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ORIGINAL PAPER

Possible future rainfall over Gangetic Plains (GP), India, in multi-model simulations of CMIP3 and CMIP5

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Abstract The Gangetic Plain (GP) of India is much sensitive to rainfall due to its large spatial and temporal variability, and therefore, Coupled Model Intercomparison Project phases 3 and 5 (CMIP3 and CMIP5)-simulated rainfall is analysed over the GP. Model evaluation is carried out with observed rainfall of India Meteorological Department (IMD) and Global Precipitation and Climatology Project (GPCP). Community Climate System Model version 3 (CCSM3), Hadley Centre Global Environment Model (HadGEM) and Model for Interdisciplinary Research on Climate (MIROC) (Hires) of CMIP3 and CCSM4, CESM1 (WACCM) and CESM1 (CAM5) of CMIP5 sound well with observations. In CMIP3, projected future changes in June-July-August-September (JJAS) rainfall show either 5–15 % excess or 5 % deficit in CCSM3 (A2 scenario) and 10 % deficit in HadGEM1. In B1, MIROC (Hires) shows 5–10 % deficit. Under A1B scenario, deficit is possible in MIROC (Hires) and HadGEM1. In CMIP5, CESM1 (CAM5) shows 5–15 % deficit in Representative Concentration Pathway (RCP) 4.5. CCSM4 and CESM1 (WACCM) show 10–20 % excess while 5–15 % deficit is possible in CESM1 (CAM5) in RCP 8.5.

Key Points

- Validation of model performance with various statistical and spatial aspect
- Comparison of rainfall in different model simulations of CMIP3 and CMIP5
- Significant deficit of rainfall in CCSM3, CCSM4 and CESM1(CAM5) models

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1 Introduction

The summer monsoon over India is a unique system. The large spatial and temporal variability of Indian summer monsoon rainfall (ISMR) over the Gangetic Plains (GP) of India largely influences agriculture and water resources. The monsoon season in India prevails during June-July-August-September (JJAS) (Rao 1976) and 80 % of the annual precipitation occurs during JJAS.

Important modes of variability of annual and seasonal rainfall over India have been studied (Hastenrath and Rosen 1983; Shukla et al. 2002; Kulkarni et al. 1992; Kripalani et al. 1991). A quantitative-subjective approach to rainfall fluctuation analysis in 49 physiographic subdivisions/provinces suggests there is a decrease in annual rainfall in recent years/decades in over ~68 % area of the country (Sontakke et al. 2008). Singh and Sontakke (2002) analysed rainfall for the period of 1829–1999 over Indo-Gangetic Plain (IGP). The significant increasing trend (170 mm/100 year.) of ISMR since 1900 is observed over western IGP. Non-significant decreasing trends of 5 mm/100 year since 1939 and 50 mm/100 year over central IGP for the period of 1900–1984 are found. Non-significant increasing trend of 480 mm/100 year for the period of 1984–1999 over eastern IGP is shown. The decreasing trend in monsoon and annual rainfall over the Ganga River Basin starting in the second half of the 1960s is also suggested by Kothyari and Singh (1996). Singh and Singh (1996) analysed summer monsoon over the Himalayan region and the Gangetic Plains through principal component analysis (PCA) and reported coherent precipitation regimes associated with large-scale spatial patterns. Pandey et al. (2007) examined time-lag correlation between monthly/seasonally geopotential height over India and monsoon rainfall over the Gangetic Plain to ascertain if any predictive relationship can be obtained for the monsoon activity which may be useful for the long-range prediction of monsoon rainfall over four meteorological subdivisions, namely Plains of West Uttar Pradesh (U.P.), East U.P., adjoining Bihar Plains and Gangetic West Bengal. Jain and Kumar (2012) carried out an analysis on trends in rainfall amount and number of rainy days in Indian River basins using daily gridded rainfall data of India Meteorological Department (IMD).

To predict ISMR, several techniques have been developed by IMD (Gowariker et al. 1989; Rajeevan et al. 2006a). The characteristics of Indian monsoon under global warming are still a matter of intense scientific debate (Sabade et al. 2011; Turner and Annamalai 2012). The possible impact of the global warming on Indian summer monsoon (ISM) using output of different global and regional climate models have been analysed; however, uncertainties exist in the regional climate projections due to biasness in the global climate models (Lal and Bhaskaran 1992; Meehl and Washington 1993; Lal et al. 1994, 1998; Rupa Kumar and Ashrit 2001; May 2002; Kripalani et al. 2005; Rupa Kumar et al. 2006; Rajendran and Kitoh 2008). The skill of predicting ISMR by global climate models is still very small (Kang and Shukla 2005). The rainfall over north Bay of Bengal (BoB) and adjoining northeast India is poorly simulated by many models (Lal and Harasawa 2001; Rupa Kumar and Ashrit 2001; Rupa Kumar et al. 2003). It is very likely that ISMR pattern and magnitude may alter through local changes in surface processes in warmer climate (IPCC 2001, 2007). The weakness of summer monsoon rainfall is due to weakening of monsoonal flows and tropical large-scale circulation in future climate (Knutson and Manabe 1995). In Coupled Model Intercomparison Project phases 3 (CMIP3) model simulations, Kripalani et al. (2007a) suggested significant increase in mean monsoon precipitation of 8 % and possible extension of the monsoon period, in doubling of CO_2 experiment of CMIP3. In the same experiment, Kripalani et al. (2007b) applied t test and F ratio and found statistical significant changes in future rainfall from −0.6 % for CNRM-CM3 to 14 % for ECHO-G and UKMO-HadCM3 for East Asian monsoon. Mandal et al. (2007) highlighted verification of quantitative precipitation forecasts of the Global Spectral Model (GSM). The rainy days are projected to be less frequent and more intense over central India. Menon et al. (2013) suggested increase in all-India summer monsoon rainfall (AISMR) per degree change in temperature of about 2.3 % K^{-1}, which is similar to the projected increase in global mean precipitation per degree change in temperature in CMIP3 (Frieler et al. 2011). Parth-Sarthi et al. (2012) suggested that under A2, B1 and A1B experiments of CMIP3, a future-projected change in spatial distribution of ISMR shows deficit and excess of rainfall in Hadley Centre Global Environment Model version 1 (HadGEM1), European Centre Hamburg Model version 5 (ECHAM5), and Model for Interdisciplinary Research on Climate (MIROC) (Hires) over parts of western and eastern coast of India which seems to be manifestation of anomalous anticyclonic and westerly flow at 850 and 200 hPa over the Arabian Sea. Shashikant (2014) examined rainfall simulation in CMIP3 and Coupled Model Intercomparison Project phases 5 (CMIP5) in five (5) general circulation models (GCMs). Multi-model average of CMIP5 simulations does not show improvements in biasness over CMIP3; however, uncertainty in CMIP5 projections is lower than that in CMIP3. Babar et al. (2014) suggested MIROC5 model of CMIP5 can be considered for climate projections in highly complex climate system of the Indian continent and near-term to century projections would be more trustworthy. Above studies are mainly focused on either observational or CMIP3/CMIP5 model simulations. The comparison of rainfall in CMIP3 and CMIP5 simulations would provide better understanding of future-projected rainfall over the GP and may be used for scientific study and policy-making.

