

# Assessment of two versions of regional climate model in simulating the Indian Summer Monsoon over South Asia CORDEX domain

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**Abstract** This study assess the performance of two versions of Regional Climate Model (RegCM) in simulating the Indian summer monsoon over South Asia for the period 1998 to 2003 with an aim of conducting future climate change simulations. Two sets of experiments were carried out with two different versions of RegCM (viz. RegCM4.2 and RegCM4.3) with the lateral boundary forcings provided from European Center for Medium Range Weather Forecast Reanalysis (ERA-interim) at 50 km horizontal resolution. The major updates in RegCM4.3 in comparison to the older version RegCM4.2 are the inclusion of measured solar irradiance in place of hardcoded solar constant and additional layers in the stratosphere. The analysis shows that the Indian summer monsoon rainfall, moisture flux and surface net downward shortwave flux are better represented in RegCM4.3 than that in the RegCM4.2 simulations. Excessive moisture flux in the RegCM4.2 simulation over the northern Arabian Sea and Peninsular India resulted in an overestimation of rainfall over the Western Ghats, Peninsular region as a result of which the all India rainfall has been overestimated. RegCM4.3 has performed well over India as a whole as well as its four rainfall homogenous

zones in reproducing the mean monsoon rainfall and inter-annual variation of rainfall. Further, the monsoon onset, low-level Somali Jet and the upper level tropical easterly jet are better represented in the RegCM4.3 than RegCM4.2. Thus, RegCM4.3 has performed better in simulating the mean summer monsoon circulation over the South Asia. Hence, RegCM4.3 may be used to study the future climate change over the South Asia.

**Keywords** Indian summer monsoon · RegCM4.2 · RegCM4.3 · CORDEX · Moisture flux · Rainfall homogenous zones · Surface net downward shortwave flux

## 1 Introduction

Temperature and precipitation over Indian landmass exhibits considerable spatial and temporal variation. The most important seasonal variation over the course of a year is associated with the rainfall. The mean rainfall pattern and its seasonal variation have an important consequence in the sectors of agriculture and water availability in the country. The weather systems in this context include the summer monsoon disturbances, winter monsoon, and western disturbances. It is well known that the summer monsoon is predominant in India, in which about 80% of the total annual precipitation is received over a large part of the country (Parthasarathy et al. 1995; Guhathakurta and Rajeevan 2006). Nowadays, many scientific communities are progressively making use of various regional models to study Indian summer monsoon. The regional models are tuned to represent the current climate as realistic as possible so as to build confidence for its subsequent use for addressing future projections under different climate change scenarios. There have been significant improvements made

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in regional models in simulating the seasonal and annual cycle as well as mean monsoon rainfall reasonably well. However, it is still a challenge for the scientists to simulate the rainfall over the homogenous monsoon zones of India.

The variability of Indian Summer Monsoon Rainfall (ISMR) from year to year results in extreme hydrological events like droughts and floods; as a consequence it affects the national economy. ISMR exhibits significant temporal and spatial variability (Mooley and Parthasarathy 1984; Thapliyal and Kulshrestha 1991; Kripalani and Kulkarni 2001; Sahai et al. 2003; Naidu et al. 2015). Several scientists have investigated the inter-annual and intra-seasonal variations of monsoon rainfall and the associated phenomena over the last several years using observed data (Webster et al. 1998; Gadgil et al. 2003) and conducting modeling studies (Ratna et al. 2011; Satyanarayana and Kar 2016; Pattnayak et al. 2016a). The key features of Indian summer monsoon include the sudden onset and gradual withdrawal, which signify the beginning and end of the rainy season respectively. There are many definitions available for identifying Indian summer monsoon onset dates (Ananthkrishnan and Soman 1988; Fasullo and Webster 2003; Joseph et al. 2006; Wang et al. 2009; Pai and Rajeevan 2009). Currently, India Meteorological Department (IMD) is using the monsoon onset criteria of Pai and Rajeevan 2009, which is based on rainfall, wind field, and OLR. The variations in the timing of onset and withdrawal of the Indian summer monsoon influence the length of the summer monsoon season and hence may impact seasonal mean rainfall (Fasullo and Webster 2003; Taniguchi and Koike 2006; Pattnayak et al. 2013a). Fasullo and Webster (2003) used a normalized spatial mean of vertically integrated moisture transport (VIMT) over the Arabian Sea as Hydrological Onset and Withdrawal Index (HOWI) to identify monsoon onset and withdrawal dates over India. Their approach of identifying onset and withdrawal dates of Indian monsoon is shown to be both robust to bogus monsoon onsets and reflective of the timing of the monsoon transitions.

Current regional models have become useful tools to generate the climatic information at high resolutions. Regional models are increasingly used to examine the circulation and precipitation patterns over several parts of the world. The circulation and precipitation over Indian landmass have large changes at the time scales of month and season. The Regional Climate Model (RegCM, Giorgi et al. 1993a, b) of the Abdus Salam International Centre for Theoretical Physics (ICTP) is one such regional model, which has been successfully used to study the Indian summer monsoon features (Dash et al. 2006, 2013, 2015; Singh and Oh 2007; Ashfaq et al. 2009; Pattnayak et al. 2013a, b, 2016a, b; Maharana and

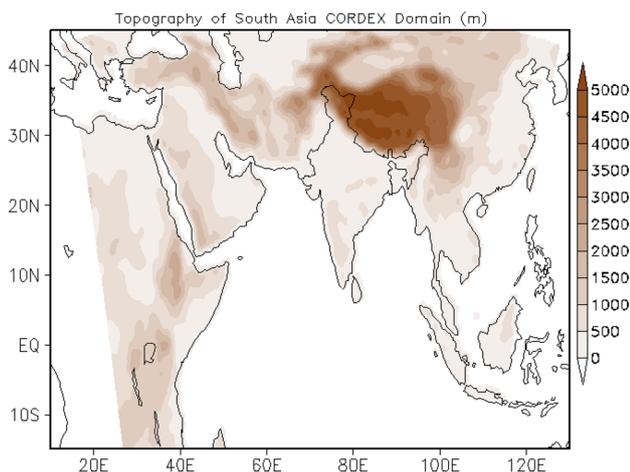
Dimri 2014, 2016). The experiments conducted by Giorgi and Marinucci (1996) with different topography indicated that resolution has a greater impact on the simulation through the model physics and dynamics rather than through the topography itself, especially for summer convection. The RegCM version 3 (RegCM3) has also been successfully integrated to simulate the salient features of Indian summer monsoon circulation and rainfall (Dash et al. 2013; Pattnayak et al. 2013a, 2016b). Dash et al. (2006) has shown that the RegCM3 simulates intra-seasonal variability of Indian summer monsoon rainfall over India reasonably well during the period 1993–1996. Ratnam et al. (2009) coupled the RegCM3 with Regional Ocean Modeling System (ROMS) and showed that the coupled model simulates more realistic spatial and temporal distributions of monsoon rainfall compared to the uncoupled atmosphere-only model. Dash et al. (2015) conducted domain size experiment by taking two different domains one over India and the other over South Asia using RegCM4. Their study suggests that South Asia domain is the better domain for studying the Indian summer monsoon using RegCM4.

