

Impact of domain size on the simulation of Indian summer monsoon in RegCM4 using mixed convection scheme and driven by HadGEM2

Impact of domain size on ISM simulations

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Received: 21 September 2013 / Accepted: 15 November 2014 / Published online: 25 December 2014
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Abstract In this study, a smaller domain over India alone and a larger South Asia (SA) domain have been used in the Regional Climate Model version 4.2 (RegCM4.2) to examine the effect of the domain size on the Indian summer monsoon simulations. These simulations were carried out over a period of 36 years at 50 km horizontal resolution with the lateral boundary forcings of the UK Met Office Hadley Centre Global Circulation Model Version 2.0. Results show that the Indian summer monsoon rainfall is significantly reduced when the domain size for the model integration is reduced from SA to the Indian domain. In case of SA domain simulation, the Equitable Threat Scores have higher values in case of very light, light and moderate rainfall events than those in case of the Indian domain simulation. It is also found that the domain size of model integration has dominant impact on the simulated convective precipitation. The cross-equatorial flow and the Somali Jet are better represented in the SA simulation than those in the Indian domain simulation. The vertically integrated moisture flux over the Arabian Sea in the SA domain simulation is close to that in the NCEP/NCAR reanalysis while it is underestimated in the Indian domain simulation. It is important to note that when RegCM4.2 is integrated over the smaller Indian domain, the effects of the Himalayas and the moisture advection from the Indian seas are not properly represented in the model simulation and hence the monsoon circulation and associated rainfall are underestimated over India.

Keywords RegCM4.2 · HadGEM2 · NCEP/NCAR reanalysis · South Asia domain simulation · Indian domain simulation · Equitable Threat Score · Vertically integrated moisture flux

1 Introduction

Amongst all the global monsoon systems, the Indian summer monsoon is found to be the strongest one. Further, it is well known that the interannual and intraseasonal variabilities in the Indian summer monsoon rainfall (ISMR) have profound impact on the agriculture, and hence the economy of India and the neighboring countries in the South Asian region. ISMR covering the months of June, July, August, and September (JJAS), accounts for about 75 % of the annual precipitation in India. The summer monsoon circulation over India is conventionally considered as an atmospheric response to the land–sea thermal contrast. The strong cross-equatorial low level flow, known as the Somali Jet is one of the important components of the summer monsoon system (Findlater 1969). This jet transports momentum and water vapor from the southern to the northern hemisphere. Strong low level (westerly/southwesterly) flow over the Arabian Sea with jet strength of 25–30 m/s below the 850 mb level (Keshavamurthy and Sankara Rao 1992) is often favorable for active monsoon condition. The lower level monsoon flow carries copious amounts of moisture due to extensive evaporation over the Indian Ocean and Arabian Sea. This moisture is essential not only for its contribution to the monsoonal rainfall but also it is important as a driving force for the summer monsoon due to the release of latent heat while phase change takes place from vapor to liquid. The increase or decrease in ISMR mostly depends on the amount of moisture transport from

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the Indian Ocean into the Indian land region (May 2002; Meehl and Arblaster 2003). In several cases, more moisture transport leads to active monsoon condition indicated by dense multi-layered and convective clouds over the central parts of the country, the eastern Arabian Sea and the Bay of Bengal. The Tibetan Plateau to the north of India acts as heat source in the summer season and a sink in the winter months. The Tibetan anticyclone in the upper troposphere (between 150 and 100 mb) is directly responsible for the easterly jet (Koteswaram 1958). According to Raghavan (1973), the location and intensity of the upper level easterly jet along with the Tibetan anticyclone is one of the important components of the monsoon circulation.

