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ORIGINAL PAPER

Performance of regional climate model in simulating Indian summer monsoon over Indian homogeneous region

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Abstract

The performance and validation of regional climate model (RegCM-4.3) simulation of Indian summer monsoon rainfall (ISMR) have been conducted with a futuristic view of climate change study with the convective parameterization schemes (CPSs) over the different homogeneous regions of India. The dynamical downscaling of RegCM-4.3 has been done over South Asian Coordinated Regional Climate Downscaling Experiment (CORDEX) domain with the lateral boundary forcing provided by ERA-Interim at 50-km horizontal resolution. The interannual and seasonal variability of ISMR over India and its different homogeneous region has been done by comparing model-simulated rainfall with observed rainfall dataset of India Meteorological Department (IMD) during 1986–2010. The analysis includes the performance and validation of RegCM-4.3 in capturing regionalized rainfall of Indian subcontinent. The analysis is done over five homogeneous regions of India, i.e., northwest India (NWI), R1; northcentral India (NCI), R2; west peninsular India (WPI), R3; eastern peninsular India (EPI), R4; and southern peninsular India (SPI), R5 during 1986–2010. The Grell CPSs simulate monsoon rainfall reasonably good over northwest India. Over northcentral India, predictability/simulation of Kuo and Grell are best performing parameterize scheme of RegCM-4.3. The western and eastern peninsular parts of India, i.e., R3 and R4 simulation of Emanuel and Mix99 schemes, are better respectively. The region consisting southern peninsular along with Western Ghats shows Tiedtke scheme, as the best simulated scheme of RegCM-4.3. The overall diversification of simulation depending upon the topographical difference of Indian subcontinent causes the regionalize difference in simulating monsoon rainfall over the Indian subcontinent.

1 Introduction

The Indian subcontinent is adherent with inhomogeneity due to its vastness and topographical features with regards to the climatic parameter. The Summer monsoon has major dominance over India and its contribution is almost 80% of the total annual precipitation of the country (Parthasarathy et al. 1995; Guhathakurta and Rajeevan 2006; Turner and Annamalai 2012). Generally, Indian summer monsoon develops due to differential heating between land and sea which is a result of general circulation features from global to local scale. The unique summer monsoon characteristic is quite complex to explain due to its vast size of the Indian subcontinent and its adjacent seas. The monsoon system of Indian subcontinent is quite different; the center of action, i.e., air mass involved and the mechanism of precipitation of Indian monsoon, is different from another monsoon system (Parthasarathy et al. 1993). Indian summer monsoon associated with important atmospheric circulation such as the role of Somali jet, strong low-level jet (LLJ) at 850 hPa, the Tibetan plateau, and tropical easterly jet (TEJ) at 110 hPa. At the lower level, strong cross-equatorial low-level jet transports momentum and water vapor from southern hemisphere to northern hemisphere (Findlater 1969). The Tibetan plateau acts as the heat source in summer and sinks in winters, Tibetan anticyclone in the upper troposphere which is directly responsible for the easterly jet. The spatio-temporal distribution and variation of ISMR are dependent on many climatic and topographical features over the Indian subcontinent. All the orographical and topographical features associated with monsoonal convection need to represent precisely using regional

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climate modeling to study and forecast ISMR. Hence, these regional differences in the monsoon rainfall variability were studied by many scientists. The significant spatial and temporal variability is associated with ISMR (Mooley and Parthasarathy 1984; Thapliyal and Kulshrestha 1991; Kripalani and Kulkarni 2001; Sahai et al. 2003; Naidu et al. 2015).

Primarily, the regional climate model (RegCM) was developed by the Earth System Physics (ESP) group of the Abdus Salam International Centre for Theoretical Physics (ICTP). Over the world, it has been widely used for simulation of seasonal to decadal monsoonal system rainfall in the last two decades. The African monsoon simulation studied by Davis et al. (2009), Steiner et al. (2009), and Sylla et al. (2013), and seasonal rainfall over South America by Rauscher et al. (2006), Rocha et al. (2012), and Giorgi et al. (2012). The RegCM is used for the simulation of surface temperature and precipitation over Europe (Giorgi and Marinucci 1996) and the intense heavy rainfall events over Arabian Peninsula (Almazroui 2011). The studies over East Asia for simulation of East Asian summer monsoon characteristics have been carried out by Liu et al. (1994), Lee et al. (2005), Singh et al. (2006), Park et al. (2008), Steiner et al. (2005), Huang et al. (2013), *and* Gao et al. (2012). *Over the Indian region, the RegCM3 was initially used by* Dash et al. (2006) to simulate the Indian summer monsoon rainfall circulation from 1993 to 1996. Dimri and Ganju (2007) studied the RegCM3 simulated temperature variability over the Himalayan region (1999–2000). Ratnam et al. (2008) coupled RegCM3 with Regional Ocean Modeling System (ROMS) used to simulate summer monsoon rainfall. Ashfaq et al. (2009) have shown with the help of nested regional model RegCM3 that enhanced greenhouse forcing results in overall suppression of summer precipitation. Saha et al. (2011) used RegCM3 to study the pre-onset land surface processes and internal interannual variability of the Indian summer monsoon during the period 1981–2008.

The applicability of RegCM3 has been utilized to study detailed Indian monsoon circulation features and sensitivity analysis of the different cumulus convection parameterization schemes for three different monsoon seasons of deficit (1987), excess (1988), and normal (1989) rainfall years by Sinha et al. (2013). The customization of RegCM4 over Indian region is studied by Nayak et al. (2017) for a 10-year simulation period (1901–2000) with different cumulus convection scheme (Kuo, Grell, and MIT) and land surface parameterization scheme (BATS, CLM3.5). Based on the state of atmosphere, several studies have been considered to define important features of Southwest Indian Monsoon (Raju et al. 2005, 2007; Dash et al. 2015; Bhatla et al. 2016). Raju et al. (2015) *have revealed the* better simulation of Indian summer monsoon characteristics using the regional climate model version 4.3 by ICTP (RegCM-4.3) with the combination of the mixed convective parameterization scheme (CPS) over South Asia CORDEX domain. Ghosh et al. (2018), Bhatla et al. (2018), *and* Bhatla and Ghosh (2015) *have significantly contributed to intra-seasonal and interannual monsoon variability using RegCM. Ghosh et al. (2018) have extensively studied the RegCM dependency with different SST forcing on the mixed scheme of RegCM for simulation of the phases of monsoon. A study of* Nayak et al. (2018) *has evaluated the performance of RegCM4 to simulate rainfall and temperature with observed global data of GPCC and University of Delaware respectively for India and its homogeneous regions.*

Hence, the output of extensive research work regarding the usage of model system to understand the climatic parameter and seasonal prediction of the Indian monsoon is still in progress. But there are some lacunae in research that the modeling system (RegCM) is not used to study the inhomogeneity of Indian subcontinent concerning sensitivity towards the selection of appropriate parameterization scheme for simulating the Indian summer monsoon rainfall. A descriptive study *of* Pal et al. (2007) proves that the selection of an appropriate convective parameterization scheme (CPS) in RCMs is a major source of error and has a significant impact on regional climate model predictions. A recent study of Maurya et al. (2018) shows the capability of RegCM4 to simulate the monsoon rainfall but its skill varies with the resolution and domain size. We are on the edge of climate change which is happening all around the world, impacting our lives. Climate change impacts the monsoon influencing sectors over Indian subcontinent such as agriculture, water resource, human health, and forestry. In India, inherent spatial and temporal variability of ISMR will be helpful for scientists and policymakers. Hence, there is a need for the regionalized study of Indian subcontinent for better understanding of local distribution characteristics of rainfall. The main objective of this paper was to identify the best performing scheme of RegCM-4.3 regarding inhomogeneity of the Indian region to simulate regionalized ISMR. In the present paper, a brief discussion on the outline of the study is given in the "*Outline of the study*" section and the results are summarized in the "Results and discussions" section. The main conclusion of the study is given in the "Conclusions" section.

