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ORIGINAL PAPER

Assessment of CMIP5 historical simulations of rainfall over Southeast Asia

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Abstract We present preliminary analyses of the historical (1986–2005) climate simulations of a ten-member subset of the Coupled Model Inter-comparison Project Phase 5 (CMIP5) global climate models over Southeast Asia. The objective of this study was to evaluate the general circulation models' performance in simulating the mean state of climate over this less-studied climate vulnerable region, with a focus on precipitation. Results indicate that most of the models are unable to reproduce the observed state of climate over Southeast Asia. Though the multi-model ensemble mean is a better representation of the observations, the uncertainties in the individual models are far high. There is no particular model that performed well in simulating the historical climate of Southeast Asia. There seems to be no significant influence of the spatial resolutions of the models on the quality of simulation, despite the view that higher resolution models fare better. The study results emphasize on careful consideration of models for impact studies and the need to improve the next generation of models in their ability to simulate regional climates better.

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1 Introduction

General circulation models (GCMs) are primary tools for the prediction of global climate (Houghton et al. 2001). The fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has stated that the globally averaged combined land and ocean surface temperature data show a warming of about 0.85 °C, over the period 1880 to 2012 (IPCC 2013). Climate projections from global models indicate that the global mean surface temperature change for the period 2016–2035 relative to 1986–2005 is likely to be in the range of 0.3 to 0.7 °C. Precipitation projections are likely to be nonuniform, and extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases (IPCC 2013).

Over Southeast Asia (SEA), the IPCC stated that the mean surface air temperature has already increased by 0.1–0.3 °C per decade from 1950 to 2000 (IPCC 2013). Climate projections indicate a continued warming and a more extreme distribution of rainfall that are likely to cause more heat waves/droughts and floods, respectively. Overall, many of the indicated climatic changes and projections have been found to be consistent with the IPCC's fourth assessment report, AR4. Some of the climate impacts that are evident are that of the decline of crop yield in many Southeast Asian countries (Thailand, Vietnam, Indonesia); massive flooding in Hanoi, Hue (Vietnam), Jakarta (Indonesia), and Vientiane (Laos); landslides in the Philippines; and droughts in many other parts of the region (ADB 2009). Water shortage, agriculture constrains, food security, infectious diseases, forest fires, and degradation of coastal and marine resources have also been increasing (IPCC 2007b; IPCC 2014).

SEA is one of those regions in the world where there are relatively fewer studies on climate compared to Europe, North America, or Australia. Hence, there is a strong need for robust climate projections over SEA to study future climate changes and their impacts. Future projections of precipitation simulated by global climate models are uncertain and are difficult for policy makers to interpret to suit their adaptive measures (Liepert and Previdi 2012; Schubert and Lim 2013; Brekke and Barsugli 2012). As the GCMs provide this primary information, it becomes essential to examine whether these global models are able to simulate the dynamics and state of the present-day climate before using this information for the future climate (Solomon et al. 2007). It is therefore imperative to assess the skill in the models in simulating the historical climates that helps to place confidence in these models towards climate projections and in the use of impact assessments (Gu et al. 2015).

There have been many studies which have evaluated the CMIP5 models over different regions of the world. Gu et al. (2015) assessed some of the CMIP5 models over China and concluded that no model was able to exhibit a good performance in simulating the historical climate. Siew et al. (2014) evaluated a suite of CMIP5 models over the Southeast Asian region and noted that though many models broadly simulated the Southeast Asian winter monsoon features, the spread of bias was very large across the models. Mehran et al. (2014) performed an analysis of 34 CMIP5 models over several parts of the world and compared them against satellite observations and suggested that the models matched well with observations over many regions but failed over arid zones and certain subcontinental areas. Kumar et al. (2013) noted that the ensemble precipitation mean over continental areas (60° S to 60° N) of CMIP5 models agreed better with observations while there were significant biases over regional trends. Rupp et al. (2013) evaluated 41 CMIP5 models over the Pacific Northwest USA and ranked them based on their performance and reported that as a group, the models were able to reproduce observations, but individually, the models generated a wide range of values for the metrics chosen for evaluation. A CMIP5 model analysis of the contemporary climate over the Greater Horn of Africa was performed by Otieno and Anyah (2013) who noted that caution needs to be exercised when choosing models. Intermodel variability has also been noted as an important source of uncertainty (Wang et al. 2014; Gu et al. 2014; Giorgi and Mearns 2002). An extensive literature on the studies based on the CMIP5 models can also be found at http://cmip.llnl.gov/cmip5/publications/allpublications.

We performed some preliminary analysis of the historical simulations (1986–2005) of rainfall over Southeast Asia, using a ten-member subset of the global climate models/earth system models under the Coupled Model Inter-comparison Project (CMIP) 5 (Taylor et al. 2012). The main objective of this paper is to assess the models' ability in simulating the historical precipitation regime over Southeast Asia so that the precipitation projections

Table 1 Models of the historical runs chosen for analyses

Model name	Institute	Horizontal resolution	Reference
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration	2.8° × 2.8°	Wu (2012), Xin et al. (2012), Xin et al. (2013)
NCAR-CCSM4	US National Centre for Atmospheric Research	1.25° × 0.95	Gent et al. (2011)
NCAR-CESM1	NSF-DOE-NCAR	1.25° × 0.94°	Hurrell et al. (2013)
CNRM-CM5	Centre National de Recherches Meteorologiques and Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	1.4° × 1.4°	Voldoire et al. (2013)
CSIRO-MK3.6.0	Queensland Climate Change Centre of Excellence and Commonwealth Scientific and Industrial Research Organisation	1.8° × 1.8°	Rotstayn et al. (2012)
UKMO-HadGEM2A0	UK Met Office Hadley Centre	1.8° × 1.25°	Collins et al. (2011), Martin et al. (2011)
IPSL-CM5	Institut Pierre Simon Laplace	2.5° × 1.2°	Dufresne et al. (2012)
NIES-MIROC5	University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1.4° × 1.3°	Watanabe et al. (2010)
MPI-ESM-MR	Max Planck Institute for Meteorology	1.8° × 1.8°	Raddatz et al. (2007)
MRI-CGCM3	Meteorological Research Institute	1.1° × 1.1°	Yukimoto et al. (2011), Yukimoto et al. (2012)

