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Long-term simulation of daily rainfall across India: Performance of cumulus convection schemes in regional climate model during southwest and northeast monsoon

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ABSTRACT

The performance of Cumulus Convection Schemes (CCSs) in Regional Climate Model (RCM) is investigated for the long-term (34 years) simulation of daily rainfall over different Homogeneous Monsoon Regions (HMRs) of India. Characteristics of both southwest monsoon (aka summer monsoon) and northeast monsoon (aka winter monsoon or return monsoon) are analysed while assessing the performance. Indian monsoon is largely affected by climate change and studies demand a long-term (climatological scale) simulation and analysis. Furthermore, the vast study area consists of wide variation of topography and climatology that cause variation in best performing CCS across the HMRs. Month-wise and season-wise performances of different CCSs, namely Grell, and its combinations with Emmanuel as mixed schemes, such as Grell over Ocean and Emmanuel over Land (GOEL), and Grell over Land and Emmanuel over Ocean (GLEO) are assessed by using these schemes in the Regional Climate Model Version 4.4 (RegCM4.4) over a span of 34 years (1982 to 2015). The spatio-temporal variation of bias, investigated using the observed and simulated rainfall, shows more realistic performance for the peak monsoon months and positive bias during onset and retreating monsoon. Additionally, the spatio-temporal variation over the HMRs is investigated and the best possible CCS or a combination of CCSs is recommended. The better ability of mixed schemes in simulating the summer monsoon is noticed, particularly late monsoon, as compared to the early monsoon. Furthermore, GOEL performs best as compared to others to capture the spatial variation including peninsular India. The spatial distribution of observed rainfall during return monsoon is also well captured by the mixed schemes. However, GLEO scheme is found to be the best during return monsoon.

1. Introduction

The South Asian monsoon is a system of trade winds characterized by seasonal reversal from northeast to southwest. The Indian monsoon has two phases: i) begins in June and covers most of India until September, referred to as the southwest (aka summer monsoon) and ii) from late October to December, referred to as the northeast (aka winter monsoon or return monsoon). Southwest monsoon contributes to more than 75% of the annual rainfall over India with spatial variation (Webster and Yang, 1992; Parthasarathy et al., 1993; Yadav et al., 2017; Dash and Maity, 2019). During the summer monsoon (June–September) the eastern regions (Orissa, Chhattisgarh and West Bengal) receive majority of rainfall due to monsoon trough and the Western Ghats and the northeast region receive orographic rainfall (Maharana and Dimri, 2014). On the other hand, northeast monsoon contributes to precipitation in the northern region during winter (December–February) and in the southern region during the post-monsoon period (October–November). Approximately, 55% percent of the population depends on the summer monsoon rainfall for agriculture. The unique geographical and topographical features of the Indian subcontinent, along with associated atmospheric and oceanic factors, influence the behaviour of the monsoon (Maity and Nagesh Kumar, 2006, 2008). These factors also contribute to the high spatio-temporal variability of the precipitation. Such variability is experienced as some parts of the country are affected by floods whereas the other parts suffer from drought simultaneously (Krishnan et al., 2020). Capturing such spatial variability in the Indian

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monsoon is challenging for the simulation models and requires a detailed scrutiny of the modelling schemes, different parameters and the climatic inputs (Kakade and Kulkarni, 2016; Dutta and Maity, 2020).

Numerous studies have been conducted to understand the mechanism and physical processes of the Indian monsoon for last couple decades and still being continued (Shukla and Paolino, 1983; Webster et al., 1998; Goswami et al., 1998; Goswami and Ajaya Mohan, 2000; Lal et al., 2000; Singh et al., 2007; Maity et al., 2007; Rajeevan et al., 2008; Wang et al., 2015; Guhathakurta et al., 2015; Kakade and Kulkarni, 2016; Kishore et al., 2016; Devanand et al., 2018a; Dutta and Maity, 2018; Bhate and Kesarkar, 2019; Suman and Maity, 2020). Modelling of Indian monsoon is indeed a challenging task due to the lack of comprehensive understanding of the interactions between small scale processes and large scale oceanic/atmospheric circulations (Ajaya Mohan and Goswami, 2003; Maity et al., 2007; Kashid and Maity, 2012). General circulation models are mostly unable to capture the inter/intra seasonal variation of monsoon rainfall due to their coarse resolution and inability to simulate small scale physical processes (Gadgil and Sajani, 1998; Goddard et al., 2003), specially at finer spatial resolution (Krishna Kumar et al., 2005; Pattanaik and Kumar, 2010; Mohanty et al., 2018). For improved simulation of the monsoonal circulations, it is required to have a modelling system that can accurately represent the sub-grid scale physical processes like convection, particularly over the tropics where it plays a major role in monsoon dynamics. For this, the Regional Climate Models (RCMs) can be effectively used as it describes and simulates the climatic features that act at local scale, more so for regions with complex topography (Ratnam and Krishna Kumar, 2005; Devanand et al., 2018b). The RCMs have a wide range of applications starting from process-based studies of climate to future projections for impact and adaptation studies (Jacob and Podzun, 1997; Huntingford et al., 2003; Jha et al., 2004; Bhaskaran et al., 2012). Such models have been found to potentially add value to the simulations of monsoon circulations over the Indian domain (Kang and Hong, 2008; Srinivas et al., 2015; Nayak et al., 2017; Martínez-Castro et al., 2018; Kumar and Dimri, 2020). Regional Climate Model (RegCM) is one of the popular RCMs that was originally developed by National Center for Atmospheric Research (NCAR) and different generations of the same have been developed over the years (Gao and Giorgi, 2017). Studies have attempted to simulate the climatology of different hydrologic variables like precipitation and temperature for a time period of 25–30 years over the India region using different versions of RegCM (Maurya and Singh, 2016; Nayak et al., 2019). Efforts have also been made to simulate Indian Summer Monsoon (ISM) using RegCM through Coordinated Regional Climate Downscaling Experiment (CORDEX) over South-Asian domain (Sinha et al., 2013; Bhatla and Ghosh, 2015; Dash et al., 2015; Raju et al., 2015; Bhatla et al., 2016; Maharana and Dimri, 2016).

RCMs use different types of Cumulus Convections Schemes (CCSs), which directly affects its performance in simulating the precipitation intensity, pattern, and inter-annual variability (Pal et al., 2007; Bhatla et al., 2016). Selection of the CCS is a major issue in RegCM since it differs significantly depending on the simulation period, the physical interactions and the region, and no specific scheme is uniquely found to be the best considering all the issues (Kang and Hong, 2008). Studies have established the sensitivity in simulation of Indian monsoon using RegCM with different CCS (Bhatla et al., 2016), particularly for the core monsoon regions where monsoon dynamics is largely influenced by convection (Dash et al., 2006; Sinha et al., 2013; Ghosh et al., 2018).

A number of schemes have been developed over the years and several studies have attempted to understand the sensitivity of different CCS in the simulation of the Indian monsoon (Mukhopadhyay et al., 2010; Devanand et al., 2018a). A detailed review on the performance of different schemes used for the Indian domain can be found in Sinha et al. (2019) and Kumar and Dimri (2020). A recent advancement in this field is the use of mixed convection schemes, i.e. one scheme for land and another for ocean (Sinha et al., 2019). Previously, Giorgi et al. (2012) suggested that using a combination of Grell over land and Emanuel over ocean, might be suitable for climate simulation over multiple regions. Sinha et al. (2013) also carried out sensitivity analysis using two different resolutions and multiple convection schemes. The RegCM version 4.4 (hereinafter RegCM4.4) contains five CCS namely, Grell, Kuo, Emanuel, Kain-Fritsch and Tiedtke, and facilitates the use of different schemes for the land and ocean. Raju et al. (2015) has compared the performance of Emanuel, Grell, and Tiedtke cumulus scheme with Grell over the ocean and Emanuel over the land and concluded that mixed scheme simulates the southwest monsoon precipitation better in terms of intensity and spatial distribution. Maity et al. (2017) conducted a study using Kuo, Grell, Emanuel, Grell over ocean and Emanuel over land and Grell over land and Emanuel over ocean and suggest better performance of the mixed schemes and Emanuel scheme in simulation of rainfall and monsoon circulations, respectively. However, the study by Ghosh et al. (2018) shows that the mixed scheme, Emmanuel over ocean and Grell over land performs better in the core monsoonal region as well as monsoon convergence zone in simulating synoptic features during the phases of summer monsoon. Further, comparing the performance of different mixed schemes, Sinha et al. (2019) carried out a study using ten combinations of four different CCS namely Grell, Emanuel, Tiedtke, and Kain-Fritsch. This study suggests that the Tiedtke/Emanuel scheme over land with Grell over ocean performs better in simulation of ISM rainfall. Though these studies have exhaustively compared the performance of the different cumulus schemes and their combination for the summer monsoon months, the second phase of the monsoon i.e. the northeast monsoon has not been considered.