Today, regional models are increasingly used to examine the characteristics of regional weather and climate over several parts of the world. The Regional Climate Model (RegCM) of the Abdus Salam International Centre for Theoretical Physics (ICTP) is one such regional climate model which has been successfully used to study the Indian summer monsoon features. Dash et al. (2006) simulated the summer monsoon characteristics over India using RegCM3 with a horizontal resolution of 55 km. They found that the Grell convection scheme performed better than other available convection schemes in simulating both summer monsoon circulation and rainfall. They also indicated that RegCM3 can be effectively used to study the summer monsoon process over the larger south Asian region. Shekhar and Dash (2005) demonstrated that the RegCM3 simulated ISMR is inversely related to snow depth over the Tibetan plateau. Singh and Oh (2007) used RegCM3 and demonstrated its sensitivity to the increase in Sea Surface Temperature (SST) by 0.6 °C over the Indian Ocean. They found that warming of the Indian Ocean increases the summer monsoon precipitation over southern peninsular India, west peninsular India and the Indian Ocean and reduces that over the northeast India. 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. Ashfaq et al. (2009) simulated the dynamical features of the summer monsoon with 25 km horizontal resolution over South Asia region and found that enhanced greenhouse forcing resulted in overall suppression of summer monsoon precipitation, delay in onset and an increase in the occurrence of monsoon break periods. Dash et al. (2012) validated RegCM3 simulated temperature and precipitation fields over Northeast India (NEI) under the IPCC A1B scenario for the period 1970–2100 and projected some future changes. Dash et al. (2013) inferred that RegCM3 performs better over the central India as compared to the other Indian regions in simulating the temperature and precipitation during the summer

monsoon months. They further explained the model bias in terms of frequency of occurrence of the extreme weather conditions such as very wet days, extremely wet days, warm days and warm nights over Central India. The regional and temporal characteristics of ISMR simulated by RegCM3 over India have been studied by Pattanayak et al. (2013). In their study, the model overestimated ISMR and this has been attributed to the surplus moisture flux over the Arabian Sea as compared against the NCEP/NCAR reanalysis.

Based on several earlier studies (Anthes et al. 1989; Jones et al. 1995; Bhaskaran et al. 1996, 2012; Giorgi and Mearns 1999; Denis et al. 2002, 2003; Gao et al. 2012), it may be stated that the domain size of model integration can have significant effects on the simulation of regional features and therefore a careful choice of the domain for integration of any regional model is essential. Anthes et al. (1989) and Giorgi and Mearns (1999) showed that the location of boundaries in relation to the regional sources of forcings in a particular climatic region can affect the regional climate model solutions. Jones et al. (1995) proposed that the regional domain must be large enough to allow the full development of small-scale features over the area of interest. While selecting an optimum size of a domain for model simulation, the objective is not to make it small suppressing the development of key mesoscale features. On the other hand Bhaskaran et al. (1996) showed that the domain should not be so large that the simulation deviates significantly from the large scale features of the driving model. They performed seasonal simulations of the Indian summer monsoon and demonstrated that the regional model results are relatively insensitive to domain size in several aspects. However, a prerequisite for such experiments was the realistic representation of large scale climatology in the driving General Circulation Model (GCM). Denis et al. (2002, 2003) introduced the concept of the Big Brother Experiment (BBE) and Little Brother Experiment (LBE) using Canadian Regional Climate Model over 1 month long simulations. The BBE had a larger domain and the output from this experiment was used to drive LBE with same resolution as BBE but over smaller domain embedded in BBE domain. They found that time mean and variability of fine scale features such as sea level pressure, temperature and precipitation are successfully reproduced over regions with strong small-scale surface forcing; over ocean and away from the surface, less reproducibility were achieved in the LBE. In a recent study, Bhaskaran et al. (2012) conducted 13-year long experiments using two domains over the Asian monsoon region at two horizontal resolutions of 25 and 50 km and examined the mechanism through which the model simulation becomes sensitive to the domain size. Their model integrations were carried out from 1979 to 1991

to capture a range of global and regional climatological features, such as strong ENSO-monsoon cycles of 1982–1983 and 1987–1988. They identified the seasonal mean hydrological cycle and the daily precipitation which make the domain size important. Their study also brings out the fact that no single optimum domain for model integration is suitable for regional model applications for all relevant sub-regions within the model domain as there is necessity of consistency of large-scale circulations between the driving and regional models. Browne and Sylla (2012) studied the sensitivity of domain on West African summer monsoon and justified a large portion of the Atlantic Ocean to be included for enough zonal moisture advection and the African Easterly Waves features. Gao et al. (2012) examined the uncertainties in monsoon precipitation over China using RegCM3 at 25 km resolution with two different GCM forcings. They found that for a variable such as precipitation which is mostly affected by local processes, the internal model processes play an important role in the simulation. The results of Zhang et al. (2008) have been confirmed by Gao et al. (2012) by using regional model forced by the reanalysis dataset.

