (R20D) are projected to increase by 10–20% and 5–20% in SDII over large parts of the East Asian domains.

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REFERENCES

Adler, R.F., Huffman, G.J., Chang, A., Ferraro, R., Xie, P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J., Arkin, P. and Nelkin, E. (2003) The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present). Journal of Hydrometeorology, 4, 1147–1167.

Baumgardner, J.R. (1994) A semi-implicit semi-Lagrangian method for the shallow water equations on a triangular mesh. In: Fourth CHAMMP Workshop for the Numerical Solution of PDEs in Spherical Geometry. Chicago, IL: Department of Energy.

Bojinski, S., Verstraete, M., Peterson, T.C., Richter, C., Simmons, A. and Zemp, M. (2014) The concept of essential climate variables in support of climate research, applications, and policy. Bulletin of the American Meteorological Society, 95, 1431–1443.

Chaudhari, H.S. (2006) Predictability and prediction of East Asian summer monsoon: experiments with GCM. Thesis, Busan, Department of Environmental Atmospheric Science, Pukyong National University.

Christensen, J.H., Kanikicharla, K.K., Aldrian, E., An, S.I., Cavalcanti, I.F.A., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., Kitoh, A., Kossin, J., Lau, N.C., Renwick, J., Stephenson, D.B., Xie, S.-P., and Zhou, T. (2013) Climate phenomena and their relevance for future regional climate change. In: Stocker, T.F., et al. (Eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York, NY: Cambridge University Press.

Doms, G. and Schättler, U. (2002) The nonhydrostatic limited-area model LM (Lokal-Modell) of DWD. Part I: scientific documentation. Offenbach: Deutscher Wetterdienst (DWD).

Endo, H., Kitoh, A., Ose, T., Mizuta, R. and Kusunoki, S. (2012) Future changes and uncertainties in Asian precipitation simulated by multi-physics and multi-sea surface temperature ensemble experiments with high-resolution Meteorological Research Institute atmospheric general circulation models (MRI-AGCMs). Journal of Geophysical Research, 117, D16118. https://doi.org/10.1029/2012JD017874.

Endo, H., Kitoh, A., Mizuta, R. and Masuyoshi, I. (2017) Future changes in precipitation extremes in East Asia and their uncertainty based on large ensemble simulations with a high-resolution AGCM. SOLA, 13, 7–12. https://doi.org/10.2151/SOLA.2017-002.

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

Freychet, N., Hsu, H., Chou, C. and Wu, C. (2015) Asian summer monsoon in CMIP5 projections: a link between the change in extreme precipitation and monsoon dynamics. Journal of Climate, 28, 1477–1493. https://doi.org/10.1175/JCLI-D-14-00449.1.

Gao, X.J., Zhao, Z.C., Ding, Y.H., Huang, R.H. and Giorgi, F. (2001) Climate change due to greenhouse effects in China as simulated by a regional climate model. Advances in Atmospheric Sciences, 18, 1224–1230.

Gao, X.J., Yu, Y., Zhao, Z., Pal, J.S. and Giorgi, F. (2006) On the role of resolution and topography in the simulation of East Asia precipitation. Theoretical and Applied Climatology, 86, 173–185.

Gao, X.J., Shi, Y. and Giorgi, F. (2011) A high resolution simulation of climate change over China. Science China Earth Sciences, 54, 462–472.

Gao, X.J., Shi, Y., Zhang, D., Wu, J., Giorgi, F., Ji, Z. and Wang, Y. (2012) Uncertainties in monsoon precipitation projections over China: result from two high-resolution RCM simulations. Climate Research, 52, 213–226.

Gao, X.J., Wang, M.L. and Giorgi, F. (2013) Climate change over China in the 21st century as simulated by BCC_CSM1.1-RegCM4.0. Atmospheric Oceanic Science Letters, 6, 381–386.

Giorgi, F. and Mearns, L.O. (2002) Calculation of average, uncertainty range, and reliability of regional climate changes from AOOGCM simulations via the “reliability ensemble averaging” (REA) method. Journal of Climate, 15, 1141–1158.

Giorgi, F., Hewitson, B., Christensen, J., Fu, C., Jones, R., Hulme, M., Mearns, L., Von Storch, H. and Whetton, P. (2001) Regional climate information—evaluation and projections. In: Houghton, J.T. (Ed.) Climate change 2001: The scientific basis. Cambridge and New York, NY: Cambridge University Press, pp. 583–638.