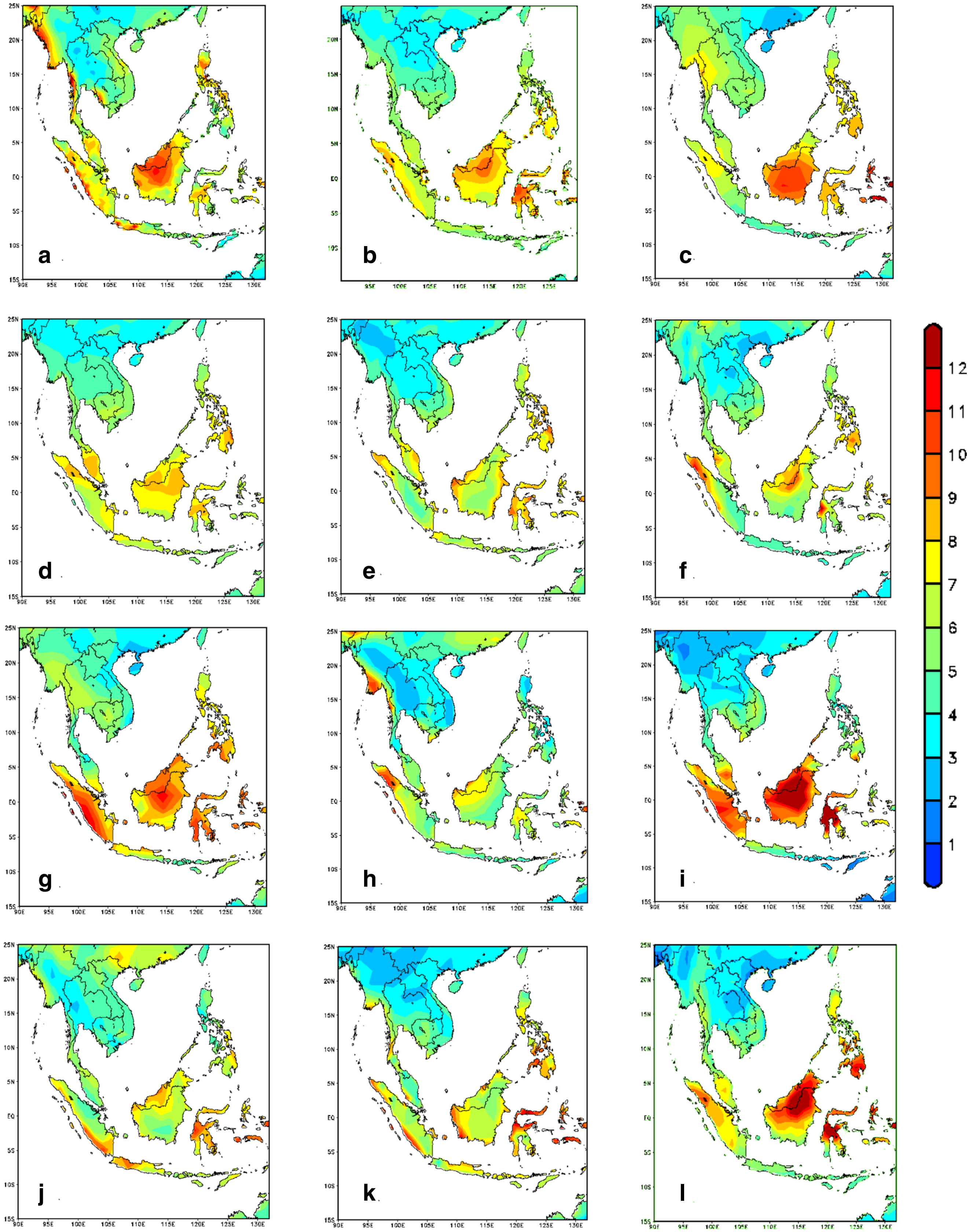


Fig. 1 Mean annual precipitation climatology of the CMIP5 GCMs: 1986–2005, (mm/day) **a** CRU. **b** ENS. **c** BCC-CSM1. **d** NCAR-CCSM4. **e** NCAR-CESM1. **f** CNRM-CM5. **g** CSIRO-Mk.3.6. **h** UKMO-HADGEM2. **i** IPSL-CM5. **j** NIES-MIROC5. **k** MPI-ESM-MR. **l** MRI-CGCM3