Earlier domain size experiments (Anthes et al. 1989; Jones et al. 1995; Bhaskaran et al. 1996) were conducted at the seasonal time scale. Browne and Sylla (2012) conducted 5 years of model integration, while Bhaskaran et al. (2012) carried out model experiments for over a decade from 1979 to 1991. Most of the earlier domain size experiments were carried out with the help of reanalysis dataset. In this study, the regional model has been driven with a GCM. This study is different from earlier such studies in the selection of the model size and also in the time scale of model integration. It may be noted that the Indian summer monsoon is a very large scale phenomenon covering almost one third of the globe. The large scale moisture convergence from Indian Ocean and adjoin seas and the dynamical and thermodynamical effects of the Himalayas and the Tibetan plateau are the two most important elements of this monsoon system. Therefore, one of the domains chosen in this experiment is that of COordinated Regional climate Downscaling Experiment (CORDEX) South Asia domain which includes both the above components. The time scale of integration is 36 years from 1970 to 2005 so as to be recognized as that of climate simulation. A brief discussion on the RegCM4.2 model and the data used are given in Sect. 2. Section 3 describes the experimental design. Section 4 provides the characteristics of the mean summer monsoon rainfall simulated by RegCM4.2. Similarly, the simulated monsoon circulation features have been examined in Sect. 5. The vertical integrated moisture fluxes have been estimated in Sect. 6. The important results obtained in this study are summarized in the concluding Sect. 7.