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Sperber, K.R., Hameed, S., Potter, G.L. and Boyle, J.S. (1994) Simulation of the northern summer monsoon in the ECMWF model: sensitivity to horizontal resolution. Journal of Climate, 12, 2461–2841.

Sperber, K.R., Annamalai, H., Kang, I.S., Kitoh, A., Moise, A., Turner, A., 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.

Sun, Y. and Ding, Y.H. (2010) A projection of future changes in summer precipitation and monsoon in East Asia. Science China Earth Sciences, 53, 284–300.

Taylor, R., Stouffer, J. and Meehl, G.A. (2012) An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93, 485–498.

Tiedtke, M. (1989) A comprehensive mass flux scheme for cumulus parameterization in large-scale models. Monthly Weather Review, 117, 1779–1800.

Willett, K.M., Berry, D.I. and Simmons, A. (2014) Surface humidity [in State of the Climate in 2013]. Bulletin of the American Meteorological Society, 95, S19–S20.

Woo, S., Singh, G.P., Oh, J.-H. and Lee, K.M. (2018a) Possible teleconnection between East and South Asian monsoon precipitation in projected future climate change. Meteorology and Atmospheric Physics, 1–13. https://doi.org/10.1007/s00703-017-05732-2.

Woo, S., Singh, G.P., Oh, J.-H. and Lee, K.M. (2018b) Projection of seasonal summer precipitation over Indian sub-continent with a high-resolution AGCM based on the RCP scenarios. Meteorology and Atmospheric Physics, 1–20. https://doi.org/10.1007/s00703-018-0612-7.

Xiang, B., Zhao, M., Held, I.M. and Golaz, J.C. (2017) Predicting the severity of spurious “double ITCZ” problem in CMIP5 coupled models from AMIP simulations. Geophysical Research Letters, 44, 1520–1527.

Xie, P. and Arkin, P.A. (1997) Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bulletin of the American Meteorological Society, 78, 2539–2558.

Yatagai, A., Arakawa, O., Kamiguchi, K., Kawamoto, H., Nodzu, M.I. and Hamada, A. (2009) A 44-year daily gridded precipitation dataset for Asia based on a dense network of rain gauges. SOLA, 5, 137–140. https://doi.org/10.2151/SOLA.2009-035.

Yim, S.-Y., Yeh, S.-W., Wu, R. and Jhun, J.-G. (2008) The influence of ENSO on decadal variations in the relationship between the East Asian and western North Pacific summer monsoon. Journal of Climate, 21, 3165–3179.

Yu, E.T., Wang, H.J. and Sun, J.Q. (2010) A quick report on a dynamical downscaling simulation over China using the nested model. Atmospheric and Oceanic Science Letters, 3, 325–329.

Yun, K.S., Shin, S.-H., Ha, K.-J., Kitoh, A. and Kusunoki, S. (2008) East Asian precipitation change in the global warming climate simulated by a 20-km mesh AGCM. Asia-Pacific Journal of Atmospheric Sciences, 44, 233–247.

Zhang, G.J. and Wang, H. (2006) Towards mitigating the double ITCZ problem in NCAR CCSM3. Journal of Geophysical Research: Atmospheres, 33, L06709. https://doi.org/10.1029/2005GL025229.

Zhang, X., Alexander, L.V., Hegerl, G.C., Klein Tank, A., Peterson, T.C., Trewin, B. and Zwiers, F.W. (2011) Indices for monitoring changes in extremes based on daily temperature and precipitation data. Wiley Interdisciplinary Reviews: Climate Change, 2, 851–870.

Zhou, T.J. and Yu, R.C. (2006) Twentieth century surface air temperature over China and the globe simulated by coupled climate models. Journal of Climate, 19, 5843–5858.

Zou, L. and Zhou, T. (2013) Near future (2016–40) summer precipitation changes over China as projected by a regional climate model (RCM) under the RCP8.5 emissions scenario: comparison between RCM downscaling and the driving GCM. Advances in Atmospheric Sciences, 30, 806–818.

Zou, L. and Zhou, T. (2016) Future summer precipitation changes over CORDEX-East Asia domain under the RCP8.5 scenario downscaled by a regional ocean–atmosphere coupled model: a comparison the stand-alone RCM. Journal of Geophysical Research: Atmospheres, 121, 2691–2704.

Zou, L., et al. (2016) Dynamical downscaling of historical climate over CORDEX East Asia domain: a comparisons of regional ocean atmosphere coupled model to standalone RCM simulations. Journal of Geophysical Research: Atmospheres, 121, 1442–1458.

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