2 Outline of the study

2.1 Model description

The ICTP's regional climate model (RegCM) has a wide range application for climate change simulation and prediction. The *state-of-art* regional climate model (RegCM) has contributed significantly to the scientific society in the past recent decades (Giorgi 2006, 2013). In this study, a high-resolution (0.5° × 0.5°) RegCM4.3 model (Giorgi et al. 2012) has been used which is an improved version of ICTP's RegCM 4 (Giorgi et al. 1993a, b). It is a hydrostatic limited area model, compressible, sigma-p vertical co-ordinate model with Arakawa B-grid system in which wind and thermodynamic variables are horizontally staggered using a time-splitting explicit integration scheme as described in Table 1. RegCM4.3 has been used for simulating Indian summer monsoon rainfall over different homogeneous regions of India. The South Asia CORDEX domain (22° S–50° N; 10° E–130° E) has been selected as a model domain with 50-km horizontal resolution and 18 sigma vertical levels (Giorgi et al. 2008). The Initial and boundary condition is derived for 6 hourly field from ECMWF's ERA-Interim reanalysis EIN15 (Simmons et al. 2007) with a horizontal grid of 1.5° × 1.5° lat/lon and 37 vertical levels. Optimum interpolated weekly sea surface temperature gridded data (OIWK SST) at 1° × 1° resolution have been obtained from the National Oceanic and Atmospheric Administration (NOAA). The radiation parameterization scheme used in this model is NCAR's community climate model version3 (CCM3) (Kiehl et al. 1996). The topography and land-use data are obtained from the United States Geological Survey (USGS) and Global Land Cover Characterization (GLCC). The land surface parameterization is given by Biosphere-Atmosphere Scheme (BATS) (Dickinson et al. 1989) and planetary boundary layer parameterization is given by the scheme of Holtslag (Holtslag et al. 1990). As a convective precipitation scheme, the Grell scheme (Grell 1993) has been used with closure assumption of the Arakawa and Schubert closure given by Grell et al. (1994). The subgrid explicit moisture scheme (SUBEX) given by Sundqvist et al. (1989) is used for the large-scale precipitation scheme.

2.1.1 Convective scheme

For the simulation and validation of variability of Indian summer monsoon rainfall over different homogeneous regions of India, four core convective parameterization schemes (CPSs), i.e., Kuo, Emanuel, Grell, and Tiedtke, are used for the study. Also, two mixed convection schemes of RegCM-4.3 have been used, i.e., Emanuel over the ocean, Grell over the land (Mix99), Emanuel over the land, and Grell over the ocean (Mix98). A detailed description of all six schemes of RegCM-4.3 is listed below:

1. ***Kuo scheme***. It is the first scheme incorporated in RegCM-4.3 known as the Kuo-type scheme of Anthes (1977). Convective activity in the Kuo scheme is based on moisture convergence.
2. *Grell scheme.*The second scheme is the simplification of Arakawa and Schubert closure (AS74) parameterization. In this scheme, clouds are considered as two steady-state circulations: an updraft and downdraft (Grell 1993). No direct mixing occurs between the cloudy air and the environment air except at the top and bottom of the circulations. The mass flux is constant with the height and no entrainment or detrainment occurs along the cloud edges. This scheme is activated when a lifted parcel attains moist convection.
3. *Emanuel. The* processes involved in this scheme are quite complex and provide an additional physical representation of convection. It assumes that the mixing in the cloud is highly episodic and inhomogeneous and considers convective fluxes based on an idealized model of sub-cloud-scale updraft and downdrafts (Emanuel 1991). Convection started when the neutral buoyancy level is higher than the cloud base.
4. *Tiedtke.* It is the fourth available convection scheme in RegCM4.3 which is based on mass flux and moisture convergence closure. It has shallow and deep convection, detrainment of the cloud base mass flux from the PBL equilibrium and mass flux closure from CAPE

Table 1 Model configuration of RegCM-4.3

Dynamics	Hydrostatics
Model domain	South Asia CORDEX domain (22° S–50° N; 10° E–130° E)
Resolution	50 km horizontal and 18 sigma vertical levels
Initial and boundary conditions	ECMWF ERA-Interim reanalysis EIN15 (Simmons et al. 2007)
SST	OI WK–OISST weekly optimal interpolation dataset
Radiation scheme	NCAR CCM3 (community climate model 3; Kiehl et al. 1996)
Land surface model	Biosphere-atmosphere scheme (BATS) (Dickinson et al. 1989)
Planetary boundary layer scheme	Holtslag (Holtslag et al. 1990).
Convective precipitation scheme	Grell scheme (Grell 1993) with closure assumption of the Arakawa and Schubert closure (AS74) (Grell et al. 1994)
Large-scale precipitation scheme	Subgrid explicit moisture scheme (SUBEX) (Sundqvist et al. 1989)
Convective parametrization scheme	1. Kuo
	2. Emanuel
	3. Grell
	4. Tiedtke
	5. Emanuel over land; Grell over ocean (Mix99)
	6. Emanuel over ocean; Grell over land (Mix98)

respectively (Ali et al. 2015). It is a mass flux type scheme which was originally designed for use in a global climate model, with particular focus on the correct representation of tropical deep convection (Bao 2013).

5. *Mixed convection scheme. This* model has the capability of running different schemes over land and ocean. Hence, the evolution of new mixed convection scheme added as different scheme has a different performance over different regions. This includes Grell and Emanuel schemes over land and ocean, vice versa, i.e., Grell over the land and Emanuel over the ocean (Mix99) and Grell over the ocean and Emanuel over the land (Mix98).

2.2 Methodology

The model domain used for the study is the South Asian CORDEX domain (22° S–50° N; 10° E–130° E). The Indian summer monsoon rainfall simulation over India and its homogeneous regions (Singh and Sontakke 1999, Bhatla et al. 2019), i.e., northwest India (NWI), R1; northcentral India (NCI), R2; west peninsular India (WPI), R3; eastern peninsular India (EPI), R4; and southern peninsular India (SPI), R5, are simulated by six CPSs of RegCM4.3 in order to find a well-suited convective parameterized scheme (CPS) (Table 2). The performance of RegCM-4.3 CPS is calibrated and validated using observed gridded rainfall data of India Meteorological Department (IMD) with the resolution of 0.25° × 0.25°. The validation of model output data using mean bias, standard deviation (SD), correlation coefficient, root mean square error (RMSE), and Willmott's index of agreement (D) have been done. An experiment was conducted with the set of 25-year simulation for the period of 1986–2010 using RegCM-4.3 during the monsoon season (June–September).

Our major concern was to find out the best-fit RegCM4.3 model convection scheme capable of running different scheme over India and its homogeneous regions because each scheme has different performance depending on the terrain and topography of the Indian subcontinent.

Table 2 Study domains considered for different homogeneous regions

Region	Homogeneous region	Domain
R1	NWI	LON 72°–79° LAT 21°–30°
R2	NCI	LON 79°–87° LAT 21°–28°
R3	WPI	LON 73°–78° LAT 16°–21°
R4	EPI	LON 78°–84° LAT 16°–21°
R5	SPI	LON 75°–80° LAT 10°–16°

NWI northwest India, *NCI* northcentral India, *WPI* west peninsular India, *EPI* east peninsular India, *SPI* south peninsular India

3 Results and discussions

3.1 Rainfall variation and distribution over Indian homogeneous regions

The summer monsoon rainfall (SMR) variability has been studied over India and its different homogeneous regions such as R1 (NWI), R2 (NCI), R3 (WPI), R4 (EPI), and R5 (SPI) during 1986–2010 (shown in Fig. 1a–g). The model RegCM-4.3 simulation for ISMR is compared with the observed dataset of IMD gridded rainfall to show mean rainfall distribution in the climatological period of 25 years. The seasonal rainfall variability over Indian subcontinent is well captured by Kuo, Grell, Mix99, and Mix98 convection schemes of RegCM-4.3 with observed rainfall data of IMD with less biasness. The Kuo-simulated rainfall mainly captured well over northwest, western peninsular and southern peninsular of India, whereas over eastern peninsular and northcentral India, its performance is very poor. The Grell and Mix99 simulation of rainfall over Indian land point is comparatively better than other schemes of RegCM-4.3. On the other side, Grell simulation over the ocean is unable to capture circulation pattern. The orographic rainfall along windward side of the Western Ghats is well observed in the Grell and Mix99 scheme. The Emanuel scheme is showing a better representation of Arabian and Bay of Bengal (BoB) branch of ISMR than the rest of the scheme. The parameterization of Emanuel scheme is complex one which is based on moisture advection. However, the Tiedtke scheme significantly simulates the ISMR rain band over the ocean and covering the southern peninsular region of India, but its performance in simulating ISMR over central and northern India is very poor.

