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Developing Reliable Climate Projections for the Continental Monsoon Regions

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Abstract: Reliable regional climate projections provide critical input for devising mitigation strategies for sustainable development, as the climate variability and change continue to play vital role in economic growth of many sectors. The Inter-governmental Panel on Climate Change (IPCC) climate experiments and multi-source observations generated huge volume of data, which continue to increase manifold and pose grand challenge in assessing regional reliability. Here, we develop a generic methodology to identify the reliable climate models based on the past observed time-scale dependent indices. Results show that not a single climate model from Coupled Model Intercomparison Project (CMIP5) qualifies reliability across all continental monsoon regions. Thus, it is necessary to identify the set of reliable models for each monsoon region independently to develop reliable projections. The reliable composite had successfully represented the past climate and also significantly revises all model composite projected scenarios for most of the monsoon regions. This provides reliable projections which are useful for regional applications.

Keywords: Regional monsoon systems; Reliability assessment; Climate projections.

Introduction

The regional monsoon systems are the most dynamic components of global seasonal cycle and its vagaries in timing, duration and intensities are of major concern in the tropics. Reliable regional climate projections provide critical input for devising mitigation strategies for sustainable development, as the climate variability and change continue to play vital role in economic growth of many sectors (Zhisheng et al., 2015; Lee et al., 2014; Wang et al., 2014; Wang et al., 2012). Studies have shown that the observed magnitude of variability and change varies significantly across different monsoon regions (McBride, 1987; Tao and Chen, 1987; Nicholson and Kim, 1997; Webster et al., 1998; Wang and Ding, 2006; Wang, 2009). Each regional monsoon system has its own dynamics, which mainly depends on its orographic, land-sea interactions, tele-connections, etc. (Wang et al., 2014). Multi-scale variations and change in continental rainfall distribution patterns are well understood for most of the regional monsoon systems like, South Asia (Higgins et al., 2003), East Asia (Zhou and Lau, 1998), Australia (Tim and Joachim, 2013), Africa (Cumhur and Malcolm, 2008), North America (Jemma et al., 2010) and South America (Fischer et al., 2005). Better understanding of past climate variability and change in regional monsoon systems leads to successful simulation of past climate as well as developing reliable projection scenarios for the future. The reliable projections provide critical input for effective policy planning and developing the mitigation strategies for a sustainable planet.

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Majority of the global population still depends on rain-fed agriculture for their livelihood, as future climate variability and change will have a significant impact on global and regional economies (Cumhur and Malcolm, 2008). Most of the agricultural practices, especially in the tropics, mainly depend on the availability of rainfall through regional monsoon systems (Higgins et al., 2003) and its change will have significant impact on agriculture productivity (Sivakumar et al., 2005; Gadgil and Gadgil, 2006; Mall et al., 2006; Gunasekara et al., 2007; Luis et al., 2009), renewable energy (Pryor and Barthelmie, 2010; Collins et al., 2013a), water resources (Seager et al., 2007; Brown et al., 2012; Arnell and Lloyd-Hughes, 2014), etc. The IPCC AR5 (CMIP5) climate models have a set of twentieth and twenty first century climate experiments, which were used in wide range of impact analysis and the projections of multiple scenarios for planning and developing pro-active mitigation strategies (Maurer et al., 2007; Gornall et al., 2010, Collins et al., 2013a; Arnell and Lloyd-Hughes, 2014). Developing the reliability of future climate projections is critical in developing successful mitigation strategies.

IPCC CMIP3 and CMIP5 model simulations of mean rainfall, multiscale variability and changes are not in the range of observed quantities, but also vary differently in different monsoon regions (Sperber et al., 2013; Koutroulis et al., 2016). The CMIP3 and CMIP5 model simulations helped us to understand the model's ability to simulate changing trends in precipitation over the Global Monsoon (GM) region under multiple scenarios (Hsu et al., 2012). The limitations of earlier studies were that there was no generic methodology to quantify the reliability and identify reliable climate models for a regional monsoon system. The main challenge in defining the reliability for a regional monsoon region is due to dispersions within the available multisource observed rainfall datasets (Ramesh and Goswami, 2014; Collins et al., 2013b). On the other hand there are huge dispersions within the CMIP5 simulated rainfall (both seasonal and annual) characteristics, which also varies between different monsoon regions. Both the dispersions make it more complex for developing a generic methodology for identifying the reliable climate models for the monsoon regions. The reliability of CMIP3 and CMIP5 simulations were quantified and identified in the reliable models which successfully captured the observed rainfall characteristics of the continental Indian summer monsoon (ISM) region (Ramesh and Goswami, 2014).

The reliability was assessed using the time-scale dependent indices like mean and trend in ISM rainfall from multiple observations and only two out of 24 climate models were identified as reliable, which captured the observed rainfall features within the acceptable error limits for the past climate (1951-2005). Thus the ability in simulating past climate by most of the climate models are not in agreement with observations (Collins et al., 2013b); the magnitude of deviation in terms of its mean, variability and trend varies between different monsoon regions. A recent study (Li et al., 2017) calibrated the Indian summer monsoon rainfall projections by removing the effects of present-day simulation errors in climate models on regional future climate projections. This statistical strategy called "emergent constraints" has been suggested to deal with the effects of model errors on future climate projections by deriving relationships between observable quantities in the present climate and projected responses of the climate system to global warming in a multi-model ensemble to constrain future climate projections (Li et al., 2016a, 2016b).

For the given complexity, we develop a generic methodology based on the observed time-scale dependent characteristics for the period of 1951-2005 to identify the reliable models for each monsoon region. The inclusion of multi-source observations in developing the generic methodology will make it more robust in identifying the reliable climate models for different monsoon regions. This methodology also incorporates time-scale dependent statistical parameters for assessing and quantifying the reliability of the climate model simulations for each monsoon region. The identified set of reliable models for each monsoon region are used to generate a reliable rainfall composite which is validated with the past observed rainfall. The future projection scenarios are estimated based on the identified reliable models for each continental monsoon region. This methodology is uniformly applied and validated across all the eight regional continental monsoon systems: (i) Australian (AUS), (ii) North American (NAM), (iii) South American (SAM), (iv) North African (NAF), (v) South African (SAF), (vi) Indian (IND), (vii) East Asian (EAS) and (viii) North Western Pacific (NWP).

Methods

Multi-source observational and reanalysis data sets were used to quantify the reliability of the climate models for the period 1951-2005. Monthly global rainfall data from Climate Research Unit (CRU) (Harris et al., 2014), Global Precipitation Climatology Centre (GPCC) (Schneider et al., 2011), NCEP (Kalnay et al., 1996) and 26 CMIP5 (Taylor et al., 2012) models were used for this study. In addition, the regional rainfall time series data were also used for Australia (Bureau of Meteorology (BOM) (Jones et al., 2009)), India (Indian Institute of Tropical Meteorology) (Parthasarathy et al., 1994) and Indian Meteorological Department (IMD, 2013)), and North America (North American Land Data Assimilation System (NLDAS) (Mitchell et al., 2004, Xia et al., 2012) and University of Washington (Maurer et al., 2002)) along with the global reanalysis data. The details of CMIP5 model used in this study are shown in Table 1.

The global monsoon region can be defined by the regions where (i) the local summer-minus-winter precipitation rate exceeds 2 mm day^{-1} and (ii) the local summer precipitation exceeds 55% of the annual total (Wang and Ding, 2008). The major monsoon regions were adopted as per the World Climate Research Programme (WCRP) and the regional monsoon regions were identified as (i) Australian (AUS), (ii) North American (NAM), (iii) South American (SAM), (iv) North African (NAF), (v) South African (SAF), (vi) Indian (IND), (vii) East Asian (EAS) and (viii) Western North Pacific (NWP). For the reliability analysis, both model and observational data were regridded to uniform 1°×1° grid. The rainy season is identified as the time at which the region is getting maximum rainfall in the long term average. The identified rainy season for the respective regions are AUS (DJF), EAS (JJA), NWP (JJA), NAM (JAS), SAM (NDJFM), NAF (JJA), SAF (JFM) and IND (JJAS). We have taken Northern hemisphere (NH) and southern hemisphere (SH) rainfall season as AMJJAS and ONDJFM respectively.

Table 1: Details of the 26 models used in this study that participated in the CMIP5 project

Model name	*Institute*	*Symbol*	*Horizontal resolution (lat×lon)*
ACCESS-1.0	CSIRO-BOM, Australia	A	1.25° × 1.875°
ACCESS-1.3	CSIRO-BOM, Australia	B	1.25° × 1.875°
BCC-CSM1-1	BCC, CMA, China	C	2.8° × 2.8°
BNU-ESM	GCESS, China	D	2.8° × 2.8°
CanESM2	CCCMA, Canada	E	2.8° × 2.8°
CCSM4	NCAR, CO, USA	F	0.94° × 1.25°
CESM1-CAM5	NSF-DOE-NCAR, USA	G	0.94° × 1.25°
CESM1-FASTCHEM	NSF-DOE-NCAR, USA	H	0.94° × 1.25°
CESM1-WACCM	NSF-DOE-NCAR, USA	I	0.94° × 1.25°
CNRM-CM5	CNRM-CERFACS, France	J	1.4° × 1.4°
CSIRO-Mk3-6-0	CSIRO-QCCCE, Australia	K	1.9° × 1.9°
FIO-ESM	FIO,SOA,China	L	2.8° × 2.8°
GFDL-ESM2M	NOAA-GFDL, USA	M	2.0° × 2.5°
HadGEM2-AO	NIMR-KMA, Korea	N	1.25° × 1.875°
INMCM4	INM, Russia	O	1.5° × 2.0°
IPSL-CM5A-LR	IPSL, France	P	1.875° × 3.75°
IPSL-CM5A-MR	IPSL, France	Q	1.25° × 2.5°
IPSL-CM5B-LR	IPSL, France	R	1.875° × 3.75°
MIROC-5	AORI-NIES-JAMSTEC, Japan	S	1.4° × 1.4°
MIROC-ESM	AORI-NIES-JAMSTEC, Japan	T	2.8° × 2.8°
MIROC-ESM-CHEM	AORI-NIES-JAMSTEC, Japan	U	2.8° × 2.8°
MPI-ESM-LR	MPI-N, Germany	V	1.9° × 1.9°
MPI-ESM-MR	MPI-N, Germany	W	1.9° × 1.9°
MRI-CGCM3	MRI, Japan	X	1.1° × 1.1°
NorESM1-M	NCC, Norway	Y	1.875° × 2.5°
NorESM1-ME	NCC, Norway	Z	1.875° × 2.5°

The generic methodology for reliability includes statistical parameters including multi scale time dependent quantities like mean, trend, and standard deviation for both annual and seasonal rainfall, and correlation between observation and models. Dispersion (σ) between different observational datasets were also taken into while defining the reliability. The percentage dispersion is calculated for annual and seasonal (mean and trend) rainfall in all monsoon regions. The percentage dispersion for trend (annual and seasonal) is calculated by giving 100% weightage to the observed mean value and the dispersion between different observations.