Further, owing to the spatial variability in the Indian monsoon rainfall, relative performance of different CCS in RegCM have been carried out at various spatio-temporal scale. Pattnayak et al. (2013) used RegCM (version 3) to produce regional precipitation characteristics of the six Homogenous Monsoon Regions (HMRs) and further reported that the surplus moisture flux over the Arabian Sea caused the prolonged rainy season in the model. Maharana and Dimri (2014) also used the RegCM (version3) model to capture the temporal variation in precipitation over India and the different homogeneous monsoon regions. This study shows the ability of the model to capture the sub-regional contribution to the total precipitation and the variation in performance of the model from region to region. Nayak et al. (2017) attempted to customize the RegCM (version 4) model for the Indian domain at the regional scale by considering two land surface schemes and three CCS namely, Kuo, Grell and Emanuel. Overall the study concludes that different regions and seasons respond variedly to the customization. Recently, Bhatla et al. (2020) showed mixed schemes are better in simulating summer monsoon over Indian homogeneous regions. However, it is important to note that firstly, most of these studies are dedicated to the southwest or summer monsoon rainfall over the Indian mainland and secondly, the time period of analysis varies from 10 to 15 years. Owing to the impact of the CCS on the model performance and high spatio-temporal variability in the rainfall over the Indian domain it is vital to assess the performance of the model considering both southwest and northeast monsoon seasons and a long-term simulation is mandatory to capture the climatology. This forms the motivation for the present study.

The objective of this study is to carry out a long-term simulation of daily rainfall across India to investigate the relative performance of different CCSs in RegCM4.4 to capture the long-term climatology during both southwest monsoon (June, July, August and September) and northeast monsoon (October, November and December). A continuous run of 34 years (1982–2015) is carried out and the RegCM4.4 is customized for the five homogeneous monsoon regions of India in terms of different CCSs. The climatology of both southwest and northeast monsoon over the Indian domains as well as the variability over five HMRs is studied using all the aforementioned schemes. The paper is arranged as follows: Section 2 gives a description of the regional climate model and the salient features of RegCM4.4 with different possible CCS.

A brief description of various data sets and methods used are given in Section 3. The results of model simulation are presented in Section 4 and the summary and conclusions with recommendations are provided in Section 5.

2. Model description

A stable version of RegCM, i.e. RegCM 4.4, built upon the hydrostatic version of the National Center for Atmospheric Research (NCAR)/Penn State Meso-scale Model MM5 (Grell et al., 1994), acquired from the Earth System Physics (ESP), Abdul Salam International Center for Theoretical Physics (ICTP), Italy, is used in this study. The Planetary Boundary Layer (PBL) are parameterised using Holtslag Scheme (Holtslag et al., 1990), land surface using Biosphere Atmosphere Transfer Scheme (BATS; Dickinson et al., 1993), and radiation represented by modified NCAR Community Climate Model version 3 (CCM3; Kiehl et al., 1996). Other than this, it has schemes for fluxes in the ocean, aerosol and 1 D thermal lake model is reactivated which can be utilised for various regional settings. Another major advancement in the version 4 of RegCM modelling framework is the division of the precipitation into two parts, namely non-convective (grid-scale) and convective (sub-grid scale). The non-convective precipitation, also known as large/resolved scale precipitation, is defined using the sub-grid explicit moisture scheme (SUBEX; Pal et al., 2000) while the convective precipitation (sub-grid scale) is represented using different CCSs explained later in this section. The SUBEX scheme links the cloud fraction and cloud water to the average humidity of a grid and, as the name suggests, it deals with the variability of clouds in each subgrid and the precipitation produced by a CCS underlines the effects of convective clouds in subgrid scale.

Three major CCSs are available in RegCM (version 4) to represent sub-grid scale precipitation as mentioned above. They are MIT Emmanuel Scheme (Emanuel, 1991), Grell (Grell, 1993; Grell et al., 1994), Kuo (Anthes, 1997). The performance of Kuo scheme in simulating ISM is extremely poor in high resolution (Sinha et al., 2013); and therefore we use Grell and Emmanuel schemes in our study. Another major advancement in RegCM4.4 is that we can choose different CCSs over land and ocean (mixed scheme) rather than making use of single CCS over the entire domain. Therefore, in addition to the three major schemes, we have two mixed schemes, such as Grell over Ocean and Emmanuel over Land and Grell over Land and Emmanuel over Ocean. In the MIT-Emanuel scheme (Emanuel, 1991), convection starts when the level of buoyancy is beyond the base of the cloud. The Grell scheme (Grell, 1993) is a mass flux deep convection parameterization in which clouds are represented as two steady state circulations that is, an updraft and a downdraft. Convection is set off when a parcel ascent in the updraft sooner attains the moist convection level. These are the two commonly used CCSs; they differ in how convection is triggered and represented in the modelling framework. While the former scheme enables only a single updraft or downdraft, the latter enables numerous convective drafts and episodic mixing in clouds. It was also reported that the combination of using two different schemes on land and ocean may improve the performance of the model (Giorgi et al., 2012; Gao et al., 2016; Li et al. Bin et al., 2016; Maity et al., 2017; Lui et al., 2018). The model description and various schemes employed in this study are mentioned in Table 1. Salient features of CCSs employed in this study are provided in Table 2. The domain of analysis is selected such that the focus mainly lies on the land areas as compared to the ocean areas.

3. Data and methodology

RegCM4.4 is used for simulation of rainfall considering three CCSs: (i) Grell scheme over both Land and Ocean, (ii) Grell over Ocean and Emmanuel over Land (GOEL) and (iii) Grell over Land and Emmanuel over Ocean (GLEO). For integration of the model, ten grid points in the lateral boundary are designated for the buffer zone where the exponential nudging technique is employed to incorporate the model fields and the boundary conditions (Giorgi et al., 1993). Initial and boundary conditions for the RegCM4.4 are obtained for every 6 h from ERA-Interim Reanalysis (EIN15), with a horizontal grid of 1.5° latitude/longitude (EIN15) and 37 levels in the vertical where in the 12 h 4D-Var data assimilation and improved model physics are employed when compared with ERA-40 reanalysis. The Optimum Interpolation (OI) weekly Sea Surface Temperature (SST; Reynolds et al., 2002) data from National Oceanic and Atmospheric Administration (NOAA) are used for SST forcing for all the simulations. The topography and land-use data are acquired from the United States Geological Survey (USGS) and Global Land Cover Characterization (GLCC).

Table 1
Model configuration used in RegCM4.4.

Configuration	Description
Dynamics	Hydrostatic
Model Domain (Latitude and Longitude range)	0° – 34°N, 64° E – 106°E
Horizontal/Vertical Resolution	50 km/18 σ levels
Initial and Boundary conditions	ERA-Interim Reanalysis (EIN15)
Sea Surface Temperature	Optimum Interpolation (OI) weekly Sea Surface Temperature (SST; Reynolds et al., 2002)
Land Surface parameterization	Biosphere Atmosphere Transfer Scheme (BATS; Dickinson et al., 1993)
Planetary Boundary Layer parameterization	Holtslag
Cumulus Convective Scheme	i) Grell ii) GOEL, Grell over Ocean and Emmanuel over Land iii) GLEO, Grell over Land and Emmanuel over Ocean
Validation	IMD gridded rainfall data (0.25° x 0.25°)

Table 2
Salient features of cumulus convection scheme.

Scheme	Emmanuel	Grell
Trigger Condition	Level of buoyancy is higher than the cloud base level	Lifted parcel attains moist convection
Assumption	Quasi equilibrium of updraft	Arakawa and Schubert (Grell et al., 1994) which relates the convective fluxes and rainfall to the tendencies in the state of atmosphere
Precipitation reference schemes	One updraft and one downdraft (Emmanuel 1991)	One updraft and one downdraft (Grell, 1993)

The model simulation is performed from December 01, 1981 to December 31, 2015. Leaving first month as the spin up time for the model, the simulation from January 01, 1982 to December 31, 2015 (34 years) is considered in further analysis and assessment of the model performance. Fig. 1 shows the extent of analysis domain (0° – 34°N, 64°E – 106°E) along with the topography. The inner box denotes the portion of Indian subcontinent used for analysis. It is indeed true that a larger domain is always better. However, since we target a long-term daily simulation of 34 years (much longer than many other studies) to investigate the climatology, we had to limit the domain size to optimum to avoid huge computational requirements. Still, the domain size is adequate to represent both the southwest and northeast monsoon without increasing the computational demands. Of course, the effect of domain size in future studies upon availability of better computational resources may be explored.

Though the precipitation from January 1982 to December 2015 has been analysed, the southwest monsoon, i.e. June, July, August and September (JJAS) and northeast monsoon, i.e., October, November and December (OND) are presented. Furthermore, the five HMRs, as specified by Indian Institute of Tropical Meteorology (IITM), Pune, have been used to test the sensitivity of the schemes to Indian monsoon over

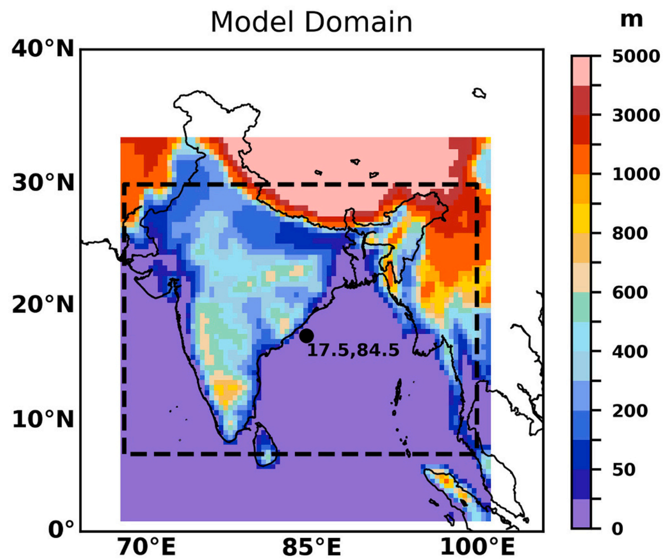

Fig. 1. Model domain and topography (in meters). The dashed line indicates the region used for analysis with the centre location marked by a black dot showing its latitude and longitude.

different regions for all the monsoon and non-monsoon months. These regions are Central North East (CNE), North West (NW), Southern Peninsula (SP), West Central (WC) and North East (NE) (Fig. 2).

