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ORIGINAL PAPER

Projected seasonal mean summer monsoon over India and adjoining regions for the twenty-first century

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Abstract In this study, we present the projected seasonal mean summer monsoon over India and adjoining regions for the twenty-first century under the representative concentration pathway (RCP) 4.5 and RCP 8.5 scenarios using the regional model RegCM4 driven by the global model GFDL-ESM2M. RegCM4 is integrated from 1970 to 2099 at 50 km horizontal resolution over the South Asia CORDEX domain. The simulated mean summer monsoon circulation and associated rainfall by RegCM4 are validated against observations in the reference period 1975 to 2004 based on the Global Precipitation Climatology Project (GPCP) and India Meteorological Department (IMD) data sets. Regional model results are also compared with those of the global model GFDL which forces the RegCM4, showing that the regional model in particular improves the simulation of precipitation trends during the reference period. Future projections are categorized as near future (2010–2039), mid future (2040–2069), and far future (2070–2099). Comparison of projected seasonal (June–September) mean rainfall from the different time slices indicate a gradual increase in the intensity of changes over some of the regions under both the RCP4.5 and RCP8.5 scenarios. RegCM4 projected rainfall decreases over most of the Indian land mass and the equatorial and northern Indian Ocean, while it increases over the Arabian Sea, northern Bay of Bengal, and the Himalayas. Results show that the monsoon circulation may become weaker in the future associated with a decrease in rainfall over Indian land points. The RegCM4 projected decrease in June, July, August, September (JJAS) rainfall under the RCP8.5 scenario over the central, eastern, and peninsular India by the end of the century is in the range of 25–40 % of their mean reference period values; it is significant at the 95 % confidence level and it is broadly in line with patterns of observed change in recent decades. Surface evaporation is projected to increase over the Indian Ocean, thereby supplying more moisture into the atmosphere. As per the RegCM4 projection, the northward flank of the southwesterly winds (i.e., over the central and north India) may become stronger and veer towards the north over the Arabian Sea, traverse trans-India over the foothills of the Himalayas and northern Bay of Bengal, and reach up to Burma. The changes in circulation lead to a change in the moisture distribution and result in a decrease of moisture convergence over central and peninsular India, the Indian Ocean, and the southern part of Bay of Bengal and an increase over the Arabian Sea, northern Bay of Bengal, and the Himalayas.

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1 Introduction

The summer monsoon has a tremendous influence on the agriculture, water resources, ecosystems, and economics of India. Good monsoons bring prosperity, and poor ones cause devastation and loss of livelihood. For this reason, the scientific community has made considerable efforts to understand underlying mechanisms, past evolution, and possible future changes of the monsoon. Recent research reveals that the monsoon has undergone significant changes during the last half century. The seasonal mean Indian summer monsoon rainfall has weakened (Ramanathan et al. 2005; Dash et al. 2007; Ramesh and Goswami 2007), and the temporal distribution of rainfall within the season has become more extreme (Goswami et al. 2006; Dash et al. 2009). The observed changes in the last 50 years are often associated with global warming and dimming, and since these are expected to continue in the future, some questions arise: How will the monsoon change in the future? Will there be weaker or stronger monsoons? Will the spatial and temporal distribution of monsoon precipitation change? These questions bear huge societal importance because they could help scientists and policy makers to develop suitable strategies to cope with and take advantage of possible future changes.

In the last two decades, a large body of research has been conducted to investigate these issues. Earlier studies generally showed an increase in the seasonal mean rainfall over South Asia with increasing carbon dioxide concentrations (Meehl and Washington 1993; Kitoh et al. 1997; Ashrit et al. 2003; Meehl et al. 2003; Kripalani et al. 2007 and Sabade et al. 2011). Kripalani et al. (2007) examined the model outputs of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) and found an increase in East Asian Summer Monsoon rainfall under doubled CO_2 scenario. Sabade et al. (2011) examined the Third Coupled Model Inter-comparison Project (CMIP3) data sets and found that ten out of a total of 25 models simulated space-time characteristics of South Asian Summer Monsoon precipitation reasonably well. The multi-model ensemble of these ten models projected a significant weakening of the South Asian Summer Monsoon (SASM) circulation under the B1, A1B, and A2 emission scenarios. However, the corresponding monsoon rainfall was projected to significantly increase. They attributed this contradiction to the intensification of the heat low over northwest India due to the increase in surface temperature. However, a few studies have indicated that the monsoon rain may become weaker or show no significant change with global warming (Zhao and Bailey-Kellogg 1998; Ashfaq et al. 2009). Studies suggest that the land-ocean contrast is likely to become stronger in the future, resulting in a northward shift of the Somali jet and increased rainfall over South Asia (Ashrit et al. 2003). Ueda et al. (2006) also found that a subset of the models in CMIP3 showed an increase in rainfall despite a weakening in monsoon circulation. Turner and Annamalai (2012) have reviewed different aspects of the current and future changes in SASM in greater detail.

In addition to examining rainfall in the South Asian region, it is also important to assess future changes over the adjoining seas and oceans, i.e., over the Arabian Sea, Bay of Bengal, and equatorial and northern Indian Ocean, since the South Asia monsoon is highly coupled with the adjoining water bodies. Most previous studies have used global climate models, which are found to be very useful in understanding the response of the climate system to greenhouse gases, aerosol loadings, and land use changes at global to sub-continental scale (IPCC 2007). Although there are remarkable improvements in these models in the last decade, the spatial resolution of most global climate models is still of the order of a hundred kilometers. This precludes them from representing the fine-scale local forcings (viz. surface topography and land surface characteristics, etc.) that crucially influence climate at regional scales and from accurately describing extreme events.

An approach that can be adopted to regionally enhance the model resolution is the use of nested (Giorgi and Mearns 1999) regional climate models (RCMs). The RCM named Providing Regional Climates for Impacts Studies (PRECIS) has been used by several researchers (e.g., Rupakumar et al. 2006; Krishnakumar et al. 2011) at 50 km resolution to study regional climate projections over India. Rupakumar et al. (2006) projected remarkable increases in rainfall (up to 20 %) and temperature (2.5 to 5 °C) over the Indian territory by the end of the twenty-first century. They also found large spatial variations in the changes. Krishnakumar et al. (2011) used three simulations corresponding to the A1B scenario of Hadley Centre Coupled Model version 3 (HadCM3) to drive PRECIS and projected an increase in mean surface temperature over India by the end of twenty-first century ranging between 3.5 and 4.3 °C. The projected monsoon precipitation also showed an increasing trend. Since climate projections may vary substantially across different models, it is therefore important to use a range of RCMs.

Successive versions of the regional climate model (RegCM) of the Abdus Salam International Centre for Theoretical Physics have been used widely for various regional climate studies (Giorgi et al. 1993a, b; Pal et al. 2007). Of interest for the South Asia region, Dash et al. (2006) simulated the Indian summer monsoon circulation and rainfall with RegCM3 (Pal et al. 2007) at 55 km grid spacing. They showed that RegCM3 can successfully capture the mean features of the Indian summer monsoon. Ashfaq et al. (2009) conducted projections of the Indian summer monsoon under enhanced greenhouse gas concentrations with a higher resolution (25 km) version of RegCM3. They found a weakening of the overall monsoon across the sub-continent associated with a decline in summer rainfall, a delay in the onset of the monsoon and more monsoon break periods. More recently, Dash et al. (2013) and Pattnayak et al. (2013) showed that the RegCM3 simulations of the Indian summer monsoon characteristics can closely reproduce observations, especially over the central India.

