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ORIGINAL PAPER

How far the CORDEX high-resolution data represents observed precipitation: an analysis across Indian mainland

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Abstract
Coordinated Regional Climate Downscaling Experiment (CORDEX) has developed high-resolution, dynamically downscaled data across the world. This paper investigates the spatio-temporal correspondence between CORDEX data for South Asia (CORDEX-SA) and observed precipitation data to assess its reliability. The entire Indian mainland is considered as study region. Both monthly and seasonal analyses are undertaken along with the extreme magnitudes during historical (1971–2005) and future (2006–2100) periods. The outputs of two regional climate models (RCMs), viz. regional climate model, version-4.4 (RegCM4) and Rossby Centre regional Atmospheric model, version-4 (RCA4), participating in CORDEX-SA program, are considered for medium (RCP4.5) and high (RCP8.5) emission scenarios. The CORDEX-SA is found to well represents in central India, but significant bias in the mean precipitation (± 200 mm) is noticed at northern, north-eastern, southern and coastal regions. The inferior performance of both the RCMs is noticed over high rainfall regions. Specifically, more than 70% area is found to have mean bias more than ± 100 mm. Performance of RCA4 is better in North and Himalayan regions, where 67% of area is found to be within the aforementioned threshold, which is 23.64% in case of RegCM4. Performance of RegCM4 is marginally better in the peninsular India as compared with RCA4. In case of extreme magnitudes, the insignificant correspondance between CORDEX-SA data and observed precipitation is noticed over the many parts of India. Results of this study are important to check the applicability of CORDEX data in various impact assessment studies.

1 Introduction

The socio-economic status of any agricultural dependent country is greatly influenced by the occurrence of precipitation. The water resource development and management of a region directly depends on the amount of precipitation in that region. Precipitation, being a vital process in the hydrological cycle, varies over short spatial scale. Therefore, the spatial variability of precipitation is essential for making suitable policies in a particular region. Hence, prior assessment of the future precipitation can be helpful in various sectors, for instance, water resource management and agricultural productivity (Ramos et al. 2012; Nepal and Shrestha 2015; Pradhan et al. 2015).

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In this context, general circulation models (GCMs) have projected the global precipitation for the twenty-first century. However, due to their coarse resolution, the GCM outputs are incapable in representing the variability of precipitation at local/regional scale (Hewitson and Crane 1996; Wilby and Wigley 1997; Musau et al. 2013; Chirivella et al. 2016; Pichuka and Maity 2016). This situation necessitates utilizing the downscaling techniques for improvising the spatial resolution of GCM outputs. There are two types of downscaling techniques available, namely, statistical downscaling (Wilby et al. 2002; Kannan and Ghosh 2011; Rashid et al. 2015; Pichuka et al. 2017) and dynamical downscaling (Maraun et al. 2010; Xue et al. 2014; Chirivella et al. 2016). The statistical downscaling is a stationary based approach which assumes the relationship between causal and target variables to be static (Wilby et al. 2002; Kannan and Ghosh 2011).

The dynamical downscaling is often referred to as regional climate model (RCM). The RCM is developed by considering the physics of topography and other fine-scale process; thereby, it provides an opportunity in replicating the sub-grid scale processes (Giorgi et al. 2015; Laprise 2008; Maraun et al. 2010). In recent years, efforts are made to improve the characterization of climate at regional scale. In this process, the World Climate Research Programme (WCRP) develops the Coordinated Regional Climate Downscaling Experiment (CORDEX). The aim of CORDEX data is to generate a coordinated ensemble of high-resolution historical/future regional climate for land regions over the globe. It focuses mainly on coordinating the efforts made by the world community in regional climate downscaling (Giorgi et al. 2009). The CORDEX divides the world's landmass into 12 domains including the North and South poles. This study focuses on the South Asia (SA) domain, hereafter referred as CORDEX-SA. The Indian Institute of Tropical Meteorology (IITM) along with its partner institutions leads the CORDEX-SA domain. The CORDEX-SA data was developed in February 2016 and was made available in the IITM website in the year 2017.

Nowadays, the CORDEX models gained popularity among the scientific community all over the world. Plethora of studies has been carried out to check the ability and applicability of CORDEX data in simulating the observations of various hydro-climatic variables in different parts of the world. For instance, the assessments using CORDEX data are carried out in the European region (Fantini et al. 2016; Smiatek et al. 2016; Rulfová et al. 2017), African region (Abba Omar and Abiodun 2017; Nikiema et al. 2017; Dosio et al. 2019), Asian region (Choudhary et al. 2017; Nengker et al. 2017; Ngai et al. 2017; Prajapat et al. 2019) and American region (Cerezo-Mota et al. 2016).

Further, the ability of modelling the extreme precipitation adds value in investigating the efficacy of CORDEX data. A few studies focus on modelling the extreme events using the CORDEX data sets. For instance, Suman and Maity (2020) investigated the change in extreme events in different parts of the South Asia region. Pichuka and Maity (2020) check the efficacy of CORDEX in modelling the extreme events over Bhadra basin in contrast with traditional downscaling approaches. Tangang et al. (2018) explored the effect of global warming on future changes in annual precipitation extremes over Southeast Asia. In this regard, the credibility of CORDEX-SA data needs to be examined before adopting for practical applications. This will help the end users, whether or not to choose the CORDEX-SA data for the regional/local scale impact assessments. Additionally, it helps in identifying the strengths and weaknesses of the RCMs used in the CORDEX-SA project, thereby providing valuable information to the policymakers.

Moreover, the climate change impact varies spatio-temporally depending upon the topographical and climatological features of the location (Pichuka and Maity 2016; Silverman and Maneta 2016). Therefore, the main objective of the present work is to investigate the spatio-temporal correspondence between the CORDEX-SA precipitation data and the observed precipitation data. The entire Indian land mass is considered as study region. In addition, the extreme event analysis is carried out during the historical and future periods. Next, the future climate is assessed using various climate change scenarios mentioned in the Intergovernmental Panel on Climate Change, Fifth Assessment Report (IPCC, AR5). Outputs from two different regional climate models (RCMs), used in CORDEX-SA, have been used for the aforementioned analysis.

2 Study area and data

2.1 Study area

India is the largest South Asian country and experiences a variety of climatic regions, ranging from very low-rainfall regions (Rajasthan) to world's maximum-rainfall region (Meghalaya). The Indian climate is largely influenced by the Himalayas and the Thar Desert. The nation is bounded by variety of geographical features such as the Alpines (Himalayas) in the north, desert in the west, the Bay of Bengal in the east, the Arabian Sea in the west, the Western Ghats in the south-west and the Indian Ocean in the south. The country is divided into various zones based on the amount of rainfall, i.e. humid zone (north-eastern part of the country) semi-arid zone (peninsular and central parts of the country) and arid zone (north-western parts of the country). There are four major seasons, i.e. pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November) and return monsoon (December-February). Thus, the study area covers a wide range of climatology to test the correspondence between CORDEX-SA and observed precipitation data.