4. Results and discussions

4.1. Performance of different convection schemes during southwest monsoon

In this section, performance of the CCSs, namely Grell and the mixed scheme - GOEL and GLEO, in simulating the rainfall are discussed for the southwest monsoon months (June–September). In order to evaluate systematic bias of the different convective schemes, rainfall simulation using each scheme is compared with IMD observed data. The climatology of IMD observed rainfall is shown in Fig. 3. The rainfall climatology reveals that the highest rainfall is observed in the month of July, close to 60 mm/day, over the west coast near Karnataka and Goa and in August it is around 50 mm/day over the same regions. Observed rainfall reveals strong precipitation belt along the west coast of India and over northeast India. The intensity of rainfall over north India along the Himalayas is also an important feature of southwest monsoon as monsoon trough movement to the south and north from the normal position decides the active and break conditions of the monsoon season. The spatial distribution of precipitation bias (CCS-IMD) for three different schemes during June to September is presented in Fig. 4. In general, the simulated rainfall obtained using all the three CCS closely follows the magnitude of observed rainfall during the southwest monsoon season. The high rainfall regions, such as west coast regions, during the south west monsoon are well captured in the simulations as noticed from Fig. 4. However, there is significant difference between the convective schemes in reproducing the spatial variation. Overall, the first mixed scheme (Grell over both land and ocean) over-estimates the rainfall at many places, particularly in June. Furthermore, overestimation is noticed in south India particularly in the Western Ghats, whereas under-estimation is noticed during peak monsoon (July and August) in most of the north and northeast India. This might be due to strong upward motion reaching moist convection levels.

All the schemes overestimate the rainfall over west coast with a positive bias of about 20 mm/day, however, the spatial extent of overestimation is minimum in case of GOEL considering all monsoon months. In June and September, the GOEL scheme yields less bias for almost all the parts in India except west coast and some pockets in the northeast. In peak monsoon months (July and September), a wet bias is noticed in peninsular India and dry bias in the northern and central part of India and some pockets in the northeast. The extent of such regions with dry bias as well as wet bias is much higher in case of GLEO. However, GLEO performs better in northeast regions. Almost all the schemes perform more or less equally well in the low rainfall northwest region. Particularly, the GOEL scheme yields almost zero bias in the northwest and west central regions in June and September. Its performance in July and August is also good over the Gangetic plains. The dry and wet bias for the season lies in the range of [−5, 5] mm/day considering most of the regions except the Western Ghats and some parts of northeast India. Interestingly, all the schemes are fairly successful over the plain areas and not so successful in hilly/mountainous terrains. This could be attributed to the strong local orographic effect over the mountainous regions (Xie et al., 2006). Furthermore, GOEL scheme yields bias that closely follows the orography (as shown in Fig. 1) in the west coast while the other two simulations have higher bias values in places over coast with lower altitudes. Among all four months, performance in September is best for all the schemes.

The observations made by other studies that have carried out similar analysis using RegCM4, but for much shorter time span, are as follows. For instance, Maity et al. (2017) simulated rainfall and other climatic variables over the Indian domain for the years 2007–2009. The results indicate that rainfall is underestimated by almost all schemes particularly for the central and northwest parts of the country. Further, the mixed schemes simulate the rainfall better as compared to the other schemes. Nayak et al. (2017) simulated rainfall considering a time period of 10 years (1991–2000). The results indicate that the simulation with Grell scheme shows dry bias in the precipitation over southern India. The bias changes from wet to dry when considering Kuo scheme and further changes (increases/decreases) while using some other schemes. Sinha et al. (2019), simulated rainfall over the Indian domain for 15 consecutive summer monsoon seasons (1982–1996). The results indicate that Grell (over both land and ocean) underestimates rainfall over most parts of India except the Western Ghats. Further, the mixed schemes better represent the pattern and magnitude of rainfall with respect to observed rainfall. Considering the Western Ghats and northwest India, the mixed schemes either overestimate or underestimate the summer monsoon rainfall. Recently, Bhatla et al. (2020) simulated Indian summer monsoon over 5 homogeneous regions and found that mixed schemes perform better for almost all regions except Grell for northwest India, which is rain devoid region. Kumar et al. (2020) investigated the performance of RegCM4 with two different global climate model and three land surface parameterization schemes in simulating the ISM for present climate (1975–2005). The moderate events of rainfall are better simulated than heavy precipitation events. The results obtained for the summer monsoon season are in line with the above mentioned findings.

The analysis of simulated experiments for JJAS suggests that the different schemes have intrinsic biases in representing the ISM and the biases are different for different regions over the study domain. In summary, it is noticed that the schemes perform differently from one region to another and from one month to another that motivates to identify the best performing scheme in different regions and months. Here note that, climatology of Indian summer rainfall has inhomogeneity in nature which is mainly associated with the topography of Indian subcontinent (Bhatla et al. 2020). Towards this, different HMRs in India are selected to identify the best performing scheme for different months. However, before that the performance of different convection schemes is analysed during northeast monsoon, also known as return monsoon, which is also significant in many parts of southern India.

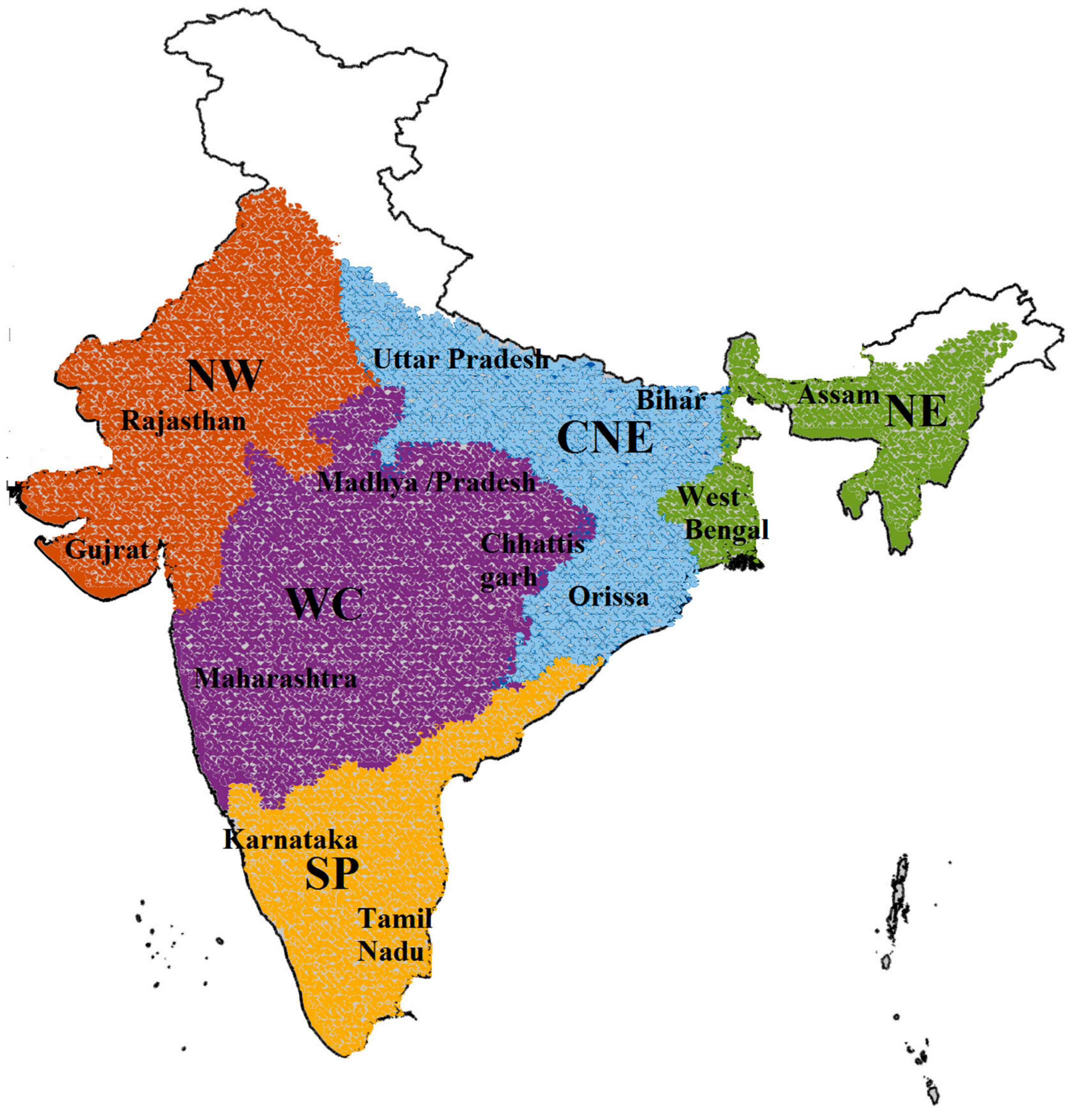

Fig. 2. Map showing Homogeneous Monsoon Regions (HMRs) in India grouped based on the rainfall characteristics (CNE: Central North East, NW: North West, SP: Southern Peninsula, WC: West Central and NE: North East). Additionally, the approximate location of a few state are also shown in the map.