Figure 2 a–e depict the overall temporal variability of Indian summer monsoon rainfall over the different homogeneous regions during 1986–2010. Also, the box and whisker plot, empirical cumulative distribution function (ECDF) plot in the statistical analysis of average climatology of monsoon rainfall output of IMD, and six CPSs of RegCM-4.3 over different homogeneous regions of India are used in analysis. For the box and whisker plot for any large and reliable sample, there is a 50% probability that future observation will lie within the box portion known as interquartile range (IQR). The ISMR analysis using the box and whisker plot summarizes the statistical characteristics such as the central tendency, dispersion, asymmetry, and extreme. The spatial distribution of monsoon rainfall analyzed using the ECDF plot is represented in Fig. 2a–e. The ECDF plot of JJAS rainfall using the six CPS schemes of RegCM-4.3 and the observed dataset of IMD

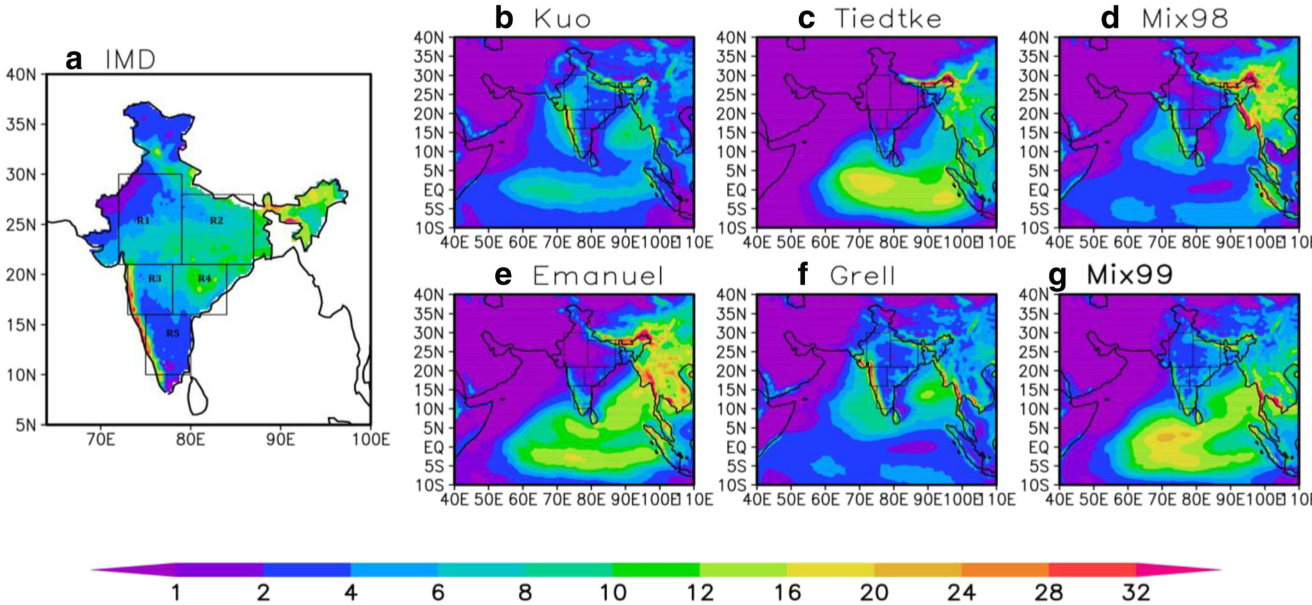


Fig. 1 **a–g** Indian summer monsoon rainfall (mm/day) over India and its homogeneous regions during the period 1986–2010. The rectangular boxes over India map show the five homogeneous sub-regions

are presented to validate how the monsoon rainfall data occur below and above the observed rainfall data values. Over the regions R3 and R5 models, performance is quite good in comparison with other regions because it shows a significant correlation value, i.e., 0.7 (Emanuel) and 0.5 (Tiedtke) (shown in Table 3). But the only correlation between model and observed data is not enough to identify the best suitable scheme of RegCM-4.3 over the homogeneous regions of the Indian subcontinent. Hence, other statistical parameters such as mean bias, standard deviation (SD), root mean square error (RMSE), and index of agreement (D) were applied to find out the best suitable scheme of the model RegCM-4.3 over the Indian subcontinent.

Now, it can be observed from Fig. 2a(i) the rainfall variability over the R1 region of the Indian subcontinent during 1986–2010. Figure 2 a(i) depicts the variability of JJAS rainfall over the R1 region which is well simulated by the Grell scheme. The validation of rainfall simulation by Grell CPS shows the maximum correlation (i.e., 0.3) and least mean bias (1.2), SD (1.1), RMSE (1.2 mm/day), and D (0.54) in comparison with the rest of the five schemes of RegCM-4.3 during 1986–2010. Figure 2 a(ii) shows the ECDF of JJAS rainfall (in mm/day) over the R1 region between observed and model output, in which it justifies that observed rainfall quantile is much closer to the Kuo and Grell convection schemes of RegCM-4.3. By the ECDF plot, it is observed that models such as Kuo and Grell are able to simulate rainfall very well but underestimate the rainfall simulation by 1 mm/day. Two CPS schemes such as Kuo and Grell are showing similar interquartile range (IQR) but Kuo overestimated rainfall distribution than Grell over R1 region as shown in Fig. 2a(iii). The Mix99 data show largely dispersed and underestimated rainfall amount from the observed rainfall in the boxplot. The performance of Emanuel, Mix98, and Tiedtke schemes in producing rainfall over the R1 region is very poor. The temporal variation of rainfall and its distribution over the R2 region is displayed in Fig. 2b(i–iii) during JJAS from 1986 to 2010. It has been observed that the IMD rainfall data showing high variability so that all model scheme shows underestimated rainfall as shown in Fig. 2b(i). Besides, the high rainfall variability of two schemes of RegCM-4.3 is well captured by Kuo and Grell scheme with the highest correlation value of 0.4 and 0.3; the lowest mean bias and RMSE, i.e., −3.7 and 3.8 respectively and the index of agreement value are closer for the both schemes, i.e., 0.29 and 0.27. In Fig. 2b(ii), the ECDF plot of the IMD rainfall shows the high monsoon precipitation value in the range of 6–10 mm/day and, comparing with the model simulation using the Kuo and Grell schemes along with Mix99 schemes, is much closer to the observed rainfall quantile value. But, other schemes such that Emanuel, Mix98, and Tiedtke are simulating very low rainfall during ISM. The boxplot represents the actual distribution of seasonal rainfall in region R2 (shown in Fig. 2b(iii)). It shows that both the convection schemes Kuo and Grell show that the rainfall distribution is closer to the observed IMD rainfall over R2 region. From Fig 2 c(i), the Indian summer monsoon rainfall variability has been observed over the western peninsular region of India during 1986–2010. The monsoon dynamics are different from the northern plane region of India. The region R3 along with Western Ghats of India explains different and complex monsoon dynamics. The Southwest Monsoon propagation over the Western Ghats is mainly determined by the performance of Arabian branch which plays a dominant role in the monsoon activity over the west coast of