2.2 Data

The regional climate model, version-4.4 (RegCM4) and Rossby Centre regional Atmospheric model, version-4 (RCA4) high spatial resolution (0.5° latitude by 0.5° longitude) precipitation data sets are procured from the IITM website. The data is constructed for the CORDEX-SA framework. The Canadian Earth System model, version-2 (CanESM2) GCM is used as the driving GCM to develop these RCM data. The RegCM4 is developed by the International Centre for Theoretical Physics (ICTP) and covers the SA region (Giorgi et al. 2012; Li et al. 2015). The outputs of RegCM4 have been utilized in several intercomparison projects to obtain the future long-term regional climate predictions (Giorgi et al. 2012). The details of RegCM4 can be found in Li et al. (2015) and Almazroui et al. (2016). The RCA4 is developed by the Swedish Meteorological and Hydrological Institute (SMHI) at Rossby Centre. The details of RCA4 are presented in Samuelsson et al. (2011). The RCM data for the South Asian region is downloaded from the IITM website (http://cccr.tropmet.res.in/home/ftp_data.jsp).

Next, the RCM data from both the models are extracted for the study region (India). The observed precipitation data with spatial resolution of 0.5° latitude by 0.5° longitude is obtained for the study area from India Meteorological Department (IMD), Pune. The data from 1971 to 2005 (35 years) is considered as the historical data and 2011 to 2100 as future data. The future data for two Representative Concentration Pathway (RCP) viz. RCP4.5 and RCP8.5 scenarios are downloaded from the IITM website.

3 Methodology

The performance of the CORDEX model is explored at different temporal scales. Firstly, the seasonal correspondence between CORDEX-SA and observed precipitation data during the historical period is examined. This provides a prospect regarding the efficacy of the CORDEX model to epitomize the diversity in the seasonal variations and to check whether the model dynamics perform well for particular season(s). This study consider three seasons for analysis, i.e. pre-monsoon (February through May), monsoon (June through September) and post-monsoon also referred to as return monsoon (October through January). Secondly, the skill of the CORDEX model is investigated at a finer temporal (monthly) scale. Thirdly, the extreme events are assessed by evaluating the 5th and 95th percentile values along with mean. This helps in analysing the consistency of CORDEX-SA data with the observed extremes during the historical period. Fourthly, the percentage disagreement in mean values between observed and CORDEX data ($\mu_{\text{obs}} - \mu_{\text{CORDEX}}$) for different regions across Indian mainland is assessed. The spatial performance of CORDEX in different regions is examined through various statistical performance measures such as the unbiased root mean square error (URMSE), the correlation coefficient (r), Nash-Sutcliffe efficiency (NSE) and degree of agreement (D_{r}). The details of performance measures are presented in this section. The expressions for the evaluation of the URMSE, r, NSE and D_{r} are written as follows:

$$\text{URMSE} = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}\left[\left(X_{\bar{i}}-\overline{X}\right)\left(Y_{\bar{i}}-\overline{Y}\right)\right]\right]^{2}} \tag{1}$$

$$r = \frac{\sum_{i=1}^{n}\left[\left(X_i-\overline{X}\right)\left(Y_i-\overline{Y}\right)\right]}{\sqrt{\left[\sum_{i=1}^{n}\left(X_i-\overline{X}\right)^2\sum_{i=1}^{n}\left(Y_i-\overline{Y}\right)^2\right]}} \tag{2}$$

$$\text{NSE} = 1-\frac{\sum_{i=1}^{n}\left(X_i-Y_i\right)^2}{\sum_{i=1}^{n}\left(X_i-\overline{X}\right)^2} \tag{3}$$

$$D_{\text{r}} = 1-\frac{\sum_{i=1}^{n}\left|X_i-Y_i\right|}{2\sum_{i=1}^{n}\left|X_i-\overline{X}\right|} \tag{4}$$

In the above equations (Eqs. 1 to 4), X_i and Y_i represent the magnitude of observed precipitation and CORDEX-SA data respectively at ith time step; $\overline{X}$ and $\overline{Y}$ represent the mean of observed and CORDEX-SA data, respectively.

The correlation coefficient (r) provides the degree of association between the observed and simulated data. In this study, it represents the association between the observed precipitation and the CORDEX-SA data. The value of NSE indicates the goodness of fit between the observed and simulated data. It is a normalized statistic that determines the relative magnitude of the residual variance compared with the measured data variance (Nash and Sutcliffe 1970). The values of NSE vary from (− ∞, 1]. Values between 0 and 1 are acceptable while values less than 0 indicate that the observed mean is a better estimation as compared with the value estimated by the model. An efficiency of 1 shows a perfect match between the modelled and observed data. The degree of agreement (D_r) provides the difference between the sum of the magnitudes of the modelled and observed deviations (Willmott et al. 2011). In a perfect model, the sum of the observed mean relative magnitudes of the observed data (X) and the RCM data (Y) is equal for any time period. For example, D_r = 0.5 signifies that the sum of the error magnitudes is equal to half of the sum of the magnitudes of perfect model deviation and observed value deviations. If D_r = 0, it represents the sum of error magnitudes and the magnitudes of sum of perfect model deviations and observed deviations are equal. The negative D_r value, for example, − 0.5, denotes that the sum of the error magnitudes is twice the sum of the magnitudes of perfect model deviation and observed deviations.

Lastly, the variation of precipitation during the future period with respect to the baseline data is explored. The outputs from RCP4.5 and RCP8.5 are considered for the impact assessment. The future period is divided into three time slices and named as 'epoch'. Each epoch consists 30 years of data, i.e. epoch-1 (2011–2040), epoch-2 (2041–2070) and epoch-3 (2071–2100), respectively. Further, to investigate the future changes with respect to observed data, 30 years (1971–2000) of observed data is considered and referred to as 'baseline period'.