4.2. Performance of different convection schemes during northeast monsoon

The northeast monsoon is limited to certain regions of India. The southern peninsular region in India receives maximum rainfall during the northeast monsoon season. The climatology of observed rainfall reveals (Fig. 5) high precipitation over the peninsular region and along east coast in the range of 4–12 mm/day during these months. The northeast India also receives significant amount of rainfall (upto 12 mm/day) in the month of October. Rainfall is limited to peninsular region during November and December. Eastern side of SP region is the only region in Indian landmass which experience noticeable precipitation during December.

The ability of different CCSs in simulating the return monsoon can be assessed from the bias plots (Fig. 6). Results show that the Grell scheme underestimates the rainfall in October across India. Its performance is better in November but fails to capture the features of return monsoon in the peninsular region. The spatial distribution of observed rainfall is fairly well captured by the mixed schemes. The schemes depict marginal dry bias along the coastal belts of India and over northeast India during October, whereas the GOEL shows wet bias over SP including the west coast, and in pockets of northeast regions. During November, underestimation of rainfall is bounded to southern east coast. As December receives least rainfall in this season, almost no bias is seen in case of all the schemes. Thus, the performance of all the schemes in December is better than October and November. Furthermore, moving to the northern states of Rajasthan, Haryana and Punjab (parts within the study domain), the results indicate very low bias considering the northeast monsoon. As compared to the other parts of the country the intensity of rainfall is lower in these regions during the winter monsoon (as observed from the rainfall climatology), however the model successfully captures the rainfall climatology. Overall, the dry and wet bias for the season lies in the range of [−1,1] mm/day across most of the regions except some of the coastal belts. It is important to note here that non-zero bias is noticed only for the high precipitation regions. Moreover, the bias values are all well within limit for all the three schemes during post-monsoon. Overall, similar conclusions remain as found in summer monsoon months that the schemes perform differently from one region to another and from one month to another. The convective schemes are sensitive to the topography and different atmospheric conditions in different months/seasons. The RegCM4.4 offers a promising performance in representing northeast monsoon, and therefore, it is essential to customize the model performance so as to improve future projections. Our study aims at looking into the performance of RegCM in

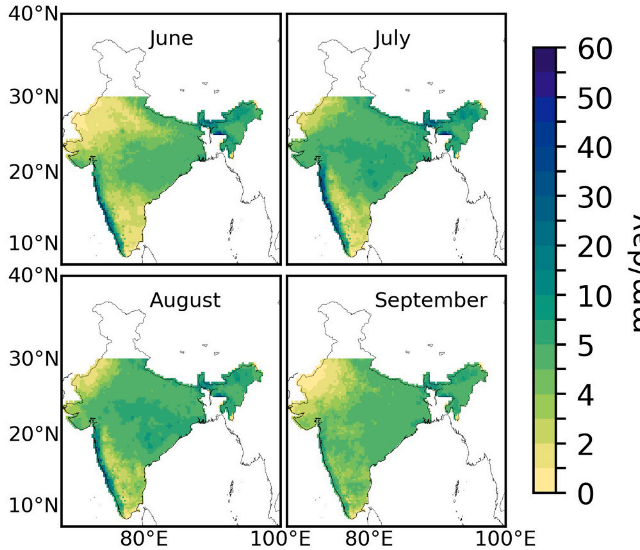

Fig. 3. Climatology of rainfall in mm/day during southwest monsoon period (June to September) from IMD observation.

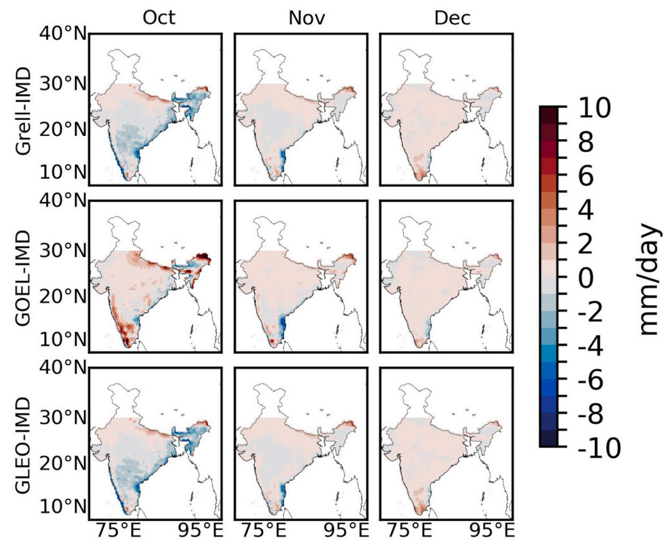

Fig. 6. Same as Fig. 4 but for October, November and December.

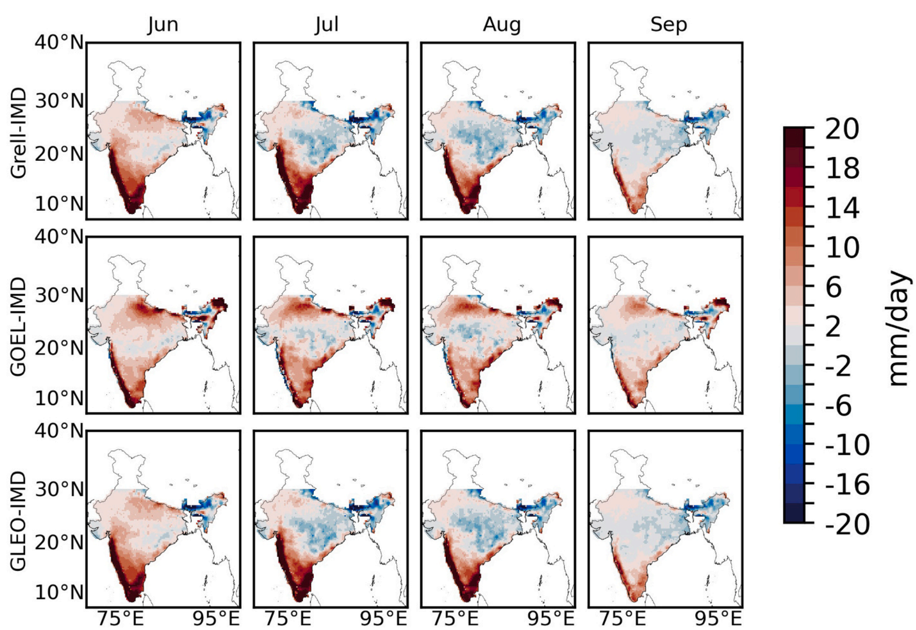

Fig. 4. Spatial distribution of precipitation bias in mm/day during June–September: Grell (Top), GOEL (middle) and GLEO (bottom).

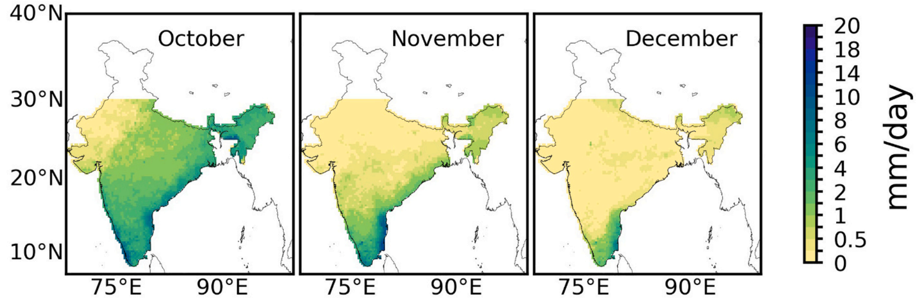

Fig. 5. Climatology of rainfall in mm/day during return monsoon period (October–December) from IMD observation.

simulating the southwest and northeast monsoon using the various convection schemes. Although there are inherent biases in the different regions, the overall performance of the model across 34 years gives us an insight into the overall features of northeast monsoon.