In this paper, we use the latest version of the RegCM modelling system, RegCM4 (Giorgi et al. 2012), to produce and analyze a twenty-first century projection of monsoon change over South Asia and surrounding oceans. The present simulation was performed as a contribution to the Coordinated Regional Downscaling Experiment (CORDEX), and therefore, the model domain and resolution follow the CORDEX (Giorgi et al. 2009) specifications. The RegCM4 is driven by the GFDL-ESM2M GCM, and the focus of the analysis is on the evolution of the summer monsoon over the Indian subcontinent and adjacent ocean areas. The simulation is also part of a broader project, the phase I CORDEX RegCM4 hyper-matrix, or CREMA (Giorgi 2014), in which the RegCM4 is run over multiple CORDEX domains as a first contribution of the RegCM4 user community to CORDEX. The model and simulation details are provided in Section 2, while validation of the model simulated climate is carried out in Section 3. Section 4 presents the projected Indian summer monsoon rainfall up to the end of the century. Description of the related future changes in surface evaporation and large-scale circulation is made in Section 5. Finally, the discussions and conclusion are provided in Section 6.

2 RegCM simulations

The Regional Climate Model version 4 (RegCM4) is used in this study. The model is described and documented in detail by Giorgi et al. (2012). In brief, RegCM4 is a hydrostatic and compressible model that runs on Arakawa B-grid and employs an explicit time splitting scheme. The model includes multiple physics options, and for the experiment presented here, it uses the NCAR CCM3 radiation package for radiative transfer calculations; the biosphere-atmosphere transfer scheme (BATS) of Dickinson et al. (1993) to represent land surface processes; the non-local formulation of Holtslag et al. (1990) to describe the planetary boundary layer; the Emanuel scheme (Emanuel and Zivkovic-Rothman 1999) and Grell (1993) schemes for convection over land and ocean areas, respectively; and the subgrid explicit moisture scheme (SUBEX) of Pal et al. (2000) for resolvable scale precipitation. The surface elevation and land cover data are obtained from the US Geological Survey Global Land Cover Characterization (GLCC).

The model was integrated from 1st January 1970 until 31st December 2099 at 50 km horizontal resolution over the South Asia CORDEX domain, which covers a broad South Asia region and adjacent ocean areas, 10° E to 130° E and 22° S to 49° N. A CMIP5 GFDL-ESM2M simulation (from IPCC AR5) is used to produce the initial and lateral boundary conditions for the RegCM4. The simulations consist of two phases: phase 1 is the historical period covering from 1970 until 2005 and phase 2 is for the future (2006–2100) under the Representative Concentration Pathway RCP4.5 (low end) and RCP8.5 (high end). The RegCM4 configuration and driving GCM were selected based on an extensive set of preliminary experiments which provided a realistic representation of the South Asia climate in present day conditions (Coppola et al. 2014). It is noted that, although some basic model validation is presented in the next section, the detailed analysis of the model performance in simulating mean climate and extremes is discussed by Coppola et al. (2014) and Giorgi et al. (2014).

3 Basic validation of model climate

Before analyzing the future projections, it is essential to verify if RegCM4 is able to satisfactorily simulate the present monsoon conditions. With that objective, the rainfall simulated in present day conditions by both the global and regional climate models are validated against observed rainfall data from the India Meteorological Department (IMD) at 0.5×0.5 grids (IMD0.5) (only over Indian land points) and against the GPCP rainfall data set over the entire South Asia domain during the reference period. The June, July, August, September (JJAS) seasonal mean rainfall simulated by RegCM4 and GFDL during the period 1979–2004 are compared with the corresponding GPCP values in Fig. 1a–c and with the IMD0.5 rainfall in Fig. 2a-c. The starting year is chosen as 1979 since the GPCP rainfall data are available from that year. The model exhibits different patterns of bias. The JJAS mean observed rainfall has two maximum rain areas (Figs. 1a, 2a): the Western Ghats and the north Bay of Bengal (BoB). RegCM4 (Fig. 1b) is able to reproduce these two rainfall zones, whereas GFDL (Fig. 1c) is less successful in simulating high rainfall intensity in these areas. Compared to GPCP, both GFDL and RegCM exhibit (Fig. 1d, e) high positive biases of up to 80 % over the Arabian Sea and BoB and negative biases over most of the Indian land points. RegCM-simulated rainfall has a positive bias (Fig. 1d) over the Western Ghats of up to 80 % and a maximum of 40 % negative bias over central and peninsular India, while most of central India has a low negative bias in the range of 10–20 %. The bias in the parent GFDL model is high, up to 80 %, especially over western India. Statistical significance tests have also been performed on the model biases. In Fig. 1d, e, the green contour lines encompassing most of the white patches depict statistical significance of the biases at 95 % confidence level, and it is interesting to note that, often, low biases in the range of −10 to +10 % are significant whereas the larger biases are not.

Figure 2b, c depicts the rainfall biases in the RegCM and GFDL simulations against the IMD0.5 data set over the Indian landmass. In most regions over India, the positive and negative biases in Fig. 2 are similar to those in Fig. 1. However, there are some exceptions. Over the Western Ghats, the RegCM-simulated rainfall has a negative bias of up to 20 % on the windward side (Fig. 2b), while on the leeward side, there is positive bias in the range of 60–80 %. In the GFDL simulation, the negative bias over eastern India is 40–60 %. These biases are evidently related to the smoothed representation of the Western Ghats in the models. It is important to note that in central India, both the GFDL and RegCM have low negative biases of about 20 %. As in the case of Fig. 1d, e, the green contour lines encompassing the white patches in Fig. 2b, c indicate that low biases lying within −10 to +10 % are significant at 95 % confidence level whereas larger biases are not statistically significant.

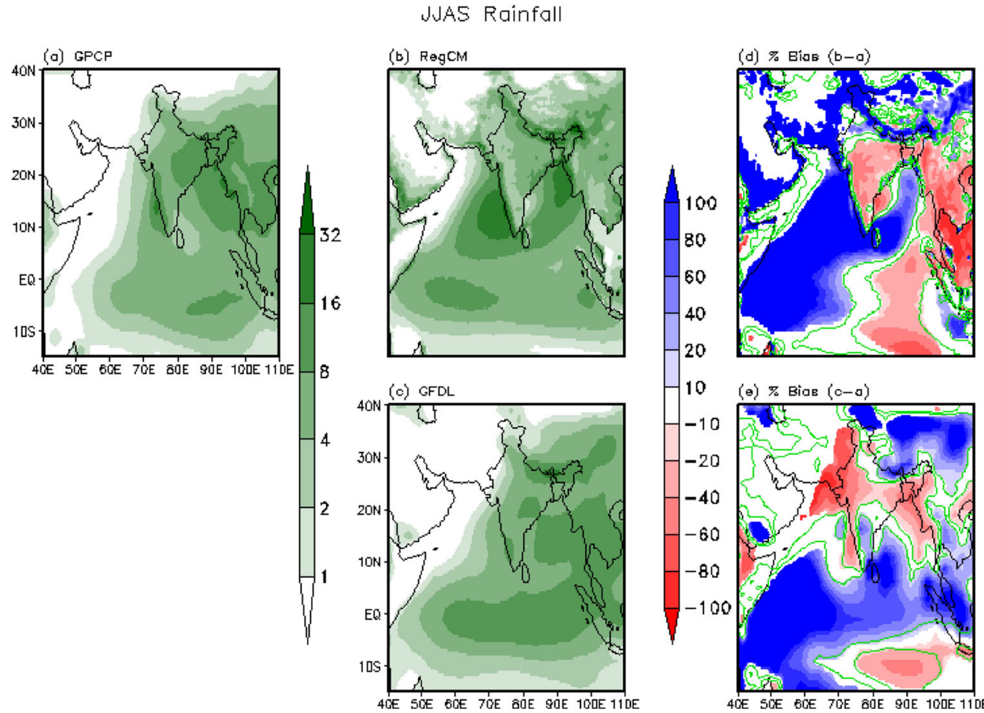

Fig. 1 Climatological JJAS mean rainfall (mm/day) during 1979 to 2004 as observed in **a** GPCP and simulated by **b** RegCM4.3 and **c** GFDL-ESM2M. The right-hand side panels show the corresponding biases (in %) in **d** RegCM4.3 and **e** GFDL simulations. The *green contour lines* encompassing most of the white patches in **d** and **e** depict that low biases lying within −10 to +10 % are significant at the 95 % confidence level whereas larger biases are not statistically significant