4 Results and discussion

4.1 Historical period

4.1.1 Assessment of CORDEX data using the performance statistics

The performance of the RegCM4 and RCA4 precipitation data against the observed precipitation is presented in Fig. 1. The results infer that moderate performance is noticed in the north-eastern and Western Ghat regions, and it is consistent in both the RCMs. The lower value (~ 350 to 500 mm) of URMSE is noticed in these regions. In other parts, URMSE ranges from 150 to 220 mm. The fair association between CORDEX and observed precipitation data ($r > 0.75$) is found in the central part of the country, whereas the same varies between 0.4 and 0.6 in the sub-Himalayan and the north-western regions. The correlation among RegCM4 and observed precipitation data is inadequate in the northern region ($\sim r = -0.25$ to 0) and the southern region ($\sim r = 0$ to 0.3). Poor value of NSE (closer to − 1) is noticed in the northern (Himalayan) region and north-western (desert) region. However, the RegCM4 outputs are found to be satisfactory in the central and eastern part of the country as assessed from all the performance measures. For instance, the D_r value in these regions is approximately 0.65 which implies that the performance of RegCM4 is promising in these regions. The performance of RCA4 is relatively better in the eastern part of India, r values varying between 0.60 and 0.80. The correspondence of RCA4 is found to be decent with the observed data (Fig. 1) in the eastern, north-eastern, northern and peninsular regions. The values of r in RCA4 (RegCM4) range between 0.20 and 0.75 (− 0.20 to 0.65) and NSE varies between − 0.25 and 0.50 (− 1.0 to 0.5) and the lowest and highest D_r values are noted as 0.35 (− 0.40) and 0.68 (0.70), respectively. Thus, the RCA4 performs better than the RegCM4 in the study region. Still, the performance is inadequate in the Himalayan, sub-Himalayan, desert part and the peninsular regions.

4.1.2 Potential variation of CORDEX data over space

The spatial variation of CORDEX is analysed through the difference in mean value between observed and CORDEX data ($\mu_{\text{obs}} - \mu_{\text{CORDEX}}$) during the historical period. Five critical regions are identified and referred to as different zones based on the amount of rainfall and its distribution over those regions. The five zones are zone I (northern and Himalayan regions), zone II (north-eastern region), zone III (east coast region), zone IV (southern peninsular region) and zone V (west coast and Western Ghat regions), respectively. The variation of difference in mean between observed and CORDEX data is shown in Fig. 2. The poor performance of RegCM4 (left panel) is depicted from Fig. 2 in zone I, zone II and zone V. The disagreement is less for RCA4 (right panel) in zone I, but it is more in zone II and zone V. The percentage area beyond mean bias value of ± 100 mm is presented in Table 1. It can be noteworthy that % area of disagreement ($\mu_{\text{obs}} - \mu_{\text{CORDEX}}$) is minimum for both the CORDEX models in zone IV (peninsular India), i.e. 18.65% (RegCM4) and 26.83% (RCA4), respectively. The maximum % area of disagreement is noticed in zone II (RegCM4 74.92%; and RCA4 78.12%). The poor performance of RegCM4 is observed in zone I (76.36%) as compared with the RCA4 (32.81%), whereas the poor performance of RCA4 is noticed in zone V (79.10%). Overall, this analysis revealed that the CORDEX data can be reliable in the central part and the peninsular regions of the country and it is unreliable in the other parts. A significant spatial variation in the

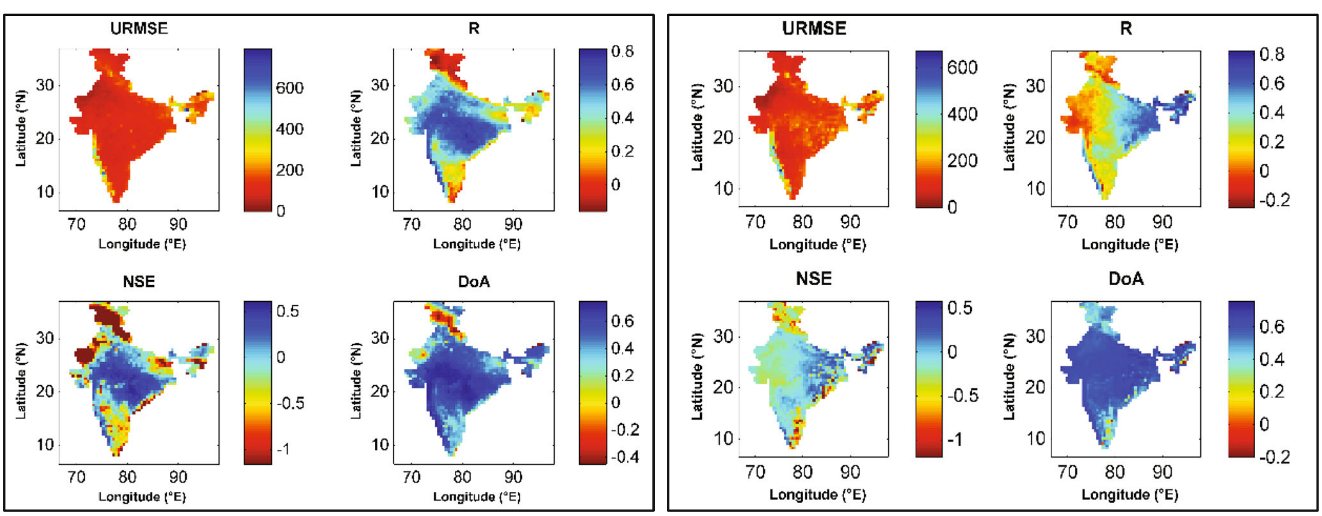

Fig. 1 Correspondence between observed and CORDEX precipitation data (RegCM4 on the left and RCA4 on the right panel). Statistics (URMSE, R, NSE and DoA) are calculated based on monthly averaged values

Table 1 Zone-wise percentage of area with more than ± 100 mm difference in monthly mean (bias) estimated from the RCMs participating in CORDEX-SA program. The lesser percentage area represents better performance in that zone. Refer to Fig. 2 for zone demarcation

Zone	RegCM4	RCA4
Zone I	76.36	32.81
Zone II	74.92	78.12
Zone III	43.24	48.64
Zone IV	18.65	26.83
Zone V	71.64	79.10

CORDEX output is observed in several parts of India such as central, western and north-western regions.

4.1.3 Seasonal and monthly scale assessments

The assessment at seasonal scale is carried out, and the corresponding plots are presented in Fig. 3. The insignificant performance of RegCM4 is portrayed from the results (Fig. 3) during the pre-monsoon (February-May) and post-monsoon (October-January) seasons in the Himalayan (zone I), sub-Himalayan and the peninsular regions (zone IV). Apart from this, over-estimation is detected during the monsoon (June-September) season in zone V and under-estimation is noticed in zone II. Overall, it is clear that the RegCM4 data succeeds in simulating the observed data in the normal rainfall regions such as central and western parts of the country and lacks for the high and low rainfall regions. The RCA4 outputs are better in displaying the observed seasonal data for almost all the regions except zone IV. However, it is noteworthy that the RCA4 under-estimates the monsoon precipitation in zone V where RegCM4 corroborates better results (refer to Fig. 3).