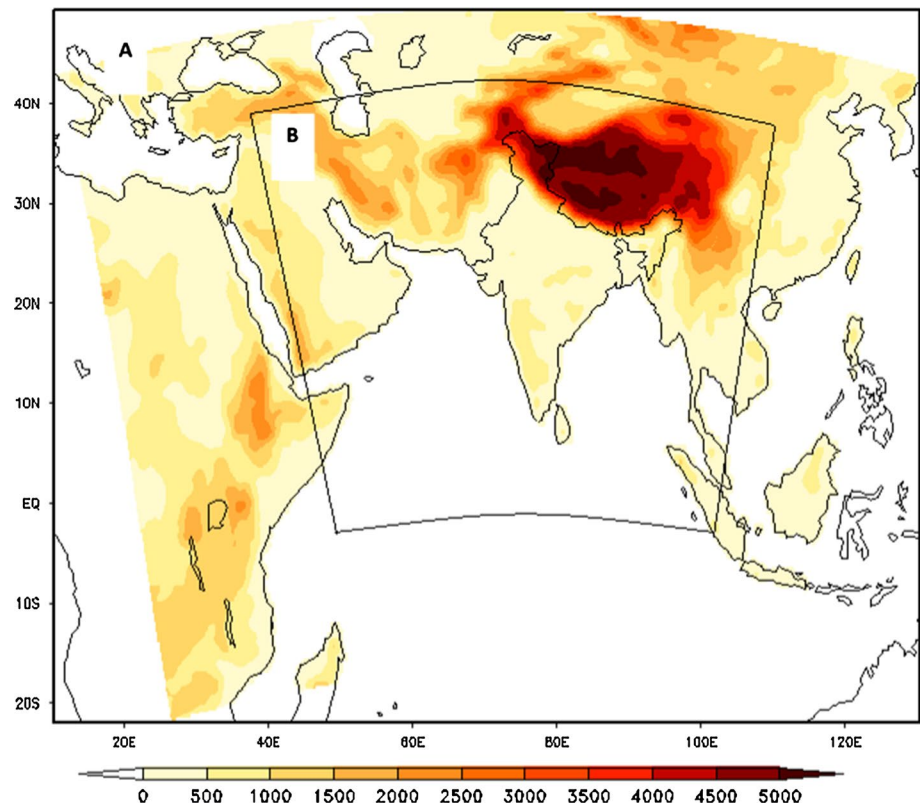
2 Model description and data used

The model used in this study is the one developed at the Abdus Salam International Centre for Theoretical Physics (ICTP) and known as the Regional Climate Model version 4.2 (RegCM4.2, Giorgi et al. 2012). RegCM4.2 is the fourth generation of the regional climate model which is the outcome of a new step in recoding (Elguindi et al. 2011) the RegCM3 (Giorgi et al. 1993a, b) model. The code base has been actively developed by a community of developers internal and external to ICTP. The UK Met Office Hadley Centre (HadGEM2) Global Circulation Model (Collins et al. 2011) output with $1.875^\circ \times 1.25^\circ$ resolution and 38 vertical levels, obtained from Coupled Model Inter-comparison Project Phase 5 (CMIP5) for Inter-governmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) has been used as the initial and boundary conditions for the period 1970–2005 at 6 hourly intervals. The elevation data used are obtained from the United States Geological Survey (USGS). USGS Global Land Cover Characterization (GLCC) dataset at 10 min resolution are used to create vegetation and landuse 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 prepared by Rajeevan and Bhate (2009) and the rainfall over the whole domain has been compared with the corresponding values in the Global Precipitation Climatology Project (GPCP) version 2.1 dataset prepared by Adler et al. (2003). Other climatic parameters such as lower and upper level winds and moisture are obtained from the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) dataset (Kalnay et al. 1996; Kistler et al. 2001).

3 Experimental design

Two sets of experiments have been conducted for two different domains both focused over India, namely larger South Asia (SA) domain and the smaller Indian Domain. The larger domain over SA has been identified in the framework of World Climate Research Programme (WCRP) coordinated experiment known as the CORDEX (Giorgi et al. 2008). It may be noted that CORDEX is an international coordinated effort to produce an improved generation of regional climate change projections world-wide for input into impact and adaptation studies within the AR5 timeline and beyond. SA is one of the domains set by this framework and hence this domain has been chosen in this study. The only difference between the two experiments conducted in this study is the domain size whereas all the physics and dynamics used in the model have been kept the same. As depicted in Fig. 1, the SA domain covers the region

Fig. 1 The physical domains with topography (in meters) over which RegCM4.2 is integrated. The domain A is South Asia CORDEX domain and the smaller domain B is used as the Indian domain



10°E–130°E and 22°S–49°N with 224 grid points along the latitude circle and 160 points along the longitudinal direction while the Indian domain covers the region 42°E–109°E and 3.5°S–41°N with 126 grid points along the latitude circle and 98 points along the longitudinal direction. RegCM4.2 has been integrated from 1st January 1970 up to the end of December 2005 spanning 36 years at 50 km horizontal resolution over both the domains. The physical parameterization schemes used in these experiments are radiation scheme of the National Center for Atmospheric Research Community Climate Model (CCM3) of Kiehl et al. (1996), planetary boundary layer scheme of Holtlag et al. (1990), MIT Emanuel scheme (Emanuel 1991; Emanuel and Zivkovic-Rothman 1999) over land and Grell scheme (Grell 1993) for cumulus scheme with Fritsch and Chappell (1980) closure over ocean, SUBEX for large scale precipitation scheme (Sundqvist et al. 1989), the biosphere atmosphere transfer scheme BATS1e of Dickinson et al. (1993) and Zeng's ocean flux parameterization (Zeng et al. 1998) scheme. SST diurnal cycle scheme (Zeng 2005) has been enabled and model desert seasonal albedo variability is disabled. In this study, three bottom model levels with no cloud are selected. It may be noted that the double convection scheme of MIT Emanuel over land and Grell over the adjoining ocean has successfully been used by Giorgi et al. (2014) in their CORDEX runs. In the two domain size experiments conducted in this study, only the domain size

is different, while all other parameters such as horizontal and vertical resolutions, initial and boundary conditions and physical parameterization schemes etc. have been kept the same. The first 5 years from 1970 to 1974 have been considered as model spin-up period and hence all the model outputs are analyzed for the period from 1975 to 2005.