Asian monsoon forecasting is still an ongoing research problem as it is still not captured accurately by any operational or research models, which still show mean state biases. Mostly, regional models are tuned and evaluated according to their ability to simulate temperature and precipitation (e.g., Giorgi et al. 2012; Pattnayak et al. 2013a; Maharana and Dimri 2014; Dash et al. 2015) over a specific region. However, the role of other climatological parameters such as radiative and moisture fluxes should also be included in the evaluation procedure of regional models (Katragkou et al. 2015; Alexandri et al. 2015). This study will assess the performance of two versions of RegCM 4 (RegCM 4.2 and RegCM 4.3) in simulating Indian summer monsoon over South Asia COordinated Regional Climate Downscaling EXperiment (CORDEX) domain. Also, this study will examine the ability of the models in simulating the summer monsoon rainfall over homogenous monsoon zones of India. Furthermore, the models will be evaluated the capacity of the models in simulating the radiative fluxes, moisture fluxes and vertical winds during Indian summer monsoon. Such comparison studies for RegCM4 have not been done before for homogenous monsoon regions of India. Outcome of this study will provide a basis for the future climate change simulations over South Asia CORDEX domain. A brief discussion on the experimental design and the data used are given in Sect. 2. Section 3 provides the characteristics of Indian summer monsoon as simulated by RegCM4.2 and RegCM4.3. The important results obtained in this study are summarized in the concluding Sect. 4.

## 2 Data and methods

For this study a couple of experiments were conducted with two versions of RegCM4, which are RegCM4.2 (Giorgi et al. 2011) and RegCM4.3 (Giorgi et al. 2013) over South Asia CORDEX domain (Fig. 1). This domain over South Asia has been adopted from the framework of World Climate Research Programme (WCRP) organized experiment known as the CORDEX (Giorgi et al. 2008). CORDEX is an international coordinated effort to produce an improved generation of regional climate change projections worldwide for input into impact and adaptation studies within the AR5 timeline and beyond. South Asia is one of the domains set by this framework and hence this domain has been chosen. RegCM4 is the fourth generation of the RegCM family. It is the outcome of a new step in recoding (Giorgi et al. 2011) of the RegCM3 (Giorgi et al. 1993a, b; Pal et al. 2007) model. The model is hydrostatic and includes a number of options for physical parameterizations (Giorgi et al. 2012). Dash et al. (2015) showed that South Asia CORDEX domain is the ideal domain for simulating Indian summer monsoon using RegCM4.2. In these two experiments, only the versions of the model are different, all the other parameters such as horizontal and vertical resolutions, lateral and surface boundary conditions and physical parameterization schemes etc. have been kept same. The South Asia domain covers the region 10°E–130°E and 22°S–49°N at 50 km resolutions in both latitudinal and longitudinal circles.

Two sets of 7-year simulations for the period 1997 to 2003 have been carried out under the same experimental setup using the two versions RegCM 4.2 and 4.3. This specific period from 1997 to 2003 has been chosen



**Fig. 1** Topography of South Asia CORDEX domain (in m) over which both the models RegCM4.2 and RegCM4.3 have been integrated

for this sensitivity study because it contains the extreme monsoon rainfall years (2002 and 2003) and El Niño years (1997–1998) and La Niña years (1998–1999 and 1999–2000). Thus the model performance has been examined during these extreme years. In both the simulations, the respective models have been integrated from 1st January 1997 up to the end of December 2003 spanning 7 years at 50 km horizontal resolution. Among these 7 years, first year i.e. 1997 has been considered as spin-up period. So the analyses have been carried out for the period 1998–2003 in both the simulations. The choice of the physical parameterization schemes has been made based on the study of Dash et al. (2015). They have shown that the specific combination of physical parameterization schemes perform better than all other available schemes in RegCM4 in simulating Indian summer monsoon over the South Asia CORDEX domain. The physical parameterization schemes used in these experiments are radiation scheme and planetary boundary layer scheme of Kiehl et al. (1996) and Holtslag et al. (1990) respectively. Different cumulus parameterization schemes were used over land and ocean such as: MIT Emanuel scheme (Emanuel 1991; Emanuel and Rothman 1999) over land and Grell scheme (Grell 1993) with Fritsch and Chappell (1980) convective closure scheme over ocean. SUBEX scheme of Sundqvist et al. 1989 have been used for large-scale precipitation scheme and Zeng's ocean flux parameterization (Zeng et al. 1998) for Ocean flux parameterization have been used for this study in both the simulations. Diurnal cycle sea surface temperature scheme of Zeng (2005) has been enabled and model desert seasonal albedo variability is disabled. Three bottom model levels with no clouds were selected. RegCM4.3 is the upgrade version of RegCM4.2. There are few changes have been made in RegCM4.2 to upgrade it to RegCM4.3. The major differences between both the versions of RegCM4 have been listed in Table 1.

The initial and boundary conditions for both the simulations were provided from the European Center for Medium-Range Weather Forecast (ECMWF) Reanalysis (ERA-interim) reanalysis  $0.75^\circ \times 0.75^\circ$  gridded reanalysis (Dee et al. 2011), which is the third generation ECMWF reanalysis product. The elevation data used are obtained from the United States Geological Survey (USGS). Global Land Cover Characterization (GLCC, Brown et al. 1999) dataset at 10 min resolution is used to create vegetation and land use file. The simulated rainfall over the Indian land points has been compared with observational data from IMD at  $0.5^\circ \times 0.5^\circ$  resolution by Rajeevan and Bhate (2009). While the wind and moisture flux were validated against the ERA-Interim (Dee et al. 2011) and surface net short wave flux was compared with National Center for Environmental Prediction and National Center for Atmospheric Research

**Table 1** Major differences between RegCM4.2 and RegCM4.3

Categories of differences	RegCM4.2 (Giorgi et al. 2011)	RegCM4.3 (Giorgi et al. 2013)
Solar constant	Hardcoded solar constant	Measured total solar irradiance
Radiation model and stratospheric layers	CCSM radiation model (30 layers)	Added extra stratospheric layers (60 layers) in the RRTM radiation model. (Iacono et al. 2000)
Method used to compute mean sea level pressure	Conventional method used to compute mean sea level pressure	Kallen (1996) algorithm used to compute mean sea level pressure
Boundary conditions and emissions for tracers	Not used	Boundary conditions or emissions for tracers, both aerosols and chemically active creation from different sources have been introduced

(NCEP/NCAR) reanalysis datasets (Kalnay et al. 1996). In order to compute the model bias against observations, the model simulated fields have been interpolated to the corresponding observations or reanalysis data grid. And then the model biases have been computed at each grid point with respect to the observations. The model simulated and the observed fields have been averaged over the months and then for the summer monsoon season i.e. from June to September (JJAS) in each of the year.

