Interannual Variability of East Asian Summer Monsoon Simulated by CMIP3 and CMIP5 AGCMs: Skill Dependence on Indian Ocean–Western Pacific Anticyclone Teleconnection

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ABSTRACT

The climatology and interannual variability of East Asian summer monsoon (EASM) are investigated by using 13 atmospheric general circulation models (AGCMs) from phase 3 of the Coupled Model Intercomparison Project (CMIP3) and 19 AGCMs from CMIP5. The mean low-level monsoon circulation is reasonably reproduced in the multimodel ensemble mean (MME) of CMIP3 and CMIP5 AGCMs, except for a northward shift of the western Pacific subtropical high. However, the monsoon rainband known as mei-yu/baiu/changma (28°–38°N, 105°–150°E) is poorly simulated, although a significant improvement is seen from CMIP3 to CMIP5. The interannual EASM pattern is obtained by regressing the precipitation and 850-hPa wind on the observed EASM index. The observed dipole rainfall pattern is partly reproduced in CMIP3 and CMIP5 MME but with two deficiencies: weaker magnitude and southward shift of the dipole rainfall pattern. These deficiencies are closely related to the weaker and southward shift of the western Pacific anticyclone (WPAC). The simulation skill of the interannual EASM pattern has been significantly improved from CMIP3 to CMIP5 MME accompanied by the enhanced dipole rainfall pattern and WPAC. Analyses demonstrate that the tropical eastern Indian Ocean (IO) rainfall response to local warm SST anomalies and the associated Kelvin wave response over the Indo–western Pacific region are important to maintain the WPAC. A successful reproduction of interannual EASM pattern depends highly on the IO–WPAC teleconnection. The significant improvement in the interannual EASM pattern from CMIP3 to CMIP5 MME is also due to a better reproduction of this teleconnection in CMIP5 models.

1. Introduction

The East Asian summer monsoon (EASM) is an important climate system and plays a crucial role in the livelihood of more than one billion people (e.g., Tao and Chen 1987; Webster et al. 1998; Zhou et al. 2009a). EASM exhibits large interannual variability, and the induced droughts and floods can cause great economic loss and casualty, such as drought in 1994 and flooding in 1998 (Park and Schubert 1997; Zong and Chen 2000). Understanding the mechanisms of interannual variability is of crucial importance to the climate prediction in this region.

To reveal the dominant interannual variability mode of EASM, Wang et al. (2008) performed a multivariate EOF (MV-EOF) analysis over the EASM region and found the principal component of the leading mode is highly correlated with the reversed western Pacific monsoon index (Wang and Fan 1999). The dominant interannual EASM mode features an anomalous anticyclone over the northwestern Pacific (NWP) [viz., the western Pacific anticyclone (WPAC)], extending westward to the northern Bay of Bengal (Zhang et al. 1999; Zhang 2001; Wang et al. 2003). This anticyclone suppresses the
convection over the NWP and transports anomalous water vapor to the mei-yu/baiu/changma region (28°–38°N, 105°–150°E), thus forming a dipole rainfall pattern, which resembles the East Asia–Pacific (EAP) or Pacific–Japan (PJ) pattern (Nitta 1987; Huang and Lu 1989). The dominant mode occurs in the decaying phase of El Niño–Southern Oscillation (ENSO) (Wang et al. 2008; Liu et al. 2008) and is closely connected to the tropical Indian Ocean (TIO) sea surface temperature (SST) through Kelvin wave response (Yang et al. 2007; Li et al. 2008; Xie et al. 2009; Wu et al. 2009). Since the TIO SST contains significant portion independent of ENSO (Cherchi et al. 2007), it may partly exert influence on the EASM independently.

The complex EASM system has provided rigorous test beds for atmospheric general circulation models (AGCMs) (Liang and Wang 1998; Zhou and Li 2002; Chen et al. 2010; Zhou and Zou 2010; Boo et al. 2011). However, because of the complex topography and model limitation, how to reliably reproduce the climatological rainfall and interannual variation of EASM still remains a challenge. For example, the mei-yu/baiu/changma rainfall band is missing in the AGCMS, although the monsoon circulation is well reproduced (Zhou and Li 2002; Chen et al. 2010). At the interannual time scale, the rainfall deficiency over the NWP is evident in the AGCMs that participated in phase 3 of the Climate Model Intercomparison Project (CMIP3) (Zhou et al. 2009b).

Recently, summer rainfall simulation skills of the CMIP3 AGCMs in the Yangtze River valley (YRV) and NWP were investigated (Wang et al. 2011; Zhang et al. 2012). Wang et al. (2011) found that the upper-level and low-level East Asian jets act as the atmospheric bridges to subtropical Pacific SST in the east and west, respectively, and further control the interannual variability of the precipitation over the YRV. According to Zhang et al. (2012), the TIO and Pacific SST are vital to the NWP rainfall anomalies in addition to the climatological Walker cell and diabatic heating. They paid much attention to ENSO, considering that the preceding ocean forcing signals may be kept through land–atmosphere interaction (Zhang et al. 2012). Sperber et al. (2012) systematically evaluated the EASM in CMIP3 and CMIP5 coupled models. They found the interannual dipole rainfall pattern is weaker in models than observed, but the reason was not illustrated.

Actually, YRV and NWP are the two centers of the dipole rainfall pattern of dominant interannual variability mode of EASM (Wang et al. 2008), so it needs to explore their interannual variability from a whole view. How to improve the simulation of the interannual variability of EASM also needs to be investigated. Hence, the objectives of this study are 1) to examine the potential improvement of EASM simulation from CMIP3 to CMIP5 AGCMs and 2) to reveal the crucial dynamical processes that determine the model performance in reproducing the interannual variability of EASM. To answer these questions, the Atmospheric Model Intercomparison Project (AMIP) experiments from 13 CMIP3 and 19 CMIP5 AGCMs are analyzed. We show evidences that the simulation of the interannual EASM pattern has been significantly improved from CMIP3 to CMIP5. A reasonable simulation of the interannual EASM pattern is strongly dependent upon the Indian Ocean–western Pacific anticyclone (IO–WPAC) teleconnection.