4.3. Inter-annual variability and region-wise performance of the convection schemes

Next, the region-wise performance of the convective schemes considering all the months, divided into three seasons namely southwest monsoon, northeast monsoon and non-monsoon, are investigated. The inter-annual variability associated with the southwest monsoon rainfall for the different HMRs namely, CNE, NW, SP, WC, and NE, are presented in Fig. 7 as a typical plot. From the figure, it is clear that the performance of the schemes differs significantly over different regions. The western coast over the SP region receives majority of the rainfall during the southwest monsoon season. From the figure, it is quite evident that over the SP, the GLEO scheme performs better whereas Grell scheme overestimates the rainfall. Comparatively lower bias is noticed for the GLEO scheme over the SP region. It is in the SP region that the schemes show significant differences in the performance over the years. The domain averaged rainfall for WC and NW regions shows good agreement with observation for all the three schemes and, among the three schemes, GOEL scheme performs the best for most of the months. The differences are less than 5 mm/day over the years. The GOEL scheme performs better than others in simulating rainfall over NE region. The Grell and GLEO schemes slightly underestimate the precipitation over NE region. A probable reason for lower skill of the model when using Grell scheme over land can be due to the fact that this scheme reduces the moisture and energy over the Indian landmasses as compared to the other schemes. Overall, it is seen that mixed scheme performs better across India. A probable reason could be the ability of different schemes is different in capturing the interactions between ocean and land. Thus, a suitable combination in the form of mixed scheme results into better rainfall simulation over the Indian domain. Fig. 8 shows the interannual variability of northeast monsoon over the homogeneous monsoon regions. Though, significant amount of rainfall is confined only to the SP region, the NE region also receives rainfall during northeast monsoon. Unlike the ISM, during the northeast monsoon, the GOEL scheme simulates better over the SP region whereas the GLEO and Grell schemes underestimate the observed precipitation for most of the years.

However, based on the region and month-wise variability in the rainfall it is very difficult to recommend a single scheme for a particular month. Thereby, the recommendation of the best scheme for a particular region in a specific month is made based on the model performance. This is assessed through three performance metrics namely, Root Mean Square Error (RMSE), Standard Deviation (SD) and Correlation Coefficient (R). These statistics are computed using the observed and the simulated rainfall for different regions. For example, considering the Central North East region, the value of R obtained by comparing the observed and simulated data lies in the range of 0.7–0.9 for the months of January, February, March, April and December. However, the performance in terms of R for the rest of the months including the monsoon months is comparatively poorer. On the other hand, considering the NW region the value of R lies within the range of 0.7–0.9 for most of the months including the monsoon season. It is interesting to note that the ability of the RegCM4.4 model to simulate rainfall over the Indian domain varies with the region and season considered.

In order to compare the relative performance of all the three schemes a Taylor diagram is developed. Taylor diagrams are designed to graphically indicate which of the several approximate representations (or models) of a system or process, in this case season-wise and month-wise rainfall simulation, is most realistic by comparative assessment of different models. Fig. 9 shows one such plot for the seasonal rainfall (summation of monthly rainfall for all the months falling in the season) considering the Southwest (June through September) and Northeast (October through December) monsoon. Considering the southwest monsoon, the correlation of the best performing scheme lies in the range of 0.7–0.9 for NW (Fig. 9a). The same for the other regions namely, CNE, SP, WC and NE lies in the range of 0.6–0.7. In general, the mixed

Fig. 7. Time series comparison for area averaged rainfall during southwest monsoon (June–September) for the five Homogenous Monsoon Regions (HMRs).

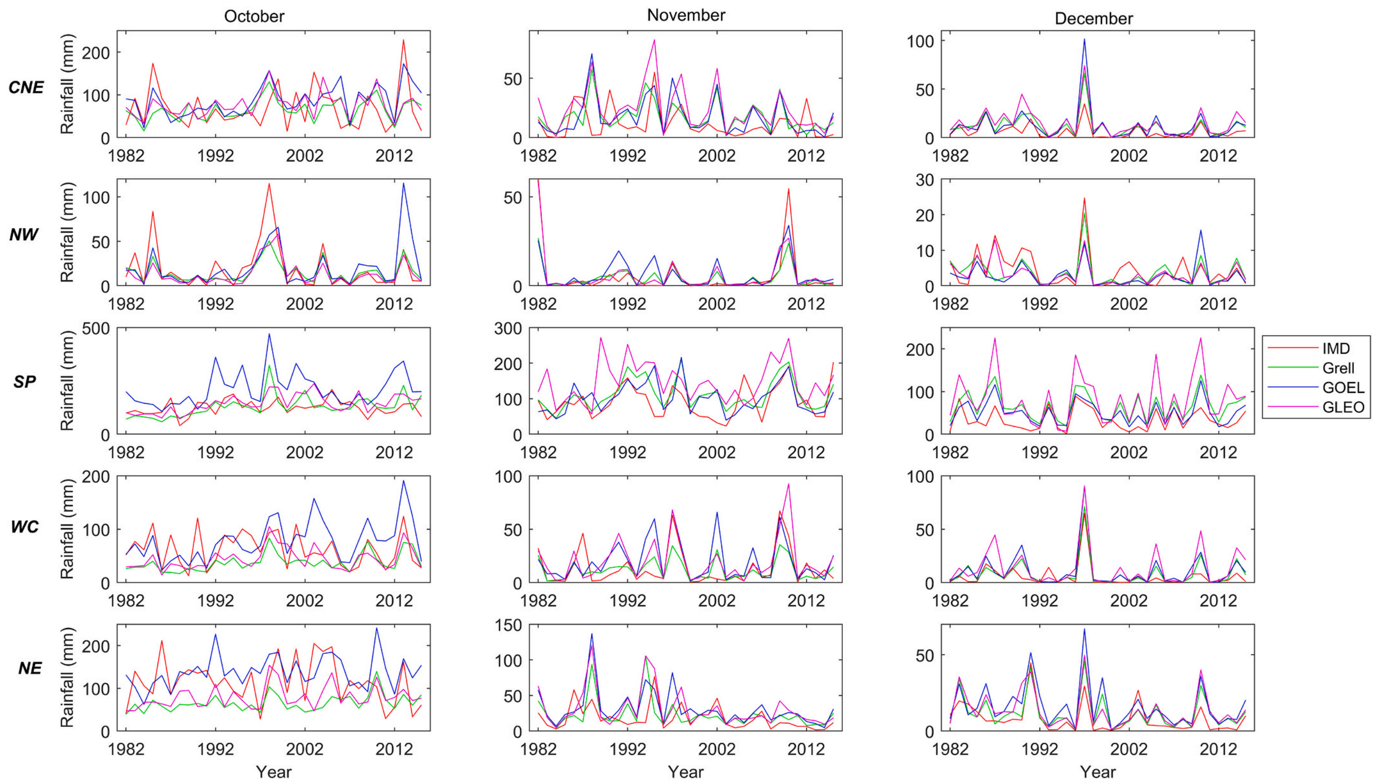

Fig. 8. Time series comparison for area averaged rainfall during return monsoon (October–December) for the five Homogenous Monsoon Regions (HMRs).

schemes (GLEO and GOEL) outperforms Grell. Similar observations are made considering the Northeast monsoon and the highest correlation (lying in the range of 0.8–0.9) of the best performance is observed for NW (Fig. 9b).

Additional performance statistics namely, Index of Agreement (Dr), Nash-Sutcliffe Efficiency (NSE), and Coefficient of determination (R^2) along with Correlation Coefficient (R) and Root Mean Square Error (RMSE) for the Southwest and Northeast monsoon seasons (both month-wise and season-wise) are shown in the Tables S1 and S2, in the supplementary document, respectively. It may be noted that the model performance, considering the SP and WC regions, is comparatively lower. As observed from Figs. 4 and 6, the model bias is high considering the Western coast and the Eastern coast lying in the southern peninsular region. In order to further scrutinize the model performance, HMRs are further subdivided by considering the western coast (WCt) and Eastern coast lying in the southern peninsular region (ECt) as two separate regions. These two regions overlap with the previously defined SP, WC and NW regions and the reduced extent of these regions, on separating out WCt and ECt, are referred to as SPr, WCr and NWr, respectively (Fig. S6). Tables S3 and S4 shows the performance statistics for the above mentioned five regions (SPr, WCr, NWr, WCt and ECt). Results clearly indicate that the model performance improves for SP and WC when the coastal regions are separated, especially for the southwest monsoon season. Thereby, it is interesting to note that in addition to considering the HMRs, further subdividing the regions based on the terrain and local climatology will provide a better insight into the performance of the different CCSs.

Next, Fig. S1, in the supplementary document, shows the comparison of different CCS in simulation of rainfall for the CNE region considering all the monsoon and non-monsoon months. Based on this figure, it may be observed that for the month of June, GLEO scheme gives the best performance as the SD value is closest to that of the observed, the RMSE is minimum and the correlation coefficient is maximum. However, a particular scheme, providing the best performance in terms of all the three statistics, may not be obtained in all the cases. In such cases, the priority is given to RMSE, then to SD and lastly to the value of R. For instance, for the month of November, Grell scheme is selected as the best performer based on the low RMSE value and the closeness to the SD of the observed data, even though the correlation is higher for the other two schemes. The Taylor diagram for all the other regions are provided in Figs. S2 to S5.