The current research deals with the comparison of CMIP3 and CMIP5 simulated future projected rainfall in different experiments over GP. Introduction and literature surveys are briefly placed in section 1. Study area, data, models and their experiments are placed in section 2. Sections 3 and 4 briefly describe model evaluation in simulating rainfall over GP and its future projection. Conclusions are placed in section 5. The paper is primarily focused on model evaluation in simulation rainfall and its future-projected changes in CMIP3 and CMIP5 over GP.

2 Study area, data, models and experiment

2.1 Study area

Any spatial and temporal variation of rainfall in future time periods over densely populated GP would affect people life, agriculture and water resources. The study area comprises of parts of Eastern Uttar Pradesh (UP), Bihar, Jharkhand and West Bengal, and these regions are prone to floods and droughts due to spatial and temporal changes in summer monsoon rainfall. GP is shown by rectangular a boundary (with red colour) in figures of sections 3 and 4.

2.2 Data, models and experiments

The gridded observed rainfall of India Meteorological Department (IMD) with resolution of 1°×1° for the period of 1961–1999 and of Global Precipitation Climatology Project (GPCP) (Adler et al. 2003) at resolution of 2.5°×2.5° for the period of 1979–1999 are considered. The simulated rainfall in CMIP3 and CMIP5 (Alexander et al. 2012) and CMIP5 (Taylor et al. 2012), in different models are considered, respectively.

Table 1 enlists CMIP3 (1961–1999) and CMIP5 (1961–1999) models, affiliated country and their resolution. The simulated rainfall in the twentieth century (20C3M) experiments

Table 1 List of CMIP3 and CMIP5 models

CMIP3			
Sr. no.	Centre/country	Models	Horizontal surface resolution
1	UK	*UKMO-HadgGEM1*	1.9×1.2
2	USA	*CCSM3.0*	1.4×1.4
3	Germany	*ECHAM5*	1.9×1.9
4	Japan	*MIROC 3.2 (Hires)*	1.1×1.1
5	USA	*GFDL CM2.1*	2.5×2.0
CMIP5			
Sr. no.	Centre/Country	Models	Resolution
1	Beijing Climate Center, China	BCC-CSM1.1	128×64
2		*BCC-CSM1.1(m)*	320×160
3	College of Global Change and Earth System Science (GCESS), China	BNU-ESM	128×64
4		CanCM4	128×64
5		CanESM2	128×64
6	National Center for Atmospheric Research (NCAR)/USA	*CCSM4*	288×192
7	Community Earth System Model Contributors (NSF-DOE-NCAR), USA	*CESM1(BGC)*	288×192
8		*CESM1(CAM5)*	288×192
9		*CESM1(FASTCHEM)*	288×192
10		*CESM1(WACCM)*	144×96
11	National Centre for Meteorological Research, France	CNRM-CM5	256×128
12		CNRM-CM5-2	256×128
13	Commonwealth Scientific and Industrial Research Organization (CSIRO-MK3L-1-2), Australia	CSIRO-Mk3L-1-2	192×96
14	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, IAP, China	FGOALS-g2	128×60
15	The First Institute of Oceanography (FIO), China	FIO-ESM	128×64
16	NASA Goddard Institute for Space Studies (NASA GISS), USA	GISS-E2-H	144×90
17		GISS-E2-H-CC	144×90
18		GISS-E2-R	144×90
19		GISS-E2-R-CC	144×90
20	National Institute of Meteorological Research/Korea Meteorological Administration (NIMR/KMA), Korea	HadGEM2-AO	192×145
21	Met Office Hadley Centre (MOHC), UK	HadGEM2-ES	192×145
22	Institute for Numerical Mathematics (INM), Russia	INM-CM4	180×120
23		IPSL-CM5A-LR	96×96
24		IPSL-CM5A-MR	144×143
25		IPSL-CM5B-LR	96×96
26	University of Tokyo, National Institute for Environment Studies, Japan	MIROC4h	640×320
27	Institute Pierre-Simon Laplace (IPSL), France	MIROC5	256×128
28	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, Japan	MIROC-ESM	128×64
29		MIROC-ESM-CHEM	128×64
30	Max Planck Institute for Meteorology (MPI-M), Germany	*MPI-ESM-LR*	192×96
31		MPI-ESM-MR	192×96
32		MPI-ESM-P	192×96
33	Meteorological Research Institute (MRI), Japan	MRI-CGCM3	320×160
34		MRI-ESM1	320×160