The dispersion and the error limit is calculated as

$$\sigma_{ann/sea} = \sum (OBS_{individual} - OBS_{mean})/\text{No. of observations}$$

$$\text{Error limit} = OBS_{mean} \pm (\sigma_{ann/sea} + (1/2)SD)$$

where $\sigma_{ann/sea}$ is dispersion in annual/seasonal rainfall, OBS_{mean} – composite mean of all observations, $OBS_{individual}$ – individual observation and SD – standard deviation.

The adopted acceptable uncertainty is defined by the difference between the maximum and the minimum in the observed values, centred at the observed composite; a relaxation by 1SD + σ and 2SD + σ respectively was given as a condition for selecting the models. The different steps for checking the reliability of models were defined as:

Step 1: The long-term mean (annual and seasonal) from both observations and models

Step 2: Linear trend (annual and seasonal) from both observations and models were used to quantify the reliability by incorporating the uncertainty within the observations and the dispersion between the models.

Step 3: Correlation with observation and selected models

Step 4: Extreme events

The extreme rainfall years were defined as the years which have > +10% (excess) and < –10% (drought) of long term average of annual rainfall. The models were grouped based on the multiple indices using different tests and conditions. The inter-annual characteristics in both annual and seasonal scales of rainfall pattern were examined for the observations as well as for the CMIP5 models. The observations (both global and regional data sets) were used as a bench mark for the selection of the better models which shows similar features with observations. The models which fall within the error limit with the mean observation were considered as the reliable ones in each monsoon region.

The conditions for defining criteria were based on (i) annual and seasonal mean, (ii) annual trend, (iii) seasonal trend, (iv) climatology with an error of 1SD and (v) climatology with an error of 2SD.

The models were classified based on different criteria and the criteria were defined as:

(i) **Criterion 1** – The model should satisfy atleast three conditions including annual and seasonal tests.
(ii) **Criterion 2** – The model should succeed in all tests based on seasonal statistical parameters (mean, trend and climatology).
(iii) **Criterion 3** – The model should succeed in all tests based on annual statistical parameters (mean, trend and climatology).
(iv) **All criteria** – The model should fall in all conditions.

The selected models in each criteria were used for the future projection (2020-2100) of rainfall in the particular monsoon region. The selected models were tested for the success rate for the GM regions using above criteria. The success rate for the selected models is calculated in two ways:

(a) If any of the criteria selection (ALL, CRI_1, CRI_2 and CRI_3), is showing better results when compared to all model average in annual trend, seasonal trend and in case of extreme events (drought, excess and normal).
(b) If ALL is showing better results when compared to all model average in annual trend, seasonal trend and in case of extreme events (drought, excess and normal).

Results and Discussion

The statistical tests for the monsoon regions were behaving in diverse way in both observations/reanalysis and IPCC models. The observed average dispersion in global annual mean rainfall is 1.7% of its composite mean, while NH and SH have (2.3%, 1.2%) for annual and (0.5%, 1.6%) for seasonal mean rainfall. The annual mean rainfall (AMR) shows highest observed dispersion for NAM (23.5%), AUS (16.3%) and NAF (14.1%) regions, while other monsoon regions show minimum dispersions within the available observations (Table 2). The highest observed dispersion in seasonal mean rainfall (SMR) is noted over NAM (54.2%) and AUS (42.9%) regions, whereas EAS (0.4%) showed the least observed dispersion among all the monsoon regions. The global AMR showed an observational dispersion of 3.6% in variability (SD), while NH and

SH showed (4.3%, 1.0%) for AMR and (5.5%, 5.4%) for SMR respectively. NAF (98.7%, 83.7%) region shows highest observational dispersion in terms of variability for AMR and SMR (Table 2). Annual and seasonal rainfall trends show high observed dispersion between multisource observations in all the monsoon regions, for example, AMR trend over EAS (4.24 mm year^{-1}), NAF (3.52 mm year^{-1}) and SMR trend over NWP (1.91 mm season^{-1}), SAM (1.41 mm season^{-1}) (Table 2). In general, the time scale dependent indices in SMR show more observational dispersions than AMR over most of the monsoon regions.

The dispersions in AMR and SMR for mean, variability (SD) and linear trend show high values among the CMIP5 models. Global mean AMR has a model dispersion of 8.9% among CMIP5 models, while NH shows 8.6% (AMR) and 14.8% (SMR), SH shows 10.9% (AMR) and 9.7% (SMR) within the CMIP5 models. There is discrete model dispersion (in percentage) within the CMIP5 models for AMR and SMR (Figure 1). The highest dispersion for AMR and SMR is seen over IND (44.6%, 36.1%). The variability (SD) also shows huge variations among the CMIP5 models. GM has a dispersion of 25.0% for AMR, while NH has 14.8% for AMR and 21.2% for SMR. SH have comparatively higher values when compared to NH and it has a dispersion of 26.9% and 31.8% respectively for AMR and SMR.

The highest dispersion is shown for NWP (30.4%) for AMR and SAM (35.5%) for SMR. The observed global annual rainfall composite had a decreasing trend (–0.14 mm year^{-1}) during 1951-2005 with a dispersion of 0.08 mm year^{-1}, which was successfully simulated by four models CSIRO-Mk3-6 (–0.12 mm year^{-1}), HadGem2-AO (–0.05 mm year^{-1}), MIROC-ESM (–0.06 mm year^{-1}), and MRI-CGCM3 (–0.10 mm year^{-1}), while rest of CMIP5 models didn't simulate the global mean land rainfall trend within the error (dispersion) limits. The observed composite over NH shows a linear trend of –0.17 mm year^{-1}/season^{-1} for both AMR and SMR over NH and SH shows –0.03 mm year^{-1} and 0.12 mm season^{-1} for AMR and SMR respectively (Figures 2 and 3). The linear trend (1951-2005) for the AMR is showing a decreasing trend for NAF, SAF, IND and NWP, while increasing trend over the rest of the monsoon regions (Figure 4). The linear trend is showing dispersion within the CMIP5 models as IND (1.06, 0.74), AUS (0.82, 0.33), EAS (0.60, 0.38), NAM (0.67, 0.30), SAM (0.62, 0.33), NAF (0.25, 0.12), SAF (0.60, 0.33) and NWP (1.25, 0.46) (mm year^{-1}, mm season^{-1}) for AMR and SMR respectively.

In this case NAF (0.25, 0.12) (mm year^{-1}, mm season^{-1}) is having least model dispersion while NWP (1.25 mm year^{-1}) is having highest dispersion in AMR trend and IND (0.74 mm season^{-1}) in SMR trend. It is clearly evident that the mean and trend (annual and seasonal) is having a large dispersion within the CMIP5 models (Figure 1). The high inter-model dispersions in mean, SD and trend in AMR and SMR cannot represent the observational characteristics as it has huge dispersions in all model composite and the observed composite (Figure 5). Hence it arises the need for identifying the reliable models for each monsoon regions for developing the reliable projection scenarios.

The models were selected as reliable, based on its ability to simulate past characteristics, and marked into two levels. In most of the monsoon regions the number of models falls in primary selection box with strict reliable conditions for few or none, and hence we relaxed reliable conditions as a secondary selection box to include more models into the reliable ones. The models which are successful are listed in Table 3. For

Table 2: Percentage dispersion in mean and standard deviation in rainfall (annual and seasonal) between available observations over different monsoon regions

Region	*GM*	*NH*	*SH*	*IND*	*AUS*	*EAS*	*NAM*	*SAM*	*NAF*	*SAF*	*NWP*
Annual mean	1.7	1.2	2.3	5.4	16.3	8.7	23.5	4.7	14.1	2.15	9.2
Seasonal mean	NA	0.5	1.6	18.3	42.9	0.4	54.2	3.4	10.0	1.46	7.2
SD annual	3.6	4.3	1.0	38.7	6.6	78.9	31.3	70.2	98.7	4.1	26.6
SD seasonal	NA	5.5	5.4	31.6	25.3	66.2	62.1	60.8	83.7	4.1	52.2
Annual trend	0.08	0.03	0.25	0.42	0.97	4.24	1.54	2.93	3.52	1.59	1.62
Seasonal trend	NA	0.02	0.19	0.61	0.39	1.37	0.62	1.41	1.12	0.24	1.91

(Global Monsoon – GM, Northern Hemisphere – NH, Southern Hemisphere – SH, Indian – IND, Australian – AUS, East Asian – EAS, North American – NAM, South American – SAM, North African – NAF, South African – SAF, North Western Pacific – NWP monsoon)

IND and NAM none of the available models falls in primary selection box, while for EAS, SAM and NAF all the models are within the secondary selection box (Figure 5). Even the identified models are also having diverse pattern for the historical precipitation within the acceptable ranges in mean, SD and linear trend in AMR and SMR (Figure 6). The detailed trend distribution for individual models, observations and for model ensembles for annual (Figure 2) and seasonal (Figure 3) rainfall shows the complexity in the behaviour of model as well as observational data.