Figure 3 shows the GPCP, GFDL, and RegCM JJAS mean rainfall in the initial and final decades of the period 1979 to 2004 and the changes during that period. The left and middle columns represent JJAS mean rainfall during 1979–1988 and 1995–2004, respectively, while the right column shows the changes occurring within the reference period. Again the starting year is chosen as 1979 since the GPCP rainfall data are available from that year. Comparison of JJAS mean rainfall simulated by GFDL (Fig. 3d, e) and RegCM (Fig. 3g, h) with that of GPCP (Fig. 3a, b) confirms that the spatial distribution of summer monsoon rainfall is closer to the observed pattern in RegCM4 than in GFDL. Figure 3c, f–i shows the percentage changes in JJAS mean rainfall that occurred within the reference period 1979 to 2004 in GPCP, GFDL, and RegCM respectively. The purpose is to examine whether RegCM, despite the fact that we are analyzing only one realization, captures the observed change in the rainfall during the reference period. This would provide increasing confidence in the ability of the model to simulate greenhouse gas-driven changes in the projected precipitation.

As mentioned earlier, Fig. 3c displays the change in observed rainfall as represented in GPCP data. We note a decrease in rainfall over central and northeastern India, as well as over the Himalayas and west coast of peninsular India up to a maximum of 20 %. On the other hand, there is an increase in rainfall over the Gangetic plain, northwest India, head of the BoB, and western part of the equatorial Indian Ocean in the range of 20–40 %. As it can be seen in Fig. 3i, in the RegCM4

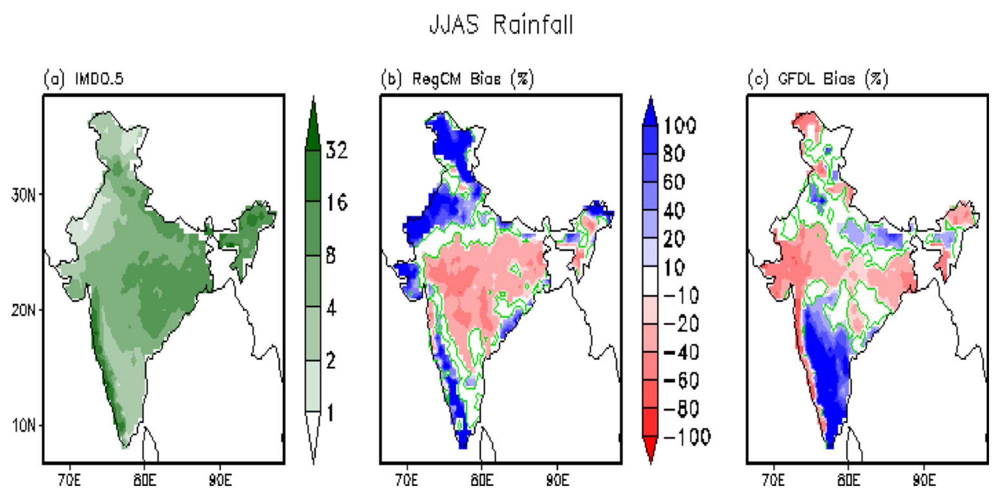

Fig. 2 Climatological JJAS mean rainfall (mm/day) over Indian land points during 1979 to 2004 as **a** observed in IMD0.5 gridded rainfall data set and the corresponding biases (in %) in **b** RegCM4.3 and **c** GFDL-ESM2M simulations respectively. The *green contour lines* encompassing the white patches in **b** and **c** depict that low biases lying within −10 to +10 % are significant at the 95 % confidence level whereas larger biases are not statistically significant

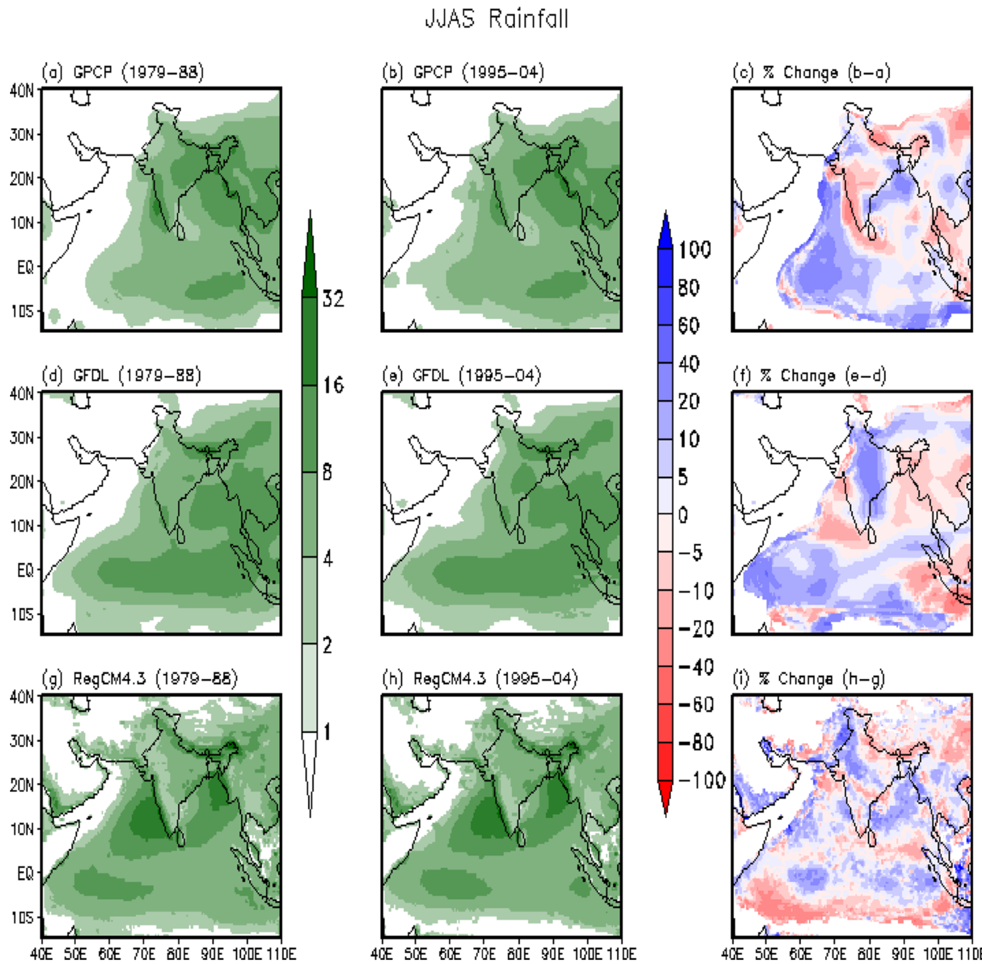

Fig. 3 JJAS mean rainfall (mm/day) and their corresponding changes (%) between the first and last decades during 1979 to 2004. The *top row* represents the observation as evident in GPCP data set. The *middle and bottom rows* represent GFDL and RegCM4.3 simulations, respectively

simulation, there is a similar reduction in rainfall over central and northeastern India and over the Himalayas and an increase over the Gangetic plain, northwest India, head of BoB, and western part of the equatorial Indian Ocean. However, over the west coast of peninsular India, the model fails to simulate the decrease in rainfall. Similarly, over the Himalayas, the model overestimates the reduction in rainfall. The GFDL does not show the increase of rainfall over the Arabian Sea and BoB (in Fig. 3f), while it is enhanced by about 35–40 % over central India.