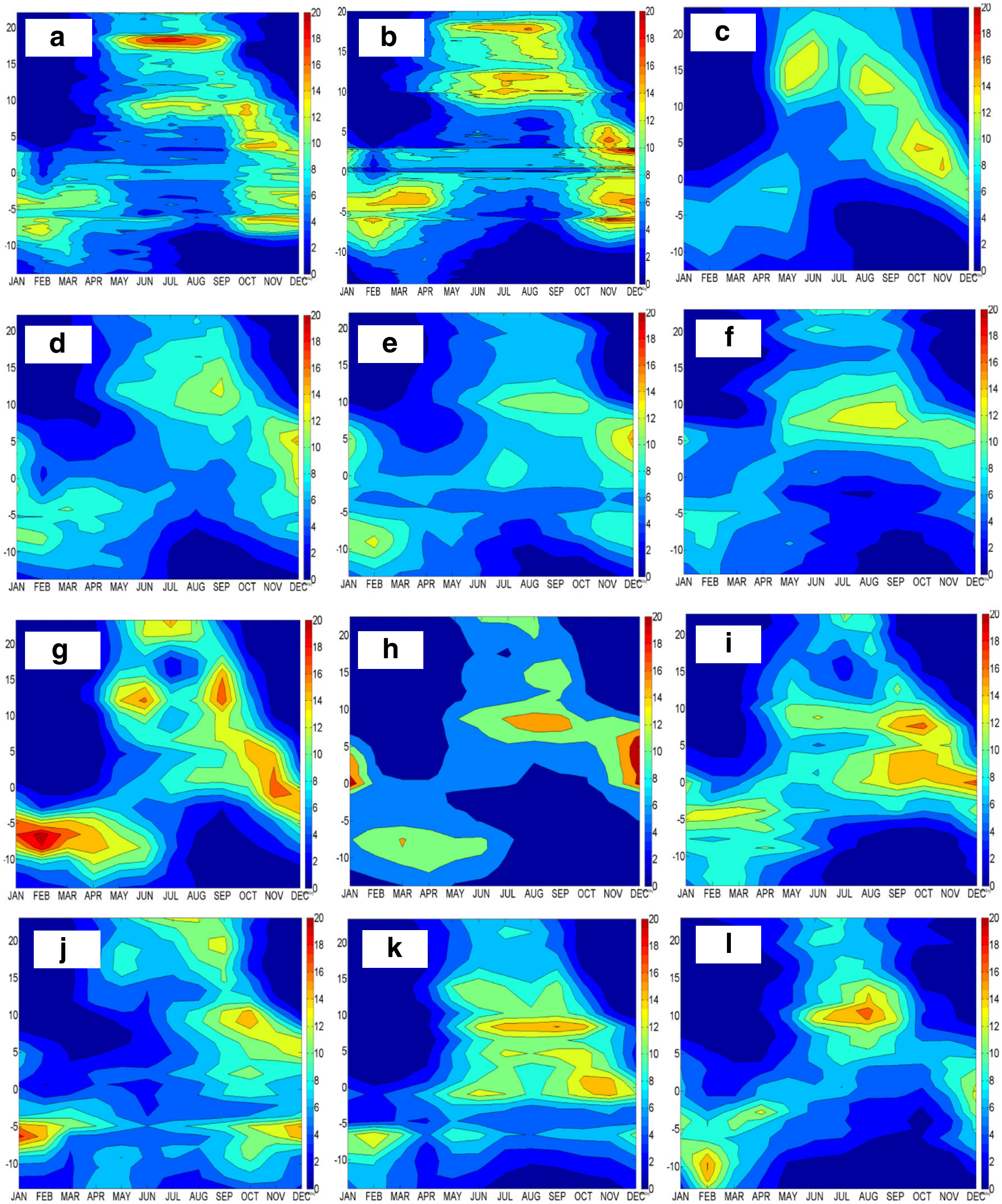


Fig. 2 Annual cycle of precipitation-Hovmoller diagram: Southeast Asia (15° S to 25° N), centered at 104° E. **a** TRMM. **b** GSMaP. **c** BCC-CSM1. **d** NCAR-CCSM4. **e** NCAR-CESM1. **f** CNRM-CM5. **g** CSIRO-Mk.3.6. **h** UKMO-HADGEM2. **i** IPSL-CM5. **j** NIES-MIROC5. **k** MPI-ESM-MR. **l** MRI-CGCM3

from these models can be used with confidence for future climate studies. The study, however, does not rank any of the models based on their performance or make any recommendations of the best models to be used for downstream studies or further downscaling but only assess the skill of the selected models in representing the present-day climate.

2 Data

2.1 Models

The climate model data used in this study have been taken from a combination of coupled GCMs and the new generation of the Earth system models made available to the

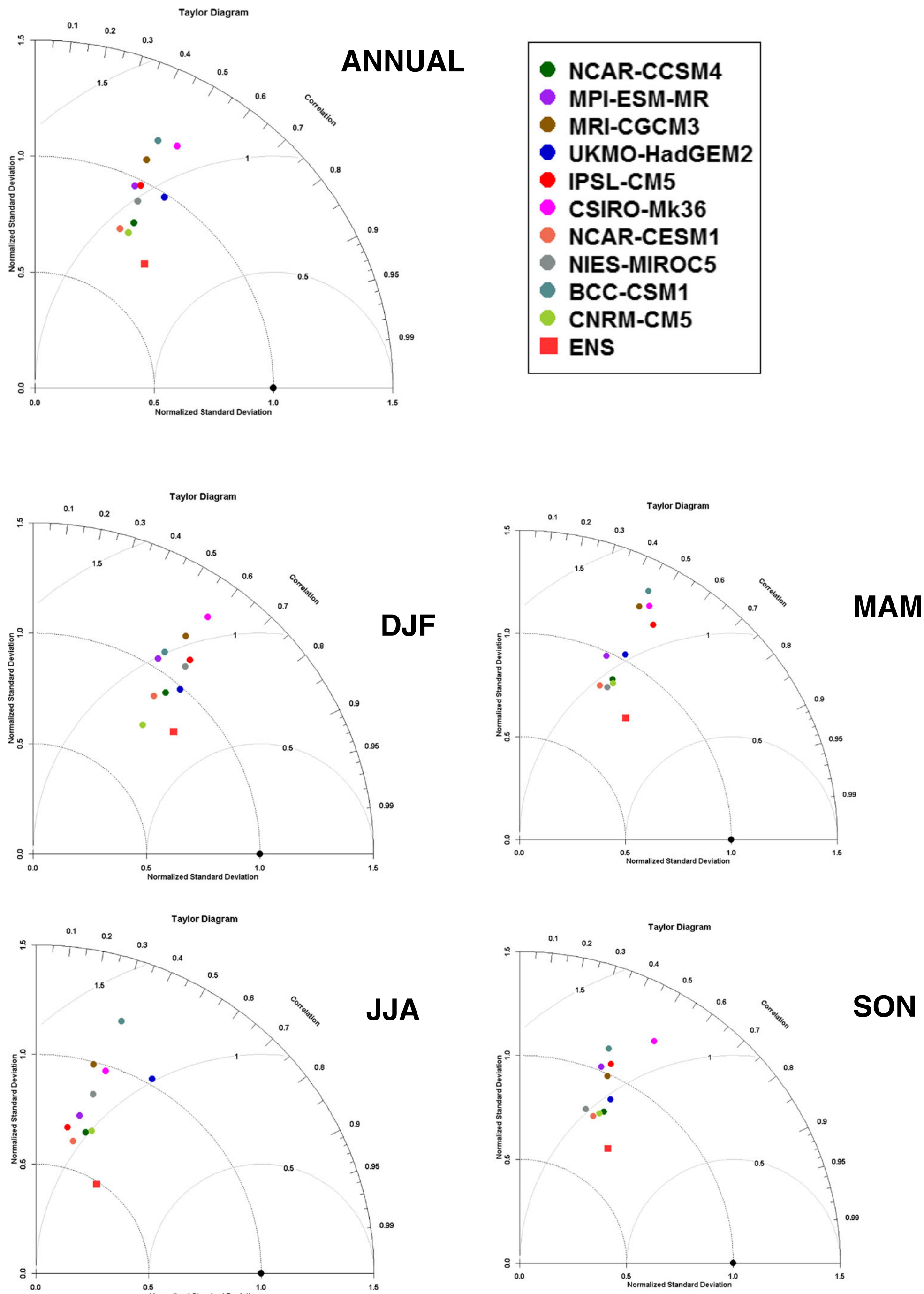


Fig. 3 Taylor diagram: annual and seasonal precipitation over Southeast Asia (land only)

research community through the Earth System Grid Federation (ESGF) data portal under the Program for Climate Model Diagnostics and Inter-Comparison (PCMDI). These data can be accessed through: cmip-pcmdi.llnl.gov/cmip5/data_portal.html. Of the big suite of models available under CMIP5, a subset of ten models (Table 1) of the historical runs was chosen for analyses. These models were chosen at random, and data analyses on a monthly scale on the model-simulated precipitation have been performed over the historical present-day climate period 1986–2005; given precipitation is one of the most widely considered variable for impact studies (Elguindi et al. 2014).