Cell entries in italics are considered models

and high (A2), mild (A1B) and low (B1) emission scenarios (Swart 2000; Alexander et al. 2012) are considered (Table 2) for the period of 2006–2044. To capture ISMR in CMIP3 simulation, listed models are able to simulate monthly variation of rainfall (Parth-Sarthi et al. 2012). CMIP5 comprises set of model simulation in historical experiment which is

Table 2 List of considered models and their respective scenarios & RCPs in CMIP3 and CMIP5

CMIP3			
Models	A2 scenario	B1 scenario	A1B scenario
CCSM3	√	√	
ECHAM5	√	√	
GFDL2-1	√	√	
HADGEM1	√		√
MIROC (Hires)		√	√
CMIP5			
Models	RCP 4.5	RCP 8.5	
BCCCSM 1.1(m)	√	√	
CCSM4	√	√	
CESM1-CAM5	√	√	
CESM1 (BGC)	√	√	
CESM1 (WACCM)		√	
MPI-ESM-MR	√	√	

equivalent to 20C3M experiment of CMIP3, and integration is carried out for 1850–2012 with external forcing and includes greenhouse gases (GHGs), solar constant, volcanic activity, ozone and aerosols, changing with time. Table 2 enlists all the available representative concentration pathway (RCP) 4.5 and 8.5 experiments (2006–2044) in CMIP5 model simulations (Fujino et al. 2006; Smith and Wigley 2006; Clarke et al. 2007; Riahi et al. 2007; Van-Vuuren et al. 2007, 2011; Hijioka et al. 2008; Wise et al. 2009; Masui et al. 2011; Riahi et al. 2011; Thomson et al. 2011) and represents radiative forcing of 4.5 and 8.5 W/m^2, and GHGs, solar constant, ozone and aerosol are kept changing with time.

3 Model's performance in simulating rainfall over GP

To evaluate CMIP3 and CMIP5 model performance in simulating rainfall, spatial distribution of simulated ISMR is

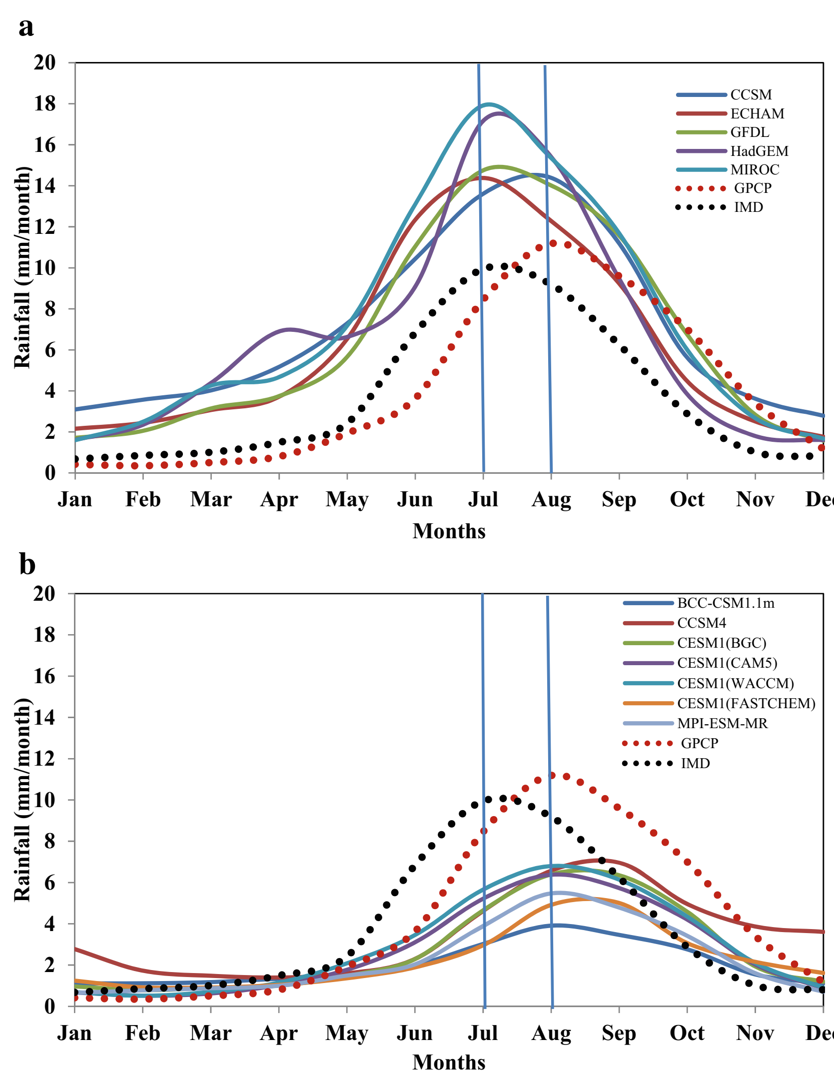

Fig. 1 **a**–**b** Annual cycle of rainfall (mm $month^{-1}$) in observation of IMD, GPCP and in simulation of **a** 20C3M experiment of CMIP3 and **b** historical experiment of CMIP5