The model validation has been carried out in simulating the annual cycle of rainfall; mean monsoon features, inter-annual variation of rainfall and summer monsoon onset dates over India. To examine onset and withdrawal, VIMT has been used instead of rainfall. It is a well-known fact that rainfall is often poorly measured and modeled over the large scale (Fasullo and Webster 2003). In contrast to rainfall, VIMT is generally well modeled and observed, and its variability, particularly over the Arabian Sea, is substantial during both monsoon onset and withdrawal. Hence the criterion adopted here to identify onset date is HOWI of Fasullo and Wester 2003. According to them, there are rapid VIMT fluctuations during monsoon onset and withdrawal over the Arabian Sea particularly over the region 62.5°E–75°E and 7.5°N–20°N. Therefore, such fluctuations across the season have been examined over the above mentioned region. The vertically integrated moisture transport (Q) is calculated as

$$Q = \int_{\text{Surface}}^{\text{Top}} \rho q V dz \quad (1)$$

where  $\rho$  is atmospheric air density,  $q$  is specific humidity,  $z$  is height and  $V$  is horizontal wind. The daily time series of the seasonal cycle of VIMT have been averaged and normalized. The normalized spatial mean of VIMT over Arabian Sea is used to calculate HOWI. As the fields used in the HOWI are of large scale, the index is intended to be regional rather than local. This reflects the timing of the

large-scale hydrologic cycle rather than the rainfall at a single point. The time series of VIMT is normalized by the following transformation equation:

$$\bar{x} = 2 \times \left\{ \frac{[\bar{X} - \min(\bar{X})]}{[\max(\bar{X}) - \min(\bar{X})]} \right\} - 1 \quad (2)$$

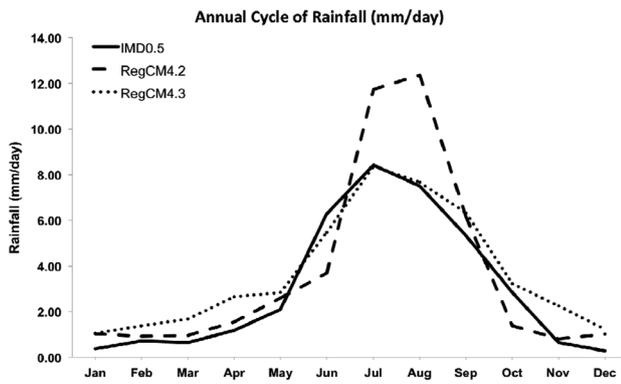
where  $\bar{X}$  is the climatological daily mean of VIMT and  $\bar{x}$  is the normalized time series of VIMT which is termed as HOWI such that the climatological daily mean cycle ranges between  $-1$  and  $1$ . The day of onset (withdrawal) is defined when HOWI greater (less) than  $0$ . All these calculations have been done over the summer monsoon period for every year starting from 1998 to 2003.

### 3 Results and discussion

This section discusses about the results obtained from both the simulations and their comparison with the corresponding observations. The basic comparison of the model simulations from both the simulations have been made in three different ways, which are annual cycle of rainfall, mean monsoon features and inter-annual variations. If the model performs better in these ways of comparison then the model simulation will be trustworthy. Thus, these comparisons have been made in detail in the following subsections.

#### 3.1 Annual cycle of rainfall

The model performance has been compared through the annual cycles based on the monthly mean rainfall over Indian land points. The annual cycles of rainfall in both the simulations and IMD0.5 gridded have been shown in Fig. 2. It is observed that the model simulated rainfall in both the simulations have similar pattern as that in the IMD observed in all the months. Both versions of the model have systematic bias in all the months. However, RegCM4.2 simulated rainfall has been overestimated by about 4–5 mm/day in July and August while RegCM4.3 simulated rainfall is much closer to the IMD observation. The rainfall has been underestimated in June in both the simulations. RegCM4.3 has overestimated the rainfall in



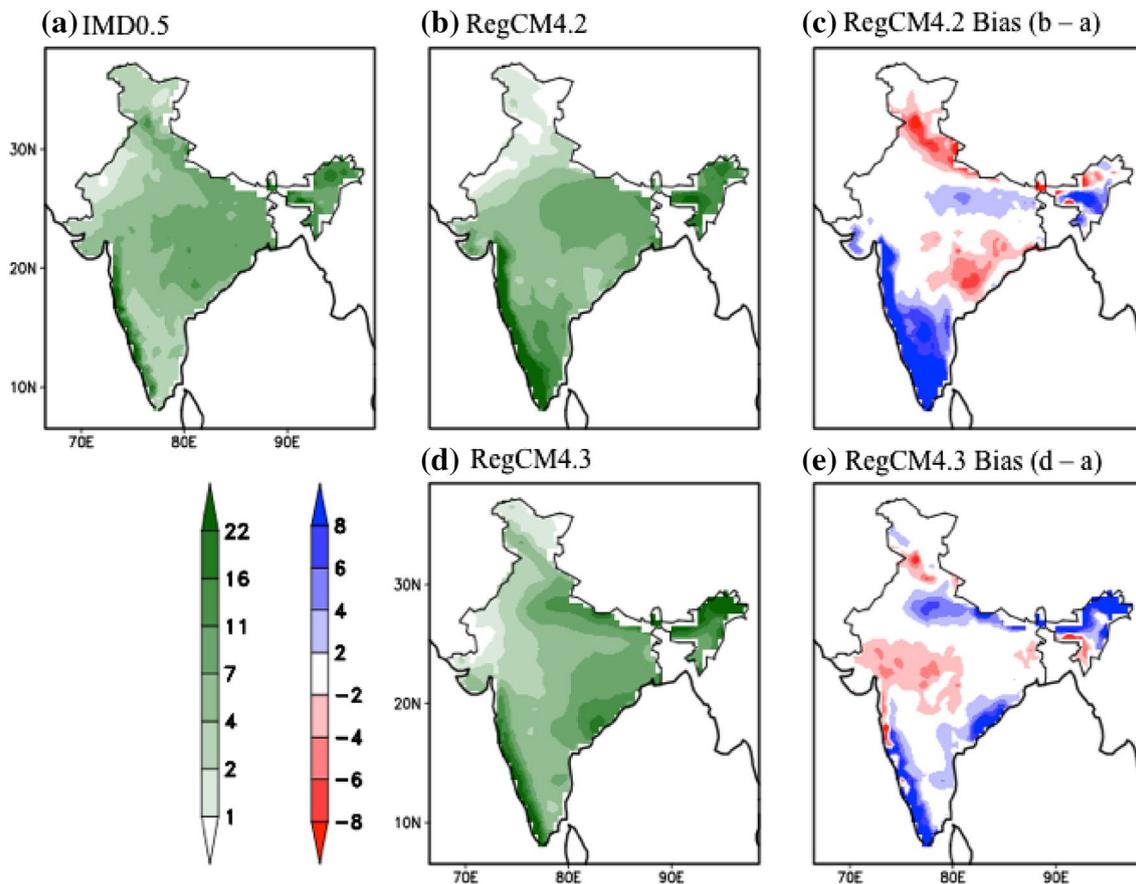
**Fig. 2** Mean annual cycle of rainfall (mm/day) recorded by IMD and simulated by RegCM4.2 and RegCM4.3 during 1998 to 2003. In this figure *solid black curve* represents IMD0.5 observation, *dashed and dotted curves* represent RegCM4.2 and RegCM4.3 simulated rainfall respectively

all other months except June, July and August. The correlation coefficient RegCM4.2 and RegCM4.3 with IMD0.5 observation is 0.91 and 0.98 respectively. Broadly, it can

be inferred that the RegCM4.3 has performed better in simulating rainfall during summer monsoon months than RegCM4.2.