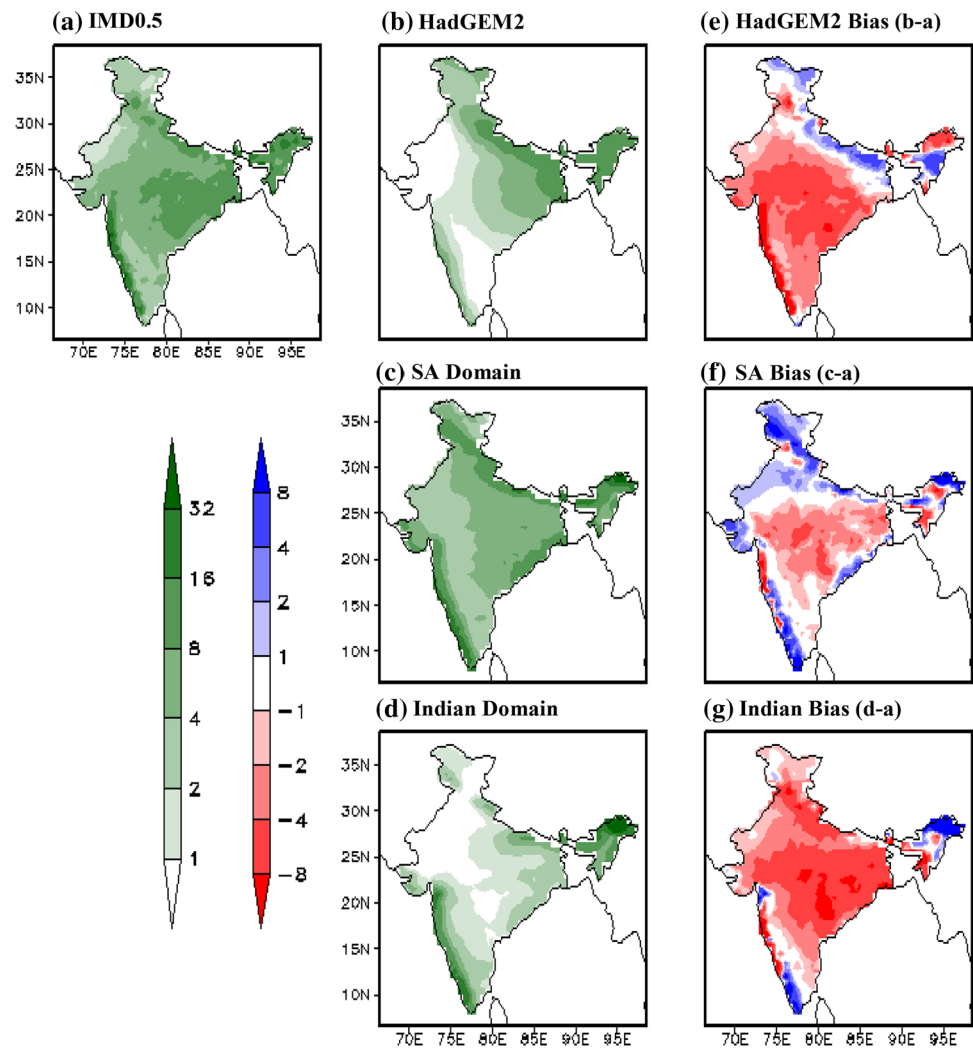
4 Model simulated JJAS rainfall characteristics

The simulated 6 hourly rainfall in each of the years of study period from 1975 to 2005 have been used here to compute their monthly means and then JJAS mean values in each year. The decadal means and the climatological values over the whole period of study 1975–2005 have also been computed. Such computations have been done only over Indian land points in case of both the model simulations over SA and Indian domains. To verify RegCM4.2 simulated rainfall characteristics against those in the IMD observations, values of Equitable Threat Score (ETS) have been computed (Schaefer 1990) for various categories of rainfall over India.