Further, the assessment at finer temporal (monthly) scale is carried out to investigate the ability of the CORDEX-SA data in characterizing the observed monthly precipitation. For demonstration, one monsoon (July) and one non-monsoon (December) months are considered and the results are plotted in Fig. 4. The figure depicts that RegCM4 is under-estimating for zone II and zone V in the monsoon month and over-estimating in the non-monsoon month for the northern part (~ 250 mm more as compared with the observed data) and Himalayan and sub-Himalayan regions (~ 150 mm more as compared with the observed data). The return monsoon is clearly indicated in the observed data in December over southern east coast region, and the RegCM4 outputs are unable to capture the same. The decent association between RCA4 and the observed data in zone II and under-estimation (~ 50 mm less compared with the observed data) in all other regions except zone V during the monsoon month are noticed. It appears to be incapable in modelling the observed monsoon in zone V (completely under-estimating). However, RCA4 is able to mimic the observed precipitation during non-monsoon season for majority of the regions. Apart from the better performance in zone I and zone II, RCA4 is also able to capture the return monsoon which is clearly visible from Fig. 4. However, it is slightly over-estimating during the non-monsoon month in the southern east coast region.

The seasonal and monthly analysis results reveal that the CORDEX performance is satisfactory in replicating the

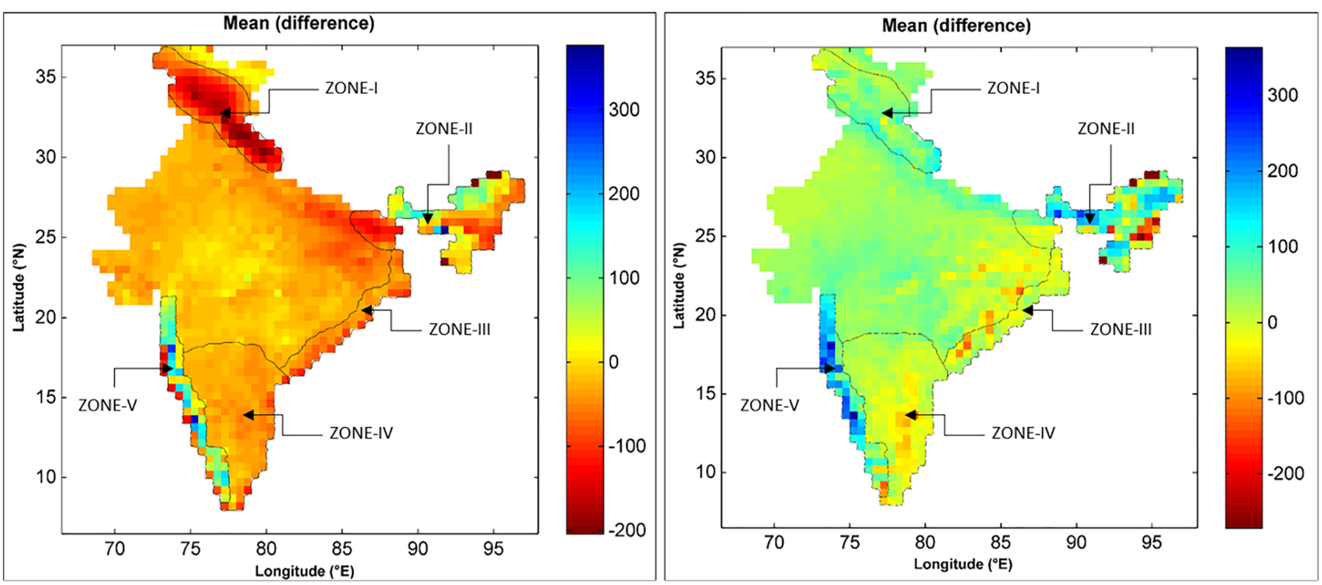

Fig. 2 Difference in mean values of observed and CORDEX (RegCM4 on left panel; RCA4 RCM on right panel) precipitation during historical period (1971–2005). The study area is divided into different homogeneous zones based on the rainfall amount and its distribution over these regions. ZONE-I covers north and Himalayan region; ZONE-II covers north-east region; ZONE-III represents east coast part; ZONE-IV represents peninsular part of India and ZONE-V covers the west coast and Western Ghats, respectively

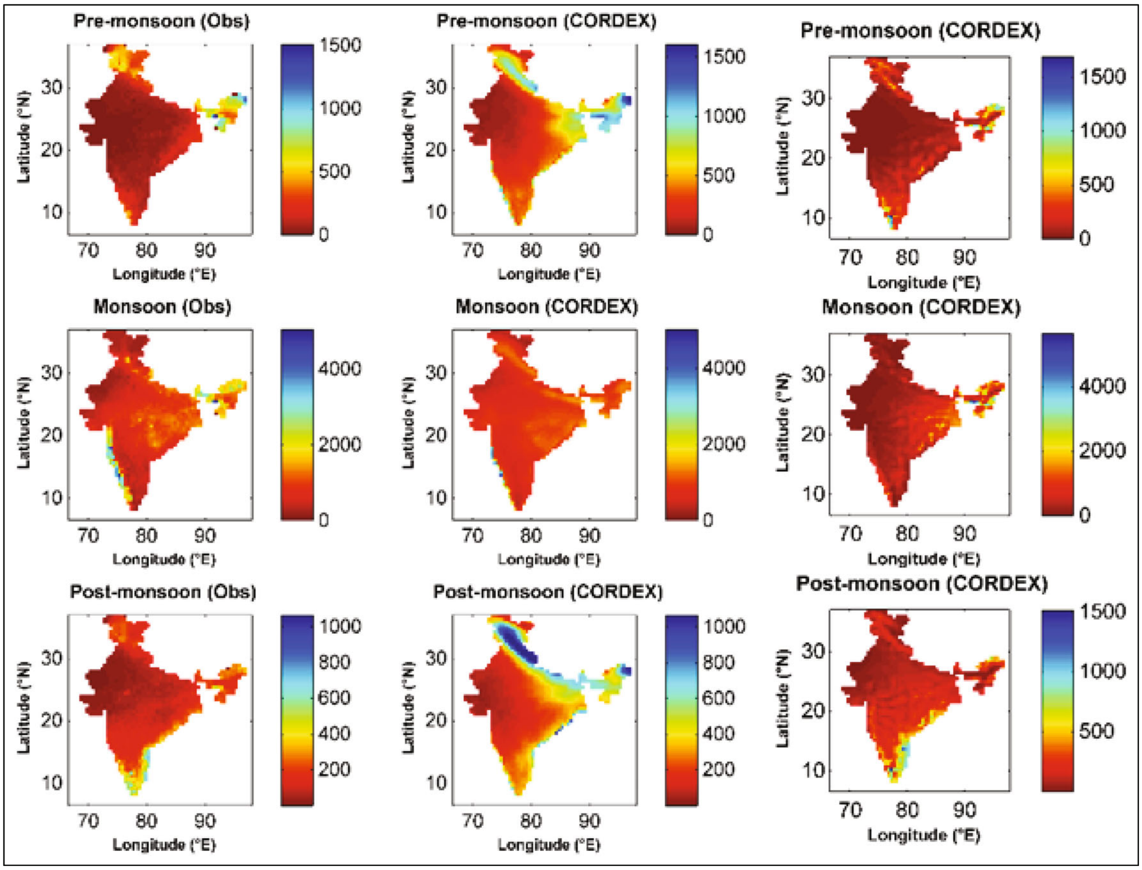

Fig. 3 Comparison of spatio-temporal variations between observed (first column) and CORDEX simulated precipitation (RegCM4 in the second column and RCA4 in the third column) during different seasons, i.e. pre-monsoon (February-May), monsoon (June-September) and post-monsoon (October-January)