The remainder of the paper is organized as follows: Section 2 provides a description of models, as well as the datasets and analysis methods used in this study. The climatology and interannual variability of the EASM are addressed in section 3. Section 4 is a summary.

2. Model, datasets, and analysis method

The AMIP experiments from 13 CMIP3 and 19 CMIP5 AGCMs are analyzed in this study. Only the first member of all models, with the same period from 1980 to 1997, is used for analysis. In the study, the 30-yr datasets covering 1979–2008 (except for 1979–2005 in CESM1 (CAM5) and NorESM1-M) in CMIP5 models are also used to confirm our conclusions based on the data covering 1980–97. All the datasets are regridded to a 2.5° × 2.5° common grid by bilinear interpolation. The details of the CMIP3 and CMIP5 models are listed in Tables 1 and 2, respectively, including the model number, horizontal resolution ranking, model acronym and expanded name, horizontal resolution, and affiliation.

Because we focus on the boreal summer, the June–August (JJA) seasonal mean is selected. An EASM index is defined by the 850-hPa zonal wind difference between the average over (22.5°–32.5°N, 110°–140°E) and that over (5°–15°N, 90°–130°E). This metric corresponds to the reversed definition of the western Pacific monsoon index (Wang and Fan 1999). According to Wang et al. (2008), this index is highly correlated to the first principal component of EASM and can be considered as a simple representation of the dominant interannual variability mode of EASM. The interannual EASM pattern is obtained by regressing the precipitation and 850-hPa wind upon the observed EASM index, considering both time evolution and spatial pattern. The SST averaged over the eastern equatorial Pacific (Niño-3.4: 5°S–5°N, 120°–170°W) in December–February (DJF) is used as the ENSO index, which is denoted as the Niño-3.4 index.

The observational and reanalysis datasets used here include the following: 1) atmospheric circulation and air temperature from the National Centers for Environment
AMIP-II reanalysis (NCEP-2), with a horizontal resolution of 2.5° × 2.5° (Kanamitsu et al. 2002); 2) atmospheric circulation from the 40-yr European Center for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40), with a horizontal resolution of 2.5° × 2.5° (Uppala et al. 2005); 3) precipitation data from the Global Precipitation Climatology Project (GPCP), with a resolution of 2.5° × 2.5° (Adler et al. 2003); 4) precipitation data from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), with a resolution of 2.5° × 2.5° (Xie and Arkin 1997); and 5) SST data from the National Oceanic and Atmospheric Administration extended reconstructed SST, version 3b (ERSST.v3b), with a resolution of 2° × 2° (Smith et al. 2008).

To evaluate the model performance in the simulation of the climatology and interannual EASM pattern over East Asia (0°~50°N, 100°~160°E), the following formula is applied to calculate the skill score of each model (Chen et al. 2013):

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

where \( R \) is the pattern correlation between the observation and model and \( SDR \) is the ratio of spatial standard deviation of the model against the observations. Obviously, both the spatial distribution and magnitude are considered in Eq. (1).

### Table 1. Details of 13 CMIP3 AGCMs used in the study, including horizontal resolution (HR).

<table>
<thead>
<tr>
<th>No. (HR ranking)</th>
<th>Model</th>
<th>Model expanded name</th>
<th>HR</th>
<th>Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (6)</td>
<td>CNRM-CM3</td>
<td>Centre National de Recherches Météorologiques Coupled Global Climate Model, version 3</td>
<td>2.8° × 2.8°</td>
<td>Centre National de Recherches Meteorologiques (CNRM), France</td>
</tr>
<tr>
<td>2 (5)</td>
<td>GFDL CM2.1</td>
<td>Geophysical Fluid Dynamics Laboratory Climate Model, version 2.1</td>
<td>2° × 2.5°</td>
<td>National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL), United States</td>
</tr>
<tr>
<td>3 (12)</td>
<td>GISS-ER</td>
<td>Goddard Institute for Space Studies Model E-R</td>
<td>4° × 5°</td>
<td>National Aeronautics Space Administration (NASA) Goddard Institute for Space Studies (GISS), United States</td>
</tr>
<tr>
<td>4 (10)</td>
<td>FGOALS-g1.0</td>
<td>Flexible Global Ocean–Atmosphere–Land System Model gridpoint, version 1.0</td>
<td>3° × 2.8°</td>
<td>Institute of Atmospheric Physics (IAP), China</td>
</tr>
<tr>
<td>5 (12)</td>
<td>INM-CM3.0</td>
<td>Institute of Numerical Mathematics Coupled Model, version 3.0</td>
<td>4° × 5°</td>
<td>Institute of Numerical Mathematics (INM), Russia</td>
</tr>
<tr>
<td>6 (11)</td>
<td>IPSL-CM4</td>
<td>L’Institut Pierre-Simon Laplace Coupled Model, version 4</td>
<td>2.5° × 3.8°</td>
<td>L’Institut Pierre Simon Laplace (IPSL), France</td>
</tr>
<tr>
<td>7 (1)</td>
<td>MIROC3.2 ( hires)</td>
<td>Model for Interdisciplinary Research on Climate, version 3.2 (high resolution)</td>
<td>1.1° × 1.1°</td>
<td>Center for Climate System Research (CCSR), National Institute for Environmental Studies (NIES), Frontier Research Center for Global Change (FRCGC), Japan</td>
</tr>
<tr>
<td>8 (6)</td>
<td>MIROC3.2 ( medres)</td>
<td>Model for Interdisciplinary Research on Climate, version 3.2 (medium resolution)</td>
<td>2.8° × 2.8°</td>
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<tr>
<td>9 (4)</td>
<td>ECHAM5</td>
<td>—</td>
<td>1.9° × 1.9°</td>
<td>Max Planck Institute for Meteorology (MPI-M), Germany</td>
</tr>
<tr>
<td>10 (6)</td>
<td>MRI-CGCM2.3.2a</td>
<td>Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 2.3.2a</td>
<td>2.8° × 2.8°</td>
<td>Meteorological Research Institute (MRI), Japan</td>
</tr>
<tr>
<td>11 (2)</td>
<td>CCSM3</td>
<td>Community Climate System Model, version 3</td>
<td>1.4° × 1.4°</td>
<td>National Center for Atmospheric Research (NCAR), United States</td>
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<td>12 (6)</td>
<td>PCM</td>
<td>Parallel Climate Model</td>
<td>2.8° × 2.8°</td>
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<td>13 (3)</td>
<td>HadGEM1</td>
<td>Hadley Centre Global Environment Model, version 1</td>
<td>1.3° × 1.9°</td>
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</tbody>
</table>
To test whether the improved skill score from CMIP3 to CMIP5 multimodel ensemble mean (MME) in both climatology and interannual EASM pattern is significant, the following method is proposed: We first divide the evaluation region ($0^\circ$–$50^\circ$N, $100^\circ$–$160^\circ$E) into 24 subregions equally spaced (each one is $25^\circ \times 5^\circ$). Then Eq. (1) is applied to each subregion to get their skill scores in both CMIP3 and CMIP5 MME. If differences of skill scores between CMIP5 and CMIP3 MME are positive over 80% of the subregions (at least 19), the