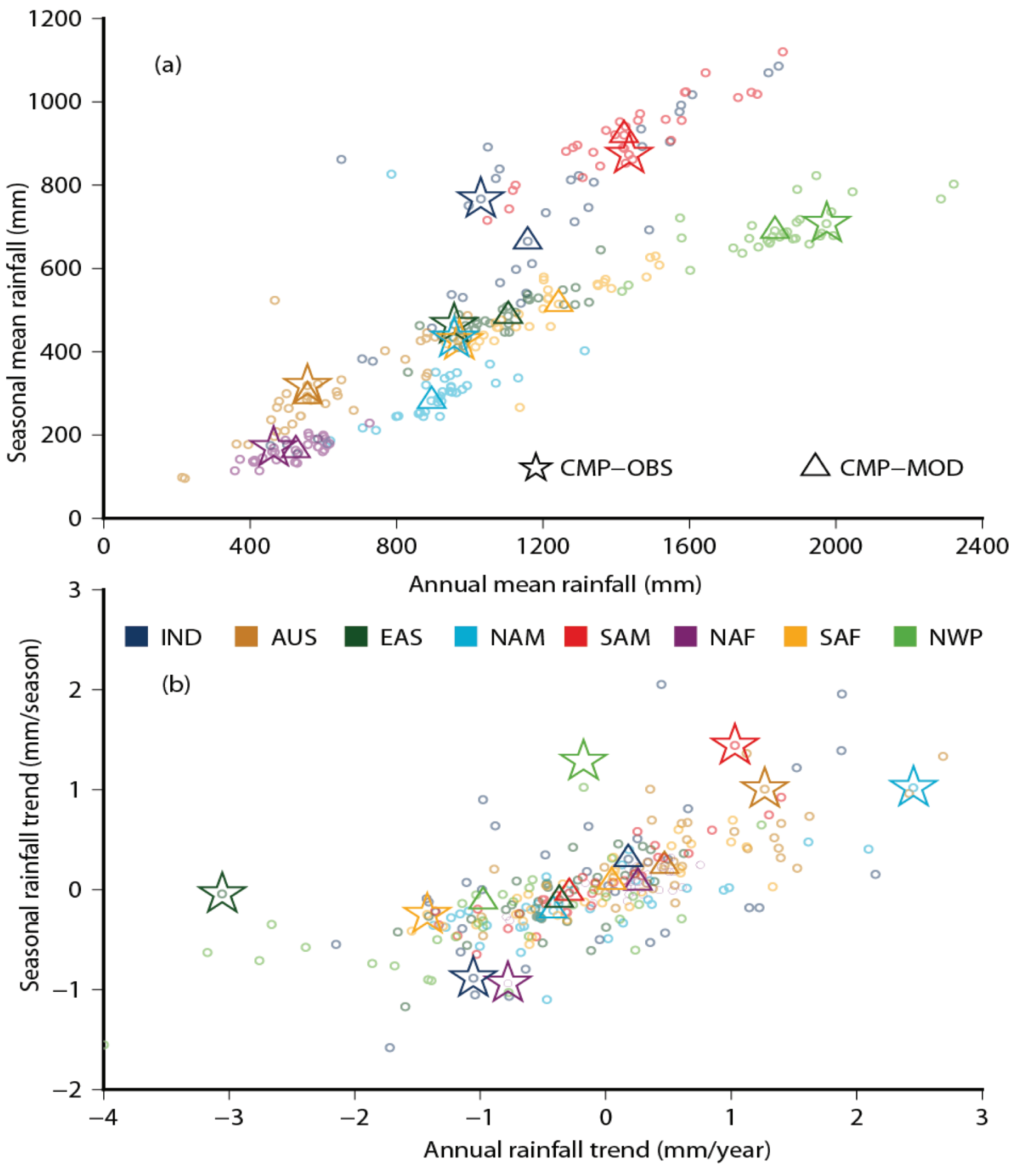

Figure 1: The annual and seasonal rainfall features in different monsoon domains. The annual values are shown over x-axis and seasonal along y-axis. (a) The annual and seasonal mean rainfall (mm) from 1951-2005 using multiple observations and CMIP5 models. The dots represents individual models, star for the composite of available observations/reanalysis and triangle represents the composite of CMIP5 models. Each region is differentiated using different colours (Indian – IND, Australian – AUS, East Asian – EAS, North American – NAM, South American – SAM, North African – NAF, South African – SAF, North Western Pacific – NWP monsoon). (b) The annual and seasonal linear trend (mm per year/season) for the period 1951-2005. The figure shows the wide dispersion among the observations as well as within the models for annual and seasonal rainfall characteristics.

Table 3: Selected models based on different criteria

Region	*Selected models*												
	Ann/Sea	Tr_ann	Tr_sea	Clim_1SD	Clim_2SD	all_conditions	any_3_excluding 2SD	Any_2_only sea(1,3 and 4)	Any_2_only ann(1,2 and 4)	Inter_ann_1D	Inter_sea_1D	Inter_ann_2D	Inter_sea_2D
NHEM	A, C, F, I, J, K, M, N, O, P, T, U, V, W, X, Y, Z	G, K	K, N, T, Y, Z	X	A, E, G, I, J, K, M, N, O, Q, V, W, X	-	K	K, N, T, X, Y, Z	K, X				
SHEM	B, S	A, B, C, E, J, K, N, S, T, U, V, X, Z	D, E, F, G, H, I, J, L, M, O, P, Q, R, S, Y, Z	B, D, F, H, S, X, Y	A, B, C, D, F, H, I, L, N, R, S, T, U, X, Y, Z	S	B, S	B, D, F, H, S, Y	B, S, X				
AUS	A, B, C, D, E, J, K, L, M, N, O, R, V, W, X	F, G, H, J, L, M, R, S, W, Y	F, J, L, R, S, W, Y, Z	A, B, C, D, E, F, G, J, K, L, M, N, P, Q, V, W, X, Y	A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z	J, W	F, J, L, M, V, W, Y	A, B, C, D, E, F, J, K, L, M, N, R, V, W, X, Y	A, B, C, D, E, F, G, J, K, L, M, N, R, V, W, X, Y	A, B, L, U	A, C, D, G, H, J, M, N, O, P, Q, R, S, X, Z	A, B, D, F, K, L, M, P, R, T, U, V, Z	A, C, D, G, H, J, M, N, O, P, Q, R, S, X, Z
EASIA	B, C, F, H, J, K, M, P, Q, R, T, U, V, W	A, B, G, H, I, K, M, N, P, R, S, U, X, Z	A, C, F, G, I, K, M, N, S, U, W, X	K, O, P, T, U, X	A, E, F, H, J, K, M, N, O, P, Q, T, U, V, W, X, Y, Z	K, U	K, M, P, U, X	A, C, F, K, M, P, T, U, W, X	B, H, K, M, P, R, T, U, X	D, E, F, I, L, M, P, S, T, X, Y	D, E, T, X	B, C, D, E, F, I, J, K, L, M, P, R, S, T, X, Y	C, D, E, K, T, U, X
NAME	A, B, C, D, F, G, H, J, K, L, M, S, V, W	E, T, Y	P, Q, W	A, D, G, N, S	A, B, C, D, F, G, H, L, N, R, S, V, X, Z	-	-	A, D, S, W	A, D, G, S, W	C, E, H, J, K, L, M, N, P, Q, R, S, W, X, Z	A, B, D, E, G, H, J, K, L, M, N, O, P, Q, S, T, U, X, Y	A, C, D, E, F, G, H, J, K, L, M, N, W, X, Y, Z	A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, X, Y
SAME	C, J, R, V, W	D, L, R, Y	D, R, Y	C, D, R	C, D, F, G, H, I, J, L, N, Q, R, T, V, W, X, Y, Z	R	D, R	C, D, R	C, D, R	Except V	A, B, C, H, I, M, N, O, P, Q, R, T, U, V, X, Y, Z	All	A, B, C, D, G, H, I, J, K, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z

(*Contd.*)

Table 3: (*Contd.*)