Following the above mentioned principles, the best performing scheme is selected for each month in each season considering all the regions. Considering the different HMRs, the best possible scheme for different months, grouped into southwest monsoon, northeast or return monsoon and non-monsoon seasons, is identified. The results show that the CCSs are highly sensitive to the region and the month/season of analysis as the performance significantly differs based on the schemes. Comparing the observed and simulated rainfall in terms of the different test statistics helps to establish the best performing scheme as mentioned in Table 3. It is interesting to note that the best performing scheme is either of the mixed schemes during the southwest monsoon months. For CNE, WC and NE, the mixed scheme GLEO performs best for almost all the monsoon months. For NW and SP, either of the mixed schemes (GLEO or GOEL) is found to be the best performing scheme. On the other hand, Grell over both land and ocean also performs good or equivalent to the mixed schemes during the low rainfall months. However, in many cases, mixed schemes are the best performer for almost all the HMRs. Thus, there exists a spatio-temporal variation in the best performing CCS and this specific information on the month/season-wise and region-wise CCS are expected to be useful in future simulation of rainfall considering its inherent spatio-temporal variation. Before concluding two issues are worthwhile to mention as a future scope of this study with the availability of better computational resources. First, an optimum domain size was considered in this analysis that can be extended to a larger domain with finer spatial resolution. Secondly, the spin-up period, which is considered as one month, can be optimized for the selected domain and additional parameterization schemes, such as land surface and radiation, can be considered with a goal to reveal more insights at finer spatial resolution.

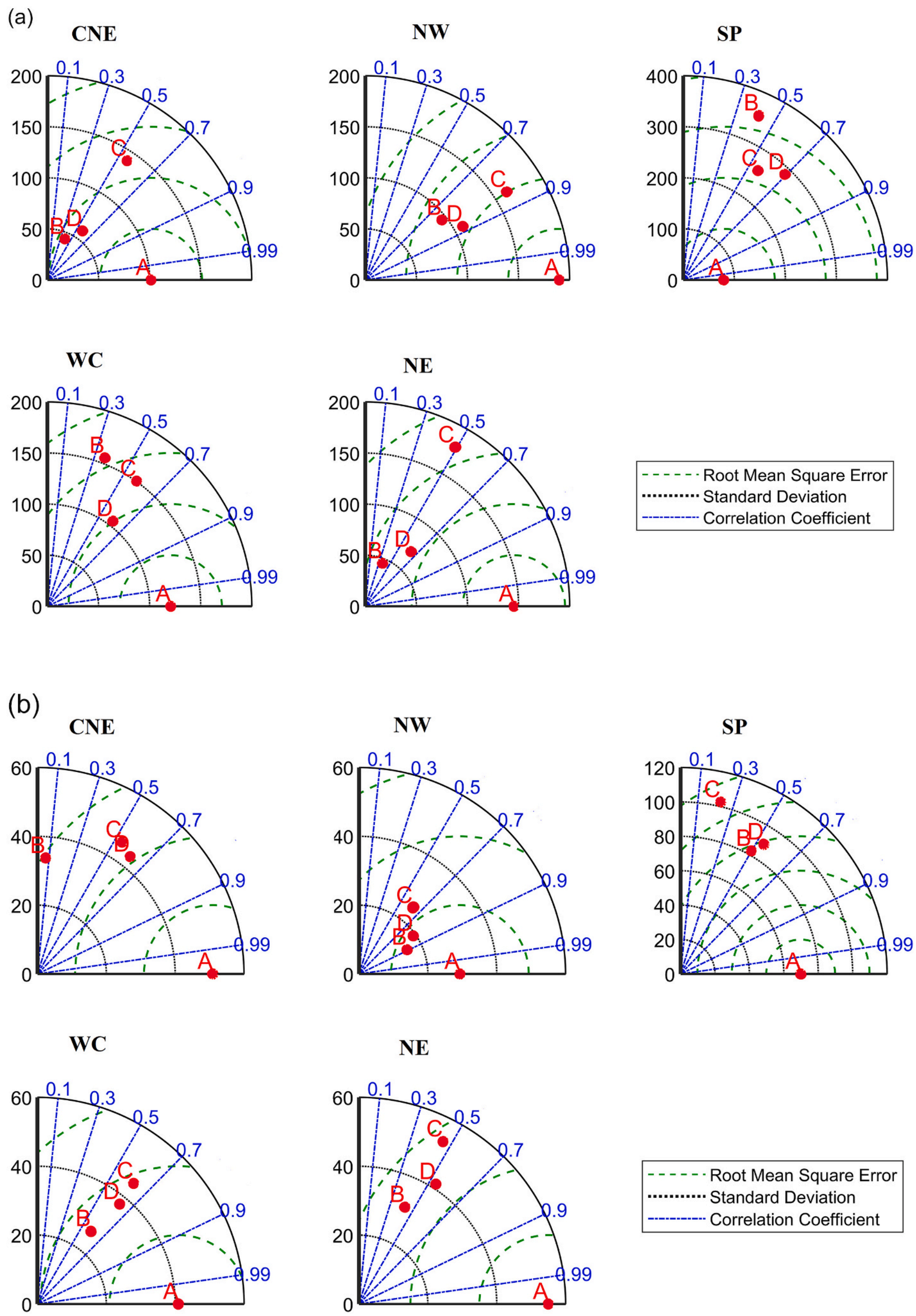

Fig. 9. Taylor diagram of performance statistics comparing the observed (marked as A) and simulated rainfall for a) southwest monsoon and b) northeast monsoon considering different schemes namely Grell (marked as B), GOEL (marked as C) and GLEO (marked as D) and five homogeneous monsoon regions.

5. Summary and conclusions

This study attempts to assess the sensitivity of three factors namely, region, season, and cumulus schemes on the simulation of long-term daily rainfall across India. The performance of RegCM in capturing the long-term climatology during the two monsoon seasons namely, the southwest and the northeast monsoon over a span of 34 years is carried out using a combination of CCS. The different CCS, namely Grell and two mixed schemes – Grell over Ocean, Emmanuel over Land (GOEL) and Grell over Land, Emmanuel over Ocean (GLEO) are used for simulating rainfall over the mainland and sub-regions. While the schemes perform more or less similar in the non-monsoon months, the mixed schemes perform better in the monsoon months. The performance of the two mixed schemes differs significantly between the two monsoon seasons, probably associated with the ability of the CCS to model/capture the air-sea interaction for simulation of Indian monsoon. In general, precipitation in the month of June (onset) and September (retreating) is over estimated, where as the model performance for the months of July and August (peak monsoon) are realistic in nature.

Considering the fact that the CCSs perform differently from one region to another and from one month to another, recommendations on the spatial variation in performance is found to be essential. Before that, three major findings on the CCS for the Indian sub-continent are as follows: (i) Overall, the mixed scheme, namely GOEL (a combination Grell over ocean and Emmanuel over land) performs better over the Indian domain. Thus, the land–sea interaction plays a major role in the capturing rainfall, (ii) Considering the monsoon seasons the spatial variation is rightly captured by the three schemes, however the performance varies in terms of the intensity, and (iii) The performance of schemes varies significantly between the different regions and the

Table 3
Month-wise best convective scheme (GLEO-Green, GOEL-Blue, Grell-Orange, Grell/GLEO-Yellow) identified based on the RCM performance for different seasons for different homogeneous monsoon regions.

Season	Month	Best Scheme				
		CNE	NW	SP	WC	NE
Southwest Monsoon	Jun	GLEO	GLEO	GLEO	GLEO	GLEO
	Jul	GLEO	GLEO	GOEL	GLEO	GLEO
	Aug	GLEO	GOEL	GOEL	GLEO	GLEO
	Sep	GLEO	GOEL	GLEO	GLEO	GOEL
Northeast Monsoon	Oct	GOEL	GLEO	GLEO	GLEO	GOEL
	Nov	Grell	GLEO	Grell	Grell	Grell
	Dec	Grell	GLEO	GOEL	Grell	Grell
Non-Monsoon	Jan	Grell	Grell/GLEO	GOEL	Grell	Grell
	Feb	GLEO	Grell	Grell	GLEO	Grell/GLEO
	Mar	GOEL	Grell/GLEO	Grell	Grell	Grell
	Apr	GLEO	Grell	Grell	GLEO	Grell/GLEO
	May	Grell/GLEO	GLEO	GLEO	GLEO	GLEO

months and therefore it is difficult to conclude the best scheme irrespective of season and region.

Based on the third findings, recommendation on the best CCS for different region and season/months is found necessary. Considering the HMRs as different regions, the best performing scheme during the southwest monsoon months is GLEO for CNE, WC and NE, whereas either GLEO or GOEL is the best for NW and SP. Considering the northeast monsoon, the mixed schemes show better performance for the month of October. However, for the months of November and December, the results vary from region to region. It is also noticed that the best scheme can be Grell over both land and ocean too for some non-monsoon months. The results clearly indicate that choice of the CCS can affect the model performance based on the region and season of analysis. Further relative performance of CCS in RegCM model can be attempted by varying the domain size and resolution in addition to the identified best performing CCS. It is a complex task to estimate sensitivity of convection schemes as various schemes have not shown a single result for all regions and seasons. However, it is noteworthy that the model is capable of capturing both the monsoonal features. As a future scope of this study, other meteorological variables, such as wind, relative humidity, and temperature can be considered. Moreover, analysis with larger domain and high spatial resolution can also be considered with the availability of better computational resources. More experiments can be carried out by changing different parameterization schemes (such as Land Surface, and Radiation) to develop a better version of the RegCM for future monsoonal simulations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2021.105675.