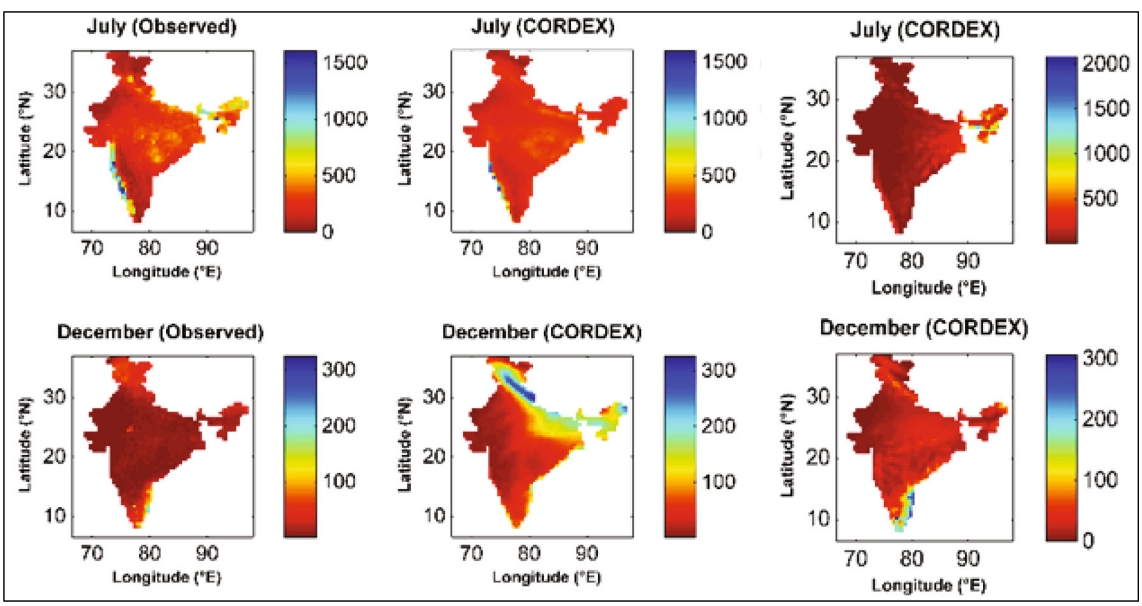

Fig. 4 Monthly correspondence of CORDEX (second column—RegCM4; third column—RCA4) models with respect to the observed precipitation (first column) data. The first row is corresponding to monsoon (July) month, and second row is for non-monsoon (December) month

observed precipitation in the central part of the country. RegCM4 outputs are better matching with the observed data in zone V and central part of the country as compared with RCA4 outputs, whereas the RCA4 outputs are much better in the zone I, zone II, zone IV and sub-Himalayan regions of the country compared with the RegCM4. The results indicate that the CORDEX models are not consistent with each other; the consistency in the CORDEX outputs is observed only in the central part of the India.

4.1.4 Assessment of extreme events

Next, the extreme events are assessed to check the potential of CORDEX in modelling the extreme events and the results are displayed in Fig. 5. It shows that the RegCM4 is over-estimating the extreme events (5th and 95th percentiles) in the zone I and sub-Himalayan regions and under-estimating in zone V. It is identified that the RegCM4 data is biased (± 200 mm) across various parts of the country. The low rainfall events are over-estimated (~ 100 mm) in zone I and zone II. The better association is noticed in the western part of the country. The 95th percentile values are over-estimated by ~ 400 mm in zone I, and the same are under-estimated (~ 1000 mm) by the RegCM4 in zone V. The outputs of RCA4 are better than RegCM4 in signifying the observed extreme events (see Fig. 5). For instance, the low extreme events (5th percentile) are slightly over-estimated, i.e. ~ 15 mm (it is noted as ~ 60 mm in case of RegCM4) in the northern and southern parts (parts of zone I and zone IV) of the country. The mean value is less biased (compared with RegCM4), i.e. ± 120 mm for all parts of the country except north-eastern and Western Ghat regions (where the bias is ± 220 mm). The higher side extreme events are also completely biased in the Western Ghat (zone V), eastern, north-eastern (zone II) and southern peninsular (zone IV) regions. A magnitude of + 800 to − 400 mm bias is observed in the mentioned regions except zone V, where the bias amount is ~ + 1200 mm (under-estimated).

4.2 Assessment of CORDEX-SA data during future period

Future data for RCP 4.5 and 8.5 scenarios are considered for the future assessment, and it is divided into three epochs each 30 years (for more details, refer to Section 3). For brevity, the results for the future climate change during the last epoch (epoch-3) are discussed. First, the seasonal variation during the future period is carried out and presented in Fig. 6. The results shows that the future precipitation is expected to intensify during the non-monsoon months (pre- and post-monsoons) in almost all parts of India. In particular, north-eastern (zone II), eastern, northern (parts of zone I) and southern parts (parts of zone III and zone IV) of India may become wetter as per RegCM4. There will be more rainy days during the non-monsoon months as per RCP8.5 scenario. However, the precipitation may decline during the monsoon season (using RCP4.5 scenario) as per both the CORDEX models (see Fig. 6) and will increase slightly as per RCP8.5 scenario. Consistency is detected in both the CORDEX models. However, RegCM4 is more biased in zone I apart from that the results are projected well in the central part of the country.