4.1 Climatology of ISMR

In this section, ISMR climatology simulated by RegCM4.2 has been validated against the corresponding

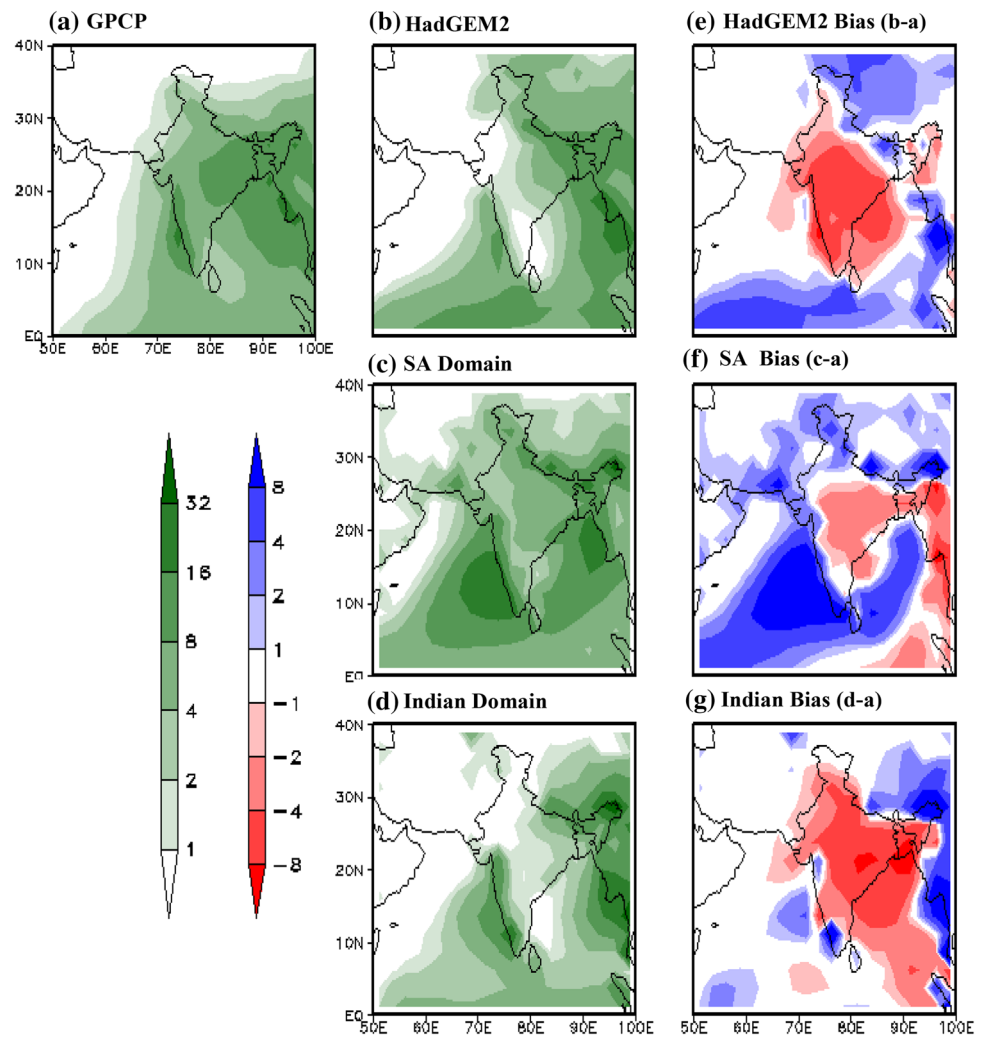
Fig. 2 Climatological JJAS Rainfall (mm/day) obtained from IMD0.5 gridded dataset (a), HadGEM2 simulation (b), and RegCM4.2 simulations for South Asia domain (c) and Indian domain (d) for the period 1975–2005. The respective differences from the IMD0.5 gridded rainfall are given in (e, f, g)