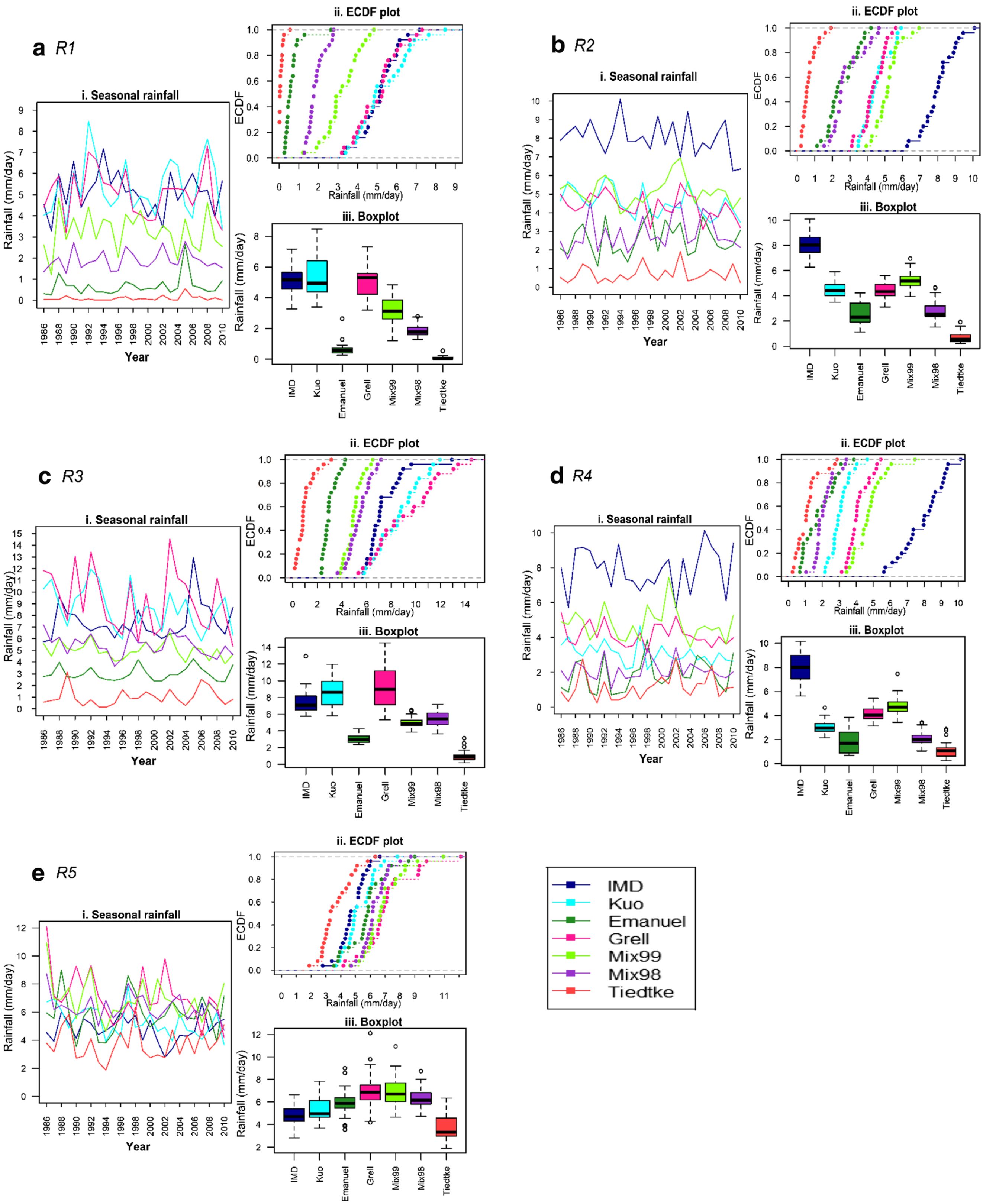


Fig. 2 **a–e** Indian summer monsoon seasonal (JJAS) rainfall variability over different homogeneous regions during 1986–2010

India. It is observed that Mix99 and Emanuel reasonably well simulate the monthly monsoon rainfall circulation and sufficient convection over Arabian Sea, which leads to produce better precipitation over the windward side of Western

Table 3 Quantitative analysis of seasonal monsoon rainfall (JJAS) using correlation coefficient (*r*), standard deviation (SD), mean bias (MB), root mean square error (RMSE) and index of agreement (D)

R1						R2					
	r	MB	SD	RMSE (mm/day)	D		*r*	MB	SD	RMSE (mm/day)	D
IMD			0.9			IMD			0.9		
Kuo	0.2	0.2	1.2	1.4	0.38	Kuo	0.4	− 3.6	0.6	3.7	0.29
Grell	0.3	− 0.1	1.1	1.2	0.54	Grell	0.3	− 3.7	0.7	3.8	0.27
Emanuel	0.1	− 4.5	0.5	4.6	0.24	Emanuel	− 0.4	− 5.4	0.8	5.6	0.19
Tiedtke	− 0.1	− 5.0	0.1	5.1	0.22	Tiedtke	− 0.3	− 7.3	0.4	7.4	0.16
Mix98	0.2	− 3.2	0.4	3.4	0.29	Mix98	0.1	− 5.2	0.9	5.3	0.20
Mix99	0.3	− 1.9	0.9	2.2	0.43	Mix99	− 0.04	− 2.9	0.7	3.1	0.30
R3						R4					
	r	MB	SD	RMSE (mm/day)	D		*r*	MB	SD	RMSE (mm/day)	D
IMD			1.6			IMD			1.2		
Kuo	− 0.3	1.3	2.3	3.3	0.11	Kuo	0.01	− 4.3	0.9	4.5	0.27
Grell	− 0.3	1.8	2.6	3.7	0.18	Grell	− 0.1	− 3.8	0.6	4.0	0.32
Emanuel	0.7	− 3.4	0.6	3.6	0.34	Emanuel	0.2	− 6.1	0.9	6.2	0.25
Tiedtke	0.3	− 6.4	0.7	6.6	0.26	Tiedtke	0.1	− 6.8	0.7	6.9	0.23
Mix98	− 0.1	− 2.0	0.9	2.7	0.35	Mix98	0.01	− 5.8	0.6	6.0	0.25
Mix99	0.1	− 2.4	0.7	2.9	0.39	Mix99	0.2	− 3.2	0.9	3.5	0.37
R5											
	r	MB	SD	RMSE (mm/day)	D						
IMD			0.9								
Kuo	− 0.05	1.6	2.0	2.7	0.35						
Grell	− 0.5	2.3	1.8	3.2	0.15						
Emanuel	0.4	1.0	1.4	1.7	0.52						
Tiedtke	0.5	− 1.0	1.1	1.5	0.53						
Mix98	− 0.07	1.5	0.9	2.0	0.33						
Mix99	− 0.1	2.1	1.4	2.7	0.26						

Ghats as compared with other schemes. After crossing the Western Ghats, branch of the Arabian Sea monsoon strikes the coast North of Mumbai and central India which provides the surplus amount of rainfall which better explain the Emanuel scheme due to warming-induced increase of atmospheric moisture advection. The Emanuel scheme includes more physical representation of convection which offers several advantages compared with the other RegCM4.3 convection schemes. This scheme is the most complex and also includes a number of parameters that can be used to optimize the model performance in different climate regimes. Over the Indian subcontinent, the Emanuel simulation for the monsoon rainfall is very poor except over western peninsular India (R3).