### 3.2 Mean monsoon features

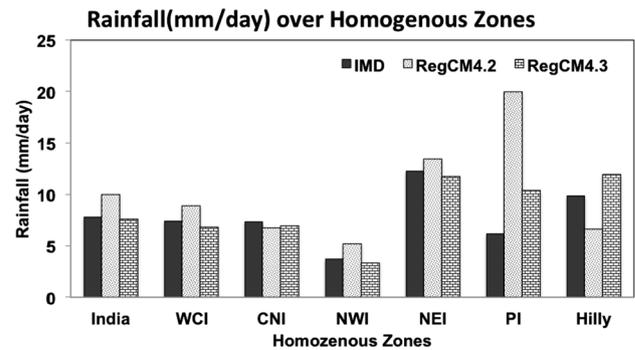
Mean summer monsoon rainfall for the period 1998 to 2003 over Indian land points from the model simulations and the observations along with the biases have been shown in Fig. 3a–e. The model simulations have been validated against IMD0.5 gridded rainfall. For this purpose, the simulated rainfall from have been interpolated to  $0.5^\circ \times 0.5^\circ$  IMD grids. In the model simulations and the IMD observation (Fig. 3a, b, d), JJAS mean rainfall value ranges from 11 to 16 mm/day over the North-east India and Peninsular India, 4–11 mm/day over the East Coast, 16–22 mm/day over the Western Ghats and 1–2 mm/day over the Northwest India. In both the simulations, the models have reproduced the major rainfall belts such as NE India, Western Ghats, and the Gangetic Plains during the summer monsoon season. Although the RegCM4.2 has simulated the major rainfall belts but the



**Fig. 3** Mean JJAS rainfall (mm/day) are obtained from **a** IMD0.5 gridded dataset, **b** RegCM4.2, **d** RegCM4.3. The model biases from **c** RegCM4.2 and **e** RegCM4.3 have been shown in the *right panel* of

the figure. In the bias plot, *shades of blue color and red color* indicate overestimation and underestimation of the models respectively

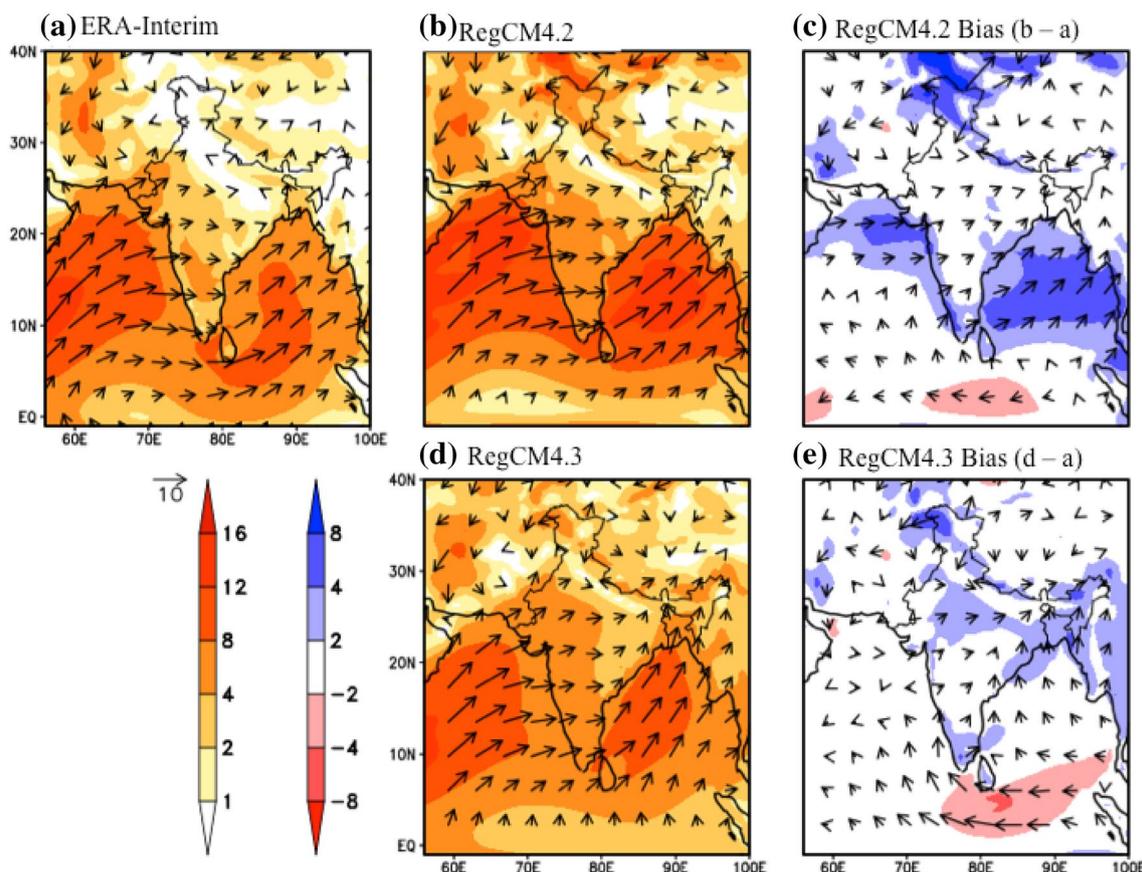
rainfall over the Western Ghats and Peninsular India has covered more land part than the observed (Fig. 3b, c). The rainfall over the Western Ghats and peninsular India in RegCM4.2 simulations is overestimated by 6–8 mm/day (Fig. 3c). Further, most of the parts of India have been overestimated in RegCM4.2 except over Himachal Pradesh, Odisha, and Chhattisgarh (Fig. 3c). But in case of RegCM4.3, the rainfall values are relatively closer to the IMD observed value over the corresponding regions (Fig. 3e). The performance of RegCM4.2 is better than RegCM4.3 only over NW India, while RegCM4.3 has performed better over rest of the country. The model biases over the major rain belt areas of India such as the Western Ghats and eastern India have very less bias in RegCM4.3 than in RegCM4.2. There is positive bias of about 100% over the Western Ghats and Peninsular India and negative bias of about 80% over north India (Supplementary Fig. S2c) can be seen in RegCM4.2 simulation. In RegCM4.3, the spatial extension of the positive bias over the Western Ghats and Peninsular India and negative bias over north India have been reduced significantly (Fig. S2e). Over Odisha and Chhattisgarh, RegCM4.2 has underestimated the rainfall as compared to the IMD observations by 20–40% (Fig. S2c), whereas the rainfall bias over the corresponding regions are within –20 to +20% in RegCM4.3 (Fig. S2 e). Over Gujarat and Rajasthan, RegCM4.3 has simulated 40% more rain as compared to IMD but RegCM4.2 has performed better over these two states where the bias is relatively less as compared to RegCM4.3 simulations. The rainfall bias in RegCM4.3 has reduced significantly over most of the regions when compared with RegCM4.2 simulations. For evaluating the models, that how they have performed over different regions of India, the mean monsoon rainfall have been computed over six homogenous monsoon zones of India. Area averaged mean JJAS rainfall over whole India and its six homogenous monsoon zones [as described by Parthasarathy et al. (1995), Supplementary Fig. S1] in the IMD observations and both the simulations have been shown in Fig. 4. The rainfall simulated is found to be 10 and 7.6 mm/day in the RegCM4.2 and RegCM4.3 simulations respectively, while the observed rainfall value is 7.8 mm/day for the period 1998–2003. It can be noted that rainfall in the RegCM4.2 simulation has been overestimated over whole of India, West Central India (WCI), North West India (NWI), North East India (NEI) and Peninsular India (PI), while the other two regions such as Central Northeast India (CNI) and Hilly region have been underestimated. The rainfall simulated in RegCM4.3 is relatively closer to IMD observations than RegCM4.2 simulations over whole India as well as all of the six homogenous zones. In sum, RegCM4.3 has performed better than RegCM4.2 in simulating the mean



**Fig. 4** Mean JJAS rainfall as recorded in IMD (black bars) and simulated by RegCM4.2 (dotted bar) and RegCM4.3 (brick bar) for the period 1998 to 2003 over whole India and its six homogeneous zones such as West Central India (WCI), Central Northeast India (CNI), North West India (NWI), North East India, Peninsula India and Hilly region

monsoon rainfall over India as well as different regions of India.