Figure 4 compares the simulated precipitation changes during the reference period with the corresponding observed values as represented in the IMD0.5 dataset. The RegCM4 (Fig. 4c) is able to reproduce the observed change pattern of IMD0.5 (Fig. 4a) with the decreasing rainfall band at the Himalayan foothills, parallel increasing band over the central Indian region and another parallel decreasing rainfall band over the peninsular India. The decrease in rainfall is about 20–25 % both in the RegCM4 simulation and the IMD0.5 observation. Again, in the GFDL simulation (Fig. 4b), most of the Indian landmass shows increasing rainfall by about 35–40 % with some decrease over western, far north, and northeast India. Thus, based on the comparison against both the GPCP and IMD0.5 data sets, RegCM4-simulated JJAS mean rainfall change in the reference period is closer to the observed change compared to that simulated by the parent GCM GFDL, both in mean and change of patterns. As a more quantitative estimate of this improvement, the correlations between RegCM4 and observed change patterns are 0.77 for GPCP (Fig. 3) and 0.62 for IMD0.5 (Fig. 4) while those between GFDL and observed change patterns are 0.72 for GPCP (Fig. 3) and 0.36 for IMD0.5 (Fig. 4). We further highlight the fact that, despite the use of a single realization, RegCM4 is capable of capturing some aspects of the observed precipitation trends during the reference period.

Figure 5 shows the model validation for the lower and upper level winds by comparison with the corresponding NCEP reanalysis data, both for mean and change in circulation. The regional model satisfactorily simulates the location of the Somali jet and upper level easterly jet. The Somali jet is underestimated in the

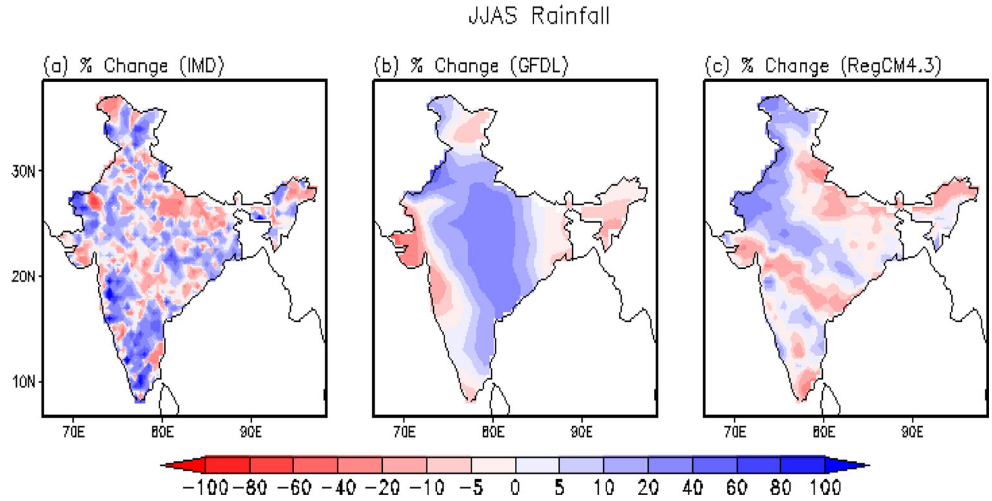

Fig. 4 Changes (in %) in JJAS mean rainfall over Indian land points between the first and last decades during the period 1979 to 2004 in **a** observation as represented by IMD0.5 gridded data set and **b** GFDL-ESM2M and **c** RegCM4.3 simulations

GFDL model, but the regional model realistically captures the cross-equatorial flow and south equatorial easterlies in the lower troposphere (Fig. 5(a1–a3)). The model agrees well with the weakening of low level westerlies over the Arabian Sea in the latter decade of the reference period (Fig. 5(b1–b3)), which the GFDL fails to simulate (Fig. 5(b1–b2)). Similar conclusions are found from the analysis of upper level wind circulations. The regional model shows that the strengths of the easterly jet and Tibetan anticyclone have weakened in the last three decades of the twentieth century, which is well supported by the NCEP/NCAR reanalysis (Fig. 5(d1–d3)). On the contrary, the GFDL model shows a sign of strengthening (Fig. 5(d1–d2)). Therefore, the wind circulation appears to be well represented in the RegCM4.3 and, in fact, better than in the forcing GFDL model. Indeed, the pattern correlation coefficients over the whole domain between the model simulated lower level wind and the NCEP/NCAR wind during the first and last decades of the period of study are 0.76 and 0.82, respectively. Similarly, the pattern correlation coefficients for the upper level winds are 0.90 and 0.93 respectively.

These comparative analyses of the circulation pattern and precipitation over India thus lead to the conclusion that RegCM4 driven by the GFDL GCM is of sufficient quality for its further use to project future changes in South Asia monsoon climate.

4 Future projections of monsoon rainfall

Here, we examine the simulated future changes in JJAS rainfall over the Indian sub-continent and its adjoining regions under the RCP4.5 and RCP8.5 scenarios. As mentioned earlier, we analyze three time slices into the future, each of 30 years length, i.e., 2010–2039 (near future), 2040–2069 (mid future), and 2070–2099 (far future). As discussed earlier, the period 1975–2004 is used as reference (or historical period). The future-projected changes are obtained by taking the differences between future and from reference periods. The JJAS mean rainfall for the reference period and in the near, mid, and far future as simulated by RegCM and the projected changes during the three time slices are shown in Fig. 6. Analysis of Fig. 6e–g shows that over southern India, there is indication of a decrease in rainfall by about 10 % in the near future to about 40 % in the far future. In the near future, there is some sign of small decreases in rainfall by 5 % over areas in the east coast (Fig. 6e), which gradually intensify up to 25 % and covers larger areas in the far future (Fig. 6g). Thus, a notable systematic decrease in the rainfall is found; the farther we go into the future, the larger being the change.

Conversely, precipitation shows a steady increase over the Arabian Sea, northern BoB, and the Himalayas, starting from a maximum of 30 % in the near future up to 40 % by the end of the century. The Northern BoB shows an increase in projected rainfall by 30 % in the near future, and this reduces to 15 % in intensity and in coverage by the end of the century (Fig. 6g). This could be explained by the fact that the decrease in the projected rainfall over central and eastern India starting from the period in the near future enhances in intensity by the far future and also covers larger areas, thus negatively affecting the projected rainfall in the northern BoB. Over the maritime continent, precipitation also decreases progressively as we proceed in time.

The 95 % significance of the changes in JJAS mean rainfall projected by RegCM4 is shown in Fig. 6e–g by the green contours surrounding the colored patches. In