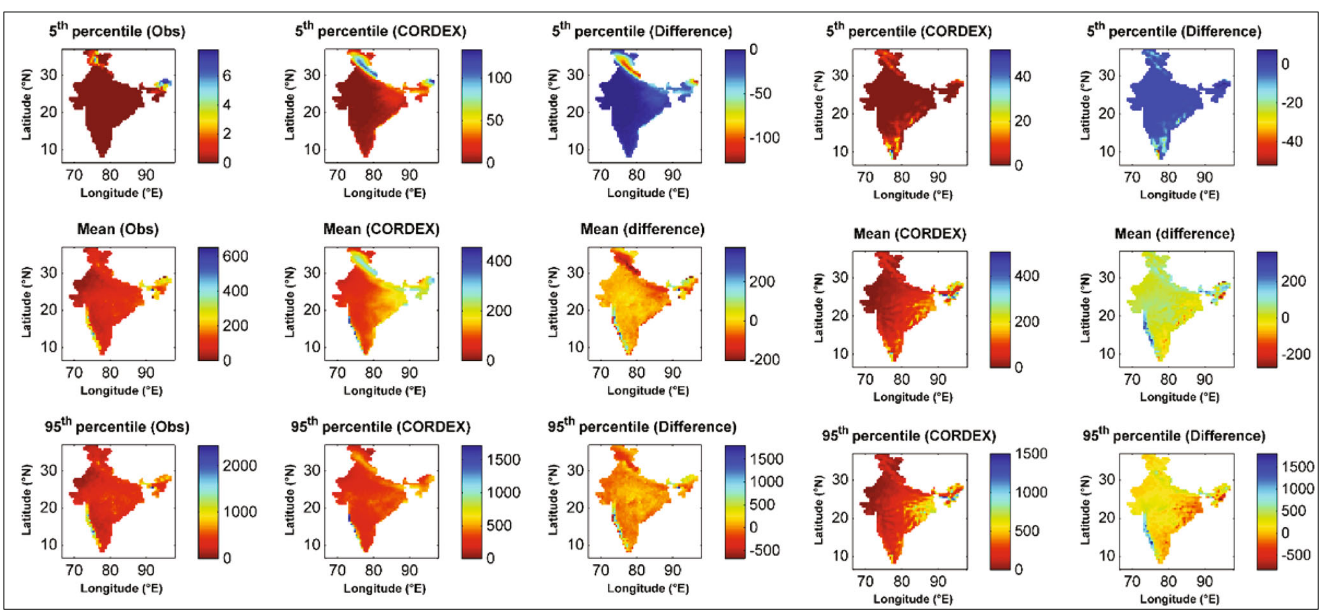

Fig. 5 Mean and extreme value comparison between observed and CORDEX precipitation data during the historical period (1971–2005). The plots (row-wise) correspond to 5th percentile, mean and 95th percentile values. The column-wise plots represent the Observed data (first column), CORDEX data and difference (Observed-CORDEX) in extreme events using RegCM4 (second and third columns) and RCA4 (fourth and fifth columns), respectively

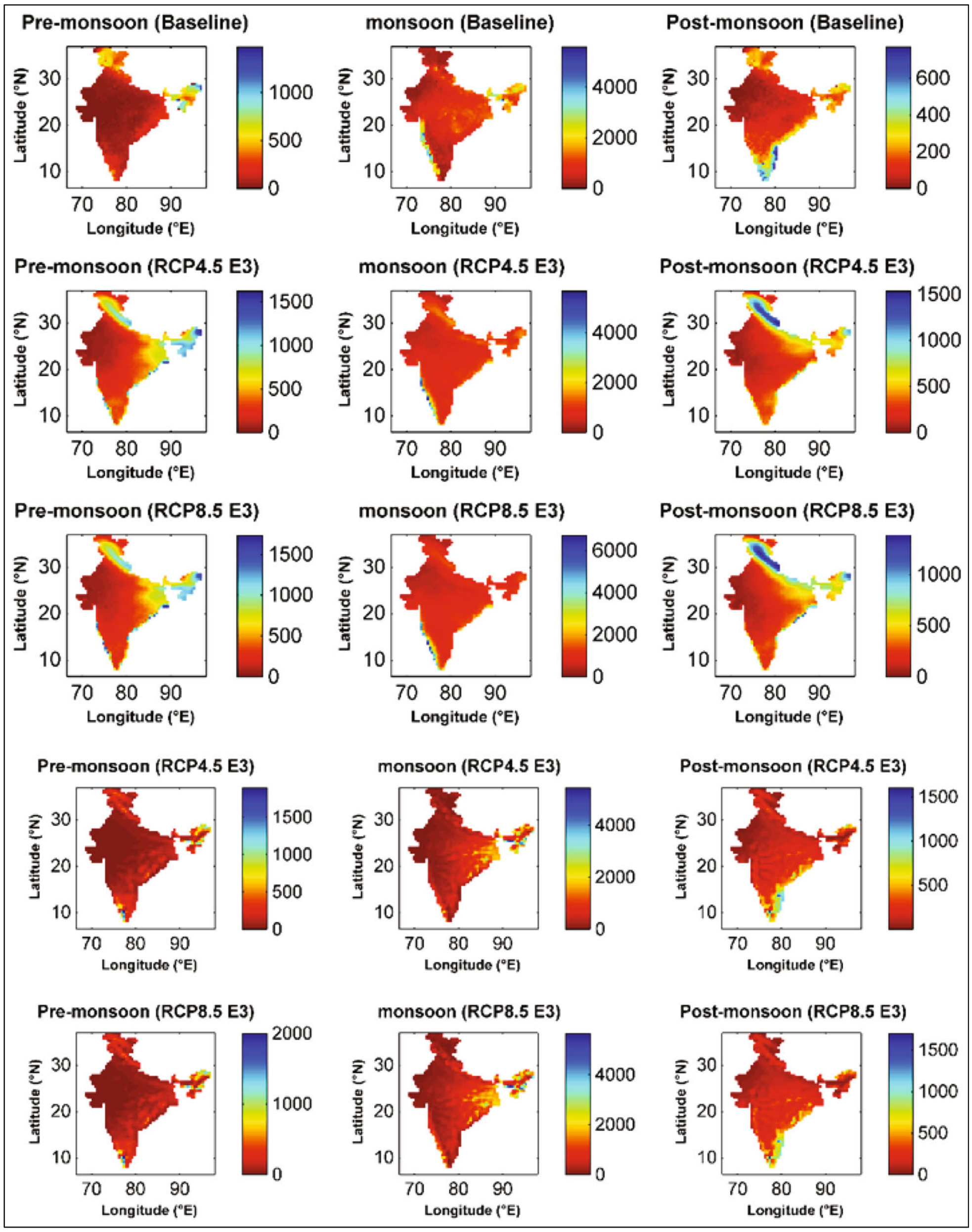

Fig. 6 Variation of total seasonal rainfall amount (in mm) during the baseline (1971–2000) and the future (2071–2100, epoch-3) periods respectively for RCP4.5 and RCP8.5 scenarios. The first row corresponding to the baseline period second and third rows are corresponding to the RegCM4 outputs and fourth and fifth rows are corresponding to the RCA4 outputs. Different seasons are as follows: pre-monsoon (February-May), monsoon (June-September) and post-monsoon (October-January)

It is worth mentioning that the return monsoon (occurs during post-monsoon period) is captured by RCA4 and fails in projecting the precipitation for zone V. It is noteworthy that a larger bias is observed during the historical period over this region. Next, the change in monthly variation during epoch-3 (2071–2100) is shown in Fig. 7. The results infer that there will be more rainy days during the non-monsoon months as per both the CORDEX model projections during the future period than the baseline period.