Figure 5 represents the wind at 850 hPa from ERA-Interim and the model simulations. The magnitude of the low-level Somali jet over the Arabian Sea during the summer monsoon is in the range of 12–16 m/s in reanalysis and both the model simulations. However, the simulated core of the jet in RegCM4.2 has a relatively larger spatial extent (Fig. 5a, b) than that in the reanalysis but the westerlies are stronger by 4–8 m/s over northern Arabian sea and these stronger westerlies have been further extended to whole Indian landmass except over Northeast India. There is another noticeable feature can be seen in the RegCM4.2 simulation is that the westerlies as strong as the Somali jet's strength over the Bay of Bengal (Fig. 5b), which is overestimated by 4–8 m/s as compared to the ERA-Interim reanalysis wind. The spatial pattern of the core of the jet in RegCM4.3 simulation is quite similar (Fig. 5a, d) with the ERA-Interim reanalysis. The RegCM4.3 has overestimated the wind by 2–4 m/s towards the north India and foothills of the Himalayas and this overestimation has been further extended up to Northeast India. It has performed well over the Bay of Bengal. From the bias plot (Fig. 5e), it is seen that the wind over the southern Arabian Sea in the RegCM4.3 simulation has a bias in the range of –2 to 2 m/s whereas, in the northern Arabian Sea, the wind is overestimated by 2–4 m/s. The percentage bias of the wind field has also been calculated and shown as Supplementary Fig. S3. In both the simulations, the models have reproduced the cross-equatorial flow and south equatorial easterlies in the lower troposphere closer to the ERA-Interim reanalysis. Overall, the key feature of lower level wind field is the Somalia jet, which is better represented in RegCM4.3 than in the RegCM4.2 simulation (Fig. 5, S3).

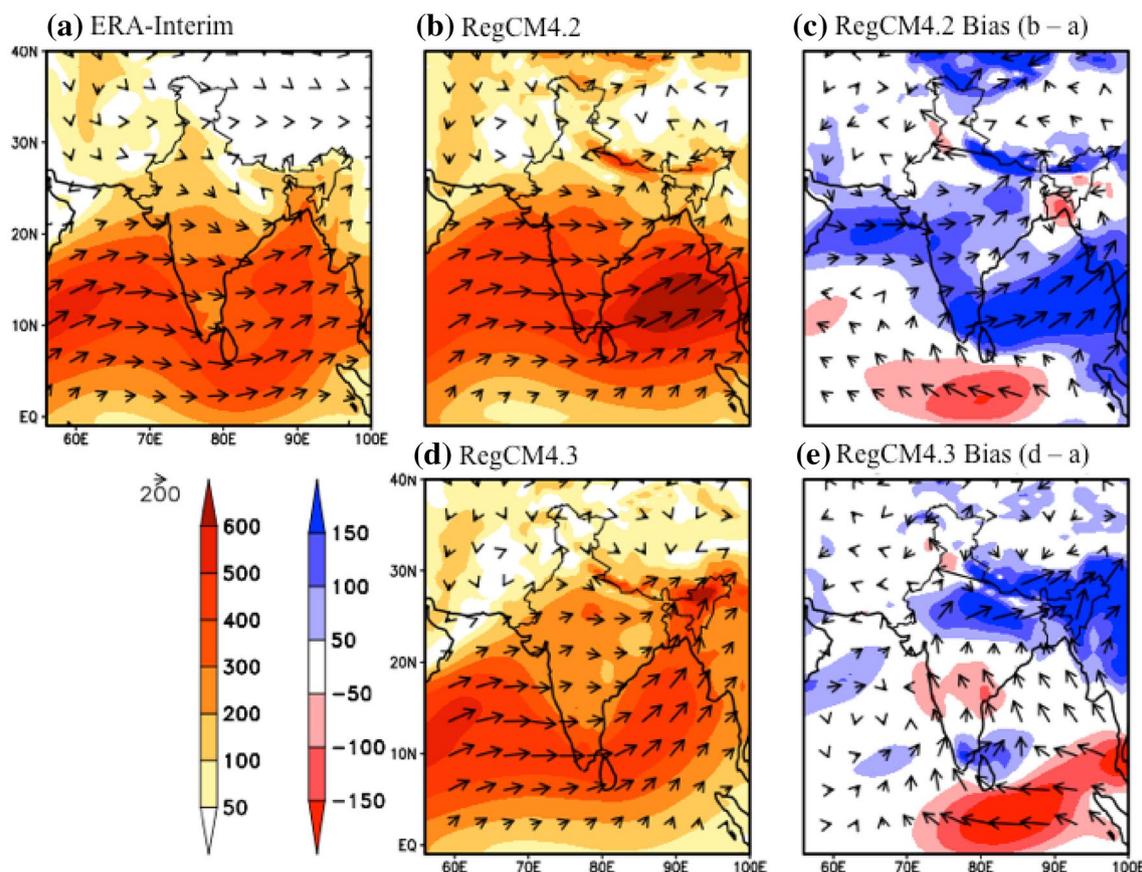


**Fig. 5** Mean JJAS wind (m/s) at 850 hPa obtained from **a** ERA Interim reanalysis, **b** RegCM4.2 and **d** RegCM4.3. The model biases from **c** RegCM4.2 and **e** RegCM4.3 have been shown in the *right panel* of the figure. The wind direction and magnitudes have been

shown in *vectors* and *shades* respectively. In the bias plot, *shades of blue color* and *red color* indicate overestimation and underestimation of the models respectively

Moisture flux transport relates to rainfall, thus insights on rainfall mechanisms can be gained by analyzing moisture flux transports. The vertically integrated moisture flux has been calculated based on the Eq. (1) in Sect. 2. The mean vertically integral of moisture flux (kg/m/s) and transport during JJAS obtained from ERA-Interim reanalysis and model simulations along with their biases has been shown in Fig. 6a–e. Here, the moisture fluxes from both the simulations have been validated against ERA-Interim reanalysis during the study period i.e. 1998–2003. Spatial pattern of the moisture flux roughly appears as the wind pattern at 850 hPa (Fig. 5). RegCM4.3 simulates the moisture flux about of 500–600 kg/m/s as that same of ERA-Interim towards the Somalia coast (Fig. 6a, d), while the moisture flux in RegCM4.2 is found to be 400–500 kg/m/s (Fig. 6b). In RegCM4.2, there is a secondary peak of about 500–600 kg/m/s can be seen over central Bay of Bengal which feature is not present in either ERA-Interim reanalysis or RegCM4.3. RegCM4.2 has overestimated the

moisture flux over PI by 100–150 kg/m/s, Central India by 50–100 kg/m/s and towards foothills of the Himalayas by 150 kg/m/s. The moisture flux in the RegCM4.3 simulation has been underestimated by 50 kg/m/s over Andhra Pradesh and Maharashtra and overestimated by 100–150 kg/m/s over the Ganges plain, foothills of the Himalayas and NEI. The pattern of moisture flux (kg/m/s) over the Arabian Sea and the Bay of Bengal is better represented in RegCM4.3 than in the RegCM4.2 simulation (Fig. 6a, b, d). However, the simulated moisture flux in RegCM4.2 is stronger by about 100 kg/m/s is seen over the northern part of the Arabian Sea and 150 kg/m/s over the Bay of Bengal (Fig. 6c). It can be seen from the percentage bias plot (Supplementary Fig. S4), the percentage bias in RegCM4.2 is more than that in the RegCM4.3. From the bias plot, it is evident that the Arabian Sea and Bay of Bengal are major contributors of moisture flux have been highly overestimated in RegCM4.2 simulation. But in case of RegCM4.3, the moisture flux pattern and transport over Arabian Sea and Bay of Bengal are more realistic.