This is due to the fact that Emanuel performance over ocean is reasonably good; that is why it is able to represent Arabian branch of rainfall band better than any other scheme. It has been observed that over the R3 region, the Emanuel scheme performance is good reasonably than rest of the schemes of RegCM-4.3 with the highest and significant correlation coefficient (i.e., 0.7). In Fig. 2c(ii), ECDF plot explained that the Kuo and Grell schemes overestimate the ISMR value in comparison with the observed rainfall; on the other hand, the Mix98, Mix99, and Emanuel schemes are underestimating the IMD monsoon rainfall. The Kuo and Grell overestimated the monsoon rainfall amount which is observed in the boxplot (Fig. 2c(iii)); but despite low distribution of the Emanuel simulation, it is the best-fit convection scheme on the basis of SD, RMSE, and index of agreement (D). The monsoon rainfall variability and its distribution over the R4 region are explained in Fig. 2d(i–iii) during 1986–2010. Over the eastern peninsular region, rainfall comprises extreme rain years (1988, 1994, 2006, and 2010) with high rainfall variability. It has been observed that whenever the extreme rainfall events took place, the model performance is badly affected. All the CPSs of RegCM-4.3 underestimated the simulated rainfall than the observed rainfall. The Kuo and Mix99 performance are closer to the observed rainfall over the southern peninsular regions (Fig. 2d(i)). In between these two-convection schemes, Mix99 simulation is best with least mean bias and RMSE, i.e., − 3.2 and 3.5 respectively. Again, from ECDF plot, the Mix99 scheme was able to simulate Indian summer monsoon rainfall much closer to the observed data, but its simulation underestimated the observed data (Fig. 2d(ii)). The boxplot over the R4 region shows the rainfall data distribution over the R4 region in which Mix99 shows a closer median value with less IQR with respect to the observed dataset of IMD. In Fig. 2e(i), temporal variation of rainfall for all six CPSs has been shown with respect to the observed IMD rainfall dataset. The southern peninsular region is quite important for the monsoonal rainfall; during the monsoon month, high rainfall is received over the windward side of the Western Ghats. The monsoon rainfall trend is slightly decreasing during the climatological period of 1986–2010 over the southern peninsular region. The Tiedtke CPSs are closer in simulation the JJAS rainfall amount with the highest correlation, least mean bias, RMSE, and highest D value, i.e., 0.5, − 1.0, 1.5, and 0.53, respectively (Table 3), among all CPSs. After this, Emanuel is the second-best convection scheme which is performing better simulation of ISMR rainfall over the southern peninsular region. In Fig. 2e(ii), rainfall quantile of observed dataset is suitably matched with the Tiedtke CPS of RegCM-4.3. The rainfall event in R5 is overestimated by all CPSs except the Tiedtke scheme.

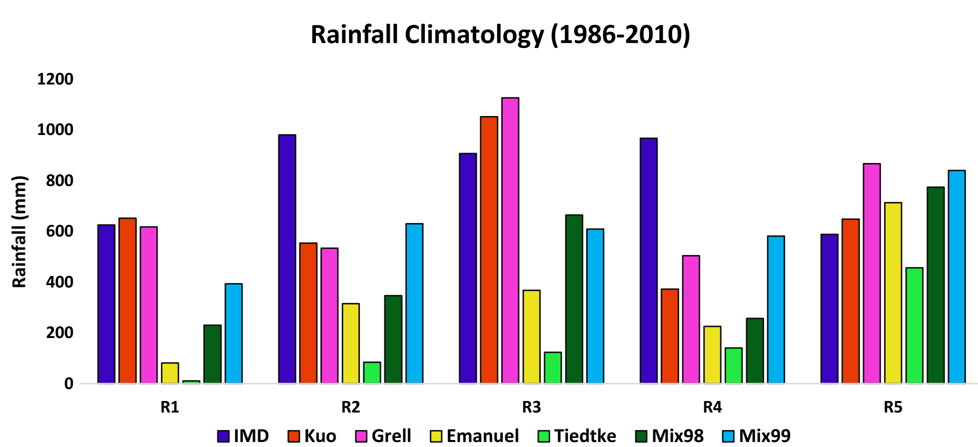
The model performance is evaluated with respect to the observed rainfall of IMD over the five different homogeneous regions of India and it is found that during Indian summer monsoon season (JJAS) over the R1 region performance of Grell scheme is better on the basis of statistical evaluation. The R2, R3, and R4 regions are the maximum contributing rainfall regions (24.1%, 22.3%, and 23.8% respectively) according to the observed rainfall climatology during 1986–2010. The region R2 consisting the northcentral region and the performance of both schemes, Kuo and Grell of RegCM-4.3, is reasonably good over R2. The ECDF plot explains that model performance is fluctuated when heavy/extreme rainfall occurs in the respective regions. In the regions R1, R2, and R3, model performance in simulating high rainfall is underestimated due to high monsoonal rainfall variability. Whereas, RegCM-4.3 simulation of Mix99 scheme over R4 region is reasonably good but showing incapability of simulating high monsoonal rainfall. Over the southern peninsular region, Tiedtke CPS simulation is the best in comparison with the rest of the schemes of RegCM-4.3. The simulation of monsoonal rainfall using RegCM-4.3 explains that the prediction/simulation is quite sensitive with extreme rainfall cases or with high variability of rainfall over India and its different homogeneous regions of India.

3.2 Climatology of ISMR during 1986–2010

The average Indian summer rainfall over five different homogeneous regions of India, i.e., R1, R2, R3, R4, and R5 during the climatological period of 25 years (1986–2010) is shown in Fig. 3. The unparalleled distribution of rainfall over India and its regions is the main reason behind this experiment of regionalized rainfall distribution. It has been done to analyze the rainfall distribution over homogeneous regional level with different convection schemes of RegCM-4.3. Though, a previous recent work has been done by Nayak et al. (2018) to evaluate the performance of RegCM4 over India and its homogeneous region with the global dataset of rainfall and temperature. With reference to this, our study is based on the effect of different convective parameterize schemes (CPSs) of RegCM-4.3 on the simulation of monsoon rainfall over India and its homogeneous regions.

The percentage contribution of ISMR is maximum over R2, R3, and R4 regions, i.e., 24.1%, 22.4%, and 23.8% respectively. Regions R1 and R5 rainfall contributions are

Fig. 3 Climatological Indian summer monsoon rainfall (ISMR) over different homogeneous regions of India simulated by six convection parameterized schemes (CPSs) of RegCM4.3 with observed IMD rainfall



minimum, i.e., 15.4% and 14.4%, during the climatological period of ISMR 1986–2010. An overall observation has been done in Fig. 3 which indicates the climatological ISMR (rainfall in mm) for a 25-year period over different homogeneous regions of India. In regions R1 and R2, two schemes of RegCM-4.3, i.e., Kuo and Grell schemes, are showing better results with observed IMD rainfall, whereas, Emanuel, Tiedtke, and Mix98 simulation have below average rainfall. In region R3, except for Emanuel and Tiedtke, all the CPSs performed better rainfall than that of the observed rainfall of IMD. The Emanuel scheme shows a better result than any other scheme of RegCM-4.3 in the R3 region.

The rainfall variability over Indian homogeneous regions is well captured by Kuo and Grell over the R2 region and Grell scheme over the R1 region, Emanuel over R3, Mix99 hold good over R4, and Tiedtke over R5 region. The region R1 consists of semiarid/desert part of Gujrat and Rajasthan, and R2 comprises the best fertile land of Indo-Gangetic plain (IGP), which means that over the plane regions Grell and Kuo simulation is the best fit with lowest RMSE value, i.e., 1.1 and 3.7 mm/day, respectively. Over three peninsular regions such as western peninsular regions (R3), eastern peninsular region (R4), and southern peninsular regions (R5), each scheme has different performance observed from Figs. 1 and 2. It was mentioned in the study of Nayak et al. (2018) that the model (RegCM4) simulation shows the best fit over northwest India, but over south peninsular India, its performance is poor with the observed data of global dataset of rainfall. On the other hand, among the six convection schemes simulation of rainfall over the R4, only the Mix99 scheme is good and well simulated with the lowest RMSE value among all schemes, i.e., 3.5 mm/day. The R5 region, consisting the southern peninsular region, is well known for the Western Ghats representing orographic rainfall during monsoon rainfall. The Tiedtke scheme holds good over R5 region with high correlation and least RMSE value. It clearly explains that the climatology of ISMR rainfall has inhomogeneity in nature which mainly depends upon the topography of Indian subcontinent; hence, the simulation of the RegCM-4.3 for climate studies is sensitive to the selection of the best-fitted convective parameterization scheme (CPS).

3.3 Seasonal variation and distribution of ISMR over the Indian homogeneous region

The monthly variation and distribution of Indian summer monsoon rainfall over the Indian subcontinent and its five homogeneous regions using RegCM-4.3 output are shown in Fig. 4. Also, the temporal variability of rainfall has been plotted and examined to understand the variability of all the CPSs of RegCM-4.3 in Fig. 5a–e. Rainfall data validation for different months, i.e., June, July, August, and September, were done by validating the model performance with the observed dataset of IMD rainfall using two statistical parameters RMSE and mean bias (depicted in Fig. 6a–j).