References

Ajaya Mohan, R.S., Goswami, B.N., 2003. Potential predictability of the Asian summer monsoon on monthly and seasonal time scales. Meteorog. Atmos. Phys. 84, 83–100. https://doi.org/10.1007/s00703-002-0576-4.
Anthes, R.A., 1997. A cumulus parameterization scheme utilizing a one-dimensional cloud model. Mon. Weather Rev. 105, 270–286.
Bhaskaran, B., Ramachandran, A., Jones, R., Moufouma-Okia, W., 2012. Regional climate model applications on sub-regional scales over the Indian monsoon region: the role of domain size on downscaling uncertainty. J. Geophys. Res. Atmos. 117, 1–12. https://doi.org/10.1029/2012JD017956.
Bhate, J., Kesarkar, A., 2019. Sensitivity of diurnal cycle of simulated rainfall to cumulus parameterization during Indian summer monsoon seasons. Clim. Dyn. https://doi.org/10.1007/s00382-019-04716-1.
Bhatla, R., Ghosh, S., 2015. Study of break phase of indian summer monsoon using different parameterization schemes of RegCM4.3. Int J Earth Atmos Sci 2, 109–115.
Bhatla, R., Ghosh, S., Mandal, B., et al., 2016. Simulation of Indian summer monsoon onset with different parameterization convection schemes of RegCM-4.3. Atmos. Res. 176–177, 10–18. https://doi.org/10.1016/j.atmosres.2016.02.010.
Bhatla, R., Verma, S., Ghosh, S., Mall, R.K., 2020. Performance of regional climate model in simulating Indian summer monsoon over Indian homogeneous region. Theor. Appl. Climatol. 139, 1121–1135. https://doi.org/10.1007/s00704-019-03045-x.

Bin, Li Y., Yung, C., Wan, T., et al., 2016. Evaluating the impacts of cumulus, land surface and ocean surface schemes on summertime rainfall simulations over East - to - southeast Asia and the western north Pacific by RegCM4. Clim. Dyn. 46, 2487–2505. https://doi.org/10.1007/s00382-015-2714-y.
Dash, S., Maity, R., 2019. Temporal evolution of precipitation-based climate change indices across India: contrast between pre- and post-1975 features. Theor. Appl. Climatol. 138, 1667–1678. https://doi.org/10.1007/s00704-019-02923-8.
Dash, S.K., Shekhar, M.S., Singh, G.P., 2006. Simulation of Indian summer monsoon circulation and rainfall using RegCM3. Theor. Appl. Climatol. 86, 161–172. https://doi.org/10.1007/s00704-006-0204-1.
Dash, S.K., Mishra, S.K., Pattnayak, K.C., et al., 2015. Projected seasonal mean summer monsoon over India and adjoining regions for the twenty-first century. Theor. Appl. Climatol. 122, 581–593. https://doi.org/10.1007/s00704-014-1310-0.
Devanand, A., Ghosh, S., Paul, S., et al., 2018a. Multi-ensemble regional simulation of Indian monsoon during contrasting rainfall years: role of convective schemes and nested domain. Clim. Dyn. 50, 4127–4147. https://doi.org/10.1007/s00382-017-3864-x.
Devanand, A., Roxy, M.K., Ghosh, S., 2018b. Coupled land-atmosphere regional model reduces dry bias in indian summer monsoon rainfall simulated by CFSv2. Geophys. Res. Lett. 45, 2476–2486. https://doi.org/10.1002/2018GL077218.
Dickinson, R.E., Henderson-Sellers, A., Kennedy, P.J., et al., 1993. Biosphere-atmosphere Transfer Scheme (BATS) Version 1e as Coupled to the NCAR Community Climate Model. NCAR Tech Rep NCAR/TN-3871STR, 72 77. https://doi.org/10.5065/D67W6959.
Dutta, R., Maity, R., 2018. Temporal evolution of hydroclimatic teleconnection and a time-varying model for long-lead prediction of Indian summer monsoon rainfall. Sci. Rep. 8, 10778. https://doi.org/10.1038/s41598-018-28972-z.
Dutta, R., Maity, R., 2020. Spatial variation in long-lead predictability of summer monsoon rainfall using a time-varying model and global climatic indices. Int. J. Climatol. 1–16. https://doi.org/10.1002/joc.6556.
Emanuel, K.A., 1991. A scheme for representing cumulus convection in large-scale models. J. Atmos. Sci. 48, 2313–2335.
Gadgil, S., Sajani, S., 1998. Monsoon precipitation in the AMIP runs. Clim. Dyn. 14, 659–689. https://doi.org/10.1007/s003820050248.
Gao, X., Giorgi, F., 2017. Use of the RegCM system over east Asia: review and perspectives. Engineering 3, 766–772. https://doi.org/10.1016/J.ENG.2017.05.019.
Gao, X., Shi, Y., Giorgi, F., 2016. Comparison of convective parameterizations in RegCM4 experiments over China with CLM as the land surface model. Atmos. Ocean Sci. Lett. 9, 246–254. https://doi.org/10.1080/16742834.2016.1172938.
Ghosh, S., Bhatla, R., Mall, R.K., et al., 2018. Aspect of ECMWF downscaled Regional climate Modeling in simulating Indian summer monsoon rainfall and dependencies on lateral boundary conditions. Theor. Appl. Climatol. 1559–1581. https://doi.org/10.1007/s00704-018-2432-6.
Giorgi, F., Marinucci, R., Bates, G.T., 1993. Development of a second-generation regional climate model (RegCM2). Part I: boundary-layer and radiative transfer processes. Mon. Weather Rev. 121, 2794–2813.
Giorgi, F., Coppola, E., Solmon, F., et al., 2012. RegCM4: model description and preliminary tests over multiple CORDEX domains. Clim. Res. 52, 7–29. https://doi.org/10.3354/cr01018.
Goddard, L., Barnston, A.G., Mason, S.J., 2003. Evaluation of the IRI'S "Net Assessment" seasonal climate forecasts: 1997–2001. Bull. Am. Meteorol. Soc. 84, 1761–1782. https://doi.org/10.1175/bams-84-12-1761.
Goswami, B.N., Ajaya Mohan, R.S., 2000. A common spatial mode for intra-seasonal and inter-annual variation and predictability of the Indian summer monsoon. J. Clim. 14, 1180–1198.
Goswami, B.N., Sengupta, D., Kumar, G.S., 1998. Intraseasonal oscillations and interannual variability of surface winds over the Indian monsoon region. In: Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences, pp. 45–64.
Grell, G.A., 1993. Prognostic evaluation of assumptions used by cumulus parameterizations. Mon. Weather Rev. 121, 764–787.
Grell, G.A., Dudhia, J., Stauffer, D.R., 1994. A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5).
Guhathakurta, P., Rajeevan, M., Sikka, D.R., Tyagi, A., 2015. Observed changes in southwest monsoon rainfall over India during 1901-2011. Int. J. Climatol. 35, 1881–1898. https://doi.org/10.1002/joc.4095.
Holtslag, A.A.M., De Bruijn, E.I.F., Pan, H.-L., 1990. A high resolution air mass transformation model for short-range weather forecasting. Mon. Weather Rev. 118, 1561–1575.
Huntingford, C., Jones, R.G., Prudhomme, C., et al., 2003. Regional climate-model predictions of extreme rainfall for a changing climate. Q. J. R. Meteorol. Soc. 129, 1607–1621. https://doi.org/10.1256/qj.02.97.
Jacob, D., Podzun, R., 1997. Sensitivity studies with the regional climate model REMO. Meteorog. Atmos. Phys. 63, 119–129. https://doi.org/10.1007/BF01025368.
Jha, M., Pan, Z., Tackle, E.S., Gu, R., 2004. Impacts of climate change on streamflow in the Upper Mississippi River Basin: a regional climate model perspective. J. Geophys. Res. D Atmos. 109, 1–12. https://doi.org/10.1029/2003JD003686.
Kakade, S., Kulkarni, A., 2016. Prediction of summer monsoon rainfall over India and its homogeneous regions. Meteorol. Appl. 23, 1–13. https://doi.org/10.1002/met.1524.
Kang, H.S., Hong, S.Y., 2008. Sensitivity of the simulated East Asian summer monsoon climatology to four convective parameterization schemes. J. Geophys. Res. Atmos. 113, 1–17. https://doi.org/10.1029/2007JD009692.
Kashid, S.S., Maity, R., 2012. Prediction of monthly rainfall on homogeneous monsoon regions of India based on large scale circulation patterns using genetic programming. J. Hydrol. 454–455, 26–41. https://doi.org/10.1016/j.jhydrol.2012.05.033.
Kiehl, T., Hack, J., Bonan, B., et al., 1996. Description of the NCAR Community Climate Model (CCM3).
Kishore, P., Jyothi, S., Basha, G., et al., 2016. Precipitation climatology over India: validation with observations and reanalysis datasets and spatial trends. Clim. Dyn. 46, 541–556. https://doi.org/10.1007/s00382-015-2597-y.
Krishna Kumar, K., Hoerling, M., Rajagopalan, B., 2005. Advancing dynamical prediction of Indian monsoon rainfall. Geophys. Res. Lett. 32, 1–4. https://doi.org/10.1029/2004GL021979.
Krishnan, R., Sanjay, J., Gnanaseelan, C., et al., 2020. Assessment of Climate Change Over the Indian region: A Report of the Ministry of Earth Sciences (MOES), Government of India.
Kumar, D., Dimri, A.P., 2020. Sensitivity of convective and land surface parameterization in the simulation of contrasting monsoons over CORDEX-South Asia domain using RegCM-4.4.5.5. Theor. Appl. Climatol. 139, 297–322. https://doi.org/10.1007/s00704-019-02976-9.
Kumar, D., Rai, P., Dimri, A.P., 2020. Investigating Indian summer monsoon in coupled regional land–atmosphere downscaling experiments using RegCM4. Clim. Dyn. 54, 2959–2980. https://doi.org/10.1007/s00382-020-05151-3.
Lal, M., Meehl, G.A., Arblaster, J.M., 2000. Simulation of Indian summer monsoon rainfall and its intraseasonal variability in the NCAR climate system model. Reg. Environ. Chang. 1, 163–179. https://doi.org/10.1007/s101130000017.
Lui, Y.S., Tam, C.-Y., Au-Yeung, Y.M., Lau, N., 2018. Role of cumulus parameterization on the seasonal and diurnal precipitation over Southeast Asia in RegCM4. Clim. Dyn. https://doi.org/10.1007/s00382-018-4517-4.
Maharana, P., Dimri, A.P., 2014. Study of seasonal climatology and interannual variability over India and its subregions using a regional climate model (RegCM3). J. Earth Syst. Sci. 123, 1147–1169. https://doi.org/10.1007/s12040-014-0447-7.
Maharana, P., Dimri, A.P., 2016. Study of intraseasonal variability of Indian summer monsoon using a regional climate model. Clim. Dyn. 46, 1043–1064. https://doi.org/10.1007/s00382-015-2631-0.
Maity, R., Nagesh Kumar, D., 2006. Hydroclimatic association of the monthly summer monsoon rainfall over India with large-scale atmospheric circulations from tropical Pacific Ocean and the Indian Ocean region. Atmos. Sci. Lett. 7, 101–107. https://doi.org/10.1002/asl.141.
Maity, R., Nagesh Kumar, D., 2008. Probabilistic prediction of hydroclimatic variables with nonparametric quantification of uncertainty. J. Geophys. Res. Atmos. 113, 1–12. https://doi.org/10.1029/2008JD009856.
Maity, R., Kumar, D.N., Nanjundiah, R.S., 2007. Review of hydroclimatic teleconnection between hydrologic variables and large-scale atmospheric circulation patterns with indian perspective. ISH J. Hydraul. Eng. 13, 77–92. https://doi.org/10.1080/09715010.2007.10514859.
Maity S, Mandal M, Nayak S, Bhatla R (2017) Performance of Cumulus Parameterization Schemes in the Simulation of Indian Summer Monsoon using RegCM4. 30:287–309. Doi: 10.20937/ATM.2017.30.04.02.
Martínez-Castro, D., Vichot-Llano, A., Bezanilla-Morlot, A., et al., 2018. The performance of RegCM4 over the Central America and Caribbean region using different cumulus parameterizations. Clim. Dyn. 50, 4103–4126. https://doi.org/10.1007/s00382-017-3863-y.
Maurya, R.K.S., Singh, G.P., 2016. Simulation of present-day precipitation over India using a regional climate model. Meteorog. Atmos. Phys. 128, 211–228. https://doi.org/10.1007/s00703-015-0409-x.
Mohanty, U.C., Nageswararao, M.M., Sinha, P., et al., 2018. Evaluation of performance of seasonal precipitation prediction at regional scale over India. Theor. Appl. Climatol. 135, 1123–1142. https://doi.org/10.1007/s00704-018-2421-9.
Mukhopadhyay, P., Taraphdar, S., Goswami, B.N., Krishnakumar, K., 2010. Indian summer monsoon precipitation climatology in a high-resolution regional climate model: impacts of convective parameterization on systematic biases. Weather Forecast. 25, 369–387. https://doi.org/10.1175/2009WAF2222320.1.
Nayak, S., Mandal, M., Maity, S., 2017. Customization of regional climate model (RegCM4) over Indian region. Theor. Appl. Climatol. 127, 153–168. https://doi.org/10.1007/s00704-015-1630-8.
Nayak, S., Mandal, M., Maity, S., 2019. Performance evaluation of RegCM4 in simulating temperature and precipitation climatology over India. Theor. Appl. Climatol. 137, 1059–1075. https://doi.org/10.1007/s00704-018-2635-x.
Pal, J.S., Small, E.E., Eltahir, E.A.B., 2000. Simulation of regional-scale water and energy budgets: representation of subgrid cloud and precipitation processes within RegCM. J. Geophys. Res. Atmos. 105, 29579–29594. https://doi.org/10.1029/2000JD900415.
Pal, J.S., Giorgi, F., Bi, X., et al., 2007. Regional climate modeling for the developing world: the ICTP RegCM3 and RegCNET. Bull. Am. Meteorol. Soc. 88, 1395–1410. https://doi.org/10.1175/BAMS-88-9-1395.
Parthasarathy B, Rupa Kumar K, Munot AA (1993) Homogeneous Indian monsoon rainfall: variability and prediction. Proc. Indian Acad. Sci. - Earth Planet Sci. 102: 121–155. Doi: https://doi.org/10.1007/BF02839187.
Pattanaik, D.R., Kumar, A., 2010. Prediction of summer monsoon rainfall over India using the NCEP climate forecast system. Clim. Dyn. 34, 557–572. https://doi.org/10.1007/s00382-009-0648-y.
Pattnayak, K.C., Panda, S.K., Dash, S.K., 2013. Comparative study of regional rainfall characteristics simulated by RegCM3 and recorded by IMD. Glob. Planet. Chang. 106, 111–122. https://doi.org/10.1016/j.gloplacha.2013.03.006.
Rajeevan, M., Bhate, J., Jaswal, A.K., 2008. Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. Geophys. Res. Lett. 35, 1–6. https://doi.org/10.1029/2008GL035143.
Raju, P.V.S., Bhatla, R., Almazroui, M., Assiri, M., 2015. Performance of convection schemes on the simulation of summer monsoon features over the South Asia