observed values obtained from IMD0.5 gridded rainfall (Fig. 2) whereas the simulated JJAS mean rainfall over India and adjoining seas have been compared with GPCP (Fig. 3). Figure 3 depicts similar biases over the Indian land points as in Fig. 2. It may be noted that Fig. 2 shows the values of climatological JJAS rainfall (mm/day) obtained from the IMD gridded dataset, the global model HadGEM2 (which is used as forcing for the regional model) and the RegM4.2 simulations over the SA and Indian domains. Since these rainfall datasets are of different resolutions, the HadGEM2 ($1.875^\circ \times 1.25^\circ$) and RegCM4.2 ($0.44^\circ \times 0.44^\circ$) simulated rainfall are interpolated to those of IMD grids at $0.5^\circ \times 0.5^\circ$ using a simple bilinear interpolation technique. It may be noted that ISMR is the area weighted mean value of JJAS rainfall over the Indian land points only which are based on the 0.5×0.5 grids of IMD dataset. As found from Fig. 2b, e, ISMR in HadGEM2 has been underestimated over the central India and most parts of peninsular India. In SA

domain simulation (Fig. 2c, f), climatological JJAS rainfall has values ranging from 8 to 16 mm/day over the Northeast India and the foothills of Himalayas, 8 mm/day over the East Coast, 16–32 mm/day over the Western Ghats and 1–2 mm/day over the Northwest India. The observed IMD rainfall (Fig. 2a) over the corresponding regions are about 16, 8, 32 and 1–2 mm/day respectively. The rainfall values in the Indian domain simulation over the corresponding regions are about 8–16, 4–8, 8–16 mm/day and 1 mm/day respectively. Though the model is able to reproduce the rainfall patterns over the major rainfall regions such as Northeast, the Western Ghats, the Gangetic plains and Eastcoast of India in the SA domain simulation, the rainfall has been overestimated by 4–8 mm/day over the Western Ghats and some parts of Northeast India and underestimated by 2–4 mm/day over Central India and Gujarat. Again, the model simulated rainfall has been underestimated over the plains of Central India such as Madhya Pradesh, interior Andhra Pradesh,

Fig. 3 Climatological JJAS Rainfall (mm/day) obtained from GPCP dataset (a), HadGEM2 simulation (b), and RegCM4.2 simulations for South Asia domain (c) and Indian domain (d) for the period 1979–2005. The respective differences from the GPCP rainfall are given in (e, f, g)