<table>
<thead>
<tr>
<th>No. (HR ranking)</th>
<th>Model</th>
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<th>HR</th>
<th>Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (7)</td>
<td>ACCESS1.0</td>
<td>Australian Community Climate and Earth-System Simulator, version 1.0</td>
<td>$1.3^\circ \times 1.9^\circ$</td>
<td>Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia</td>
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<tr>
<td>2 (16)</td>
<td>BCC_CSM1.1</td>
<td>Beijing Climate Center, Climate System Model, version 1.1</td>
<td>$2.8^\circ \times 2.8^\circ$</td>
<td>Beijing Climate Center, China</td>
</tr>
<tr>
<td>3 (16)</td>
<td>BNU-ESM</td>
<td>Beijing Normal University Earth System Model</td>
<td>$2.8^\circ \times 2.8^\circ$</td>
<td>Beijing Normal University, China</td>
</tr>
<tr>
<td>4 (16)</td>
<td>CanAM4</td>
<td>Fourth-generation Canadian Centre for Climate Modelling and Analysis AGCM</td>
<td>$2.8^\circ \times 2.8^\circ$</td>
<td>Canadian Centre for Climate Modeling and Analysis, Canada</td>
</tr>
<tr>
<td>5 (3)</td>
<td>CCSM4</td>
<td>Community Climate System Model, version 4</td>
<td>$0.9^\circ \times 1.3^\circ$</td>
<td>NCAR, United States</td>
</tr>
<tr>
<td>6 (3)</td>
<td>CESM1 (CAM5)</td>
<td>Community Earth System Model, version 1 (Community Atmosphere Model, version 5)</td>
<td>$0.9^\circ \times 1.3^\circ$</td>
<td>NCAR, United States</td>
</tr>
<tr>
<td>7 (5)</td>
<td>CNRM-CM5</td>
<td>Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5</td>
<td>$1.4^\circ \times 1.4^\circ$</td>
<td>CNRM and Centre Europeen de Recherches et de Formation Avance en Calcul Scientifique (CERFACS), France</td>
</tr>
<tr>
<td>8 (19)</td>
<td>FGOALS-g2</td>
<td>Flexible Global Ocean–Atmosphere–Land System Model gridpoint, version 2</td>
<td>$3^\circ \times 2.8^\circ$</td>
<td>IAP and Tsinghua University, China</td>
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<tr>
<td>9 (12)</td>
<td>FGOALS-s2</td>
<td>Flexible Global Ocean–Atmosphere–Land System Model, second spectral version</td>
<td>$1.7^\circ \times 2.8^\circ$</td>
<td>IAP, China</td>
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<tr>
<td>10 (14)</td>
<td>GISS-E2-R</td>
<td>Goddard Institute for Space Studies Model E, coupled with the Russell ocean model</td>
<td>$2.0^\circ \times 2.5^\circ$</td>
<td>NASA GISS, United States</td>
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<tr>
<td>11 (7)</td>
<td>HadGEM2-AO</td>
<td>Hadley Centre Global Environment Model, version 2–Atmosphere and Ocean</td>
<td>$1.3^\circ \times 1.9^\circ$</td>
<td>Met Office Hadley Center, United Kingdom</td>
</tr>
<tr>
<td>12 (9)</td>
<td>INM-CM4.0</td>
<td>Institute of Numerical Mathematics Coupled Model, version 4.0</td>
<td>$1.5^\circ \times 2^\circ$</td>
<td>INM, Russia</td>
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<td>13 (15)</td>
<td>IPSL-CM5A-LR</td>
<td>L’Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, low resolution</td>
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<td>14 (5)</td>
<td>MIROC5</td>
<td>Model for Interdisciplinary Research on Climate, version 5</td>
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<td>Atmosphere and Ocean Research Institute (AORI), NIES, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan</td>
</tr>
<tr>
<td>15 (10)</td>
<td>MPI-ESM-LR</td>
<td>Max Planck Institute Earth System Model, low resolution</td>
<td>$1.9^\circ \times 1.9^\circ$</td>
<td>MPI-M, Germany</td>
</tr>
<tr>
<td>16 (10)</td>
<td>MPI-ESM-MR</td>
<td>Max Planck Institute Earth System Model, medium resolution</td>
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<td>MPI-M, Germany</td>
</tr>
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<td>17 (2)</td>
<td>MRI-AGCM3-2H</td>
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<td>MRI, Japan</td>
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<tr>
<td>19 (12)</td>
<td>NorESM1-M</td>
<td>Norwegian Earth System Model, version 1 (intermediate resolution)</td>
<td>$1.9^\circ \times 2.5^\circ$</td>
<td>Norwegian Climate Centre, Norway</td>
</tr>
</tbody>
</table>
improvement from CMIP3 to CMIP5 MME is thought to be significant. This way is also used to evaluate the significance of skill difference of the IO–WPAC teleconnection between CMIP5 and CMIP3 MME.