compared with observation of IMD and GPCP. Only Community Climate System Model version 3 (CCSM3), MIROC (Hires) and HadGEM1 of CMIP3 seems to capture spatial distribution of observed ISMR. In CMIP5, out of 34 models of historical experiment, only seven models sound well with observation and out of them, only CCSM4 and versions of CESM1 shows good agreement with observations. The annual cycle of simulated rainfall of five models in 20C3M experiment of CMIP3 and seven models of historical experiment of CMIP5 along with observed rainfall of IMD (black dotted line) and GPCP (red dotted line) is shown in Fig. 1a, b. It is difficult to extract information of annual pattern of a particular model (Sperber and Annamalai 2014); however, it may be summarized that how well each model simulated "pattern" (i.e. annual cycle of rainfall) is comparable with the observed rainfall of IMD and GPCP.

Taylor's diagram method (Taylor 2001) is useful in assessing relative performance of models which simulated rainfall over observed values. In this method, correlation coefficient and root-mean square error (RMSE) difference between two fields (simulated and observed), along with ratio of standard deviations (SD) of two patterns, is indicated by a single point on a two-dimensional (2D) plot. Statistics show how accurately simulated values may be close to observation and quantify the degree of similarity between simulated and observed rainfall. The simulated pattern of each model, marked with alphabets, and those sounds well with observation and will lie nearest the point marked with rectangle (indicating observed rainfall) on positive X-axis. The simulated rainfall will be close to observation, when there would be relatively high correlation, low RMSE and minimum difference of standard deviation with respect to observation.

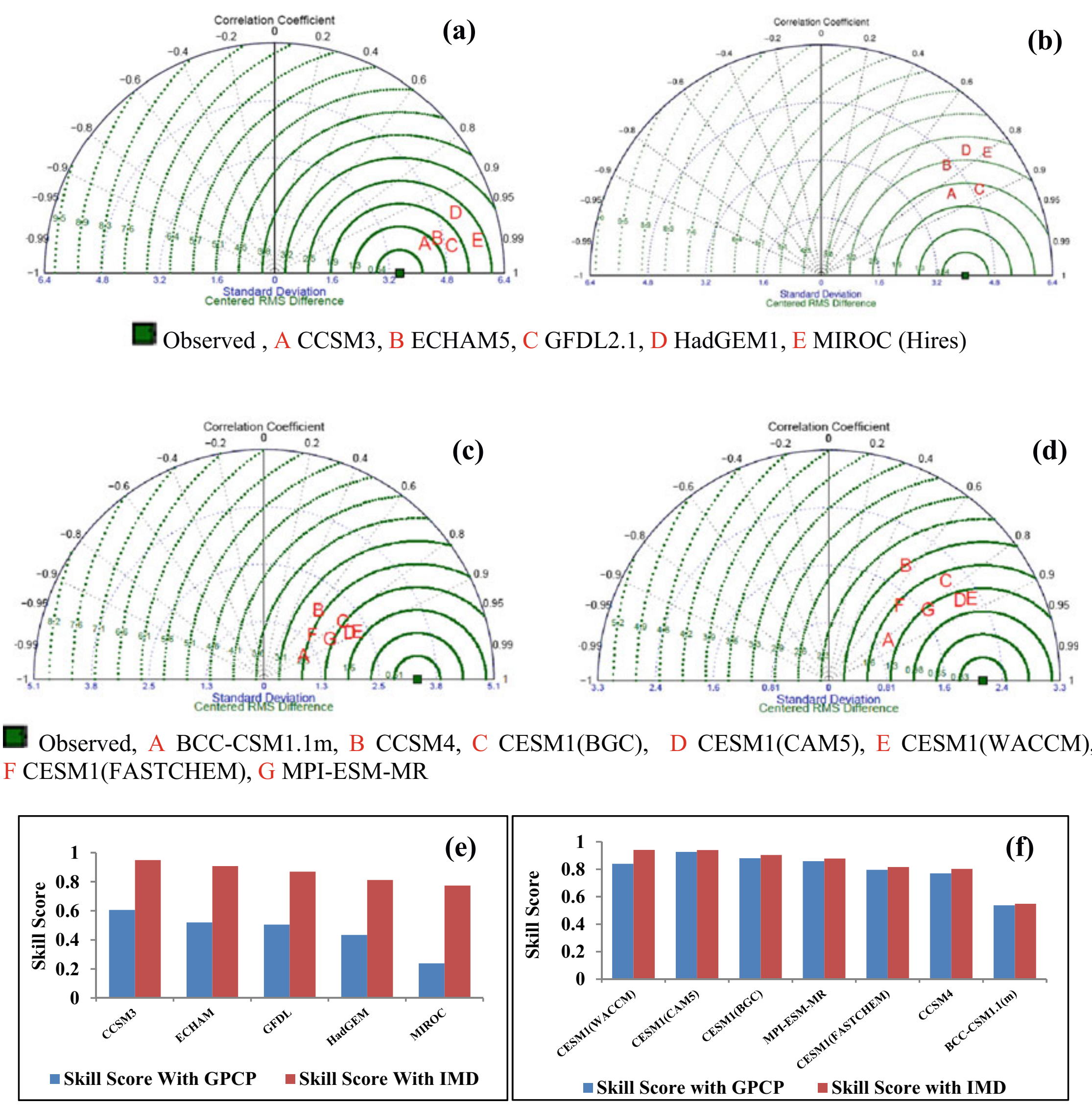

Fig. 2 **a**–**d** Taylor diagram for **a** IMD vs CMIP3, **b** GPCP vs CMIP3, **c** IMD vs CMIP5 and **d** GPCP vs CMIP5. **e**–**f** Model skill score in simulating ISMR for the period of 1961–1999 with observation in 20C3M and historical experiments of CMIP3 and CMIP5, respectively