2.2 Observations

2.2.1 CRU data

Developed at the Climatic Research Unit (CRU) at the University of East Anglia, UK, the CRU TS (Time-

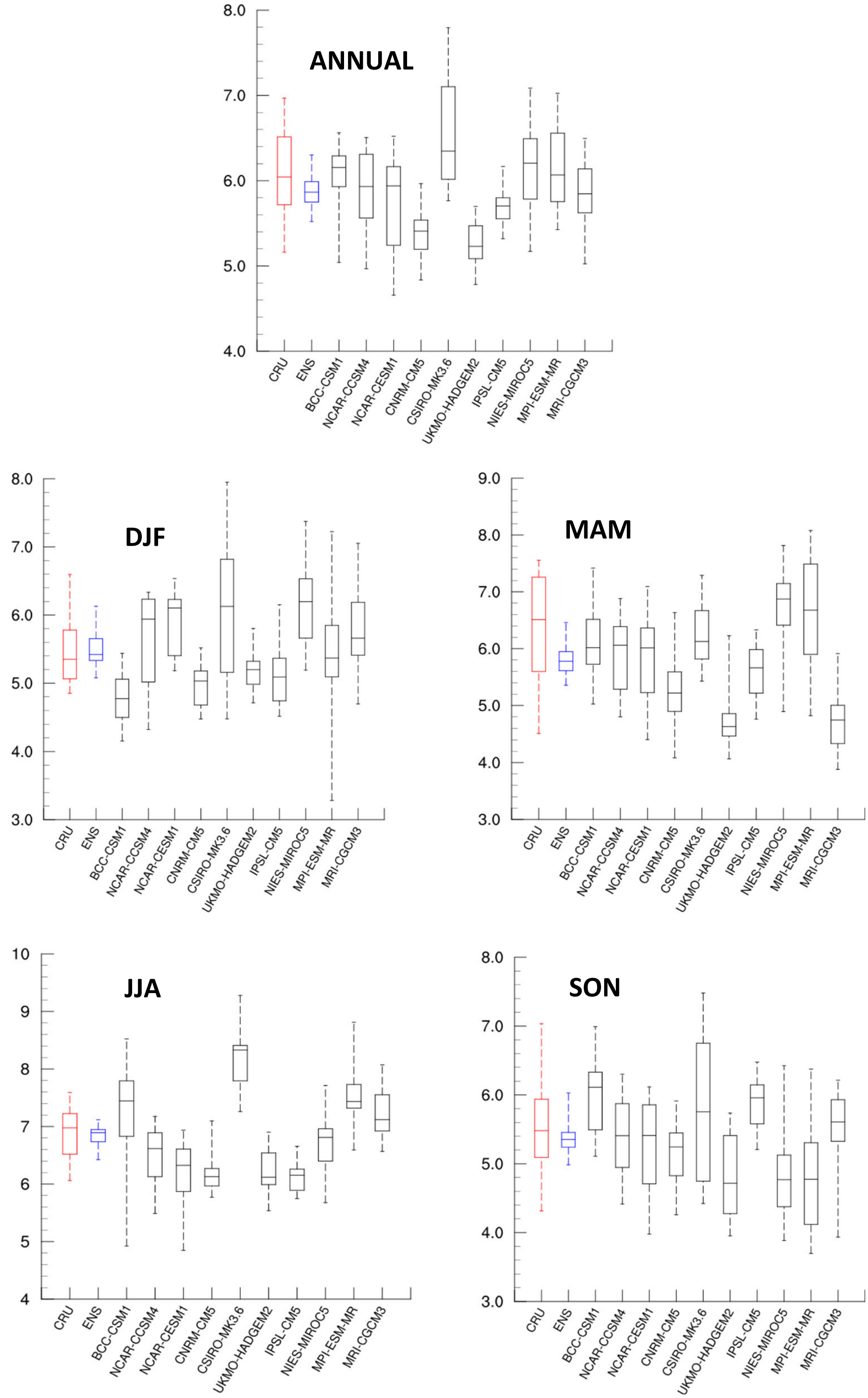


Fig. 4 Seasonal average rainfall (land only), 1986–2005 (mm/day), Southeast Asia (95° E to 130° E; 10° S to 25° N)

Series) version 3.21 dataset (Harris et al. 2014), used in this study, comprises monthly grids of observed climate, for the period 1901–2006 covering the global land surface at 0.5° of horizontal spatial resolution. This dataset is one of the most extensively used dataset by the climate modeling community. The precipitation