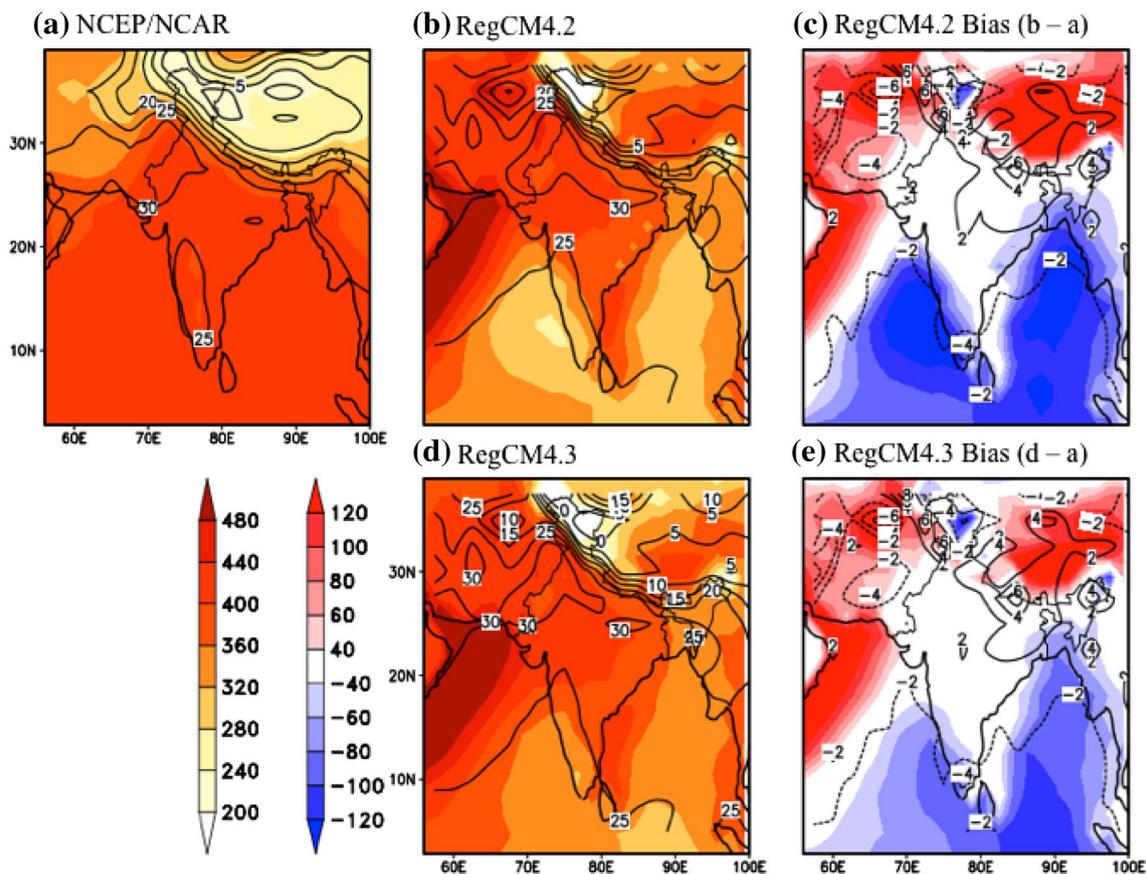


**Fig. 6** Mean JJAS vertically integral of moisture flux ( $\text{kg/m/s}$ ) obtained from **a** ERA Interim, **b** RegCM4.2 and **d** RegCM4.3. The model biases from **c** RegCM4.2 and **e** RegCM4.3 have been shown in the *right panel* of the figure. The moisture flux direction and magni-

tudes have been shown in *vectors and shades* respectively. In the bias plot, *shades of blue color and red color* indicate overestimation and underestimation of the models respectively

The ability of regional models to assess surface solar radiation pattern has not received much attention despite the fact that it plays a vital role in various climatic processes. Therefore, mean surface net downward shortwave fluxes in summer monsoon from both the simulations have been evaluated against NCEP/NCAR reanalysis (Fig. 7). In both the versions the net shortwave flux is calculated to be about  $400 \text{ W/m}^2$  (Fig. 7b, d) over northwest India,  $360 \text{ W/m}^2$  over west Maharashtra, Odisha, Bihar and Andhra Pradesh and about  $280\text{--}320 \text{ W/m}^2$  (Fig. 7b, d) over the Western Ghats and northeast India. In the NCEP/NCAR reanalysis, the most parts of India receive the net shortwave flux about  $400 \text{ W/m}^2$  (Fig. 7a) except northeast India, Jammu and Kashmir and foothills of the Himalayas, which receives about  $280\text{--}360 \text{ W/m}^2$ . From the bias plots (Fig. 7c, e), it can be seen the both the model biases show a dipole like structure. Northern part of the domain shows an overestimation and southern part is underestimated in both the models. However, it is clearly visible that the bias in RegCM4.3 (Fig. 7e)

is relatively less as compared to RegCM4.2 (Fig. 7d). Which indicates that the inclusion of measured solar irradiance in RegCM4.3 in place of hardcoded solar constant (RegCM4.2) improved the performance of the model in representing the mean feature of surface net shortwave flux. Furthermore, temperature at 2-m height has been plotted as contours in Fig. 7. Both the simulations able to replicate the spatial pattern of heat low over northwest India and Pakistan region (Fig. 7a, b, d), but underestimated by about  $2\text{--}4 \text{ }^\circ\text{C}$  over Pakistan. In RegCM4.2, the model has overestimated the temperature over central India by  $2 \text{ }^\circ\text{C}$  and this overestimated has been further extended to northeast India (Fig. 7c). In RegCM4.3, the corresponding regions have less bias as compared to RegCM4.2 simulations (Fig. 7c). Use of solar radiance improves the simulation of shortwave flux as shown in Fig. 7. This improved shortwave flux, which improves heating of the land surface and the oceans. The differential heating of Indian land surface compared to surrounding ocean is the key drivers of the summer monsoon. This



**Fig. 7** Mean JJAS surface net downward shortwave flux (Watt/m<sup>2</sup>) and surface temperature (°C) have been obtained from **a** NCEP/NCAR reanalysis, **b** RegCM4.2 and **d** RegCM4.3. The model biases from **c** RegCM4.2 and **e** RegCM4.3 have been shown in the *right*

*panel* of the figure. The surface net downward shortwave flux and surface temperature have been shown in *shaded* and *contours* respectively. In the bias plot, *shades of red color* and *blue color* indicate overestimation and underestimation of the models respectively