3. Results

a. The climatology of EASM simulated by CMIP3 and CMIP5 AGCMs

The climatology of 850-hPa wind and precipitation in observations and CMIP3 AGCMs is shown in Fig. 1. To evaluate the models' performance, different observational datasets are compared to ensure the consistency between observations. Hence, two observational precipitation datasets (GPCP and CMAP) and atmospheric circulation datasets (NCEP-2 and ERA-40) are used. In NCEP-2 (Fig. 1a), the westerly winds dominate the Indochina peninsula and South China Sea (SCS) and south-westerly winds flow through eastern China, the Korean Peninsula, and Japan. The monsoon rainband is dominated by the western Pacific subtropical high (WPSH) (the anticyclone circulation over the western Pacific). Corresponding to the strong westerly winds and WPSH,
there are four precipitation centers in GPCP (Fig. 1a): the Indochina peninsula, SCS, western Pacific Ocean, and monsoon rainband called mei-yu/baiu/changma (along 30°N). Such features are also evident in ERA-40 and CMAP (Fig. 1b), with the pattern correlation coefficients of 0.95 and 0.89 with NCEP-2 and GPCP, respectively. The MME of CMIP3 features a northward shift of the WPSH, resulting in an underestimation of precipitation along the monsoon rainband but overestimation of precipitation over the SCS. Many CMIP3 models show biases in reproducing the position of the WPSH and the associated magnitude of the monsoon rainfall band, as with previous models (Zhou and Li 2002; Chen et al. 2010). Similar biases are also evident in CMIP5 models, but the precipitation simulation is improved in CMIP5 compared to CMIP3. For example, three precipitation centers (the Indochina peninsula, SCS, and western Pacific Ocean) over the tropics in CMIP5 MME are closer to the observations in magnitude and more distinguished in spatial structure (Fig. 1c versus Fig. 2a). Although the monsoon rainband is almost missing in both CMIP3 and CMIP5 MME, there are more models in CMIP5, which can reproduce the monsoon rainband (Fig. 1i versus Figs. 2f,r,s).

As shown above, two observational datasets are highly consistent in the climatology of wind and precipitation. Thus, NCEP-2 and GPCP are selected as the observational metrics. The skill scores of CMIP3/CMIP5 models using Eq. (1) in reproducing the climatological EASM are displayed in Fig. 3, which shows the skill scores of 850-hPa wind and precipitation. The skill scores of wind are higher than those of precipitation in most models, indicative of a better reproduction of wind than precipitation. Among 13 CMIP3 AGCMs, IPSL-CM4 performs best in the precipitation simulation with the skill score of 0.76. Among 19 CMIP5 AGCMs, MRI-AGCM3-2H, MRI-AGCM3-2S, and CCSM4 show reasonable precipitation performances, as evidenced by skill scores of 0.77, 0.75, and 0.74, respectively. The skill score of wind in CMIP3 MME is the same as that in CMIP5 MME (0.84), but the precipitation simulation has been improved from CMIP3 (0.75) to CMIP5 (0.77). Using our proposed test method, differences of precipitation (850-hPa wind) skill scores between CMIP5 and CMIP3 MME are positive over 19 (13) of 24 sub-regions. It is suggested that the climatological precipitation is significantly improved from CMIP3 to CMIP5 but the 850-hPa wind is not. For both CMIP3 and CMIP5 models, there is a robust positive linear relationship between the skill score of wind and precipitation, significant at the 5% level. It indicates that the simulation of monsoon circulation is closely related to that of monsoon precipitation.

To discuss the possible relationship between the skill score and the horizontal resolution of models, the skill score of each model in CMIP3 and CMIP5 is displayed according to its original horizontal resolution, as shown in Figs. 3b and 3c. No evident relationship is seen between model skills and resolutions (Figs. 3b,c). Even though many models have the same resolution, their skills are still different. On the other hand, although MIROC3.2 (hires) and MIROC3.2 (medres) have different horizontal resolutions (but the same physics scheme), they share almost the same low-level circulation skill (0.83 versus 0.84). As previously noted (Chen et al. 2010), model physics schemes are important in the simulation of monsoon system. The increase of horizontal resolution will take into account the topography’s influence on the precipitation. However, the physics scheme (e.g., convection scheme) may also need to be developed accordingly to produce the best possible results.

b. The interannual EASM pattern simulated by CMIP3 and CMIP5 AGCMs

The time series of the EASM index derived from CMIP3 and CMIP5 models are compared to NCEP-2, which is regarded as the observed EASM index, in Figs. 4a and 4b. The interannual variation of the EASM is well reproduced in both CMIP3 and CMIP5 MME. The correlation coefficient of the EASM index between NCEP-2 and the CMIP3 and CMIP5 MME is 0.70 and 0.68, respectively: both are statistically significant at the 1% level. To discuss whether the correlation is dependent on the model’s horizontal resolution, the correlation coefficients of CMIP3 and CMIP5 models are shown in Figs. 4c and 4d, respectively, according to the horizontal resolution ranking. Except for CCSM3, all the models show positive correlations with NCEP-2, with 8 of 13 CMIP3 and 11 of 19 CMIP5 models’ results statistically significant at the 5% level (Figs. 4c,d). Again, the correlation coefficient is not sensitive to the horizontal resolution. For example, the models with the highest correlation are FGOALS-g1.0 (0.82) in CMIP3 and FGOALS-g2 (0.74) in CMIP5. However, FGOALS-g1.0’s horizontal resolution is lower than most CMIP3 models and, among CMIP5, FGOALS-g2 is the last model in terms of resolution ranking.