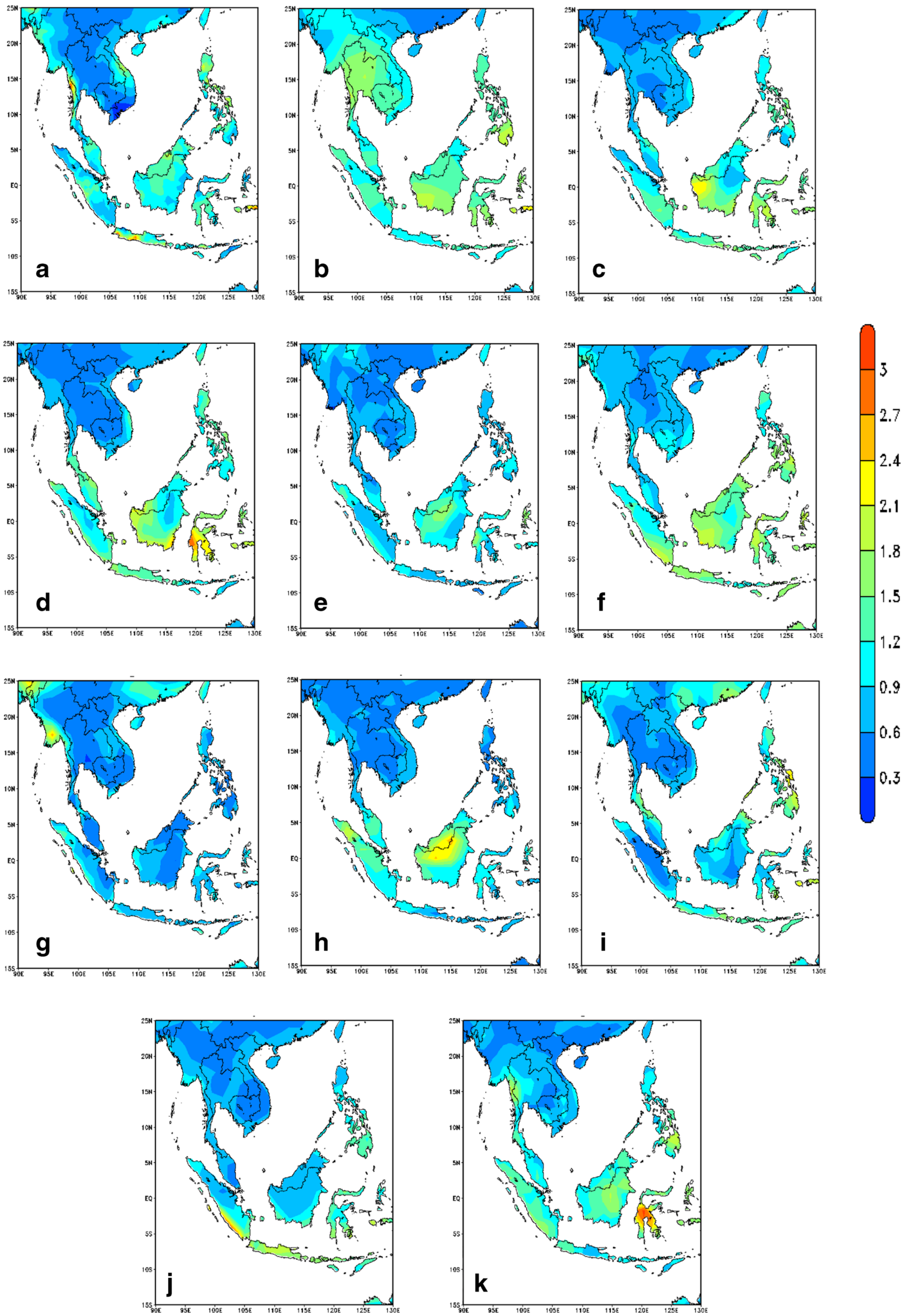
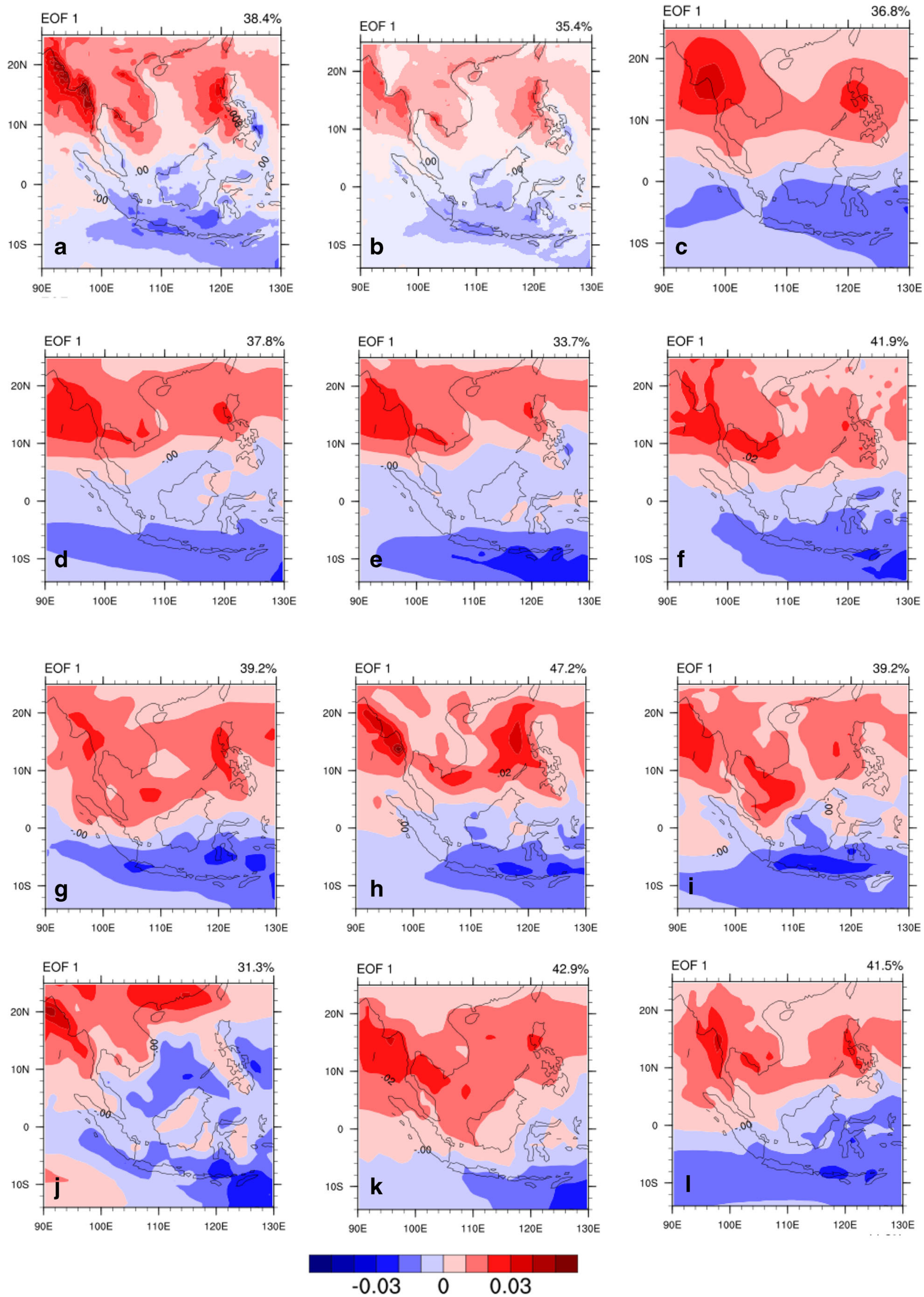