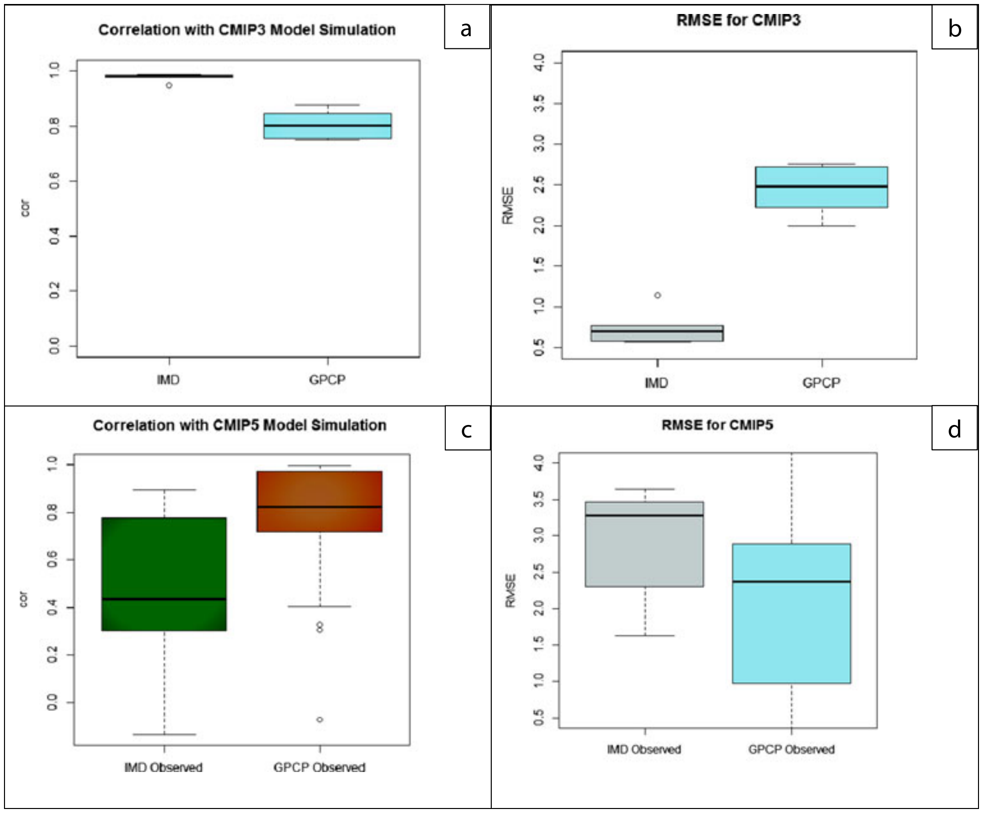

Fig. 3 **a**–**d** Boxplot distribution of model skill scores in simulating JJAS rainfall (mm month^{-1}) for CMIP3 models in **a** correlation between IMD and simulation and **b** RMS error, and for CMIP5 models in **c** correlation between IMD and simulation and **d** RMS error. The *box* shows the interquartile range and outliers are given by *circles*

Figure 2a–d shows Taylor diagram for simulated ISMR in 20C3M experiment of CMIP3 and historical experiment of CMIP5 with observations (IMD and GPCP). In Fig. 2a, b, CCSM3, HadGEM1 and Geophysical Fluid Dynamics Laboratory (GFDL) 2.1 shows high correlation and lower RMSE with IMD while CCSM3, HadGEM1 and GFDL2 simulated rainfall is comparable with GPCP. In Fig. 2c, d, CCSM4 and CESM1 (WACCM) are able to capture JJAS rainfall (mm month^{-1}) for the period of 1961–1999.

Sometimes, skill score is used to rank model performance in accurately simulating magnitude and pattern of rainfall. In the past, several skill scores have been proposed (Murphy 1988; Murphy and Epstein 1989; Williamson 1995; Watterson 1996; Watterson and Dix 1999; Potts et al. 1996). Traditionally, skill scores have been defined to vary from zero (least skilful) to one (more skilful). The simplest non-dimensional skill score is defined by the following relation:

$$\text{Skill Scores}(S) = 4(1+R)/(\sigma+1/\sigma)^2(1+R_0)$$

where R is spatial correlation coefficient between simulation and observation while σ is spatial standard deviation of simulation divided by that of observation and R_0 is the maximum correlation attainable (i.e. 1). Model skill score for simulating rainfall of 20C3M experiment (CMIP3) and historical experiment (CMIP5), with observations (IMD and GPCP), is shown in Fig. 2e, f. In CMIP3, CCSM3 shows maximum skill score with IMD and GPCP; however, score is more with IMD in comparison to that of GPCP. In CMIP5, CESM1(CAM5), out of seven models, shows maximum skill score with IMD and GPCP.

Figure 3a–d shows distribution of statistical measures (correlation and RMSE) between model simulation of CMIP3, CMIP5 and observations. The spacing between different parts of box indicates degree of dispersion (spread), skewness and outliers in model simulation for rainfall. In CMIP3, models have high correlation and less RMSE with IMD in comparison to that of GPCP. Similarly, models of CMIP5 show high correlation and less RMSE with observations. When CMIP3 and CMIP5 are compared with IMD, large distribution of correlation (large RMSE) is seen in CMIP5. In case of GPCP, CMIP5 shows high correlation (relatively low RMSE) in comparison to CMIP3.