Region	*Selected models*												
NAFR	A, V, W	D, P	P, U	B, G, J, N, R, W	A, B, D, E, G, H, I, J, K, L, M, N, O, P, Q, R, T, U, V, W, X, Y	-	-	W	W	Except C, S	B, D, F, H, J, L, M, N, Q, S, U, X, Y	All	A, B, C, D, E, F, H, I, J, K, L, M, N, O, Q, S, T, U, W, X, Y, Z
SAFR	E, K, N, V, W, X	C, H, J, K, M, R, S, U, X	B, C, F, H, K, R, S	G, T, U, X	A, E, G, J, K, L, N, O, P, Q, R, T, U, V, W, X	-	X	K, X	K, U, X	A, B, C, D, E, I, L, N, R, S, T, Y, Z	F, I, M, O, W, Z	A, B, C, D, E, F, G, I, J, L, M, N, O, P, Q, R, S, T, U, V, Y, Z	B, E, F, G, I, K, M, O, S, T, U, W, X, Z
NWPAC	A, C, D, F, G, H, I, J, N, Q, R, X, Y, Z	A, B, C, D, G, I, J, K, M, N, P, S, T, U, X, Y, Z	D, O, P, Q, R, V, Z	A, C, D, E, F, G, H, I, J, L, M, N, O, P, Q, U, V, W, X, Y, Z	A, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z	D, Z	A, C, D, G, I, J, N, P, Q, X, Y, Z	A, C, D, F, G, H, I, J, N, O, P, Q, R, V, X, Y, Z	A, C, D, F, G, H, I, J, M, N, P, Q, U, X, Y, Z	B, C, D, E, F, J, L, N, R	A, B, D, E, F, G, H, J, K, L, M, N, P, T, U, V, W, X, Y, Z	B, C, D, E, F, G, H, J, L, N, O, P, R, T, X, Z	A, B, D, E, F, G, H, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z
IND	M, W, Y, Z	D, J, K, M, O, Y	J, N, O, T, U, Y	E, G, K, M, O, P, V, W, X, Y	A, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z	Y	M, O, Y	M, O, W, Y	K, M, O, Y	B, C, D, E, F, H, I, L, M, N, T, V, W, Y, Z	A, B, G, S, T, W, X, Y, Z	B, C, D, E, F, H, I, J, K, L, M, N, O, R, S, T, U, V, W, X, Y, Z	B, C, E, G, H, J, K, M, N, O, P, Q, S, T, U, W, X, Y, Z

The standard deviation and linear trend for AMR and SMR in each monsoon region along with the correlation with different model ensembles are shown in Table 4. The composite observation is showing a significant positive trend for AUS (AMR and SMR) and SAM (AMR and SMR) whereas other regions have a significant negative trend for EAS (AMR and SMR), SAF (AMR and SMR), NWP (AMR) and IND (AMR and SMR). The linear trend for observations is matching (with reasonable error limits) after the criteria selection in all the regions except for NAF, NAM and NWP (SMR). The criteria selection is improving the correlation with observation when compared to all model average. The correlation with observed composite has shown significant improvements by adopting the concept of criteria selection using different temporal aspects. The correlation for Criteria 3 (annual based) is showing better results when compared to other criteria in all regions except for SAM.

The reliability of climate models were also checked for the extreme rainfall years viz, excess, normal and drought, for the monsoon regions. The number of years which is matching with the observation varies with place as well as models. The ratio between the number of

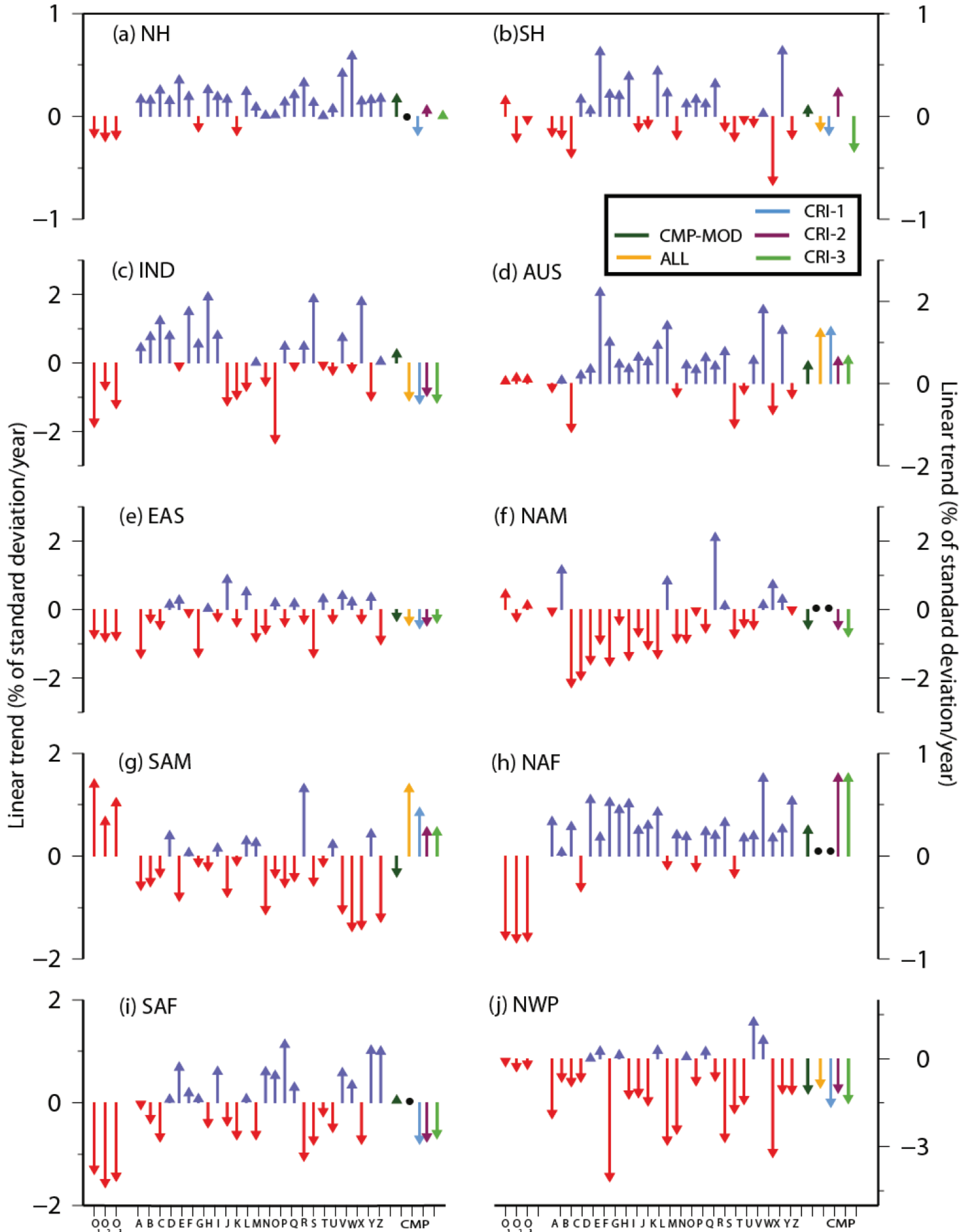

Figure 2: Annual rainfall trend for the different monsoon regions. First three arrows represent observations and the next 26 arrows respective model simulations and remaining five based on different criteria. The black dots show none of the models qualified in that category.

excess and weak monsoon years in different monsoon regions (Figure 7) also gives a complex pattern within the models. The ratio is calculated with the number of drought, excess and normal years which are matching with observation (exact years are treated as a count) and the remaining years in each individual model (Table 5). The inter-annual variability and the ability of models for extreme years were also showing a wide spread within the models and with observations. The models were also tested for the annual and seasonal contribution of rainfall in all the monsoon regions (Figure 8).

The multi model ensemble (MME) based on different selection criteria are used to develop the reliable future projections for RCP26, RCP45, RCP60 and RCP85

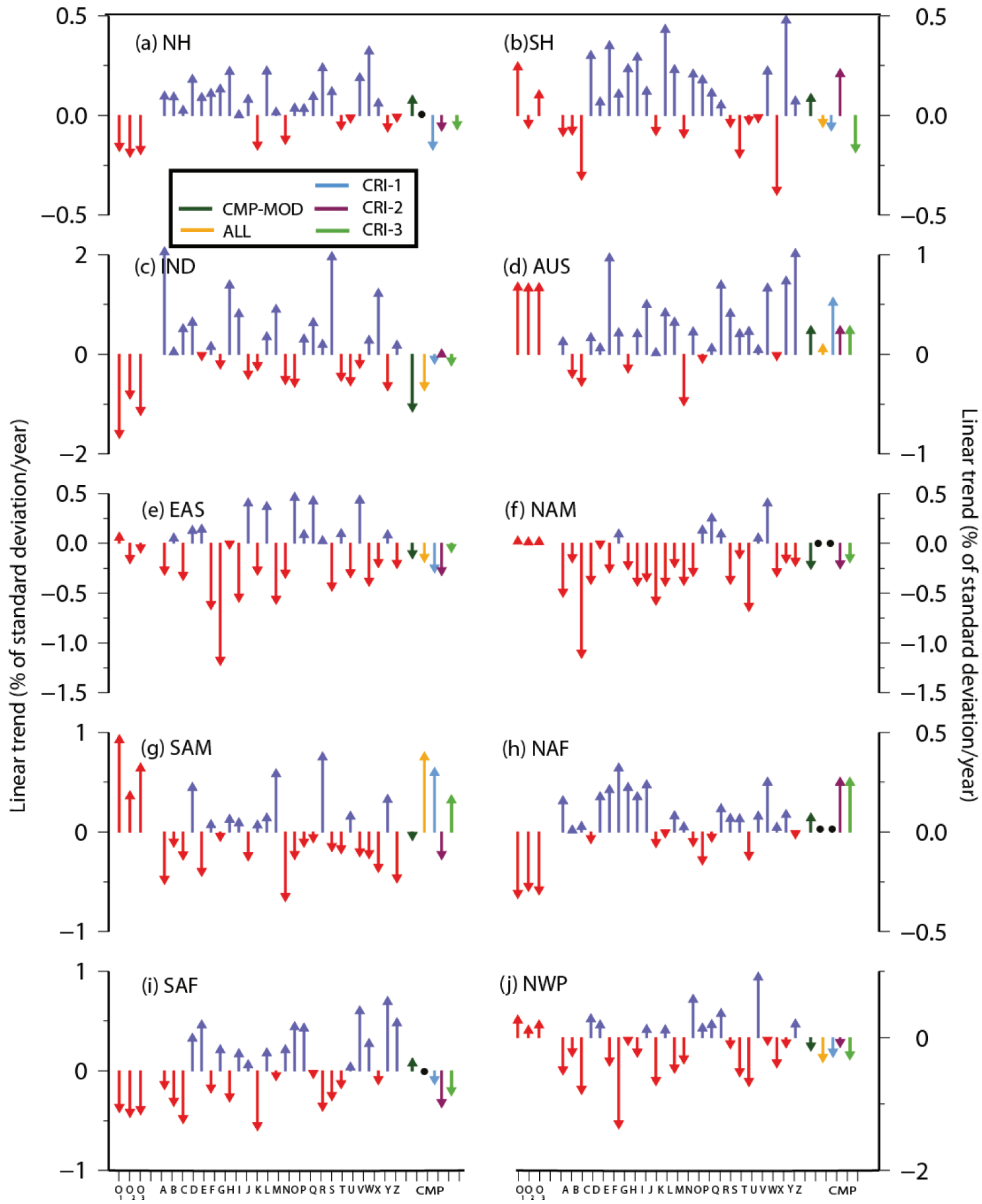

Figure 3: Seasonal rainfall trend for the different monsoon regions. First three arrows represent observations and the next 26 arrows represent model simulations and remaining five based on different criteria. The black dots show none of the models qualified in that category.