3.3.1 Spatial rainfall distribution of monthly rainfall over the Indian homogeneous regions

During monsoonal months (JJAS), rainfall distribution over India and its homogeneous region shows the unparalleled distribution of monsoon rainfall (ISMR) over northcentral India, and the southwest peninsular part of India gets benefited by the surplus amount of rainfall as the onset of monsoon reaches to Kerala coast. The moisture-laden Arabian branch supplies sufficient rainfall to the coast of Kerala. The RegCM-4.3 simulation using two convective schemes viz Kuo and Grell has been able to represent the movement of ISMR over India during June. The maximum rainfall is observed over Western Ghats and northeast India (16–32 mm/day). The Emanuel and Tiedtke schemes are unable to simulate rainfall over the northern part of India, whereas over the ocean and southern peninsular India, the propagation of rainfall (8–32 mm/day) is clearly shown. Also, it can be observed that the Grell scheme is reasonably good in simulating rainfall distribution over land, but over some regions, it was overestimated. The maximum distribution differences are observed in the simulation of eastern peninsular region because the observed IMD rainfall shows 4–8 mm/day but the schemes Kuo and Grell show overestimated rainfall. Figure 4 shows the ISMR distribution over India and its homogeneous region during the advancement of the monsoon season, i.e., July and August. The rainfall over central India (8–16 mm/day) is observed from IMD spatial plots mentioned in Fig. 4. During July, two schemes Kuo and Grell are able to simulate ISMR rainfall propagation and distribution over all regions. Over the central region, all the RegCM-4.3 CPSs underestimated the rainfall from the observed IMD rainfall, i.e., 4–8 mm/day. The rainfall simulation of Grell over land and Emanuel over ocean performed well so that the performance of Mix99 was comparatively good in simulating ISMR rainfall over the Indian subcontinent. The performance of Tiedtke in simulating ISMR is not good over the northern region, but over peninsular India and Indian ocean, its distribution is quite good but it does not consider the total homogeneity of ISMR distribution over India. During the month of September, the observed ISMR plotted for IMD (Fig. 4) which covers central India and peninsular India with a range of 2–8 mm/day. The maximum rainfall observed over West Bengal and northeast India is 8–16 mm/day. In the withdrawal of monsoon, all the CPSs of RegCM-4.3 underestimate the rainfall than the observed value. Besides, Kuo, Grell, and Mix99 well represented the rainfall spatial distribution with less biasness.

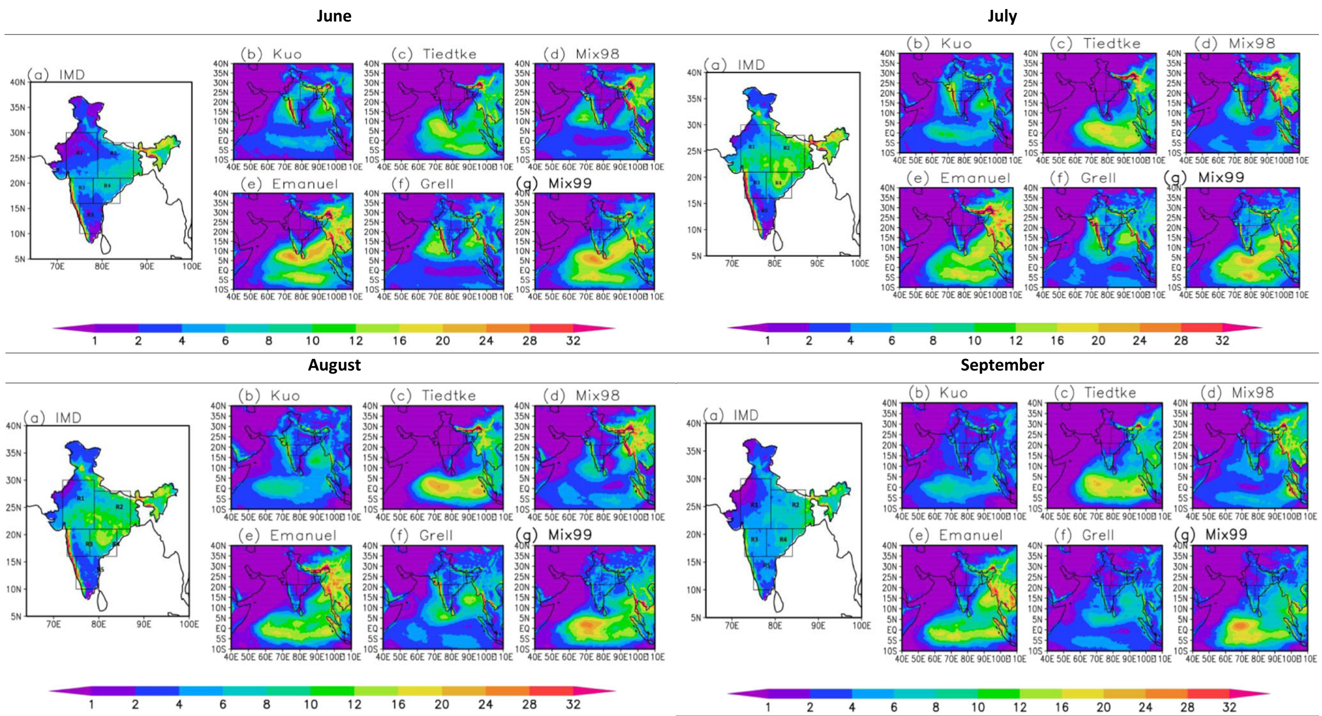


Fig. 4 Indian summer monsoon variation over India and its homogeneous sub regions during June, July, August, and September for the period of 1986–2010

3.3.2 Monthly rainfall variability over the R1 (NWI) region

Figure 5 a represents the monthly rainfall variability over region R1 during the period of 1986–2010. This temporal plot of rainfall over the R1 region depicts the behavior of monsoon rainfall during 1986–2010 through the observed data of IMD. During the June and September rainfall distribution, extremes and variability were very high, and hence, the simulation of the rainfall pattern during the onset and withdrawal month is more important for the study. In June, IMD extremes reach up to 5 mm/day rainfall which is well explained by the model output of Kuo and Grell schemes but with positive biasness. The Mix98 and Mix99 schemes show less data distribution but they depict lowest mean biases and RMSE values. During July and August, observed dataset shows the extreme rainfall value of 10 mm/day and these extreme rainfall behaviors in the northwestern part of India. It may be due to spatial changes in Indian summer monsoon circulation characterized by the strengthening of the Arabian Sea branch and weakening of Bay of the Bengal branch (Jones et al. 1986). The RegCM-4.3's three schemes, Kuo, Grell, and Mix99, show high disperse rainfall data which overestimates the observed rainfall dataset during July and August from Figs. 5b, c and 6a, b. Besides, the fact that the Mix98 scheme shows less variability in data shows the lowest mean bias and RMSE value for July and August. The summer monsoon rainfall decreases over the R1 region as withdrawal started. One of the schemes of RegCM-4.3, i.e., Mix99, well simulated the extreme variability of rainfall with the lowest mean bias and RMSE value (− 1.0 and 3.9 respectively). The Tiedtke and Emanuel schemes show very less distribution and variability in rainfall data over the 25-year temporal plot of summer monsoon rainfall. Hence, the Grell scheme is much better than all other schemes of RegCM-4.3 over the R1 region.