It seems that due to different physical schemes used in models, statistical measures are differing here, and therefore model's future projection may differ.

4 Projected future changes in rainfall over GP

To know the significance of future-projected percentage changes in rainfall, Student *t* test at 99 and 95 % confidence levels are applied in CMIP3 and CMIP5 simulations. In CMIP3, future-projected changes in JJAS rainfall

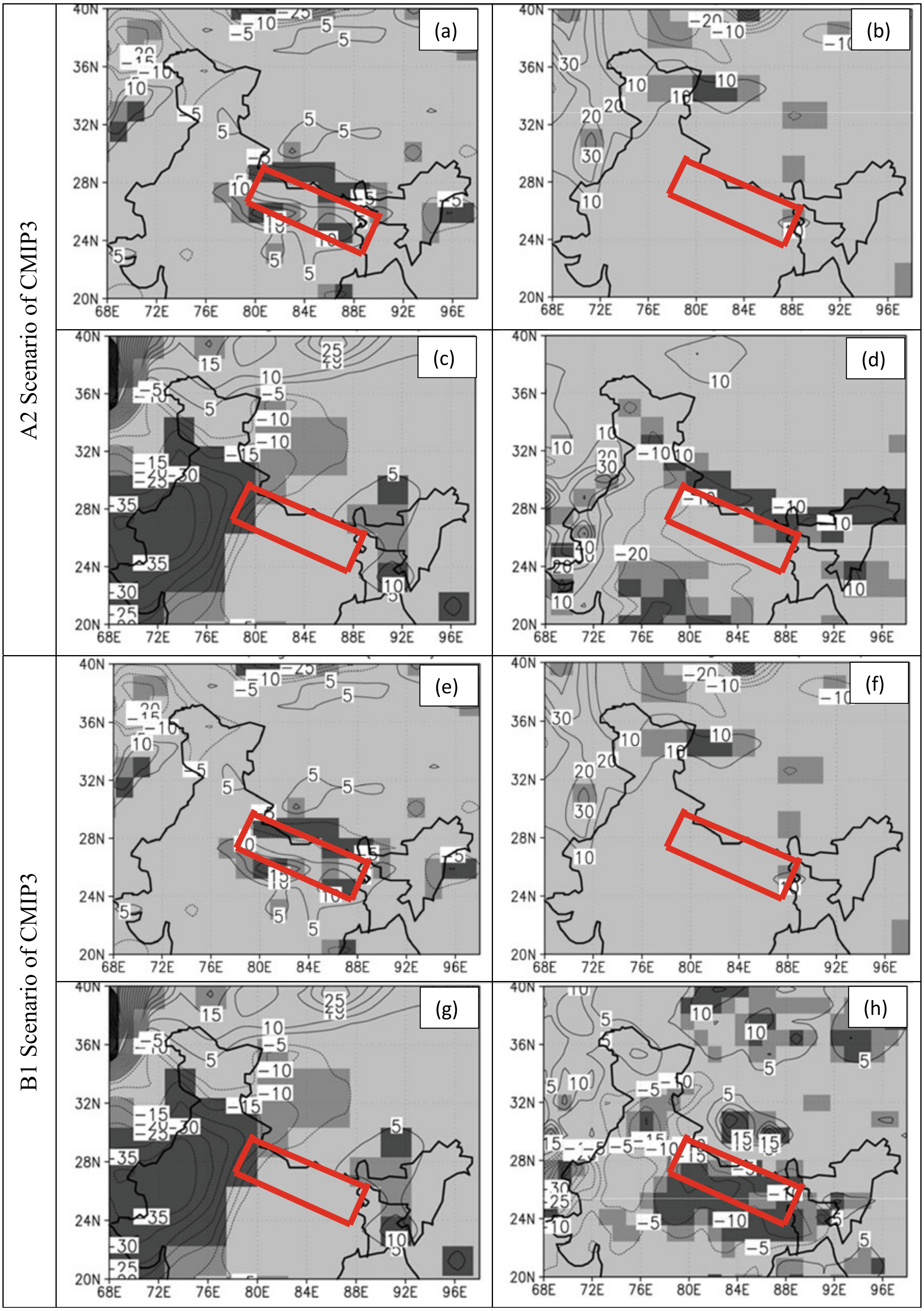

Fig. 4 **a**–**u** Projected changes (2006–2044) in rainfall (mm month^{-1}) at 99 % (*dark grey shaded*) and 95 % (*light grey shaded*) significance levels in CMIP3 simulation under A2 scenario for **a** CCSM3, **b** ECHAM5, **c** GFDL2.1, **d** HadGEM1; under B1 scenario in **e** CCSM3, **f** ECHAM5, **g** GFDL2.1, **h** MIROC (Hires); and under A1B scenario for **i** HadGEM1 and **j** MIROC (Hires). In CMIP5, model simulation under RCP 4.5 and 8.5 models for **k** BCC-CSM1.1m, **l** CCSM4, **m** CESM1(BGC), **n** CESM1(CAM5), **o** MPI-ESM-MR and **p** BCC-CSM1.1m, **q** CCSM4, **r** CESM1(BGC), **s** CESM1(CAM5), **t** CESM1(WACCM) and **u** MPI-ESM-MR, respectively, is also considered