To investigate the simulation of the interannual EASM pattern, the precipitation and 850-hPa wind are regressed upon the observed EASM index. The results are shown in Figs. 5 and 6 for CMIP3 and CMIP5, respectively. In NCEP-2 (Fig. 5a), the WPAC is evident with increased southwesterly winds over southeastern China and westerly winds along the YRV and Japan. On the southern flank, the enhanced easterly winds prevail over the tropics.
Correspondingly, the precipitation anomalies in GPCP exhibit the dipole pattern with a negative southern lobe over the NWP and a positive northern lobe along the YRV to southern Japan. The southern lobe consists of three centers similar to climatological distributions and the northern lobe includes two centers over the YRV and southern Japan. The results from ERA-40 and CMAP (Fig. 5b) show almost the same results as NCEP-2 and
GPCP with the pattern correlation coefficient of 0.98 (0.93) for wind (precipitation). The interannual EASM patterns derived from different observational datasets are highly consistent, so the wind from NCEP-2 and precipitation from GPCP are regarded as the observations to evaluate the simulation skills in models in the rest of the study.

The WPAC in the CMIP3 MME is weaker than observed (Fig. 5c). Accordingly, the dipole rainfall pattern is also weaker, consistent with the results derived from coupled model studies in Sperber et al. (2012). Most models reproduce the WPAC and dipole rainfall pattern, but CNRM-CM3, CCSM3, and PCM show almost opposite spatial patterns. The CMIP5 MME shows similar patterns to the CMIP3 MME but with enhanced WPAC and a stronger dipole rainfall pattern (Fig. 6a). The negative southern (positive northern) lobe is improved mainly over the NWP (southern China) with about $-0.7$ mm day$^{-1}$ (0.6 mm day$^{-1}$) from CMIP3 to CMIP5 MME.

To show the dipole rainfall pattern more clearly, the precipitation averaged over the NWP ($10^\circ$–$20^\circ$N, $105^\circ$–$150^\circ$E) and mei-yu/baiu/changma region ($28^\circ$–$38^\circ$N, $105^\circ$–$150^\circ$E) is displayed in Fig. 7. The magnitude of precipitation averaged over the NWP is about 2 times that of the precipitation averaged over mei-yu/baiu/changma in GPCP. There are 8 of 13 CMIP3 models and 14 of 19 CMIP5 models with the same signs as the observation, but most models underestimate the magnitude of precipitation in these two regions. The CMIP3 (CMIP5) MME only accounts for 21.7% (17.3%) of the observed magnitude over the mei-yu/baiu/changma region, while this percentage reaches 43.7% (59.8%) over the NWP. Over the mei-yu/baiu/changma region, only INM-CM3.0 in CMIP3 is comparable to observations (91%) and no model exceeds the observations. Compared to the mei-yu/baiu/changma region, more models have the similar magnitude to the observations (four models in CMIP5) and are even stronger over the NWP (two models in CMIP3 and three models in CMIP5).

Major limitation of CMIP3/CMIP5 models in the interannual EASM pattern is the southward shift of the dipole rainfall pattern (Figs. 5c, 6a). This deficiency may be partly due to the lack of air–sea interaction in the AMIP experiment, since the southward shift of the positive northern lobe may include the incorrect response to the positive SST anomalies over the NWP (Figs. 10c–f). In coupled models, this deficiency almost disappears (see Fig. 10 in Sperber et al. 2012). This kind of deficiency is partly responsible for the underestimation of the dipole rainfall pattern.

Given the dominance of WPAC on the anomalous water vapor transport and thereby monsoon rainfall anomalies, we further evaluate the model performance in the simulation of WPAC (Fig. 8). The ridge latitude position is defined as $u = 0$ and $\partial u / \partial y > 0$, where $u$ is the zonal wind (Li and Chou 1998). In NCEP-2 (Fig. 8a), the WPAC ridge is located at $22.5^\circ$N, but it shifts southward about $2^\circ$ in both CMIP3 and CMIP5 MME (Fig. 8a). The WPAC ridge in ERA-40 is $22.7^\circ$N, almost the same as NCEP-2, indicative of consistency between observations. Considering the models' horizontal resolution, the differences of $2^\circ$ may not be significant. However, there are 9 out of 13 CMIP3 models and 14 out of 19 CMIP5 models with a WPAC ridge south to that of NCEP-2. Hence, we suggest that the southward shift of WPAC relative to the observations is a common phenomenon among models. The southward extension of the WPAC...
is closely related to the southward shift of the dipole rainfall pattern.

The WPAC extends from the SCS to nearly the dateline in the observations (Fig. 8b), which suppresses the convection over the NWP and transports anomalous water vapor to the mei-yu/baiu/changma region along 30°N. The intensities of WPAC derived from CMIP3 and CMIP5 MME are weaker than NCEP-2. To quantify the differences of WPAC magnitude among models and observation, a WPAC index is defined as sea level pressure (SLP) anomalies averaged over the NWP (10°–30°N, 120°–160°E) and regressed upon the observed EASM index, shown in Figs. 8c and 8d for CMIP3 and CMIP5, respectively. CMIP3 (CMIP5) MME only accounts for 54.9% (64.4%) of the observed magnitude. There are 10 of 13 CMIP3 models and 15 of 19 CMIP5 models in which the WPAC is weaker than observed. The weakened WPAC underestimates the suppressed convection over the NWP and water vapor transport to the north. The intensity of the WPAC in CMIP5 MME is relatively stronger than CMIP3 MME, consistent with the stronger dipole rainfall pattern. Hence, the dipole rainfall pattern and WPAC are tightly related, not only in the position but also in the magnitude.