Thereafter, the extreme events at 5th percentile, mean and 95th percentile values are calculated and portrayed in Fig. 8 (RCP4.5 scenario) and Fig. 9 (RCP8.5 scenario). The mean value is expected to increase between 100 and 200 mm as per RegCM4 during epoch-3 in contrast with the baseline data over the majority parts of the country (see Fig. 8). Interestingly, it shows decreasing trend (100 to 200 mm) using the RCA4 outputs for the entire study region except eastern, east coast (zone III) and peninsular regions (zone IV). The other extreme magnitudes (5th and 95th percentiles) are expected to increase consistently for both the CORDEX models in most of the regions.

Lastly, the same analysis for RCP8.5 is presented in Fig. 9. Similar observations (as in case of RCP4.5) are noted as far as extreme magnitudes (5th and 95th percentiles) are concerned. However, the mean value seems to be decreasing in the central and western parts of India for both the models (see Fig. 9). However, the difference (negative) with the baseline period data is increasing for the RegCM4 using RCP8.5 scenario which indicates that the magnitude of extreme events may

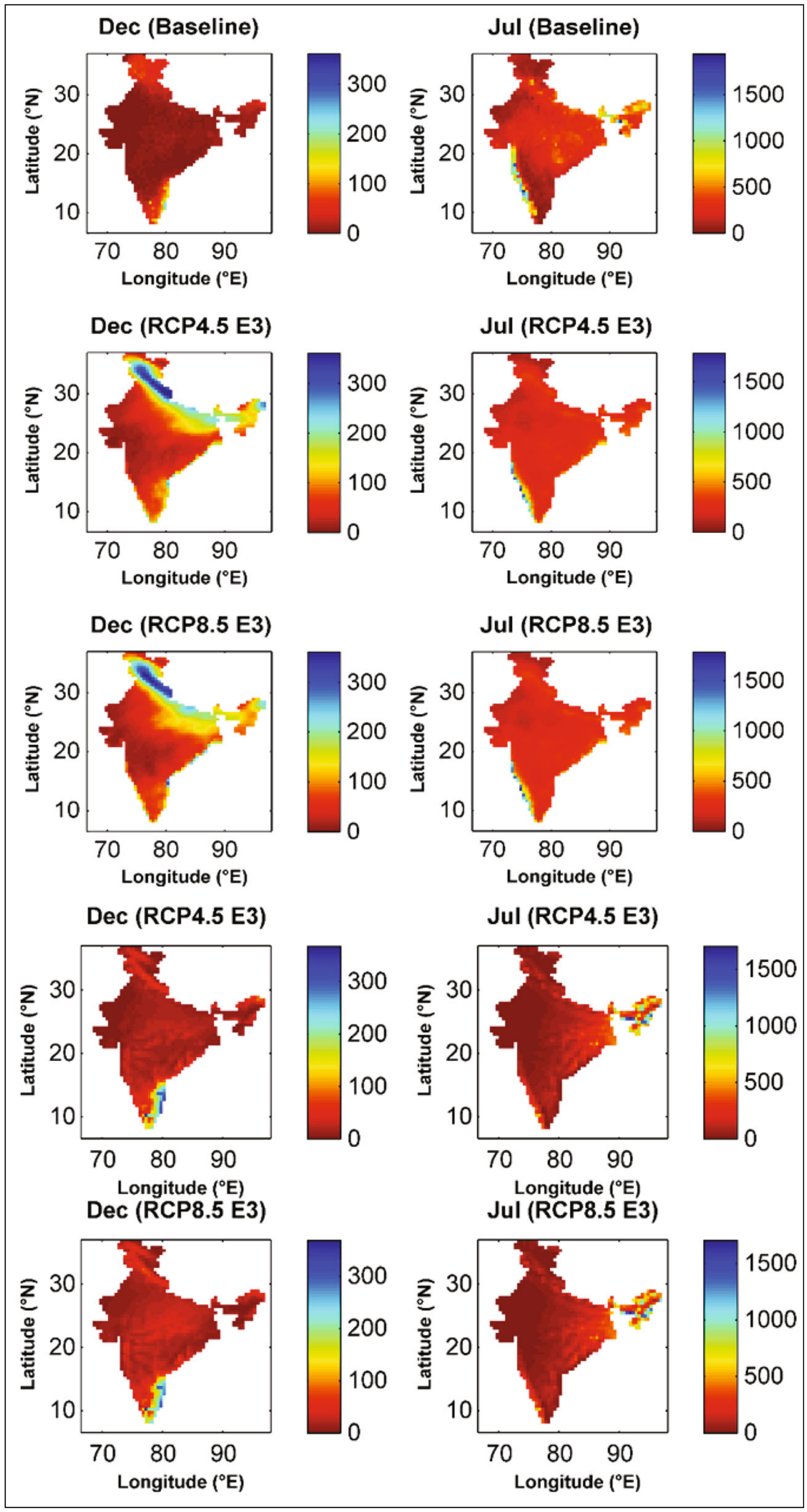

Fig. 7 Comparison of spatial distribution of total precipitation (in mm) in one monsoon (July) and one non-monsoon (December) month during baseline period (1971–2000) and the future period (2071–2100, epoch-3) for RCP4.5 and RCP8.5 scenarios. The first row corresponding to the baseline data; second and third rows are corresponding to the RegCM4 outputs; and fourth and fifth rows are corresponding to the RCA4 outputs

increase in some regions (e.g. east coast and peninsular India) of the country.

Overall, the results indicate that there will be wetter non-monsoon (pre- and post-monsoon) months along with relatively no/slight change in the monsoon months. The extreme events are expected to intensify during the future period in contrast with the baseline period. The CORDEX-SA outputs are reliable in the central India and parts of western India.