(Figure 9). The projections show a strong positive trend in NWP, EAS and AUS whereas the other regions are more or less having a mild positive trend for RCP85. NWP is having a highest positive trend based on all the selected criteria and it shows a significant positive trend for the region. The trends are varying in different MME and especially for SAM. In SAF and AUS there is a significant change in trend for different criteria. The success rate for IND, AUS, EAS, SAM and NWP is showing good results in the historical studies whereas it is failing in NAM, NAF and SAF (Figure 9). The success rate for future projections are based on all model composite and any of the defined criteria. The success rate shows that the selection criteria and the ensemble based on criteria used in this study improved the quality of simulations when it is compared to take the MME of all models without checking its reliability.

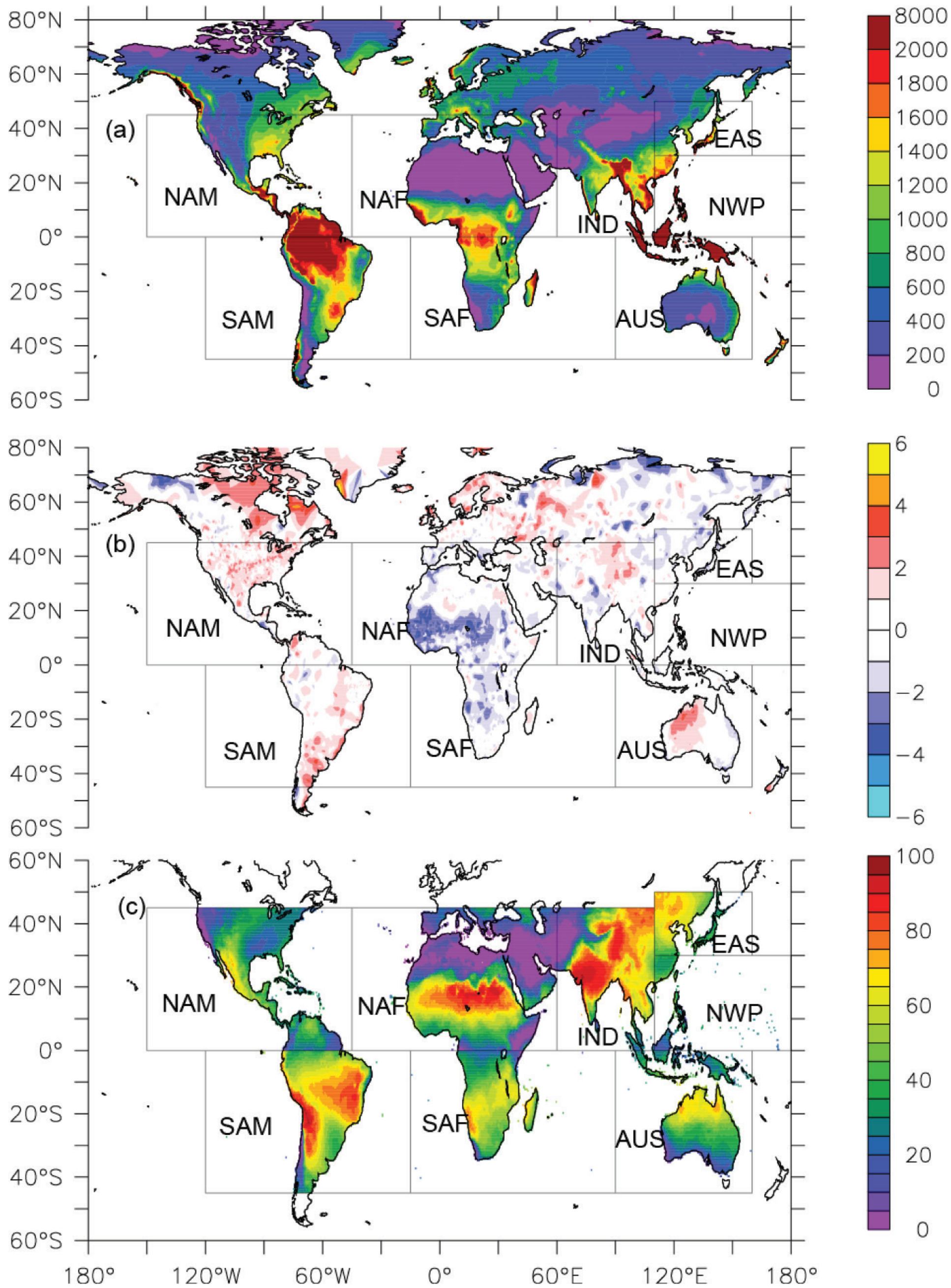

Figure 4: (a) The annual mean rainfall (1951-2005) in different monsoon regions (NAM – North America, SAM – South America, NAF – North Africa, SAF – South Africa, IND – India, EAS – East Asia, NWP – North West Pacific and AUS – Australia) (b) The linear trend (in percentage) which is normalized with SD [(trend/standard deviation) × 100] for different monsoon regions. (c) The seasonal contribution in annual rainfall in different monsoon regions (in percentage) (seasonal/Annual) × 100.

Summary and Conclusions

The reliability studies are important in each monsoon region. It is clearly shown that we can't rely on a single model or an ensemble of all the models for the climate related studies in a regional scale. All the climate models are simulating the observational features in different ways. Hence it is important to study each individual model and its ability to simulate the observational features before going for future studies especially in

Table 4: The statistical results for the model ensembles for different regions and for different criteria

	Correlation with OBS					*Std deviation*					*Trend*			
	ALL	*CRI-1*	*CRI-2*	*CRI-3*	*OBS*	*ALL*	*CRI-1*	*CRI-2*	*CRI-3*	*OBS*	*ALL*	*CRI-1*	*CRI-2*	*CRI-3*
AUS_ Ann	-0.05	-0.09	-0.05	-0.047	93.34	21.90	48.48	45.52	28.68	0.639	0.467	1.038	1.344	0.61
AUS_ Sea	0.12	-0.0004	0.014	0.153	61.18	13.6	29.89	24.43	17.5	0.667	0.236	0.546	0.519	0.24
EASIA_ Ann	0.213	0.18	0.16	0.186	49.47	14.34	26.61	24.61	22.77	-0.607	-0.370	-0.578	-0.684	-0.536
EASIA_ Sea	0.13	0.166	0.257	0.18	28.44	7.15	16.09	18.07	13.53	-0.04	-0.101	-0.136	-0.2429	-0.268
NAM- Ann	-0.058	NA	NA	0.011	49.557	15.857	NA	NA	25.59	0.815	-0.417	NA	NA	-0.37
NAM_ Sea	0.004	NA	NA	0.115	29.24	6.163	NA	NA	12.477	0.015	-0.208	NA	NA	-0.20
SAM_ Ann	-0.05	-0.12	0.01	-0.043	59.30	15.41	83.30	44.69	34.71	1.028	-0.29	1.301	0.846	0.462
SAM_ Sea	-0.045	0.032	0.171	-0.091	30.37	11.83	53.85	32.70	27.33	0.607	-0.03	0.708	0.564	-0.222
NAF_ Ann	-0.193	NA	NA	0.244	25.767	8.974	NA	NA	33.37	-0.779	0.246	NA	NA	0.755
NAF_ Sea	-0.053	NA	NA	-0.081	11.08	3.669	NA	NA	13.92	-0.289	0.069	NA	NA	0.249
SAF_ Ann	0.053	0.335	0.258	0.335	61.80	14.51	38.48	55.18	38.48	-1.42	0.047	-0.659	-0.705	-0.66
SAF_Sea	0.072	0.111	0.031	0.119	32.06	6.56	20.165	27.526	15.39	-0.388	0.077	-0.314	-0.083	-0.20
NWP_ Ann	0.192	0.168	0.206	0.196	108.75	26.85	41.21	38.42	35.13	-0.176	-0.976	-1.718	-1.474	-1.34
NWP_ Sea	0.005	-0.221	-0.148	-0.142	35.466	8.896	12.334	10.789	8.52	0.183	-0.117	-0.292	-0.215	-0.07
IND_ Ann	0.201	-0.113	0.298	0.308	105.24	32.33	158.82	94.37	83.29	-1.04	0.18	-1.15	-1.42	-1.41
IND_Sea	-0.003	-0.105	0.106	0.079	89.84	23.18	115.63	60.01	48.34	-1.12	0.31	-0.62	-0.09	0.001

regional scales. Here we develop a methodology for the selection of models based on different time-dependent indices and we show that none of the CMIP5 models are suitable for simulating for all regional monsoon rainfall. The previous studies which are giving the monsoon projections in different scenarios, didn't check the reliability of the models before proceeding to the future projections. Here we incorporate different space and time statistical tests to identify the reliable models for the projections. The models were selected based on different criteria. The criteria include annual/seasonal mean, linear trend and SD.