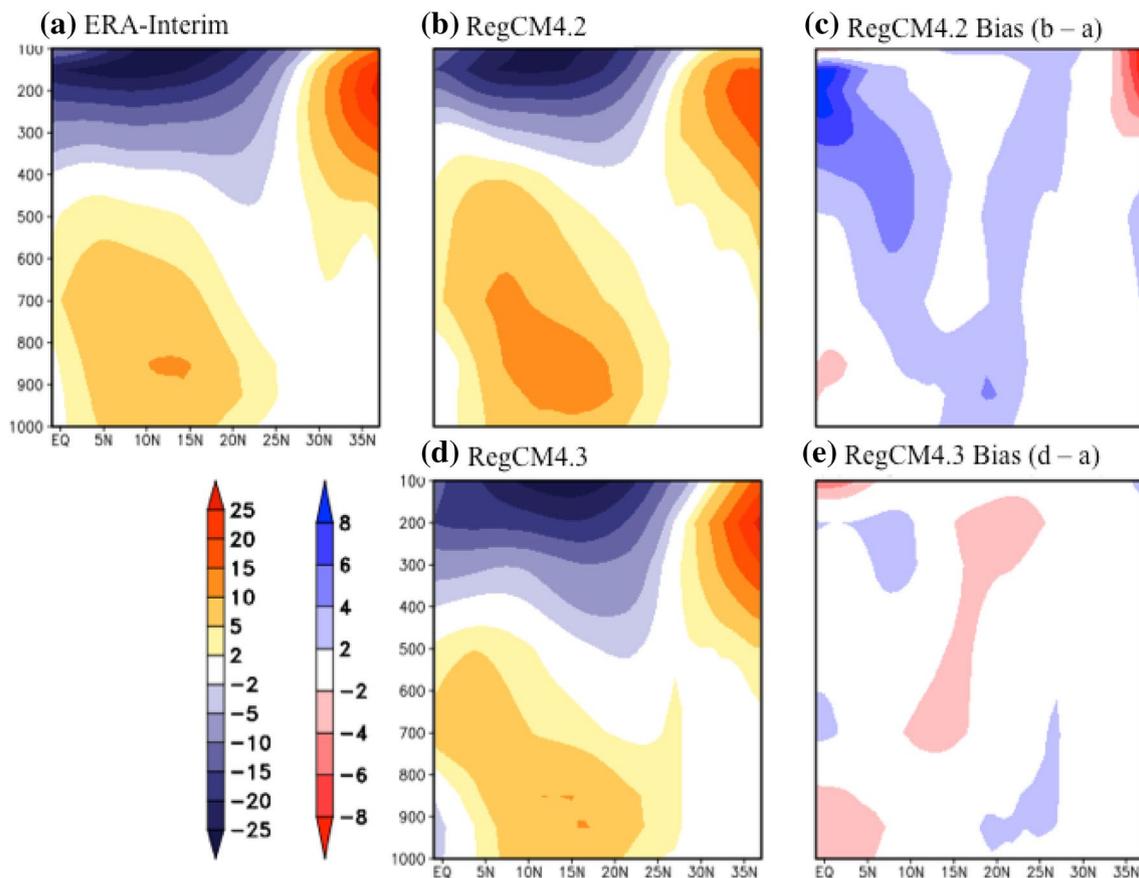
differential heating phenomenon is better represented in RegCM4.3 than in the RegCM4.2 as a consequence RegCM4.3 has performed better.

The mean vertical cross section of the zonal wind during JJAS over India (averaged over the longitudes 56–100°E) for the period 1998–2003 in ERA-Interim, RegCM4.2 and RegCM4.3 are shown in Fig. 8. The Tropical Easterly Jet (TEJ) at the level 200 hPa, which is centered at 5–20°N is well captured by both the model simulations (Fig. 8a, b, d). However, the depth and structure of TEJ are better represented in RegCM4.3 simulation (Fig. 8c) as compared to the RegCM4.2 simulation (Fig. 8b). The depth and structure of the Somali Jet are centered at 10–15°N at the lower level is well captured by RegCM4.3 compared to RegCM4.2 against the ERA-Interim dataset. The intensity of core of the Somali Jet is slightly less in RegCM4.3 as compared to ERA-Interim data. Thus, RegCM4.3 has performed better in reproducing the low-level Somali Jet and the upper-level TEJ than that in RegCM4.2. From the bias plot, it is evident that

the vertical structure of the zonal wind has less bias in RegCM4.3 (Fig. 8e) as compared to RegCM4.2 (Fig. 8c).

### 3.3 Inter-annual variation of summer monsoon rainfall

Figure 9 shows the inter-annual variations of rainfall over whole India and its six homogenous monsoon zones during summer monsoon season by IMD observation and model simulations for the period 1998–2003. The rainfall values have been averaged and weighted over the Indian land points (in case of whole India) and the grid points lie within the boundary (in case of homogeneous monsoon regions of India, Supplementary Fig. S1) in each of the year starting from 1998 to 2003. A comparison shows that the simulated JJAS rainfall over whole India and three zones out of six zones (viz. WCI, CNI, and NWI) in RegCM4.3 are close to that observed in IMD gridded dataset in each of the years, whereas the rainfall values are overestimated in the RegCM4.2 simulation. According to IMD, the years 2002 (deficient) and 2003 (normal) were contrasting rainfall



**Fig. 8** Mean vertical cross section of the zonal wind during JJAS over India (averaged over the longitude 56E to 100E) in **a** ERA-Interim, **b** RegCM4.2 and **d** RegCM4.3 for the period 1998 to 2003. The model biases from **c** RegCM4.2 and **e** RegCM4.3 have been

shown in the right panel of the figure. In the bias plot, shades of blue color and red color indicate overestimation and underestimation of the models respectively