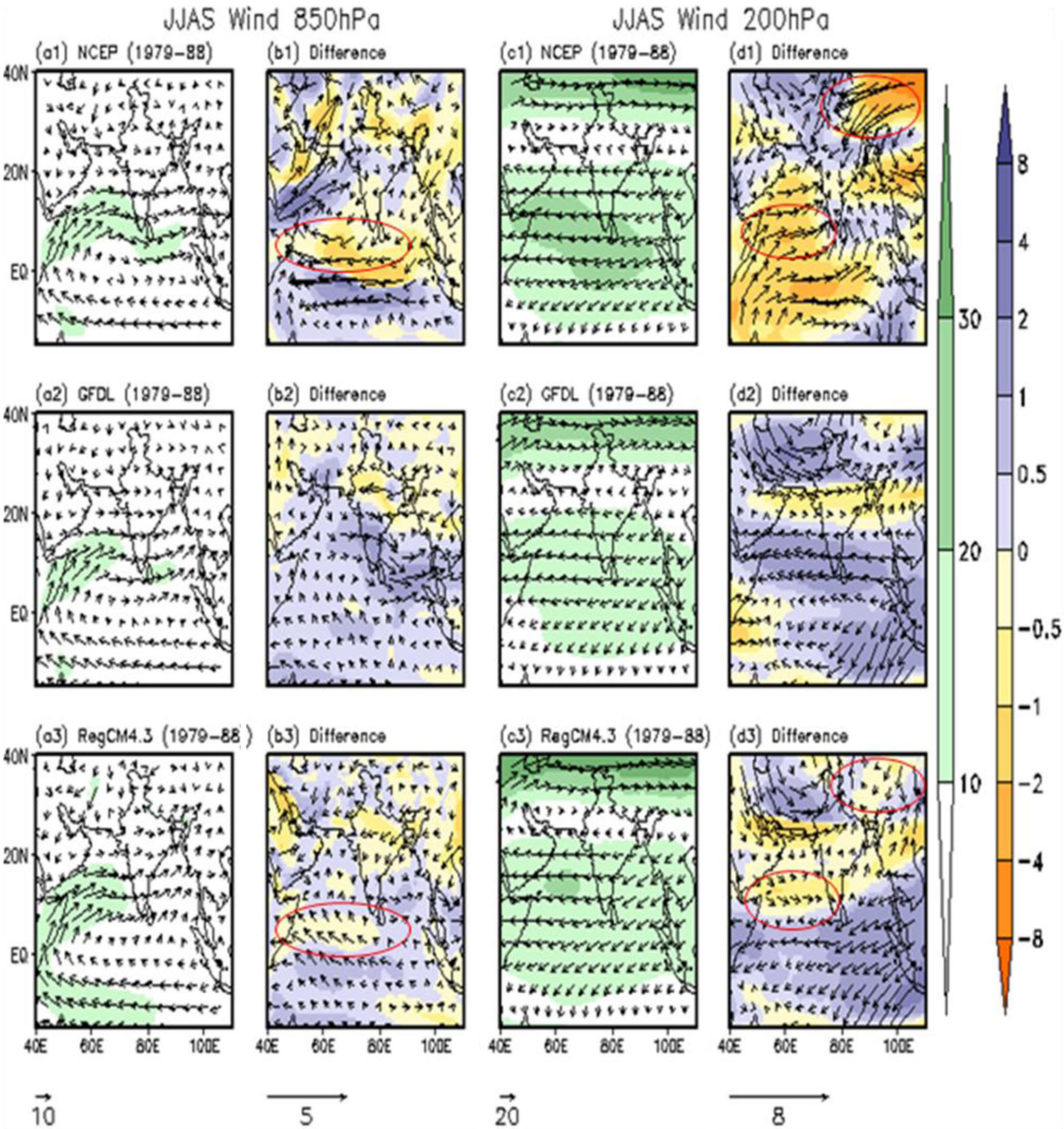

Fig. 5 JJAS mean winds (m/s) and their changes (%) between the first and last decades during 1979 to 2004 at 850 hPa (*first two columns*) and 200 hPa (*last two columns*) vertical levels. The *top row* represents NCEP/NCAR reanalysis. The *middle and bottom rows* represent GFDL and RegCM4.3, simulations respectively

the near future (Fig. 6e), the projected changes are small and statistically significant over small regions in the north Indian Ocean, Arabian Sea, and BoB. In the mid and far future, the intensity of projected changes enhances and simultaneously the regions of statistical significance are also enlarged systematically. In particular, by the end of the century, the weakening of projected summer monsoon rainfall become statistically significant over large areas in central, eastern, and peninsular India.

Figure 7 is similar to Fig. 6, but for the simulated rainfall change in the GFDL model. Comparison

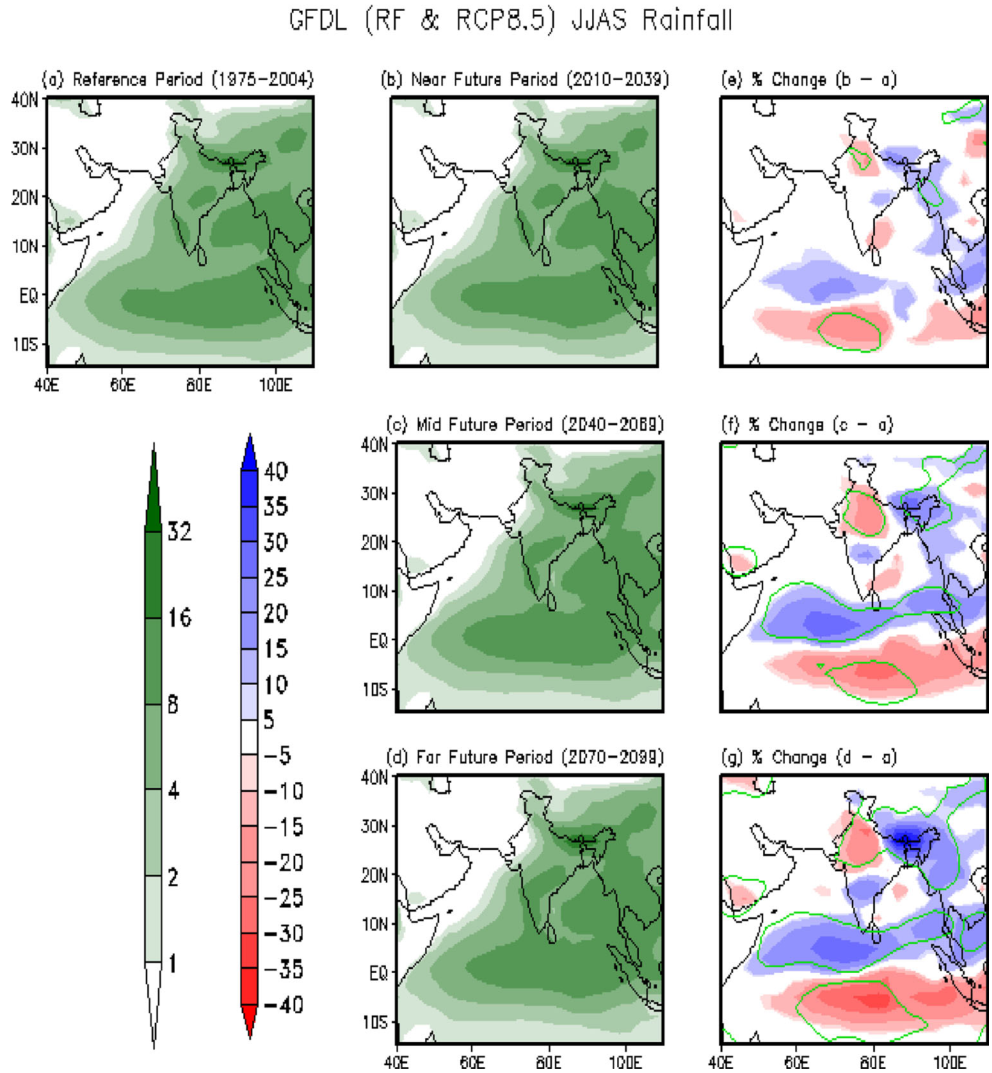

Fig. 6 JJAS mean rainfall (mm/day) as simulated by RegCM4.3 during the **a** reference period (1975 to 2004) and projected in the **b** near future (2010 to 2039), **c** mid future (2040 to 2069), and **d** far future (2070 to 2099) under RCP8.5 scenario. The *right-hand side panels* show the corresponding projected changes (%) in the **e** near future, **f** mid future, and **g** far future periods. The *green contour lines* encompassing the colored patches in **e**, **f**, and **g** depict that these changes are significant at the 95 % confidence level whereas other changes are not statistically significant

between rainfall changes in RegCM4 (Fig. 6e–g) and GFDL (Fig. 7e–g) brings out the effects of downscaling by the regional model. In the global model, the region of decrease in projected rainfall covers northern India starting from 20 % in the near future up to 35 % in the far future. On the other hand, the regional model shows a progressive reduction in rainfall over the eastern, central, and peninsular India similar to the observed decrease in rainfall over certain pockets in the same regions (Fig. 4a–c). The green contours in Fig. 7e–g indicate that the projected changes in this region are significant at the 95 % confidence level.