The models which are selected in each region are based on its ability to simulate the observational features. Here we are proposing a methodology to develop MME studies in all the monsoon regions for regional rainfall studies in historical and future projections. Here we are giving the set of models which can be used for GM studies in regional level. The suggested reliable models based on different criteria are shown in Table 6. The selected models in each region and their statistical characteristics show that they give better matching with the observation than all model average (Figure 10, Table 4). The success rate shows that the selection of the models are showing better results than just taking MME. The future projections are made using the selected models in different criteria. Most of the regions show an increasing trend for the future rainfall in the time period of 2020-2100.

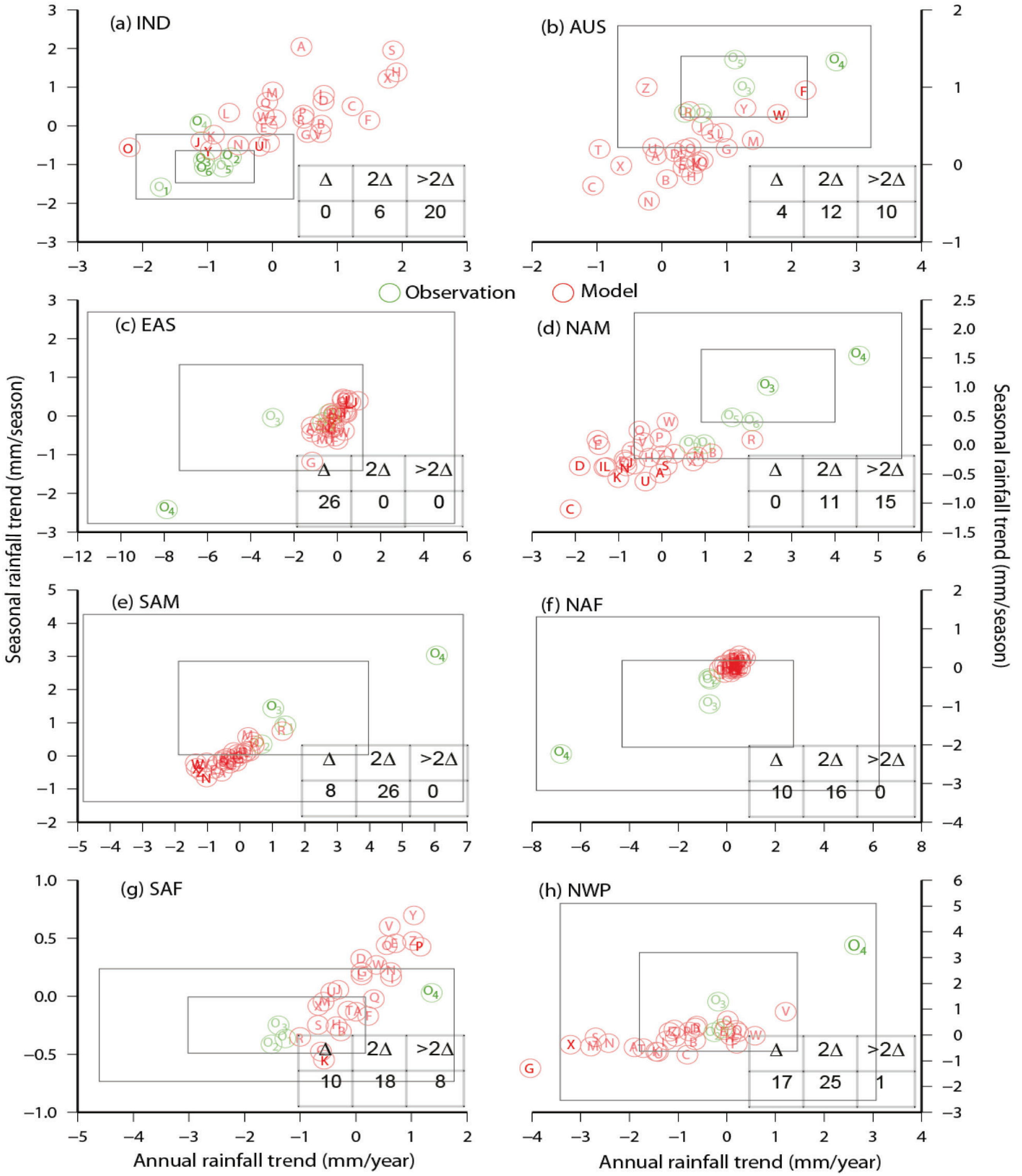

Figure 5: The dispersion in annual and seasonal rainfall trend in different monsoon domains (Indian – IND, Australian – AUS, East Asian – EAS, North American – NAM, South American – SAM, North African – NAF, South African – SAF, North Western Pacific – NWP monsoon). The red circles show the model simulations and the green circles are observations. The inner rectangle is drawn with 1SD+dispersion within the observations and the outer rectangle is with 2SD+dispersion within the observations. The number of model simulations in each box are shown in the table.

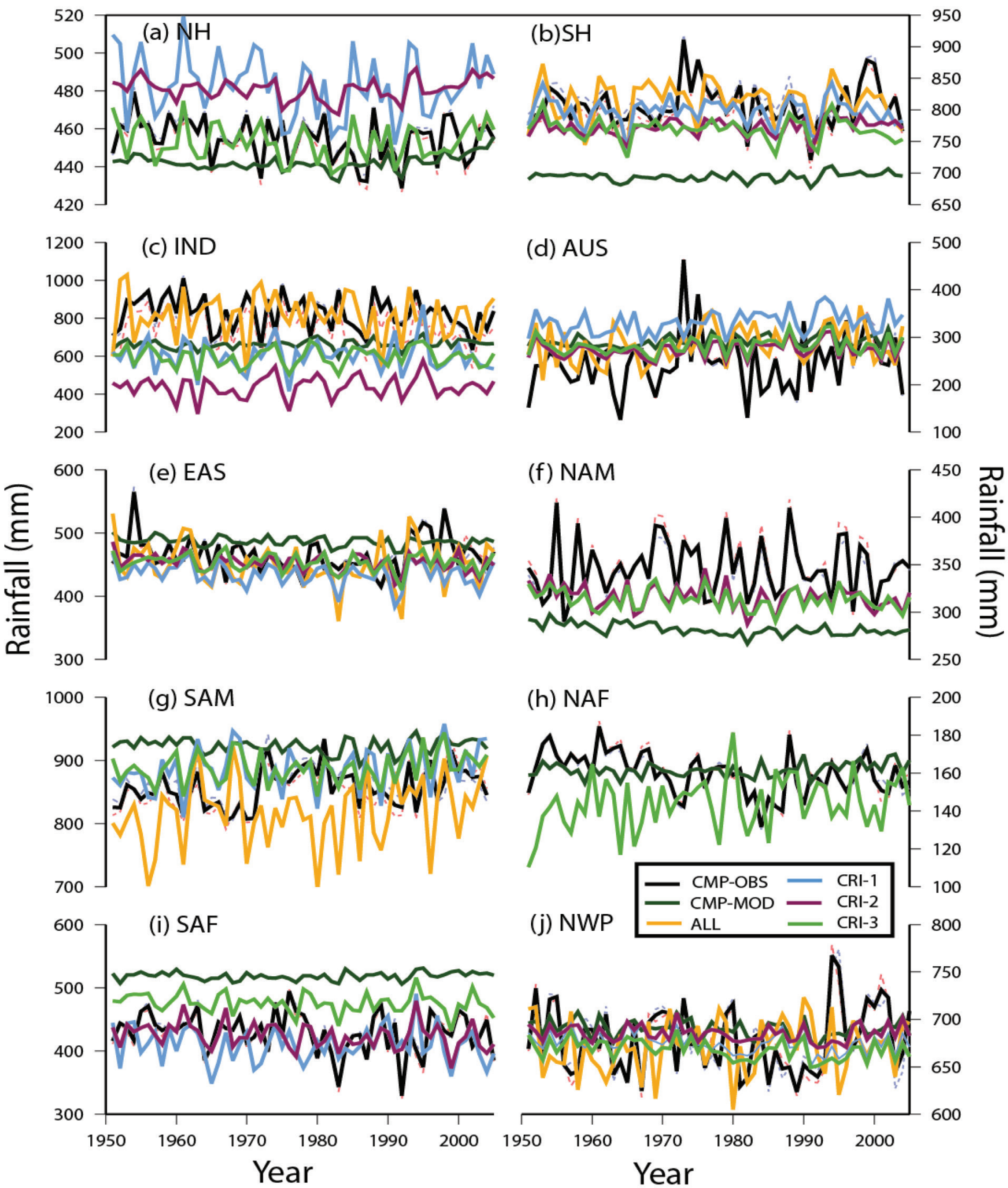

Figure 6: Annual mean rainfall (mm) for observations and the composite of models based on composite observation (CMP-OBS), composite model (CMP-MOD), All criteria (ALL), Criteria 1, 2, 3 (Cri-1,2,3) (for the time period 1951-2005 (Indian – IND, Australian – AUS, East Asian – EAS, North American – NAM, South American – SAM, North African – NAF, South African – SAF, North Western Pacific – NWP monsoon).