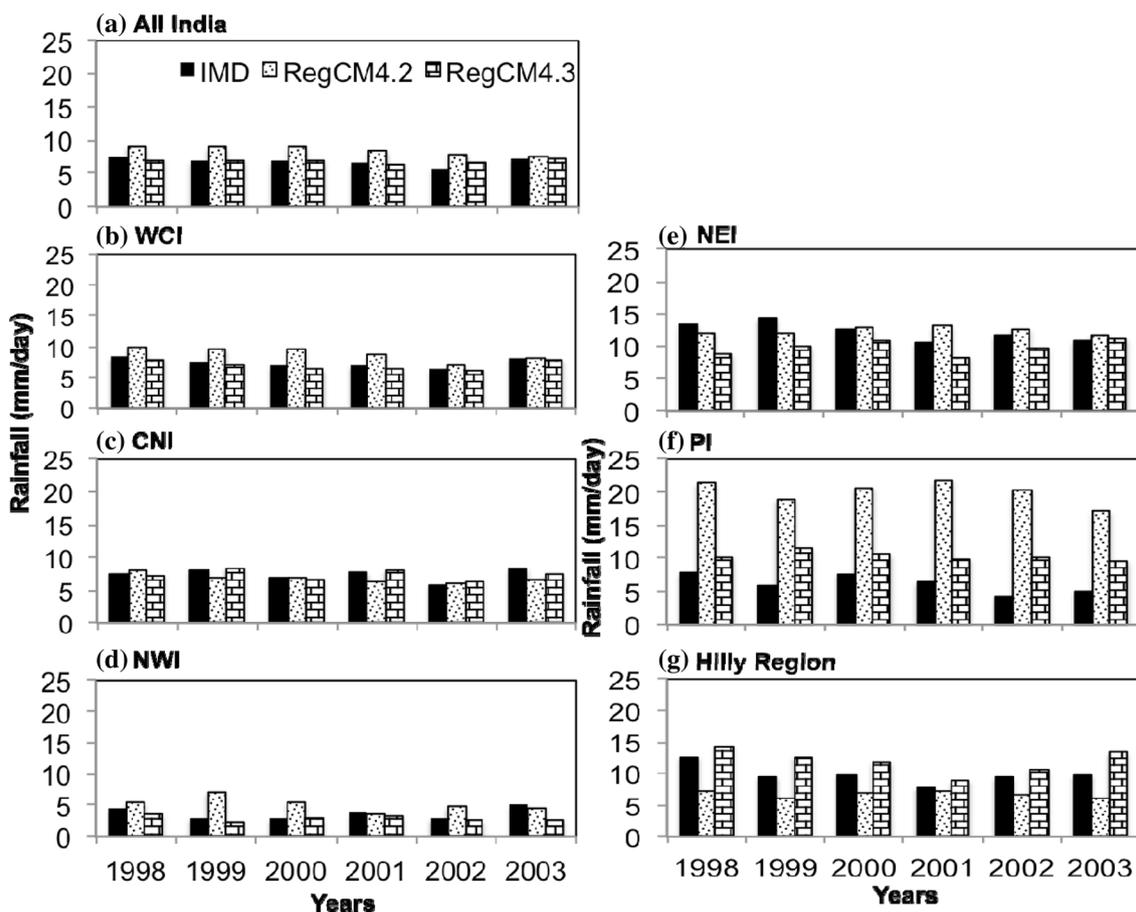
years during the period of this study 1998–2003 over whole India. This contrasting feature was seen over WCI, CNI, NWI and PI in the IMD records, while this contrasting rainfall feature in 2002 and 2003 were absent in both model simulation. The rainfall over the PI (Fig. 9f) is highly overestimated and underestimated over Hilly region (Fig. 9g) in all the years by RegCM4.2 when compared with the IMD observations. The rainfall is slightly overestimated over Hilly region and PI (Fig. 9g) all the years in RegCM4.3. Thus, the inter-annual variation of JJAS rainfall indicates that the rainfall is better represented in RegCM4.3 than that in the RegCM4.2 over four homogenous zones (viz. WCI, CNI, NWI and PI).

Further, the model validation has been carried out in simulating summer monsoon onset dates over India. It is found that the onset dates in RegCM4.3 simulation are close to the ERA-Interim reanalysis than in the RegCM4.2 simulation in all the years (Fig. 10). RegCM4.2 has shown a consistently delayed onset throughout the study period. From the analysis, it is confirmed that RegCM4.3 more

realistic than RegCM4.2 in representing the inter-annual variation of summer monsoon rainfall and monsoon onset dates.

#### 4 Summary

The primary objective of this study is to examine the strength and weakness of the two versions of RegCM (i.e. RegCM4.2 and 4.3) in simulating some of the features of Indian summer monsoon over South Asia CORDEX domain during the period 1998–2003. This sensitivity study has been carried out with the aim to estimate the uncertainty in future climate projections with the best possible versions of the climate model. Results confirm that the RegCM4.3 performs better in simulating the all India summer monsoon rainfall than the RegCM4.2 during the period 1998–2003. RegCM4.3 has performed fairly well in reproducing the mean JJAS rainfall over four out of the six homogenous zones such as WCI, CNI,

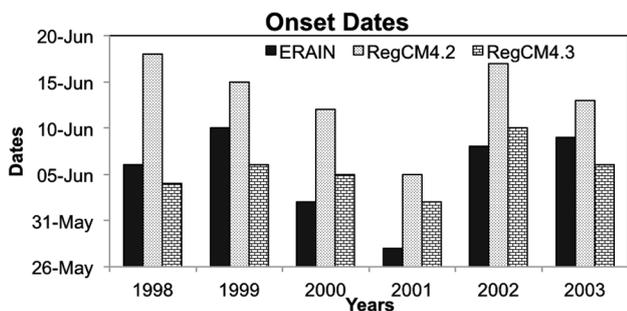


**Fig. 9** Inter-annual variations of JJAS rainfall as recorded in IMD (black bars) and simulated by RegCM4.2 (dotted bar) and RegCM4.3 (brick bar) during 1998–2003 over **a** All India, **b** West Central India

(WCI), **c** Central Northeast India (CNI), **d** North West India (NWI), **e** North East India, **f** Peninsula India and **g** Hilly region

NWI, and PI. Thus, RegCM4.3 is more realistic than that of RegCM4.2 in simulating the all India rainfall during the period 1998–2003. The strength and magnitude of the

lower level wind, moisture flux, surface net short wave flux, temperature and vertical structure of zonal wind have been well captured by RegCM4.3 in comparison to RegCM4.2. The low-level southwesterly winds and moisture flux are stronger over the northern Arabian Sea resulting in excessive rainfall over the Western Ghats, Peninsular region and over foothills of the Himalayas in RegCM4.2. While this phenomenon is better represented in the RegCM4.3. Excess moisture flux over the Ganges plain and NEI resulted in an overestimation of rainfall in RegCM4.3. Inter-annual variation of JJAS rainfall study reveals that the RegCM4.3 has done fairly well over four out of the six homogenous zones such as WCI, CNI, NWI, and PI. As the onset of Indian summer monsoon is important for India, the onset dates calculated by RegCM4.3 is relatively closer to the ERA-Interim reanalysis whereas the RegCM4.2 simulation has shown a delayed onset date. The annual cycle of ISMR simulated by RegCM4.3 during the period has shown a similar pattern to that of IMD, while the rainfall simulated in RegCM4.2 is highly overestimated. The intensity as well



**Fig. 10** Inter-annual variations of monsoon onset dates from 1998 to 2003 based on ERA Interim dataset and RegCM4.2 and RegCM4.3 simulations. The criterion for identifying monsoon onset dates has been used here is Hydrological Onset and Withdrawal Index (HOWI) adopted from Fasullo and Wester 2003

as the latitudinal expansion of the Somali Jet in RegCM4.2 is much more than that of ERA-Interim and hence it has simulated excess rainfall over India. The low-level Somali Jet and the upper-level TEJ are well represented in the RegCM4.3 simulation. In spite of the variability seen in both the versions of RegCM, RegCM4.3 has been more realistic than RegCM4.2.

It is a well known fact that the surface solar radiation is a key process in the various climatic processes like evapotranspiration, hydrological cycle, photosynthesis, oceanic heat budget, global energy balance and temperature and precipitation. Thus inclusion of measured solar irradiance in RegCM4.3 in place of hardcoded solar constant (RegCM4.2) improved the model performance in representing the mean feature of surface net shortwave flux and the surface temperature pattern in RegCM4.3. In turn, the differential heating of Indian land surface compared to surrounding ocean, which is the key drivers of the summer monsoon has been better represented in RegCM4.3. As a consequence, the various climatic processes during the Indian summer monsoon has been better simulated in the RegCM4.3. Thus, RegCM4.3 performs better in representing the mean summer monsoon circulation over India and its adjoining ocean. Hence, RegCM4.3 may be a good tool to study the future climate changes over South Asia.

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