As shown in Fig. 8, the patterns of projected changes in RegCM under the RCP4.5 scenario are in general consistent with the corresponding patterns obtained under RCP 8.5 and depicted in Fig. 6. As expected, the magnitudes of changes are lower under the RCP4.5 scenario compared to the respective changes in the RCP8.5. In the near future, there is hardly any decrease in the projected rainfall; the decrease starts with 5 % in the mid future and intensifies to 15–25 % by the end of the century. In the adjoining north BoB, there is an increase of projected rainfall by 30 % in the near future and shows signs of reduction to 10 % in the far future. Figure 9 shows JJAS mean projected rainfall as simulated by GFDL under the RCP4.5 scenario. They are similar to those in Fig. 7 under the RCP8.5 scenario, but with lower magnitudes. However, there is one exception. In the near future, the global model indicates more pronounced decreases compared to those in the mid and far future under the RCP 4.5 scenario. After downscaling, the regional model projects a progressive decrease in rainfall (Fig. 8e–g), consistent with the projection under the RCP8.5 (Fig. 6e–g).

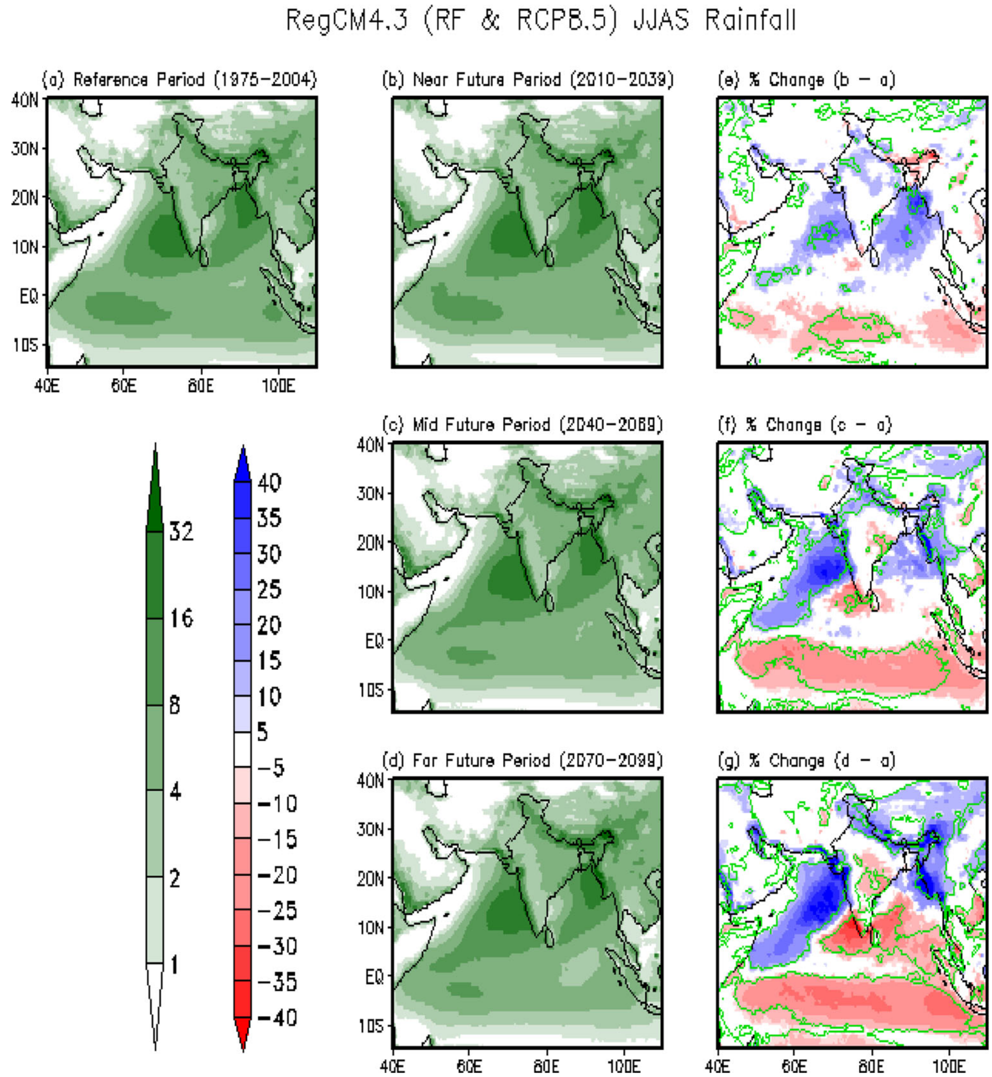

Fig. 7 JJAS mean rainfall (mm/day) as simulated by GFDL-ESM2M during the **a** reference period (1975 to 2004) and projected in the **b** near future (2010 to 2039), **c** mid future (2040 to 2069), and **d** far future (2070 to 2099) under RCP8.5 scenario. The *right-hand side panels* show the corresponding projected changes (%) in the **e** near future, **f** mid future, and **g** far future periods. The *green contour lines* encompassing the colored patches in **e**, **f**, and **g** depict that these changes are significant at 95 % confidence level whereas other changes are not statistically significant

5 Evaporation and circulation in the future period

On the seasonal timescale, rainfall derives from a balance of surface evaporation and moisture convergence due to large-scale circulation. The projected changes in the seasonal mean local evaporation and large-scale moisture convergence are shown in Fig. 10 for the far future periods under the RCP8.5 scenario. Surface evaporation shows a substantial increase over the ocean regions up to 0.8–1.0 mm/day over the Arabian Sea and BoB (about 25 % of the present day values). The middle panel of the figure shows the large-scale moisture convergence. It decreases over central and peninsular India and over the Indian Ocean and southern Bay of Bengal, while it increases over the Arabian Sea and northern BoB. Close comparison of Figs. 10b and 6g suggests that the pattern of changes in large-scale moisture convergence generally follows the pattern of the changes in rainfall. The changes in surface evaporation and large-scale moisture convergence are found to be similar over the Indian sub-continent, Arabian Sea, and head of the BoB. The contribution of large-scale moisture convergence is relatively greater—about 75 % over the region. However, over the Indian Ocean, although there is an increase in surface evaporation, the reduction of large-scale moisture convergence outweighs its effect and leads to the decrease in rainfall.