Acknowledgements

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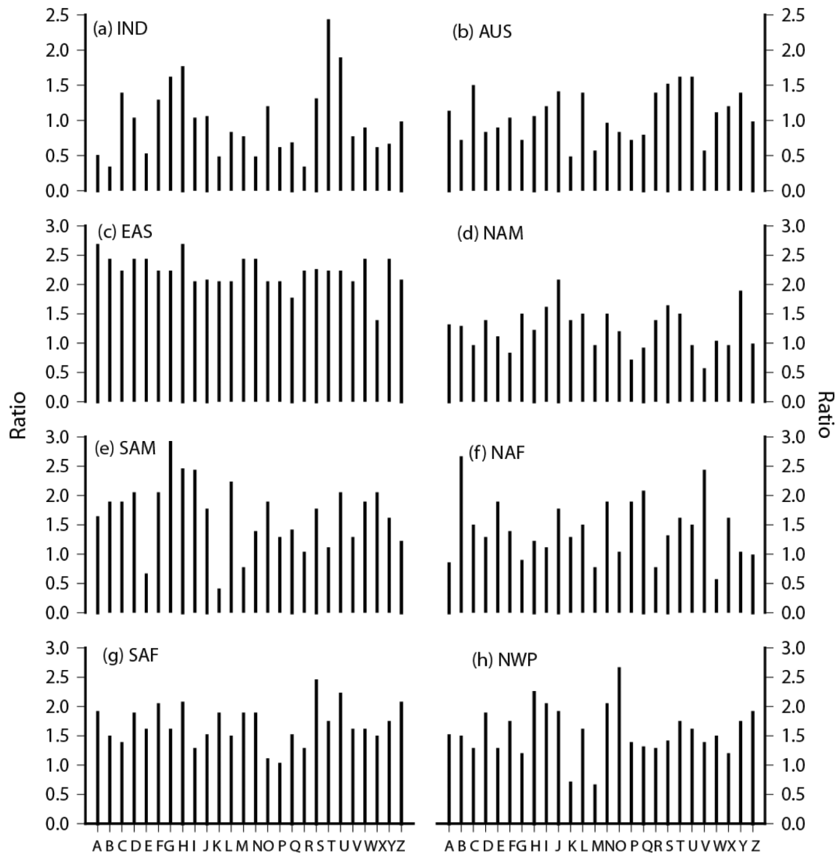

Figure 7: Ratio between drought, normal and excess years in different model simulations in different monsoon regions. The ratio is calculated with the number of drought, excess and normal years (exact years are treated as a count) similar to observations and the remaining years.

Table 5: The number of years captured by the respective models in excess, below normal and normal rainfall occurrences with respect to observation

No. of years	*N/N*	*D/D*	*E/E*	*Total*	*Remaining*
ACCESS-1.0	11	3	3	17	33
ACCESS-1.3	6	4	4	14	36
BCC-CSM1-1	12	3	1	16	34
BNU-ESM	23	1	2	26	24
CanESM2	11	3	3	17	33
CCSM4	17	3	0	20	30
CESM1-CAM5	22	4	3	29	21
CESM1-FASTCHEM	22	2	1	25	25
CESM1-WACCM	21	0	1	22	28
CNRM-CM5	18	3	5	26	24
CSIRO-Mk3-6-0	8	3	1	12	38
FIO-ESM	13	3	4	20	30
GFDL-ESM2M	16	3	3	22	28
HadGEM2-AO	8	4	2	14	36
INMCM4	19	1	2	22	28

(*Contd.*)

Table 5: (*Contd.*)

No. of years	*N/N*	*D/D*	*E/E*	*Total*	*Remaining*
IPSL-CM5A-LR	9	3	6	18	32
IPSL-CM5A-MR	12	4	4	20	30
IPSL-CM5B-LR	8	6	4	18	32
MIROC5	16	1	1	18	32
MIROC-ESM	29	0	0	29	21
MIROC-ESM-CHEM	27	1	0	28	22
MPI-ESM-LR	16	2	2	20	30
MPI-ESM-MR	18	1	2	21	29
MRI-CGCM3	5	5	4	14	36
NorESM1-M	14	1	5	20	30
NorESM1-ME	15	2	2	19	31

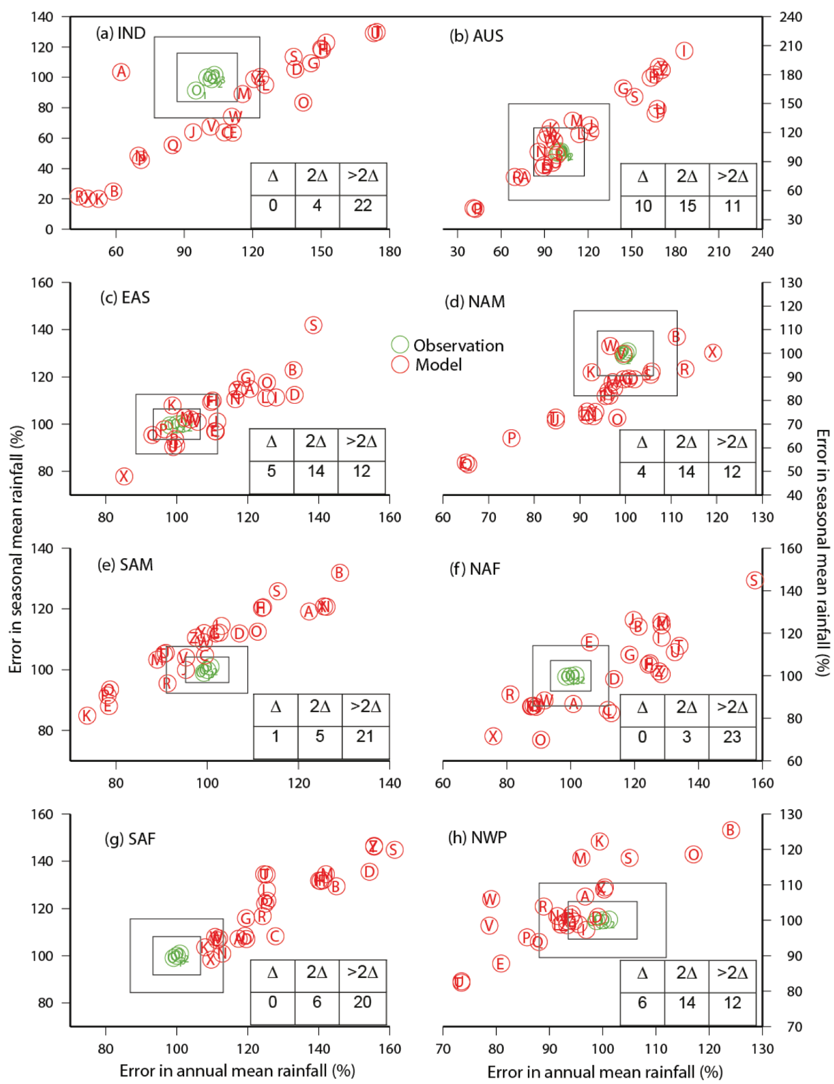

Figure 8: Annual and seasonal contribution of rainfall. The red circles show the model simulations and the green circles are observations. The inner rectangle is drawn with 1SD+dispersion within the observations and the outer rectangle is with 2SD+dispersion within the observations. The number of model simulations in each box are shown in the table.