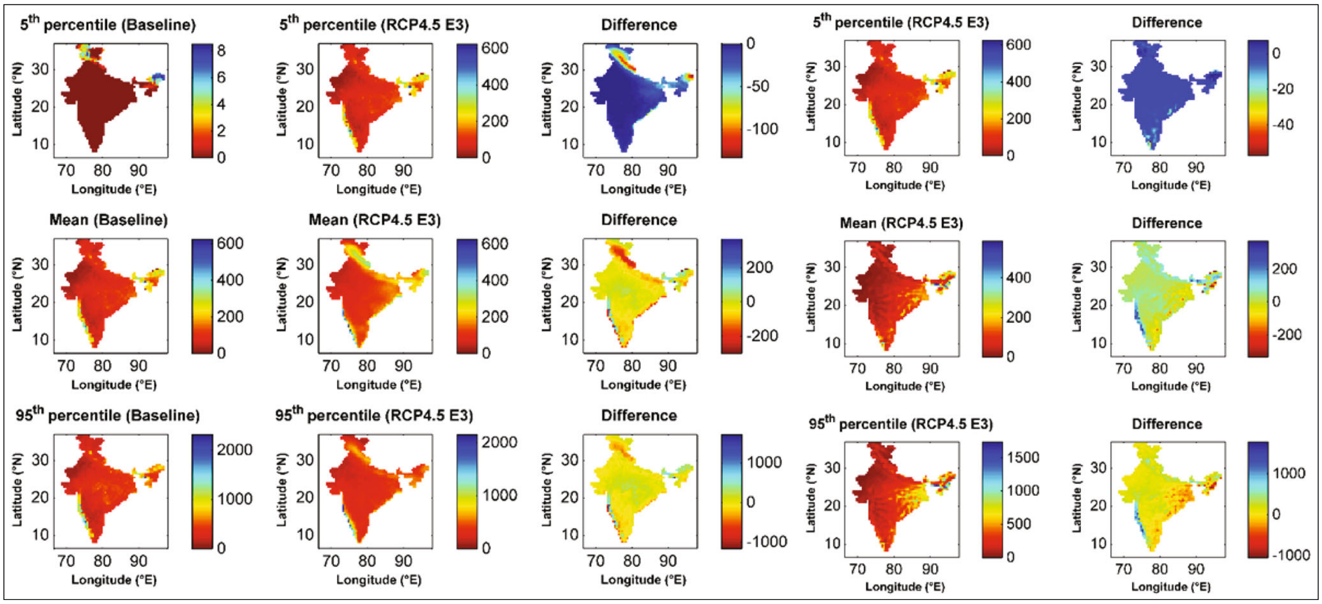

Fig. 8 Mean and extreme value comparison between observed precipitation during baseline period (first column) and CORDEX simulated values, i.e. RegCM4 (second and third columns) and RCA4 (fourth and fifth columns) in future (during the epoch-3) for RCP4.5 scenario

However, they are biased in remaining parts of the country. The outputs are needed to be bias corrected before using for any impact assessment studies.

5 Summary and conclusions

It is established that the outputs from CORDEX simulations are largely biased and exhibit significant discrepancy with respect to the observed precipitation data in some regions. Thereby, it is essential to check the quality of CORDEX outputs in representing the observed data before using them for any local scale impact assessments or for policymaking. This study attempts to investigate the spatio-temporal correspondence between observed and CORDEX-SA precipitation across Indian mainland that consists of a wide range of climate regimes. The outputs from two RCMs (RegCM4 and RCA4), used in CORDEX-SA program, are considered. The future changes in monthly and seasonal precipitation are also assessed including the extreme magnitudes by considering RCP4.5 and RCP8.5 emission scenarios. The important findings obtained from this study are summarized as follows:

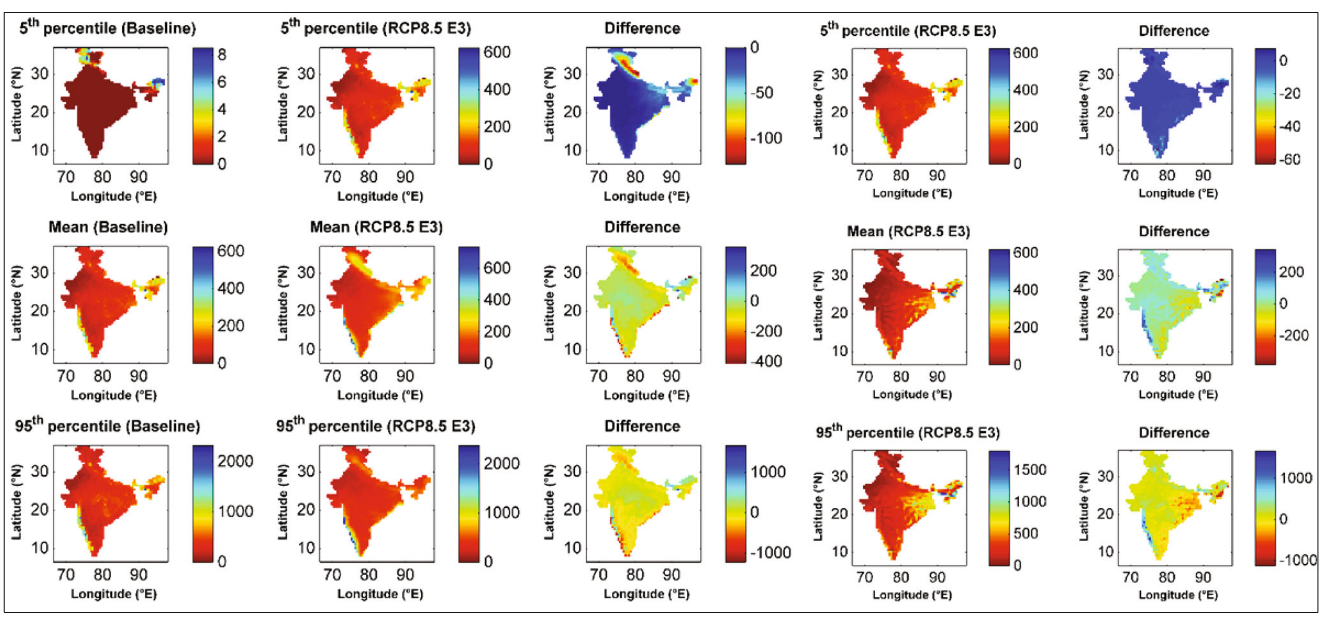

Fig. 9 Same as Fig. 8 but for RCP8.5

1. The correspondence between observed and CORDEX-SA precipitation is spatially non-uniform in representing the mean and extreme magnitudes across Indian mainland.
2. The monthly and seasonal scale analyses during the historical period reveal a satisfactory performance of the CORDEX-SA data over central parts of India during the monsoon months. However, it is highly under-estimated in the north-eastern and Western Ghat regions. The model results exhibit poor correspondence during the pre-monsoon and post-monsoon months. The return monsoon in the southern peninsular region is better captured by RCA4 as compared with RegCM4.
3. The extreme magnitudes in the high rainfall regions (except Western Ghats) are over-estimated by both the RCMs, and the presence of large bias in the mean (± 200 mm) is also observed across different parts of India.
4. In general, the RCA4 performs better than RegCM4 in the northern part and Himalayan region (hilly regions), whereas RegCM4 outputs corresponds better in the southern peninsular region (coastal part) when compared with RCA4. The correspondence is poor in the high rainfall regions (north-east, Western Ghat regions), and it is consistent from both the RCMs.
5. The future analysis reveals that precipitation amounts are expected to intensify during non-monsoon months and agreed by both the RCMs, whereas the monsoon precipitation may increase as per RegCM4 in both the scenarios (RCP4.5 and RCP8.5) during epoch-3.

Overall, the correspondence between observed and CORDEX-SA data (RegCM4 and RCA4 outputs) is found to be non-uniform across different climate regimes. It is satisfactory over central parts of India during the monsoon months and, in general, poor in the high or above normal rainfall regions with hilly terrain, such as sub-Himalayan, north-east and Western Ghat regions.

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