c. The simulated skill of the interannual EASM pattern and its origins

Equation (1) is applied to evaluate the simulation of interannual EASM pattern over East Asia (0°–50°N, 100°–160°E) (Figs. 5, 6). The skill scores of precipitation and 850-hPa wind are shown in Fig. 9. The skill score of 850-hPa wind is higher than that of precipitation in most models, consistent with results of climatology. From CMIP3 to CMIP5 MME, precipitation (850-hPa wind) is improved from 0.43 (0.59) to 0.54 (0.76). Using our proposed test method, there are 20 of 24 subregions in which differences of precipitation and 850-hPa wind skill scores between CMIP5 and CMIP3 MME are positive. It is suggested that both precipitation and 850-hPa wind have been significantly improved from CMIP3 to CMIP5 MME. Among CMIP3 models, ECHAM5 performs best in the interannual EASM pattern, with the highest skill score for precipitation (0.62) and 850-hPa wind (0.86), consistent with Wang et al. (2011). In CMIP5 models, CanAM4 gets the best score for precipitation (0.64), while the best score for 850-hPa wind is from MPI-ESM-LR (0.88). Generally, CMIP5 models show higher skills in the interannual EASM pattern than
CMIP3. For example, 13 of 19 CMIP5 models show a wind skill score higher than 0.7 but only 5 of 13 CMIP3 models reach this value. In addition, the skill score ranges from 0.01 to 0.86 for 850-hPa wind in CMIP3 models, while the range decreases from 0.43 to 0.88 in CMIP5 models.

What is responsible for the different simulation skills in the interannual EASM pattern? As its most important low-level circulation system, the WPAC in the boreal summer is maintained mainly by TIO warming through the Indian Ocean capacitor effect (Yang et al. 2007; Xie et al. 2009). Hence, the skill origins may be rooted in the TIO warming, as also noted by Zhang et al. (2012). To demonstrate this hypothesis, composite analysis is conducted. The highest nine models and lowest eight models based on precipitation skill score are selected to represent high-skill models (HSMs) and low-skill models (LSMs) (Table 3). The TIO warming is often preceded by ENSO in the previous winter, so the relationship between ENSO and the models in Table 3 is first investigated. The

FIG. 5. The horizontal distribution of precipitation (shaded; units: mm day$^{-1}$) and 850-hPa wind (vectors; units: m s$^{-1}$) regressed on the observed EASM index (NCEP-2 index, except for ERA-40) in (a) GPCP and NCEP-2, (b) CMAP and ERA-40, (c) MME, and (d)–(p) each model of CMIP3. The red boxes shown in (a) are the mei-yu/baiu/changma (28°–38°N, 105°–150°E) and NWP (10°–20°N, 105°–150°E) regions, respectively. The red dots indicate that the regressed precipitation is significant at the 10% level by Student’s $t$ test.
correlation coefficient between the Niño-3.4 index in the previous winter and the EASM index in HSMs reaches 0.43, statistically significant at the 10% level, but it is only 0.17 in LSMs. It indicates that the ENSO teleconnection to EASM is well captured in HSMs but not in LSMs.

For HSMs and LSMs, the SST, 850-hPa wind, and precipitation regressed on the observed EASM index
are shown in Fig. 10. Associated with a stronger EASM, positive SST anomalies are mainly distributed over the SCS and TIO, especially in the north Indian Ocean (NIO) (Fig. 10). The correlation of temporal variation between the EASM index and TIO (20°S–20°N, 40°–100°E) SST is 0.53 [the correlation is 0.64 for NIO (0°–20°N, 40°–100°E)] during 1980–97, significant at the 5% level. However, in the SCS and the Bay of Bengal, positive SST anomalies correspond to negative precipitation anomalies in observations (Figs. 10a,b), indicating that positive SST anomalies are due to atmospheric forcing. In the northwestern Indian Ocean (NWIO) and tropical eastern Indian Ocean (TEIO), positive SST anomalies are associated with positive precipitation anomalies, indicative of the SST forcing on the atmosphere. In the AMIP experiment, it is meaningful to investigate the possible influence of SST on the atmosphere over the NWIO and TEIO. Two observational datasets show similar results, but the precipitation anomaly in CMAP is slightly stronger than in GPCP, especially in the TIO (Figs. 10a,b).

As the low-level Kelvin wave response to the heat released by precipitation over the TIO, easterly winds dominate the Indo-Pacific equatorial region (Figs. 10a,b). The easterly winds have the maximum magnitude over the equator and decrease with the latitude. The anticyclone wind shear over the NWP induces Ekman divergence and maintains the WPAC (Wu et al. 2009; Xie et al. 2009). In CMIP3 MME (Fig. 10c), positive precipitation centers over the TEIO and NWIO are well reproduced, except with a weaker magnitude over the...
Accordingly, the easterly winds are also much weaker than observed. The precipitation and associated easterly winds are improved from CMIP3 to CMIP5 MME (Fig. 10d). At the same time, the WPAC and precipitation over the NWP are also ameliorated. In the HSMs, the precipitation over the TEIO and easterly winds is comparable to the observed but the precipitation over the NWIO is stronger (Fig. 10e). Compared to the HSMs, the precipitation response in the LSMs is much weaker over the TIO and related easterly winds are almost missing along the equator (Fig. 10f).