CORDEX domain using RegCM-4.3. Int. J. Climatol. 35, 4695–4706. https://doi.org/10.1002/joc.4317.
Ratnam, J.V., Krishna Kumar, K., 2005. Sensitivity of the simulated monsoons of 1987 and 1988 to convective parameterization schemes in MM5. J. Clim. 18, 2724–2743. https://doi.org/10.1175/JCLI3390.1.
Reynolds, R.W., Rayner, N.A., Smith, T.M., et al., 2002. An improved in situ and satellite SST analysis for climate. J. Clim. 15, 1609–1625.
Shukla, J., Paolino, A.D., 1983. The southern oscillation and long-range forecasting of the summer monsoon rainfall over India. Mon. Weather Rev. 111, 1830.
Singh, A.P., Mohanty, U.C., Sinha, P., Mandal, M., 2007. Influence of different land-surface processes on Indian summer monsoon circulation. Nat. Hazards 42, 423–438. https://doi.org/10.1007/s11069-006-9079-9.
Sinha, P., Mohanty, U.C., Kar, S.C., et al., 2013. Sensitivity of the GCM driven summer monsoon simulations to cumulus parameterization schemes in nested RegCM3. Theor. Appl. Climatol. 112, 285–306. https://doi.org/10.1007/s00704-012-0728-5.
Sinha, P., Maurya, R.K.S., Mohanty, M.R., Mohanty, U.C., 2019. Inter-comparison and evaluation of mixed-convection schemes in RegCM4 for Indian summer monsoon simulation. Atmos. Res. 215, 239–252. https://doi.org/10.1016/j.atmosres.2018.09.002.
Srinivas, C.V., Bhaskar Rao, D.V., Hari Prasad, D., et al., 2015. A study on the Influence of the land surface processes on the southwest monsoon simulations using a regional climate model. Pure Appl. Geophys. 172, 2791–2811. https://doi.org/10.1007/s00024-014-0905-9.
Suman M, Maity R (2020) Southward shift of precipitation extremes over South Asia: Evidences from CORDEX data. Sci. Rep. 6452. Doi: https://doi.org/10.1038/s41598-020-63571-x.
Wang, B., Xiang, B., Li, J., et al., 2015. Rethinking Indian monsoon rainfall prediction in the context of recent global warming. Nat. Commun. 6, 1–8. https://doi.org/10.1038/ncomms8154.
Webster, P.J., Yang, S., 1992. Monsoon and enso: selectively interactive systems. Q. J. R. Meteorol. Soc. 118, 877–926. https://doi.org/10.1002/qj.49711850705.
Webster, P.J., Magaña, V.O., Palmer, T.N., et al., 1998. Monsoons: processes, predictability, and the prospects for prediction. J. Geophys. Res. Ocean 103, 14451–14510. https://doi.org/10.1029/97JC02719.
Xie, S.P., Xu, H., Saji, N.H., et al., 2006. Role of narrow mountains in large-scale organization of Asian monsoon convection. J. Clim. 19, 3420–3429. https://doi.org/10.1175/JCLI3777.1.
Yadav, B.P., Das, D.A.K., Singh, K.V., Manik, S.K., 2017. Rainfall Statistics of India, 01, pp. 12–110.