3.3.3 Monthly rainfall variability over the R2 (NCI) region

The monthly summer monsoon rainfall variability and distribution of IMD and model-simulated rainfall over region R2 are explained in Fig. 5b for the 1986–2010 period. In the R2 region, i.e., northcentral region, the major monsoon impacted the region of central India, and the Indo-Gangetic plain (IGP) has been covered. This region is important as an agro-economic zone of India and several studies have been done regarding monsoon variability. The modulation of summer monsoon behavior using observed and model-simulated rainfall over the R2 region during June and July is explained in Fig. 5, and its validation is shown in Fig. 6c–d using mean bias and RMSE. During the months of June and July, the variability of the rainfall model data with the observed dataset is high. The Grell scheme shows a better representation of data distribution with a low negative mean bias (− 1.0), and Grell and Mix99 show the lowest RMSE, i.e., 2.8. Three schemes of RegCM-4.3, i.e., Emanuel, Tiedtke, and Mix98, show the maximum negative mean bias in the dataset with the observed rainfall. The convection schemes, Tiedtke and Emanuel representation of rainfall data, are very poor in the R2 region. The variability of actual

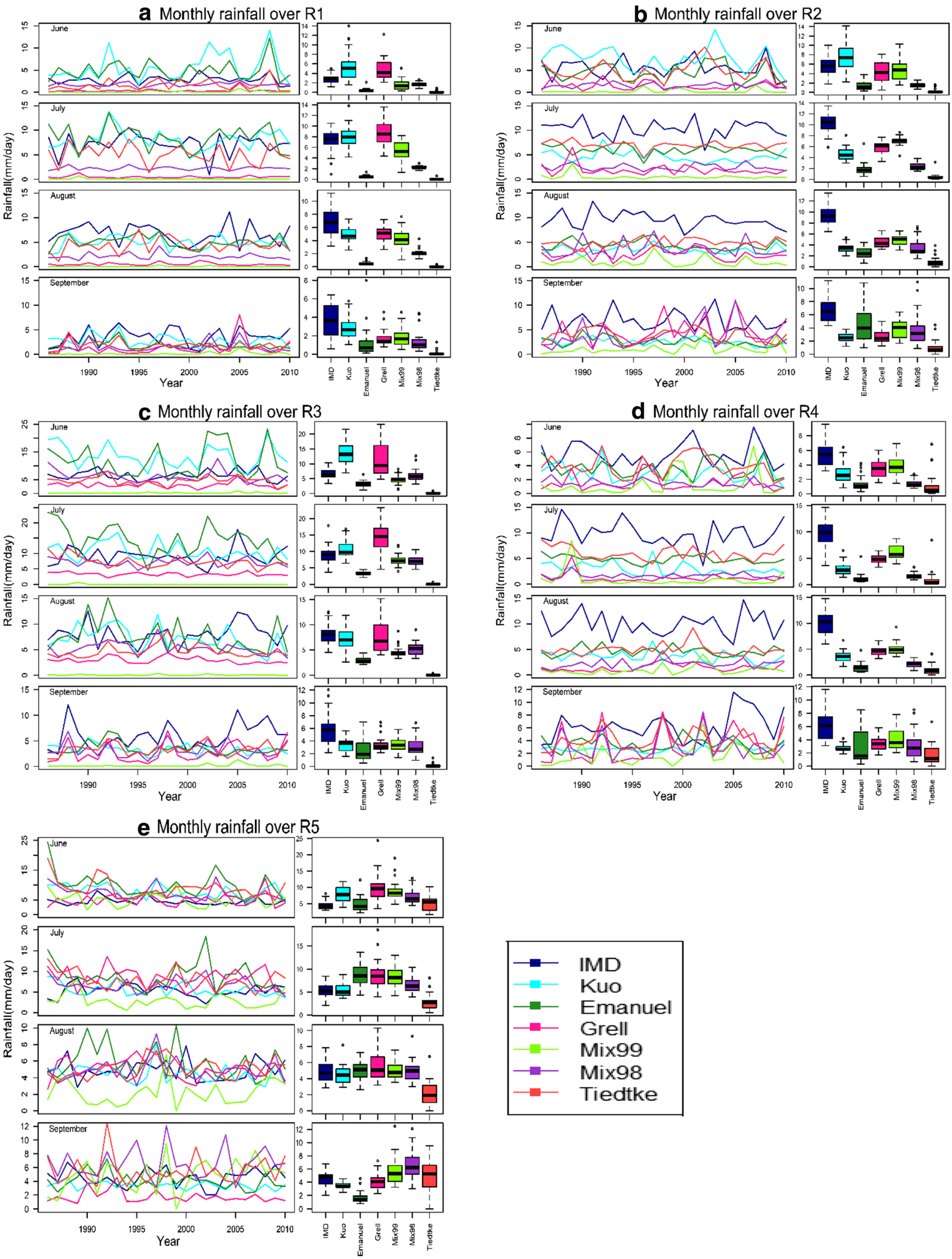


Fig. 5 **a–e** Monthly rainfall variation and distribution over five homogeneous regions of India during 1986–2010

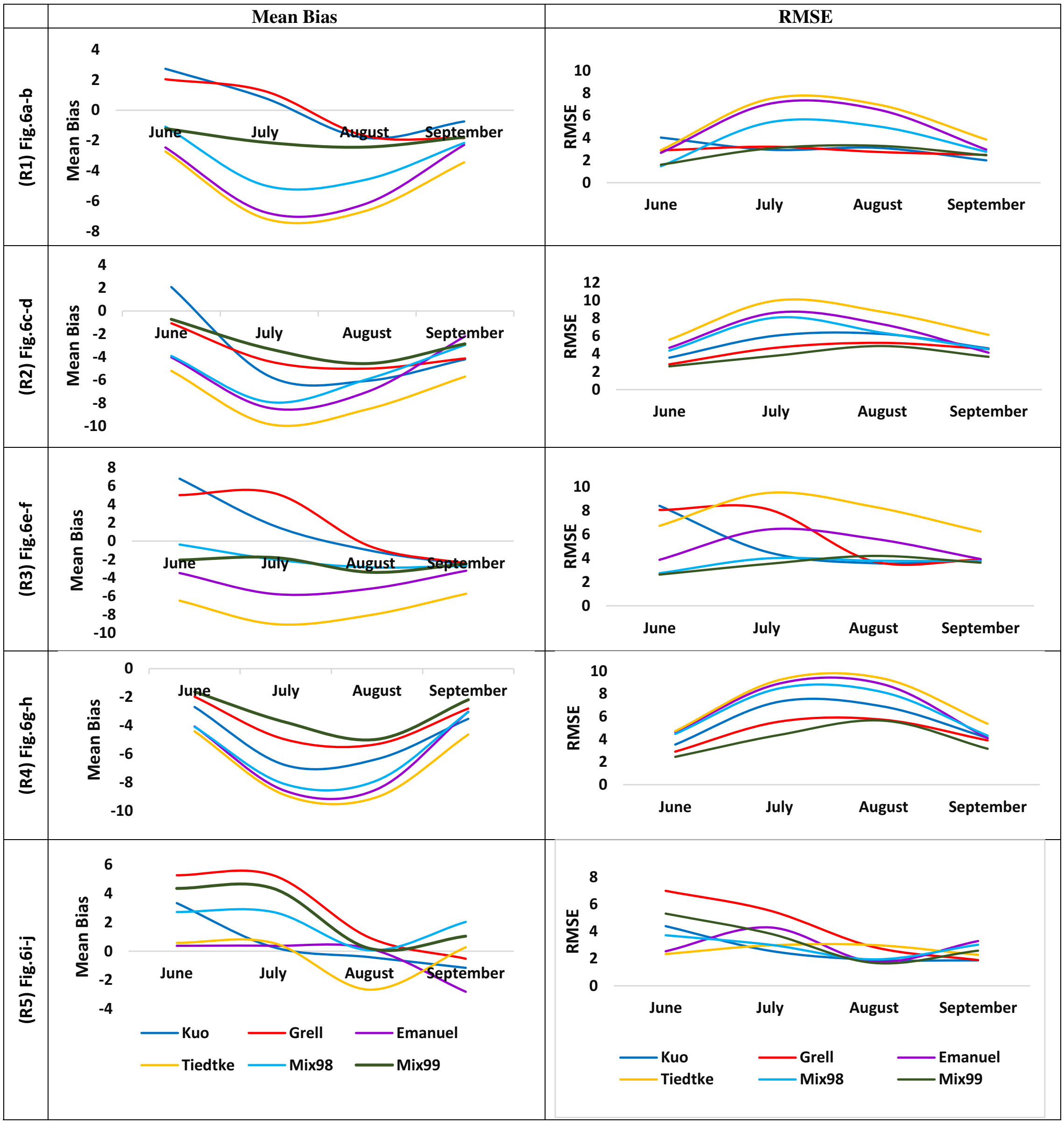


Fig. 6 **a–j** Monthly variation of mean bias and RMSE for Indian summer monsoon rainfall over five homogeneous regions of Indian subcontinent

rainfall series from 1986 to 2010 is well captured by Grell and Mix99 with the lowest mean bias and RMSE value in July. During August and September, the maximum variability of ISMR is observed; due to this, all the schemes of RegCM-4.3 show a large negative biasness from the observed dataset. In the month of August, Mix98 well represent the variability, extreme, and distribution of data. Except for Mix98, all the schemes show large biasness and hence not suitable for considering the simulation of ISMR. In the September month, due to high variability and high rainfall value (12 mm/day), the model performance was impacted. Over the region R2, simulations of Kuo and Grell schemes are good in comparison with other schemes. Hence, the model prediction/simulation is quite sensitive with extreme rainfall cases or with high variability of rainfall.