The positive SST anomalies and associated precipitation anomalies over the TIO can warm the total troposphere and induce the upper-level circulation changes. The total tropospheric temperature and 200-hPa wind regressed on the observed EASM index are shown in Fig. 11. Tropospheric warming emerges as a Matsuno–Gill (Matsuno 1966; Gill 1980) pattern with the heating anchored over the TIO and exhibits a wedge penetrating into the NWP (Figs. 11a,b). Westerly winds dominate the equatorial Indo–western Pacific region, as the high-level Kelvin wave response of the Matsuno–Gill pattern. The tropospheric temperature and 200-hPa wind anomalies are consistent between two observational datasets, except for the stronger warming over the TIO in ERA-40 (Figs. 11a,b). The westerly winds in CMIP3 MME are much weaker than observations but have enhanced in CMIP5 MME. In CMIP5, the warming is also shortened over the NWP, more similar to the observations than CMIP3. In the HSMs, the tropospheric warming pattern is similar to that in CMIP3 and CMIP5 MME. However, the westerly winds over the equator are stronger than those in CMIP3 and CMIP5 MME. The westerly winds are almost missing in the LSMs, consistent with the missing easterly winds in the low levels (Fig. 10f). The tropospheric warming pattern covers more latitude range over the NWP in LSMs than that in HSMs, even though the anchored warming over the TIO can be well reproduced.

The above evidence indicates that both precipitation response to local warm SST anomalies over the NWIO and TEIO and the associated Kelvin wave response may be of vital to the reasonable reproduction of the WPAC. Thus, precipitation over the NWIO (0°–25°N, 150°–80°E) and TEIO (5°S–20°N, 85°–100°E) and zonal wind at 850 and 200 hPa over the equatorial Indo-Pacific (15°S–15°N, 90°E–180°) are selected to investigate how the IO–WPAC teleconnection works in models. As the overall measure of the IO–WPAC teleconnection, the total

### Table 3. Nine high-skill models and eight low-skill models in the interannual EASM pattern based on precipitation skill score.

<table>
<thead>
<tr>
<th>High-skill models</th>
<th>Low-skill models</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMIP3</td>
<td>CNRM-CM5; GISS-ER; INM-CM3.0; CSM3; PCM</td>
</tr>
<tr>
<td>ACCESS1.0; CanAM4; MIROC5;</td>
<td>BCC_CSM1.1; CSM4; CNRM-CM5</td>
</tr>
<tr>
<td>MRI-AGCM3-2H; MRI-AGCM3-2S; NorESM1-M</td>
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FIG. 9. The skill score of the interannual EASM pattern of (left) precipitation and (right) 850-hPa wind in (top) CMIP3 and (bottom) CMIP5 models.
tropospheric temperature is also selected. The NWIO precipitation skill is not significantly correlated to the EASM precipitation skill (figure not shown). Note the NWIO precipitation is mainly distributed over the Indian summer monsoon (ISM) region (Figs. 10a,b). As discussed in Sperber et al. (2012), the controlling mechanisms of the interannual variability are different for ISM and EASM.

The simulation skill of TEIO precipitation, equatorial zonal wind, and tropospheric temperature against EASM skill are shown in Fig. 12. The TEIO precipitation skill is positively proportional to the EASM skill and this relationship is significant at the 5% level in both CMIP3 and CMIP5 models. Besides this, both the low-level and high-level equatorial zonal wind skills are significantly correlated to EASM skill at the 5% level. We also investigate the relationship between the TEIO precipitation skill and equatorial zonal wind skill and find they are largely independent. These two processes consist of the IO–WPAC teleconnection and affect the interannual variation of EASM considerably. The total tropospheric temperature is also proportional to EASM skill, significant at the 5% level, confirming the influence of IO–WPAC teleconnection on the EASM. The TEIO precipitation skill, equatorial zonal wind skill, and tropospheric temperature skill for CMIP5 MME are higher than CMIP3 MME, and these skill differences are tested to be significant by the proposed test method. For example, the Kelvin wave response region is divided into 18 subregions spaced equally (15° × 10°) and the skill difference of low-level Kelvin wave response between CMIP5 and CMIP3 MME is positive over 16 of those
subregions. It is suggested that the significantly higher EASM skill in CMIP5 MME than in CMIP3 MME is due to the better-simulated IO–WPAC teleconnection in CMIP5. Hence, the IO–WPAC teleconnection, which consists of the TEIO precipitation response to local warm SST anomalies and associated Kelvin wave response, exerts large influence on the interannual variability of EASM.

To further confirm our results, 30-yr datasets covering 1979–2008 in CMIP5 models are used to extend our analysis. The same method is used to get the interannual EASM pattern and Eq. (1) is applied to evaluate the skill with respect to NCEP-2 and GPCP. The skill of the interannual EASM pattern is displayed in Fig. 13. Compared to 18-yr (1980–97) results (Fig. 9), the precipitation skill decreases to 0.47 but the 850-hPa wind skill slightly increases to 0.79 during 1979–2008 in CMIP5 MME. MPI-ESM-LR stands out as the best model with a precipitation (850-hPa wind) skill of 0.73 (0.91). However, the main distributions of skills among models are similar to the results derived from the 18-yr period.

To investigate the dynamical processes responsible for the simulation skill, we select four HSMs (ACCESS1.0, MPI-ESM-LR, MRI-AGCM3-2H, and MRI-AGCM3-2S) and four LSMs (BCC_CSM1.1, FGOALS-g2, IPSL-CM5A-LR, and MPI-ESM-MR) based on precipitation skill score to conduct composite analysis. The observed SST, 850-hPa wind, and precipitation regressed on the observed EASM index are displayed in Fig. 14. The correlation between the observed EASM index and TIO

![Fig. 11. The total tropospheric (850–200 hPa) temperature (shaded; units: K) and 200-hPa wind (vectors; units: m s$^{-1}$) regressed on the observed EASM index (NCEP-2 index, except for ERA-40) in (a) GPCP and NCEP-2; (b) CMAP and ERA-40; (c) CMIP3 MME; (d) CMIP5 MME; (e) high-skill models; and (f) low-skill models. The wind with magnitude of less than 0.6 m s$^{-1}$ is omitted. The black dots indicate that the regressed temperature is significant at the 10% level by Student’s t test.](image-url)
(NIO) SST is 0.50 (0.62) during 1979–2008, significant at the 1% level. The HSMs show better precipitation response than LSMs over the TIO, especially in the TEIO region (Figs. 14c,d). Correspondingly, the low-level Kelvin wave response is also much weaker in LSMs than HSMs. The similar results as shown in Fig. 11 demonstrate that the IO–WPAC teleconnection is really important for the simulation of the interannual EASM pattern.