Rainfall, winds, and evaporation are coupled with each other, as rainfall leads to the release of latent heat which in turn drives the circulation that subsequently regulates surface evaporation through surface level winds. Figure 10c shows the projected changes in the low level (850 hPa) winds for the far-future periods. This figure indicates that the aforementioned circulation over the southern part of the Arabian Sea and Peninsular India becomes weaker by 2 to 3 m/s in the

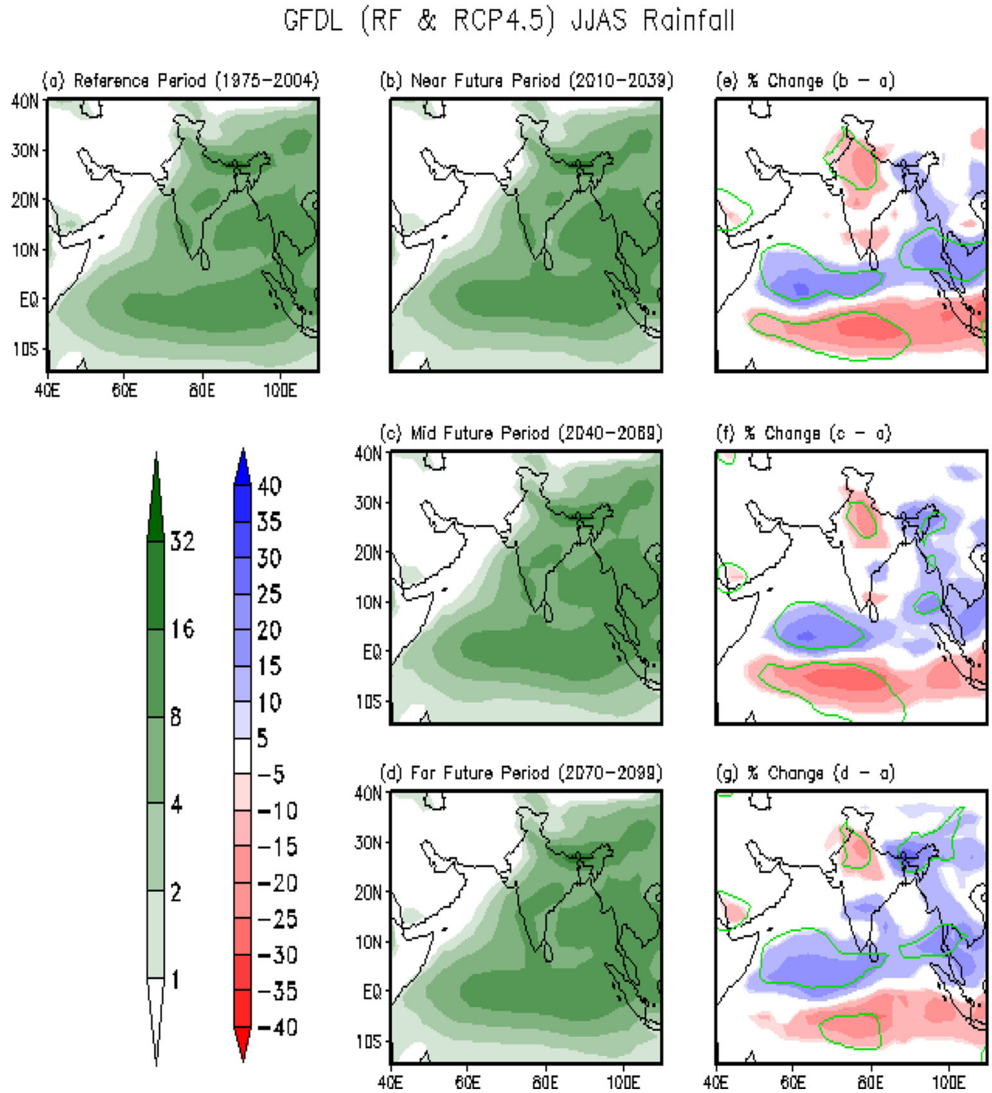

Fig. 8 JJAS mean rainfall (mm/day) as simulated by RegCM4.3 during the **a** reference period (1975 to 2004) and projected in the **b** near future (2010 to 2039), **c** mid future (2040 to 2069), and **d** far future (2070 to 2099) under RCP4.5 scenario. The *right-hand side panels* show the corresponding projected changes (%) in the **e** near future, **f** mid future, and **g** far future periods. The *green contour lines* encompassing the colored patches in **e**, **f**, and **g** depict that these changes are significant at 95 % confidence level whereas other changes are not statistically significant

far future, and this change is associated with the weakening of the rainfall belt over the Indian sub-continent. Less rainfall leads to reduced heating in the atmosphere that in turn leads to weaker circulation, which weakens the large-scale moisture convergence over the region. Another notable change is given by the strengthening of the circulations over the northern Arabian Sea and central and north India by about 1–2 m/s in the far future, which diverts the flow northward from the northern Arabian Sea, to the northern BoB, and up to Burma. This is associated with the enhancement of rainfall over the northern part of Arabian Sea and BoB.

Evaporation over ocean surfaces is governed by the sea surface temperature (SST), specific humidity at 2-m height, and wind speed at the lowest model level, with soil water being an additional factor over land surfaces. Figure 11 shows the former three fields for the reference and far-future periods. Over the entire domain, surface temperature increases in the future by up to 4° over the Arabian Sea, 2.5 °C over the BoB, and 3 °C over the Indian Ocean. The Indian sub-continent also warms up by 4–5 °C, relatively more over the western parts of the sub-continent. Similarly, almost everywhere over the seas and ocean, 2-m specific humidity increases in the future by up to 4 g/kg over the western and northern Arabian Sea and the northern BoB. Wind speeds at the bottom model level decrease over the region of low level easterlies, cross-equatorial flow, and Somali jet and increase over the rest of the oceanic regions. Over the Indian Ocean, despite the increase in low level moisture and wind speed, there is an enhancement in evaporation, which indicates that the effect of increased surface temperature outweighs the other two factors. Over the northern