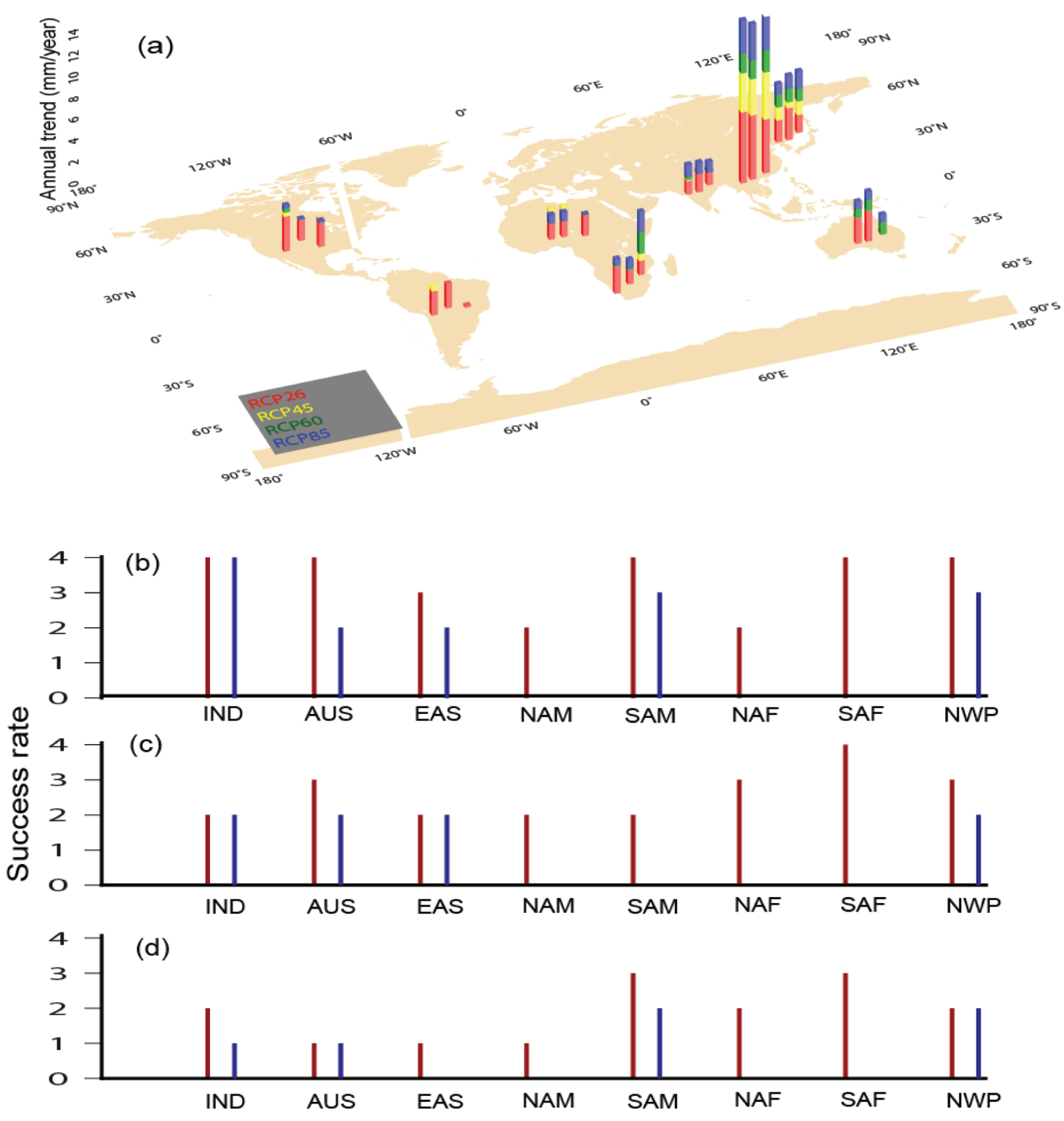

Figure 9: (a) The trend for different RCP projections with selected models based on three different criteria in a single region. The colour bars representing different RCP scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) with the respective colours shown in the figure. Success rate for global monsoon region by selected models for (b) Historical, (c) RCP45 and (d) RCP85. The red lines are showing the success rate when compared to all model average and any of the selected criteria and the blue lines are showing the rate when compared with all model average and all criteria. (Indian – IND, Australian – AUS, East Asian – EAS, North American – NAM, South American – SAM, North African – NAF, South African – SAF, North Western Pacific – NWP monsoon).

Table 6: The list of selected models based on different criteria in different monsoon regions

Criteria / *Regions*	*The model should fall in all conditions*	*The model should satisfy atleast 3 conditions including annual and seasonal tests*	*The model should succeed in all tests based on seasonal analysis*	*The model should succeed in all tests based on annual analysis*
NAM	-	-	ACCESS-1.0, BNU-ESM, MIROC-5, MPI-ESM-MR	ACCESS-1.0, BNU-ESM, CESM1-CAM5, MIROC-5, MPI-ESM-MR
SAM	IPSL-CM5B-LR	BNU-ESM, IPSL-CM5B-LR	BCC-CSM1-1, BNU-ESM, IPSL-CM5B-LR	BCC-CSM1-1, BNU-ESM, IPSL-CM5B-LR
NAF	-	-	MPI-ESM-MR	MPI-ESM-MR
SAF	MRI-CGCM3	MRI-CGCM3	CSIRO-Mk3-6-0, MRI-CGCM3	CSIRO-Mk3-6-0, MIROC-ESM-CHEM, MRI-CGCM3
IND	NorESM1-M	GFDL-ESM2M, INMCM4, NorESM1-M	GFDL-ESM2M, INMCM4, MPI-ESM-MR, NorESM1-M	CSIRO-Mk3-6-0, GFDL-ESM2M, INMCM4, NorESM1-M
AUS	CNRM-CM5, MPI-ESM-MR	CCSM4, CNRM-CM5, FIO-ESM, GFDL-ESM2M, MPI-ESM-LR, MPI-ESM-MR, NorESM1-M	ACCESS-1.0, ACCESS-1.3, BCC-CSM1-1, BNU-ESM, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, FIO-ESM, GFDL-ESM2M, HadGEM2-AO, IPSL-CM5B-LR, MPI-ESM-LR, MRI-CGCM3, NorESM1-M	ACCESS-1.0, ACCESS-1.3, BCC-CSM1-1, BNU-ESM, CanESM2, CCSM4, CESM1-CAM5, CNRM-CM5, CSIRO-Mk3-6-0, FIO-ESM, GFDL-ESM2M, HadGEM2-AO, IPSL-CM5B-LR, MPI-ESM-LR, MRI-CGCM3, NorESM1-M
EAS	CSIRO-Mk3-6-0, MIROC-ESM-CHEM	CSIRO-Mk3-6-0, GFDL-ESM2M, IPSL-CM5A-LR, MIROC-ESM-CHEM, MRI-CGCM3	ACCESS-1.0, BCC-CSM1-1, CCSM4, CSIRO-Mk3-6-0, GFDL-ESM2M, IPSL-CM5A-LR, MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-MR, MRI-CGCM3	ACCESS-1.3, CESM1-FASTCHEM, CSIRO-Mk3-6-0, GFDL-ESM2M, IPSL-CM5A-LR, IPSL-CM5B-LR, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3
NWP	BNU-ESM, NorESM1-ME	ACCESS-1.0, BCC-CSM1-1, BNU-ESM, CESM1-CAM5, CESM1-WACCM, CNRM-CM5, HadGEM2-AO, IPSL-CM5A-LR, IPSL-CM5A-MR, MRI-CGCM3, NorESM1-M, NorESM1-ME	ACCESS-1.0, BCC-CSM1-1, BNU-ESM, CCSM4, CESM1-CAM5, CESM1-FASTCHEM, CESM1-WACCM, CNRM-CM5, HadGEM2-AO, INMCM4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MPI-ESM-LR, MRI-CGCM3, NorESM1-M, NorESM1-ME	ACCESS-1.0, BCC-CSM1-1, BNU-ESM, CCSM4, CESM1-CAM5, CESM1-FASTCHEM, CESM1-WACCM, CNRM-CM5, GFDL-ESM2M, HadGEM2-AO, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM-CHEM, MRI-CGCM3, NorESM1-M, NorESM1-ME

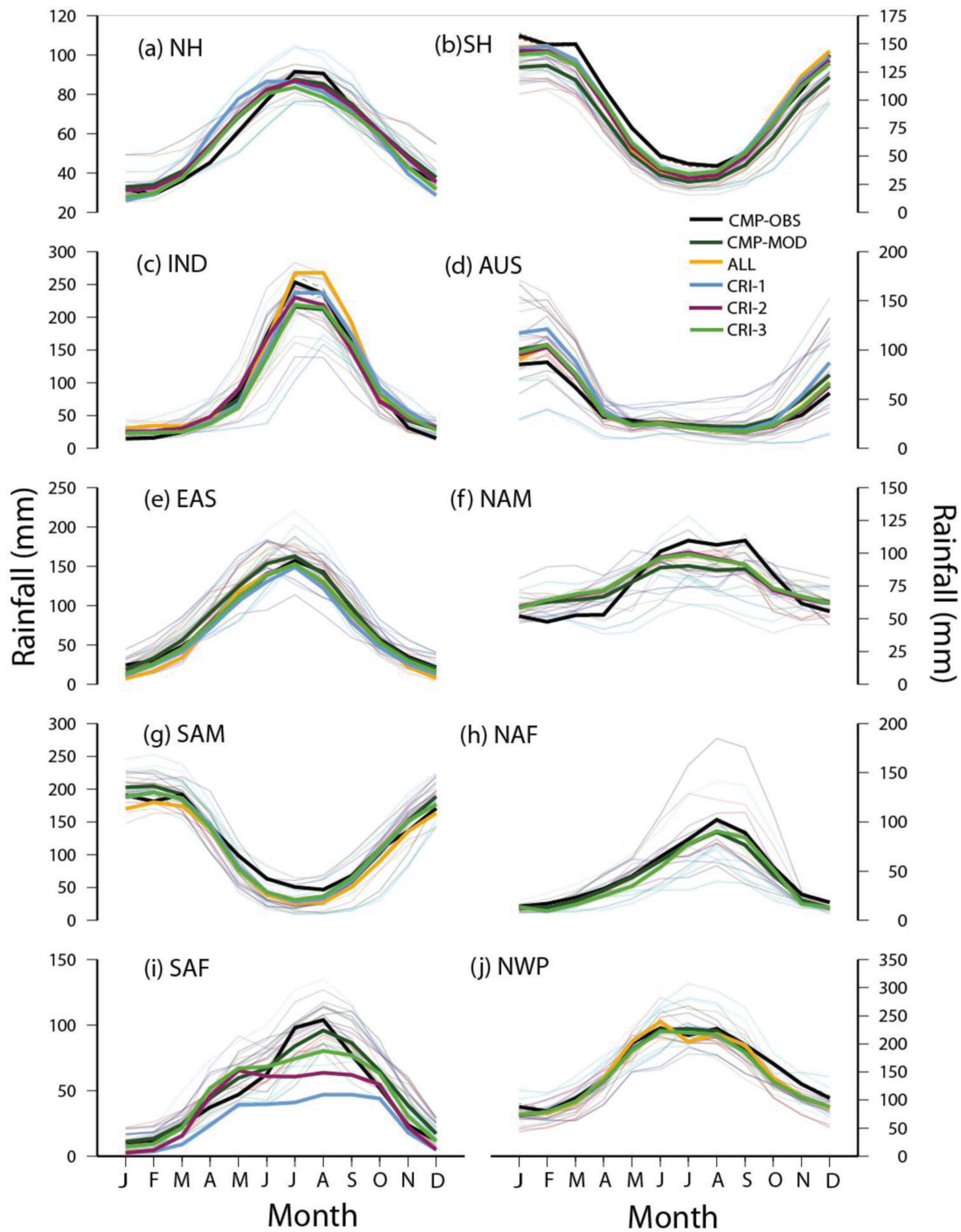

Figure 10: The climatological mean (mm) of rainfall in different monsoon regions. The bold lines are showing rainfall based on different criteria and the faded lines are for individual model simulations.

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