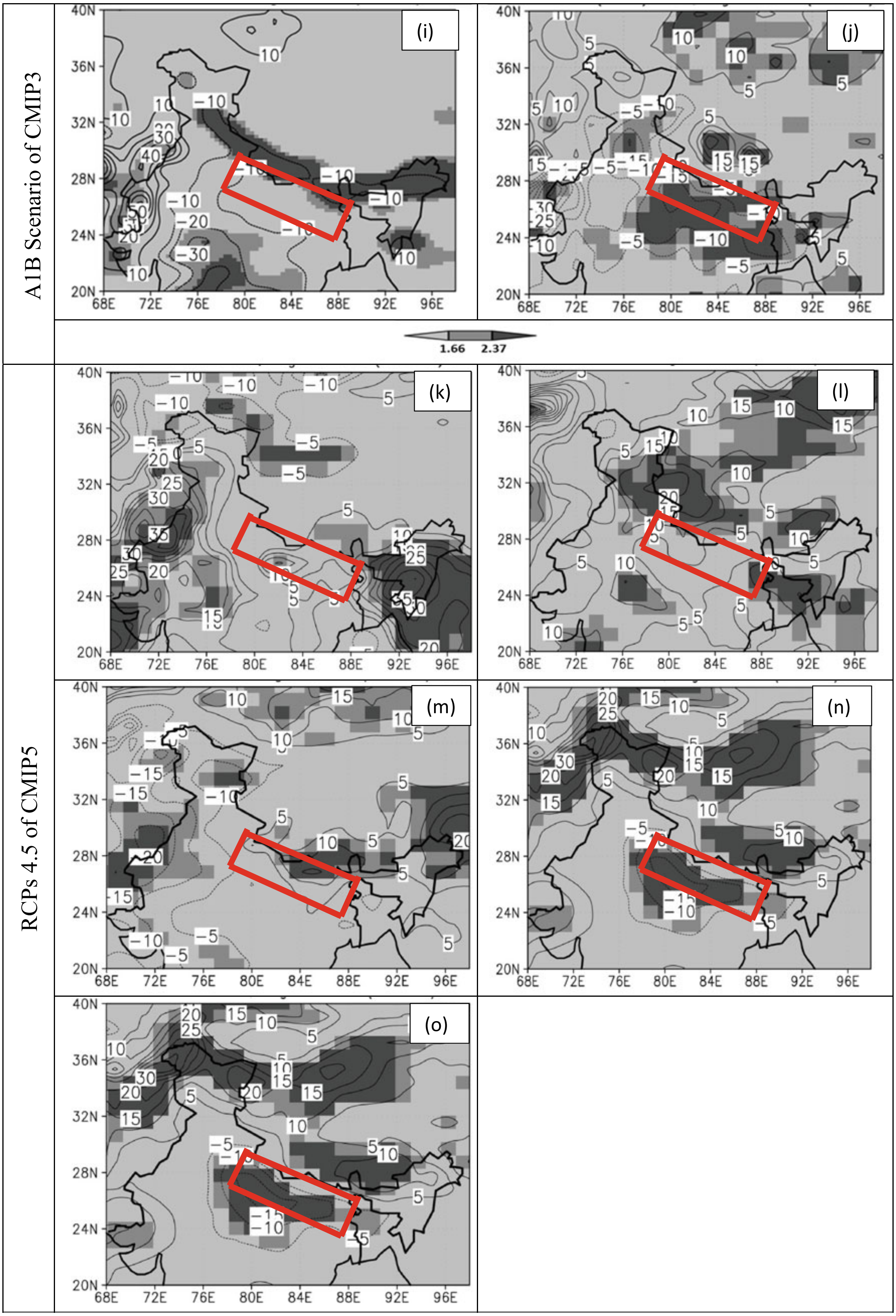

Fig. 4 (continued)