Fig. 5 Interannual variability, 1986–2005 (mm/day). **a** CRU. **b** BCC-CSM1. **c** NCAR-CCSM4. **d** NCAR-CESM1. **e** CNRM-CM5. **f** CSIRO-Mk.3.6. **g** UKMO-HADGEM2. **h** IPSL-CM5. **i** NIES-MIROC5. **j** MPI-ESM-MR. **k** MRI-CGCM3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◀ **Fig. 6** EOF1 comparisons between observations and CMIP5 models. **a** TRMM. **b** GSMaP. **c** BCC-CSM1. **d** NCAR-CCSM4. **e** NCAR-CESM1. **f** CNRM-CM5. **g** CSIRO-Mk.3.6. **h** UKMO-HADGEM2. **i** IPSL-CM5. **j** NIES-MIROC5. **k** MPI-ESM-MR. **l** MRI-CGCM3

dataset used in this study comprise data obtained from many land-only locations around the globe. Data from the period 1986–2005 are used in this study for climate model evaluations.

2.2.2 TRMM data

The Tropical Rainfall Measuring Mission (TRMM) data were also used in this study to enable comparison of the model results over ocean areas. The TRMM satellite carried an active Precipitation Radar (PR) and a passive microwave radiometer, the TRMM Microwave Imager (TMI). In the process of generating the 3B43 rain rate product, 3-hourly precipitation estimates from each of the microwave sensors were calibrated and combined on a 0.25° spatial grid between 50° S to 50° N and 0° to 360° E. The rain rate product used in our analysis is the TRMM 3B43v7, which was based on the TRMM Multi-satellites Precipitation Analysis (TMPA) products generated from all the available sensors, including sensors from other satellites (Huffman et al. 2007). Though the historical period considered in this study is 1986–2005, we consider the rainfall climatology over the period 1998–2005, as the data are available only from 1998 onwards. It is to be mentioned that the TRMM mission has been discontinued at the time of writing this paper.

2.2.3 GSMaP data

The GSMaP, basically a satellite-derived product, is also sued in this study to supplement the TRMM data in comparison against the global models. The GSMaP project was conducted by the Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Agency and is currently under the Japan Aerospace Exploration Agency (JAXA). Using a combination of multi-sensors, GSMaP covers quasi global (60° N–60° S) at a horizontal grid spacing of 0.1° at hourly time intervals. The version v5.222 of GSMaP-MVK dataset was used in this study on a climatological 10-year period from December 2000 to November 2010.

3 Methodology

The CMIP5 models have been evaluated against the observed data using some of the fundamental metrics such as the mean climatological spatial distributions, annual cycles (Hovmoller diagrams), root mean squared errors and correlation coefficients (Taylor diagrams), regional area averages (box plots), interannual variability, and empirical orthogonal function (EOF) analyses. Wherever applicable, the CMIP5 models have been regridded to the resolutions of the observed data.