Similar to Fig. 12, the scatterplots of the IO–WPAC teleconnection skill versus the EASM skill are shown in Fig. 15. The results are also consistent with those derived from the 18-yr period, all significant at the 5% level. When the TEIO precipitation is simulated well, it is suggested that the response to the local warm SST anomalies over the TIO is captured (Fig. 15a). When the low-level and high-level zonal winds over the Indo–western Pacific region are reproduced, it is suggested that the Kelvin wave response to the latent heat released by the TEIO precipitation is captured in the models (Figs. 15b,c). When the above two processes are reproduced well in models, the captured IO–WPAC teleconnection leads to the reproduction of interannual EASM pattern (Fig. 15d). Xie et al. (2009) suggested that the NIO SST warming is the most important for the Kelvin wave and WPAC, but our study suggests that, among the NIO, the TEIO warming is more important than NWIO for the WPAC.

Finally, we acknowledge that in the AMIP experiment, in which the observed SST is specified, the improvement from CMIP3 to CMIP5 is due to the atmospheric response to the TIO warming. In this study, we suggest that the improvement of the atmospheric processes, such as TEIO rainfall response and equatorial Kelvin response, is important to the EASM simulation. The relation between the temporal variations of EASM and the atmospheric responses is also analyzed. Most CMIP5 models show better temporal correlation than CMIP3 models. For example, the correlation coefficients between EASM and TEIO precipitation are statistically significant at the 5% level in 17 of 19 CMIP5 models, but only 9 models have significant correlations in the 13 CMIP3 models. The correlation coefficient between
EASM and TEIO precipitation is 0.84 for CMIP5 MME but 0.78 for CMIP3 MME. The improvement from CMIP3 to CMIP5 AGCMs is also reflected in the temporal variation, which is consistent with the spatial pattern.

4. Summary

The climatology and interannual variability of the EASM simulated by 13 CMIP3 AGCMs and 19 CMIP5 AGCMs are assessed in this study. The interannual EASM pattern is obtained by regressing the precipitation and 850-hPa wind on the observed EASM index. The performances of models in the simulation of the climatology and interannual EASM pattern are measured by a skill score formula quantitatively, which combines the spatial distribution and magnitude together. The forcing mechanisms of the interannual EASM pattern are investigated by considering the IO–WPAC teleconnection. The main findings are summarized below:

1) The climatological distribution of the precipitation and 850-hPa wind is well reproduced in CMIP3 and CMIP5 MME, but it differs from one model to another. Major limitations of CMIP3/CMIP5 models are the northward shift of the WPSH, which leads to the simulation bias of the mei-yu/baiu/changma rainfall band (28°–38°N, 105°–150°E). The skill score of precipitation is significantly enhanced from CMIP3 MME (0.75) to CMIP5 MME (0.77), based on the proposed test method. The skill scores of 850-hPa wind are significantly proportional to those of precipitation, indicating that the improvement of wind is closely
related to the representation of precipitation. The impacts of model horizontal solution on the skill scores of 850-hPa wind and precipitation are not evident.

2) The interannual variation of EASM measured by a monsoon index is reasonably reproduced, as evidenced by the statistically significant correlation coefficients of 0.70 and 0.68 for CMIP3 and CMIP5 MME, respectively. The correlation is also not sensitive to the horizontal resolution. The interannual EASM pattern in models is obtained by regression on the observed EASM index. Both CMIP3 and CMIP5 MME reasonably reproduce the pattern but with two deficiencies compared to the observation: weaker precipitation anomalies and southward shift of the dipole rainfall pattern. The southward shift of the dipole rainfall is closely related to the southward shift of the WPAC, and the weaker precipitation magnitude is accompanied by the weaker WPAC in the CMIP3 and CMIP5 models. Both the magnitude of WPAC and dipole rainfall pattern are significantly improved from CMIP3 to CMIP5 MME. Because of this improvement, the simulation skill of the interannual pattern is also largely enhanced from CMIP3 to CMIP5 MME. The skill score of precipitation (850-hPa wind) is significantly improved from 0.43 (0.59) in CMIP3 to 0.54 (0.76) in CMIP5 MME.

3) Based on the precipitation skill of the interannual EASM pattern, nine HSMs and eight LSMs are selected to conduct the composite analysis. Through composite analysis, we find the HSMs reproduce the northwestern Indian Ocean (NWIO) and tropical eastern Indian Ocean (TEIO) precipitation anomalies as in the observations. The high-level equatorial westerly winds and low-level equatorial easterly winds as the Kelvin wave response are also captured well. However, in the LSMs, the precipitation anomalies and the related Kelvin wave responses are not reasonably simulated. Further analysis confirms that the TEIO precipitation skill and the related Kelvin wave response are significantly proportional to the EASM skill in both CMIP3 and CMIP5 models. It indicates that the simulation of interannual EASM pattern highly depends on the reasonable reproduction of the IO–WPAC teleconnection. Since this teleconnection is better reproduced in the CMIP5 MME, the EASM skill is also significantly improved compared to CMIP3 MME. The improvement from CMIP3 to CMIP5 AGCMs is also reflected in the temporal variation. This conclusion based on the data covering 1980–97 is further confirmed by 30-yr period (1979–2008) analysis based on CMIP5 models.
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