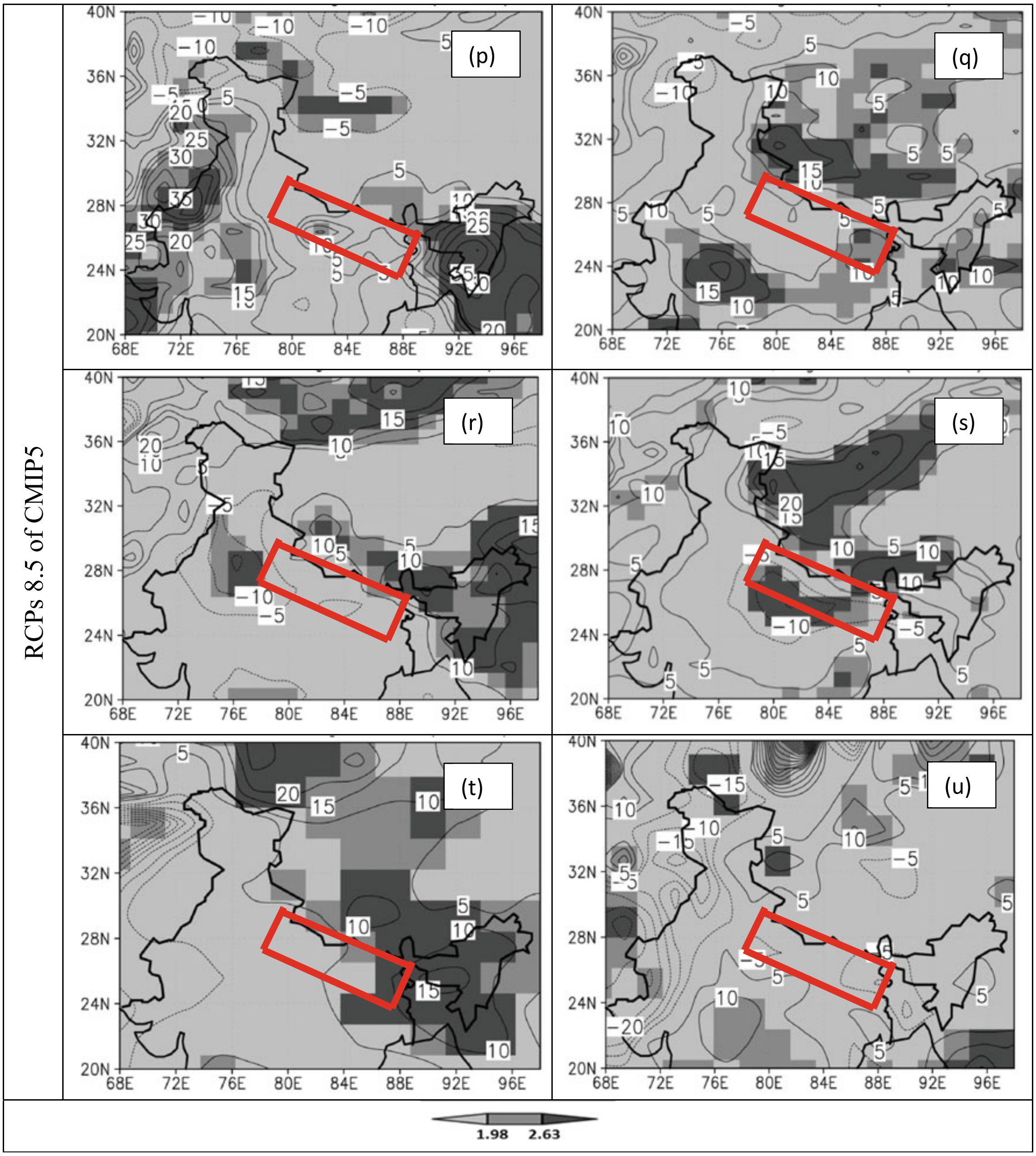

Fig. 4 (continued)

(mm month^{-1}) under A2, B1 and A1B scenarios (2006–2044) with respect to baseline (1961–1999) in CCSM3, ECHAM5, GFDL2.1, HadGEM1 and MIROC (Hires) are shown in Fig. 4a–j. In A2 scenario (Fig. 4a–d), CCSM3 shows either 5–15 % excess or 5 % deficit of rainfall over GP. No significant changes are noticed in ECHAM and GFDL, while 10 % deficit of rainfall in HadGEM1 simulation is possible. In B1 scenario (Fig. 4e–h), MIROC (Hires) depicts 5 to 10 % deficit rainfall at 99 % confidence level. In A1B scenario (Fig. 4i, j), there is a possibility of deficit at 99 % confidence level in MIROC (Hires) and 10 % deficit at 95 % confidence level in HadGEM1 simulation.

The future-projected percentage change in JJAS rainfall (mm month^{-1}) in RCP experiments of 4.5 and 8.5 (2006–2044) with respect to historical experiment (1961–1999) in BCC-CSM1.1(m), CCSM4, CESM1(BGC), CESM1(CAM5), CESM1(WACCM) and MPI-ESM-MR is shown in Fig. 4k–u. RCPs 4.5 and 8.5 in CESM1(FASTCHEM) and RCP 4.5 in CESM1(WACCM) is not available, therefore not discussed here. Student t test is applied at 99 and 95 % confidence levels for six (6) models, namely BCC-CSM1.1(m), CCSM4, CESM1(BGC), CESM1(CAM5), CESM1(WACCM) and MPI-ESM-MR. In RCP 4.5 (Fig. 4k–o), at 95 and 99 % confidence, CESM1(CAM5)

(Fig. 4n) shows 5–15 % deficit rainfall. Other models do not show much significant changes. In RCP 8.5 (Fig. 4p–u), at 95 and 99 % confidence levels, CCSM4 and CESM1 (WACCM) show 10–20 % excess rainfall, at part of GP, while 5–15 % deficit over larger part of GP in CESM1(CAM5).

5 Conclusions

In CMIP3 and CMIP5, model performance in simulating rainfall (1961–1999) close to observations (IMD and GPCP) over the Gangetic Plain (GP), India, is evaluated. Taylor diagram methods and skill score shows that CCSM3 model of CMIP3 and CCSM4, CESM1 (WACCM) and CESM1(CAM5) models of CMIP5 are able to simulate rainfall better than other models. In comparison between CMIP3 and CMIP5, statistical measures in CMIP5 show large distribution of correlation and RMSE with IMD observation and high correlation (relatively low RMSE) with GPCP observations. It seems that model validations of CMIP5 are relatively closer in GPCP when compared to IMD; however, settings of 20C3M and historical experiments are different.

In CMIP3, 5–10 % deficit of JJAS rainfall at 99 % confidence level in A2 scenario of CCSM3 and HadGEM1 and in B1 and A1B scenarios of MIROC (Hires) is possible. Ten-percent deficit of JJAS rainfall at 95 % significant level in HadGEM1 simulation may be possible. Only CCSM3 model shows possibility of 5–15 % excess of JJAS rainfall in A2 scenario. In CMIP5, 5–15 % deficit of JJAS rainfall at 99 and 95 % significant levels in CESM1(CAM5) in RCP4.5 and CCSM4 and CESM1(WACCM) in RCP8.5 is possible, while 5–15 % deficit of rainfall in CESM1(CAM5) may be possible over parts of GP. It seems that significant deficit of JJAS rainfall in CCSM3 model simulations of CMIP3 and CCSM4 and CESM1(CAM5) of CMIP5 is possible over the GP.

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