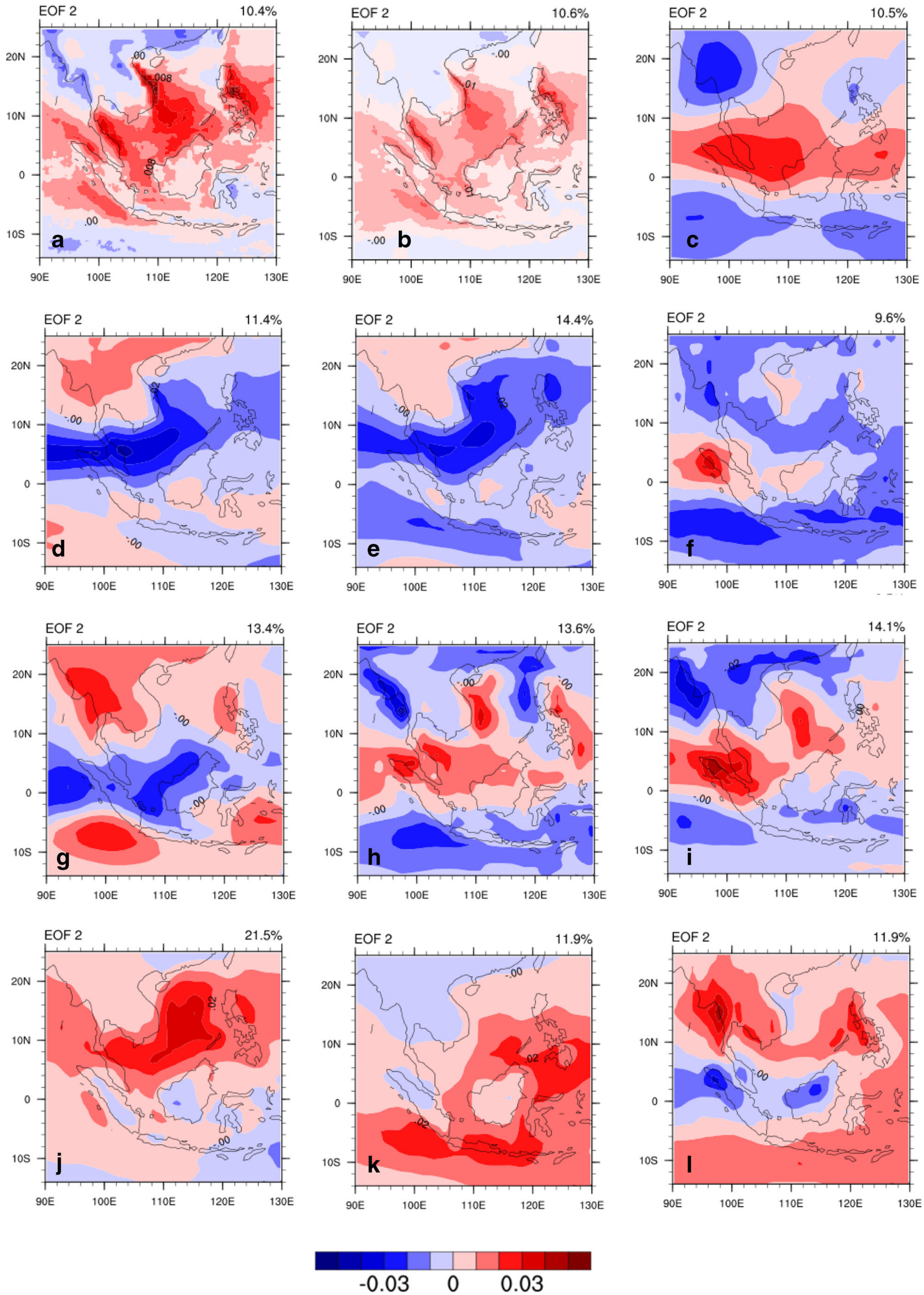
4 Results

4.1 Mean annual precipitation climatology

Figure 1 illustrates the annual climatological precipitation for the period 1986–2005. In general, dominated by the Intertropical Convergence Zone (ITCZ), the land areas of Southeast Asia experience heavy rainfall during summer monsoon (southwest monsoon) (Kripalani and Kulkarni 1998) and the northeast monsoon rainfall occurs due to transport of moisture from the South China Sea that results in a wetter precipitation regime over the maritime continent (Chang et al. 2005; Juneng and Tangang 2005). The figures show a wide range of discrepancies among these ten models in terms of the spatial distributions of rainfall. Though the northern regions of the domain (between 5° N and 25° N) show some similarities in the spatial distributions when compared to CRU, the southern parts over Indonesia, Malay Peninsula, and Borneo show substantial differences. Especially, the high rainfall over Borneo island is absent in six out of the ten chosen models. The coastal rainfall over Myanmar, Thailand, and Cambodia are not seen in any of the models. This could be due to the poor representation of topography in the global models, owing to their coarse resolution. Yet, even the model with the highest resolution among all, MRI-CGCM3, does not capture this feature. Other regions of the maritime continent such as over Indonesia, Malay Peninsula, and some islands of the Philippines exhibit strong biases. While no particular model shows a closer agreement to observations, the ensemble mean of all the models, denoted as “ENS” in the figure, shows some comparable distributions of rainfall against CRU albeit the high Borneo rainfall and the maritime continent still exhibiting negative biases of about 2–3 mm/day.

4.2 Annual cycle of precipitation—Hovmoller diagram

The Hovmoller diagram shows the annual cycle of rainfall over the Southeast Asian domain in Fig. 2. Testing the annual cycle of the regional precipitation is a fundamental aspect in model evaluation, and the Hovmoller diagram is a good way to represent this feature. TRMM data (1998–2005) is chosen as the climatological observation in this case instead of CRU, as the comparisons are made over the entire SEA region, over both land and the ocean areas. TRMM data shows a strong summer monsoon precipitation of about 20 mm/day between latitudes 16° N and 18° N. The summer monsoon is also quite pronounced over the latitudes between 8° and 10° N but at a lower rainfall rate. Over the southern atmosphere (5° S–10° S), TRMM clearly shows the effect of northeast monsoon rainfall from November to February with an average rainfall of 12–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◀ **Fig. 7** EOF2 comparisons between observations and CMIP5 models. **a** TRMM. **b** GSMaP. **c** BCC-CSM1. **d** NCAR-CCSM4. **e** NCAR-CESM1. **f** CNRM-CM5. **g** CSIRO-Mk.3.6. **h** UKMO-HADGEM2. **i** IPSL-CM5. **j** NIES-MIROC5. **k** MPI-ESM-MR. **l** MRI-CGCM3

14 mm/day, especially during November and December. It can be seen that none of the models are able to fully replicate the observed patterns of the seasonal cycle. Summer (June–July–August, JJA) season rainfall over the southern hemispheric regions is poorly resolved in most of the models. The high rainfall observed between 15° N and 20° N is faintly reproduced by MPI ESM, MRI CGCM3, and IPSL CM5, but the rainfall region is placed more southerly. The rainfall observed (between 5° S and 10° N) during September–October–November–December months is replicated barely only by a few models such as CSIRO MK3.6, IPSL CM5, and BCC CSM1. It can be seen that even MRI-CGCM3 is unable to reproduce the observed rainfall regime. The analysis shows that nearly all models are unable to capture observations irrespective of their model resolutions resulting in a large latitudinal spread in the regional rainfall during different seasons.

4.3 Taylor diagram

Figure 3 shows the ability of the chosen 10 GCMs in simulating the SEA regional precipitation. Based on the Taylor diagram, this diagram provides a concise statistical summary of how well patterns match each other in terms of their correlation, their root mean square difference and the ratio of their variances and is useful in evaluating complex models (Taylor 2001). In this study, the diagram has considered only land points over the SEA region and hence compared only against CRU data (and not TRMM). On an annual scale, it can be seen that all models cluster between a correlation coefficient of 0.4 to 0.6. The models UKMO HadGEM2, NCAR CESM1, and CSIRO MK 3.6 are close to CRU in terms of the normalized standard deviation. The rest of the models fall between a standard deviation of 0.75 to 1.25 with a root mean square value between 1 and 1.25 mm/day. On seasonal scales, the figures indicate that mostly all models perform poorly during JJA, indicating that the models are unable to simulate the summer season well enough. During the other seasons, the models exhibit relatively higher correlations between 0.5 and 0.7. The ensemble of all models (indicated by a red color square in the figure), during both annual and seasonal scales, shows a correlation of about 0.85, but with relatively poor root mean squared errors but larger variability.

4.4 Regional-seasonal average precipitation (box plots)

In this section, we discuss the climatological average precipitation over SEA on the annual and seasonal scales over the land regions only, compared against CRU data. The seasonal averaged rainfall over the subcontinent was computed for four seasons: December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON). The box plots (Fig. 4) shows these annual and seasonal averages of precipitation calculated from the ten GCMs compared against CRU observations. There is a large spread among the GCMs exhibiting both underestimation and overestimation of rainfall compared to CRU during all the four seasons. In the annual scale, three out of ten models underestimate the area averaged rainfall. CSIRO MK 3.6 simulates a larger variability with higher magnitudes of rainfall. Only NCAR CCSM4 and MPI ESM-MR simulate a similar range of observed variability. During the DJF season, five models underestimate the rainfall compared to CRU. Only MPI ESM-MR simulates a similar range of observed variability while all other models show larger variability. In the summer season, six models show underestimation when compared to CRU. However, most of the models indicate a narrow range of variability compared to the other seasons. CSIRO MK 3.6, once again, shows itself as the wettest among all models. The SON season shows larger variability than JJA and the CRU observations show that there is a larger variability during MAM than the rest of the seasons which none of the models reproduce. However, no particular GCM shows any systematic bias in the seasonal rainfall estimates. The ensemble of all the GCMs ("ENS" in the figure) compares well against CRU during DJF and JJA with its median lying closer to CRU. The median response of the ensemble of the GCMs is relatively closer to the CRU observations on the annual scale and all seasons except MAM. In general, rainfall varies within a small range of 5.5–7 mm/day over all seasons.