3.3.4 Monthly rainfall variability over the R3 (WPI) region

The summer rainfall distribution and variability of region R3 are simulated by six CPS schemes of RegCM-4.3 during June, July, August, and September with observed IMD rainfall data in Fig. 5c. The region of Western Ghats near Arabian Sea encompasses one of the peninsular regions of India known as the western peninsular India. The monsoon propagation over the Western Ghats is mainly determined by the performance of Arabian branch which plays a dominant role in the monsoon activity over the west coast of India. In the month of June, IMD rainfall distribution is very less, and in the peak monsoon months, July and August, rainfall distribution wide spreads over the R3 region as seen from the box plot. As compared with the observed precipitation, Mix98 and Mix99 schemes show more reasonable summer precipitation with less biasness in the range of − 0.3 to − 3.0 and low RMSE value in the range of 2.6–4.0 mm/day during June, July, August, and September. Other schemes such as Kuo and Grell show very high positive mean biasness with high RMSE value. This overestimation of Grell scheme also impacts the performance of mixed convection schemes such as Mix99 and Mix98, whereas mixed convection scheme performance is better over the R1 and R2 regions. It is observed that Emanuel reasonably well simulates the monsoon rainfall circulation and sufficient convection over Arabian Sea during September, which leads to producing better precipitation over the windward side of Western Ghats as compared with other schemes (Figs. 4 and 6e–f). Except for Grell and Kuo schemes, all the others schemes underestimate the rainfall during 1986–2010 which is shown in Figs. 5c and 6e–f. The observed rainfall shows unexpectedly high variability and extreme precipitation (12 mm/day) as compared with the model output during September. It is observed from the analysis of rainfall that whenever extreme cases of rainfall occur, the overall model performance gets affected to simulate the actual rainfall. Besides the fact of high biasness in the data, only Emanuel and Mix99 schemes show reasonably good monthly rainfall variability than the other schemes of RegCM-4.3 over the R3 region (Fig. 5c) it might be explained by physical parameterization of the Emanuel scheme which is based on warming-induced increase of atmospheric moisture advection.

3.3.5 Monthly rainfall variability over the R4 (EPI) region

The ISMR variability over the eastern peninsular region (R4) is analyzed with different schemes of RegCM-4.3 during 1986–2010 for the months of June, July, August, and September (Fig. 5d). The monthly variation of monsoon rainfall is very high over the R4 region. The model-simulated summer monsoon rainfall using the Grell and Mix99 schemes during June, July, August, and September is simulated reasonably well with the observed dataset with least mean bias and RMSE. During the initial months of monsoon, June and July, the Mix99 scheme underestimated the rainfall from the IMD rainfall which is also justified by the negative mean biases and least RMSE value. Also, in the months of August and September, Mix99 is the best scheme to simulate summer monsoon rainfall and its distribution pattern among all the selected scheme of RegCM-4.3. The performance of Tiedtke, Emanuel, and Mix98 schemes over the eastern peninsular (R4) are not considerable as compared with the observed rainfall.

3.3.6 Monthly rainfall variability over the R5 (SPI) region

A salient feature of monsoon rainfall over southern peninsular linked with monsoon and post-monsoon rainfall. The southeast peninsula is benefitted by the JJAS summer monsoon rainfall, whereas the southwest peninsula region experiences its wettest season during the post-monsoon rainfall (retreating monsoon) from October to December. Hence, the monsoon distribution mainly concerns with the southeast peninsula region. During June and July, all the schemes overestimate the rainfall simulation with observed IMD rainfall, in which only Tiedtke performance are reasonably good (Fig. 5e) with the lowest mean bias and RMSE values except in the month of August (Fig. 6i, j). The unique ability of deep convection and entrainment process in the Tiedtke scheme may be the region behind the better performance of the Tiedtke scheme with moderate rainfall distribution. The reason for less rainfall simulated by Tiedtke scheme is well explained by the slow convective process which decreases the ascending motion of the air before the condensation level and creates less precipitation (Ali et al. 2015) possibly due to less surface latent heat flux and entrainment. This is the reason why the seasonal variation of the Tiedtke scheme results is closer to the observed data during June, July, and August. The variability and distribution of observed rainfall increases during August and September (Fig. 5e). Among the six CPSs of RegCM-4.3, performance of Tiedtke scheme improved in observing the temporal and spatial distribution of summer monsoon rainfall over the southern peninsular region.

Overall, the spatial and temporal behavior of summer monsoon rainfall over India and its different meteorological homogeneous region is very complex and unique in nature. Hence, the simulation of monsoon rainfall with the six CPSs of RegCM-4.3 is dependent on the homogeneity of the climate and topography. Several studies based on the sensitivity experiment on the selection of best convection scheme over a region highlight that no single convective parameterization scheme can perform best due to their geographical and atmospheric system. The convective parameterization schemes are sensitive to the topography, atmospheric condition, etc., and it is a complex task to estimate the good agreement between model result and observation as the result of the various models or its schemes have not shown a single result for all regions and climate variables. So, the better way to describe the agreement is to choose the single field, such as precipitation, and analyze the performance of each convective scheme using various validation and verification techniques. The observed climate change in India is very complex to understand because of topographical differences and complex interaction between natural and anthropogenic sources at different temporal and spatial scales. Therefore, to understand the past, present, and future climate change studies, a seamless dynamical downscaling of global climate data and evaluation of model performance is necessary for the climate research group.

4 Conclusions

The analysis includes the performance and validation of RegCM-4.3 in capturing regionalized rainfall over the Indian subcontinent. The analysis is done over five homogeneous regions of India, i.e., R1 (NWI), R2 (NCI), R3 (WPI), R4 (EPI), and R5 (SPI), during the climatological period 1986–2010. The rainfall variability over Indian homogeneous regions is well captured by Grell CPS over the R1 region, consisting of semiarid/desert part of Gujrat and Rajasthan which contributes the least rainfall among the entire homogeneous region. The northcentral India, which comprises the best fertile land of Indo-Gangetic plain, receives a maximum average monsoon rainfall over this region, and the predictability/simulation by Grell and Kuo are the best CPSs among the all convection parameterize schemes of RegCM-4.3. Over the maximum rainfall region over western and eastern peninsular regions of India such as R3 and R4, Emanuel and Mix99 schemes' simulations are the best fitted in simulating the ISMR respectively. The performance of mixed convection scheme to simulate monsoon rainfall over southern peninsular region is comparatively better than the single Grell or Emanuel CPSs (Ali et al. 2015). Over the southern peninsular region of India, performance of Tiedtke is reasonably good with a significant correlation, least mean bias, and RMSE value among all schemes, i.e., 0.5, − 1.1, and 1.5 mm/day respectively. Over three peninsular regions such as the western peninsular region (R3), eastern peninsular region (R4), and southern peninsular region (R5), each scheme has different performance. One more finding is observed in simulating ISMR by the help of ECDF plot which shows the incapability of model performance in predicting/simulating heavy and extreme rainfall over NWI, NCI, and WPI regions and, whereas, simulation of low rainfall is affected in the region eastern and southern peninsular India, i.e., R4 and R5. This contrasting nature in the simulation of monsoonal rainfall is mainly affected by the topographical difference of Indian subcontinent which causes the regionalize difference in simulating monsoon rainfall.

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