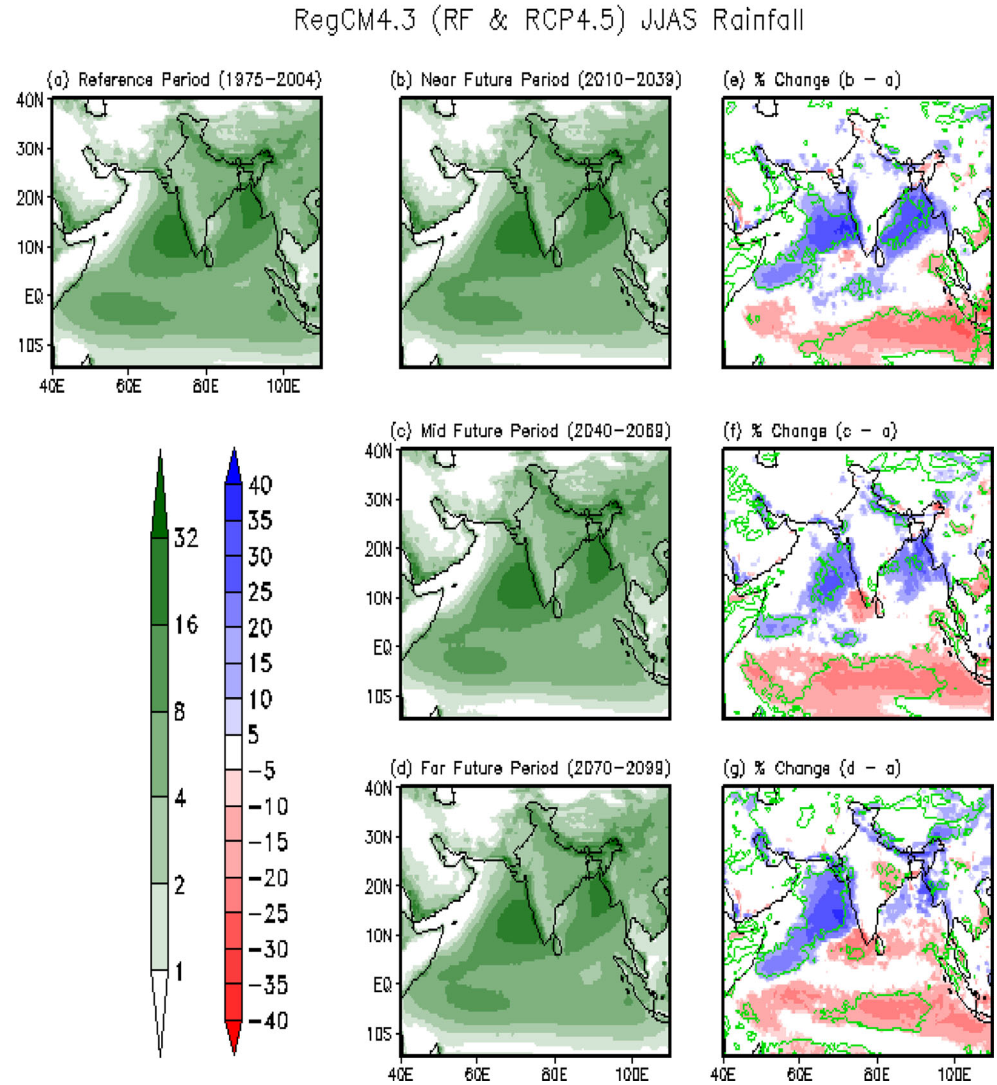

Fig. 9 JJAS mean rainfall (mm/day) as simulated by GFDL-ESM2M during the **a** reference period (1975 to 2004) and projected in the **b** near future (2010 to 2039), **c** mid future (2040 to 2069), and **d** far future (2070 to 2099) under RCP4.5 scenario. The *right-hand side panels* show the corresponding projected changes (%) in the **e** near future, **f** mid future, and **g** far future periods. The *green contour lines* encompassing the colored patches in **e**, **f**, and **g** depict that these changes are significant at 95 % confidence level whereas other changes are not statistically significant

Arabian Sea and BoB, the wind speed also increases, which further accentuates the evaporation. Over the Indian land, soil moisture is found to decrease by 100–200 kg/m^2 in the future (now shown here). This is attributed to the less rainfall and increased potential evapotranspiration over the region.

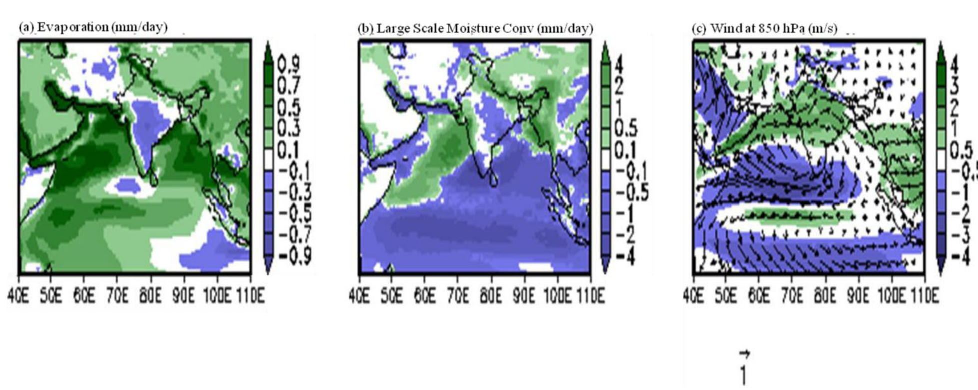

Fig. 10 Changes in JJAS mean RegCM4.3 simulated **a** evaporation (mm/day), **b** large scale moisture convergence (mm/day), and **c** low level winds between the reference period (1975 to 2004) and the far future (2070 to 2099) under RCP8.5 scenario

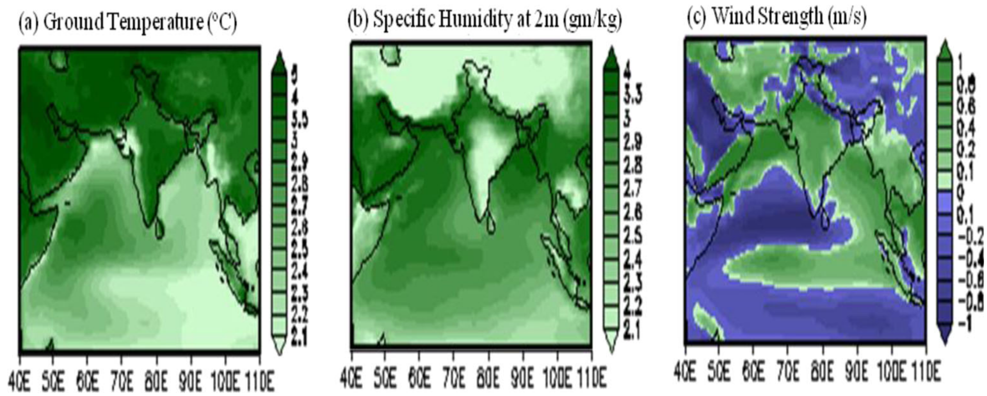

Fig. 11 Changes in JJAS mean RegCM4.3 simulated **a** ground temperature (°C), **b** specific humidity at 2 m height (g/kg), and **c** wind strength at the lowest model level between the reference period (1975 to 2004) and the far future (2070 to 2099) under RCP8.5 scenario

6 Discussions and conclusions

In this study, RegCM4 was integrated over the South Asia CORDEX domain under the RCP 4.5 and 8.5 scenarios using GFDL-ESM2M CMIP5 lateral meteorological forcing. The regional model performance in simulating the Indian summer monsoon circulation and rainfall was first validated over the reference period 1975–2004 using observed rainfall from GPCP and IMD0.5 gridded precipitation data and wind data from the NCEP/NCAR reanalysis. RegCM4 is found to satisfactorily simulate the main characteristics of the Indian summer monsoon rainfall distribution over the region: the occurrence of maximum rainfall over the head of BoB, its extension south of the equator between 80° E and 100° E, and the second maxima over the western coast of India. The spatial distribution of rainfall over the Indian sub-continent is also adequately captured, with wet zones over the eastern and northeastern parts of India and the dry zones over northwest India and east coast of peninsular India. More importantly, despite the use of a single experiment, RegCM4 captures various features of the observed changes in circulation and rainfall during the Indian summer monsoon season in recent decades. Compared to the driving global model, RegCM4 shows different mean precipitation bias patterns which in some respect are an improved one. So far, as the future projections are concerned, RegCM brings out some details of sub-regional precipitation changes more in agreement with changes observed in recent decades than found in the driving model.

The future projections for both the RCP4.5 and 8.5 scenarios reveal a systematic change over most of the Indian sub-continent whose magnitude increases with time. This consists of a weakening of monsoon precipitation over most of the Indian land mass and the northern and equatorial Indian Ocean. It is found that the RegCM4 projected decrease in JJAS rainfall under the RCP8.5 scenario over the central, eastern, and peninsular India by the end of the century is in the range of 30–40 % of their mean reference period values. These changes are found to be statistically significant at 95 % confidence level. Under the RCP4.5 scenario, similar decreasing estimates lie in the range of 15–25 %, also significant at 95 % level. On the other hand, increased precipitation is projected over the Arabian Sea and the northern BoB. Comparison between the global forcing fields and the downscaled fields shows that RegCM4 produces change patterns more in line with observed trends than the driving GFDL global model. We also discussed how the simulated changes in monsoon precipitation are related to changes in evaporation and moisture convergence.

The two main results we highlight are i) the ability of RegCM4 to reproduce areas of decreased monsoon precipitation found in the historical period and ii) the simulation of a decrease in monsoon precipitation over mid-continental India, the main agricultural region of the country, which, over some sub-regions, is in disagreement with the driving GCM. In particular, the latter result is in line with observed monsoon precipitation trends, but in disagreement with most global model projections (e.g., Christensen et al. 2007). The main caveat underlying these two conclusions is that we used a single regional model driven by a single global model. An ensemble is needed to provide more robustness to this result, and we plan to compare our projection with other available ones within the CORDEX framework.

Acknowledgments In this study, the observed rainfall data from GPCP and IMD along with NCEP/NCAR reanalyzed wind data are used for model validations. The authors are thankful to the anonymous reviewers whose suggestions helped improved the quality of the paper. Part of the analysis done in this paper is due to a research project sponsored by the Department of Science and Technology, Government of India.

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