4.5 Interannual variability

Figure 5 shows the interannual variability (over land areas) of the ten GCMs over the historical period 1986–2005 compared to CRU. There is a better agreement of the models against CRU over the northern hemispheric regions of the domain than over the southern regions/maritime continent. Of the ten models, about six to seven models simulate greater variability over the maritime continent. It can be seen that one model, IPSL CM5, simulates a higher order of variability over Borneo. Given that Borneo experiences highest rainfall within the region, it is possible that this area exhibits larger variability, but not seen in the CRU observations, possibly due to lack of gauges in this mountainous regions. The BCC-CSM1 shows larger variability over the northern hemispheric regions of Southeast Asia while NCAR CESM1 and NIES MIROC5 simulate larger variability of about 3 mm/day over the island of Sulawesi, Indonesia. The observed variability over the coasts of Thailand/Myanmar seen in CRU is not reproduced by any of the models, probably due to the coarse resolution of the models that do not account for regional scale features.

4.6 EOF analysis

The EOF analyses in this study involve calculation of the eigenvalues for a correlation matrix that is based on the normalized precipitation values for each month for all grid points over the SEA region. The normalization is done to remove the intra-seasonal variability related to ITCZ. The EOF method adopted in this study closely follows the method used by Liew et al. (2010). Detailed discussions on EOF can also be found in Hannachi (2004), Wilks (1995), and Dommenget and Latif (2002) among several others. Similar EOF analyses can also be found in the studies of Otieno and Anyah (2013), Zveryaev and Aleksandrova (2004), and Wang and Ding (2008).

Figures 6 and 7 show the EOF patterns for the first and second modes, respectively. The models are compared to two satellite products TRMM and GSMaP, as the GCM simulations include the ocean areas. The figures show the annual spatial pattern of the first and second EOF modes. It can be seen that the observations (TRMM and GSMaP) account for nearly 35–38% variance which indicates that the monsoon influences dominating the region. The SEA region is influenced by two monsoon seasons, the northeast during DJF and the southwest during JJA. Most of the models are able to capture the first mode pattern fairly well. MIROC5 underestimates the extent of the northeast monsoon while the MPI ESM simulates the extent of the monsoonal influences deeper south. The northeast monsoon is also stronger in IPSL CM5 and CNRM CM5. The second EOF mode that accounts for about 10% of observed variance suggests a transitional phase from northeast to southwest monsoon that is evident from strong positive meridional loadings. This clearly displays the northeast monsoon rainfall on most of the northern hemispheric regions. Such patterns have also been mentioned by Giannini (2005) and Liew et al. (2010). But none of the models replicate this feature though MIROC5 shows some similarities to the observations. It is likely that these differences and the limitations of the models in reproducing the observed patterns of rainfall could be attributed to the biases in the sea surface temperatures (SSTs) in the simulations.

5 Discussions and conclusions

Ten models form the CMIP5 suite of GCMs and ESMs were chosen in this study to evaluate their performance in simulating the precipitation regime over Southeast Asia. The evaluations suggest that, in general, the performance of these models is not consistent over any particular region, though some models perform better over a few regions and some models, otherwise. No particular model considered in this study is able to reproduce the observed patterns of annual and seasonal rainfall and variability over Southeast Asia well enough. Although the ensemble mean of the models is a better representation of the observed climate, the spread among the individual models is large. The models are also unable to simulate the observed annual/seasonal cycles and the inter-annual variability of rainfall over the region. However, the spatial patterns of the EOF1 shows that the models are able to capture the large scale circulation in terms of the most dominant models of rainfall over the region, namely, the northeast and the southwest monsoons. The analyses also suggest that uncertainties in the GCM simulated rainfall over a smaller region are higher than over larger areas, and in general, most of the models suffer from simulating the summer season rainfall well enough. It has been indicated that the quantification of such model errors and uncertainties is crucial as any poor performance in the historical climate will likely affect the future projections (Knutti et al. 2010; Brands et al. 2012; Otieno and Anyah 2013), and hence, these findings suggest that careful consideration is warranted when choosing the models for downstream impact studies that directly use the output of these GCMs/ESMs or for further downscaling for desired regions of interest. The global climate models have been designed using the principles of physics, chemistry, and fluid dynamics and the different physical parameterizations applied in different models are possible sources of uncertainties that lead to inadequate or poor representation of key physical processes (Gu et al. 2015). Such intermodel variability has also been studied in detail at global and regional scales: Gu et al. (2014), Wang et al. (2014), Wang (2004), and Giorgi and Mearns (2002), to name a few. Despite improvements in model resolutions since the CMIP3 phase, it is understandable that these model uncertainties stem from a large suite of other uncertainties such as model physics and dynamics, parameterizations, and physical processes. This paper has limited itself in discussing uncertainties in precipitation, but a detailed analysis of monsoons and other climate features unique to Southeast Asia may likely augment uncertainties. It should also be mentioned here that other than the uncertainties in models themselves, one of the main issues in evaluating models is the lack of dense and robust observations at the appropriate spatial and temporal resolutions. Given that the gauge and network coverage over this region is still far from being robust, adequate steps must to taken to improve to the data accuracy that would facilitate various climate studies.

Very few studies on climate modeling over Southeast Asia exist compared to the developed regions of the world, and Southeast Asian climate is one of the important global tropical climate systems that exhibits large climate variability due to teleconnections such as the El Nino Southern Oscillation (ENSO), the Madden–Julian Oscillation (MJO), and the Indian Ocean Dipole (IOD) and on precipitation extremes.

Much more detailed studies are warranted on these features for which the best source of data are the global models but is out of scope of this study.

A feedback to the global climate modeling community on the performance of these models over this region (and from similar other studies on other regions) may not be inappropriate as it could provide room to improve the quality of simulations in the subsequent versions of model developments. Therefore, it may be prudent for the global modeling community to focus on the development and improvement of a handful of models which might relatively perform well over many regions of the world rather than expanding the models in number, many of which may not perform well enough in continental or regional scales.

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