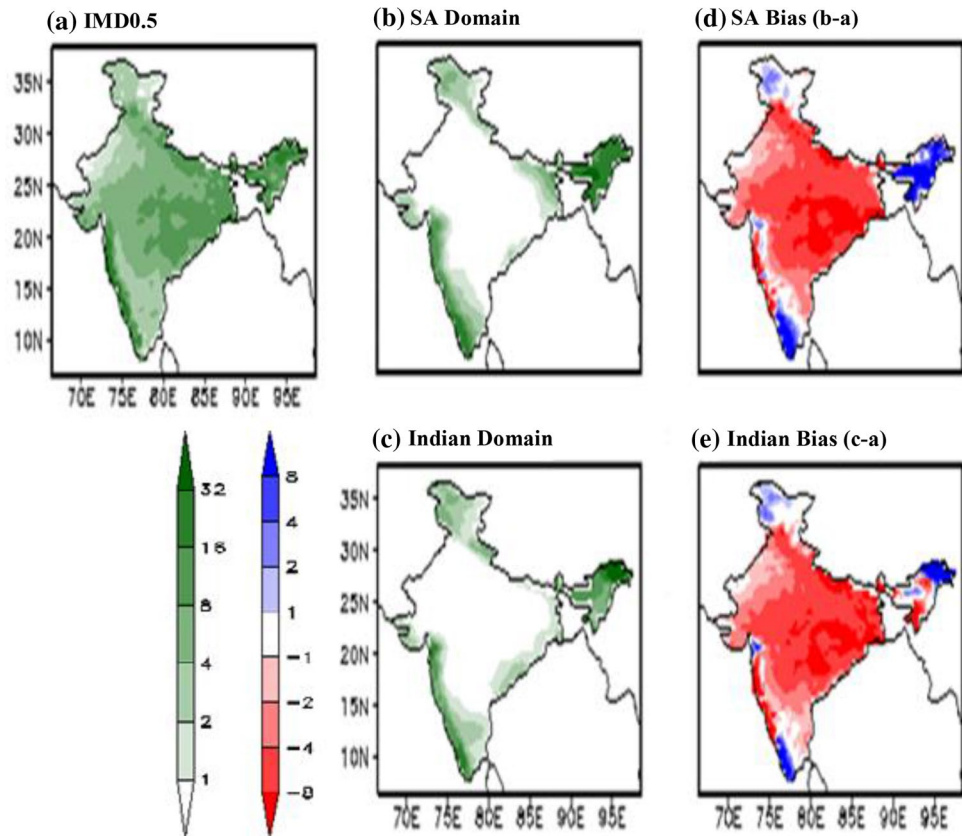


Vidarbha, western Odisha and Chhattisgarh. Also Punjab, southern part of Northeast India, simulated rainfall in SA domain values are comparatively less than the respective observations. Whereas, the rainfall in the Indian domain simulation has been underestimated over almost all the regions of India except over the Western Ghats and Arunachal Pradesh. The climatological ISMR value in SA and Indian domains simulations are 6.84 and 4.01 mm/day respectively, while the corresponding IMD observed value is 6.68 mm/day. As noted earlier, JJAS mean rainfall values over the Indian land points are used to compute ISMR. The biases in the HadGEM2 (Fig. 2e) simulations have been reduced noticeably in the SA domain simulation (Fig. 2f), whereas those worsened (Fig. 2g) in the Indian domain simulation. The rainfall underestimate over most part of India in the Indian domain simulation is more than that the SA domain simulation. In SA domain, the rainfall has been overestimated over the adjoining oceans whereas in the Indian domain simulation, the rainfall has been underestimated. Since the global model HadGEM2

is poor in simulating the ISMR, RegCM4.2 when integrated over the larger SA domain improved on the global model precipitation and made it closer to the observations. The same could not happen in the Indian domain simulation. Thus RegCM4.2 has performed considerably well in case of SA domain as compared to the Indian domain.

Two additional sensitivity experiments were carried out with a single convection scheme Grell over the land and ocean while integrating RegCM4.2 over SA and Indian domains for a period of 20 years from 1970 to 1990. The initial and lateral boundary conditions and other physical parameterization schemes as mentioned in Sects. 2 and 3 were kept the same. The simulated mean summer monsoon rainfall in both the domains and the model biases with respect to IMD0.5 dataset are shown in Fig. 4. Comparison of biases obtained in the double and single schemes (Figs. 2, 4) in both the cases of SA domain and Indian domain show that (1) double convection scheme performs better than the single scheme and (2) SA domain simulation yields less bias compared to that obtained from

Fig. 4 Climatological JJAS Rainfall (mm/day) obtained from IMD0.5 gridded dataset (a), RegCM4.2 simulations using single convection scheme Grell over South Asia domain (b) and Indian domain (c) for the period 1979–1990. The respective differences from the IMD0.5 gridded rainfall are given in (d, e)



the Indian domain. The result from double scheme simulation (Fig. 2c) is very close to the observation as compared to that from the single cumulus scheme (Fig. 4b) in case of SA domain simulation. Here it may be noted that, Giorgi et al. (2014) have used the same double convection scheme instead of a single convection scheme. Further comparisons of Figs. 2f with g and 4d with e indicate that the domain size has very small effect on the simulated bias in precipitation when a single convection scheme is used. In case of single convection scheme, the smaller domain shows some what reduced negative bias compared to SA domain simulation. Based on the findings of these additional runs, it may be inferred that the results presented in this study due to the double convection scheme may not hold true for other combinations of convection schemes. In the double convection scheme, while using Grell scheme over the ocean, the Zeng's Ocean flux has been modified. Since the SA domain covers much larger oceanic area in the Indian Ocean than the smaller Indian domain, in this particular case more moisture might have been supplied from the larger oceanic region into the landmass. Hence in the double convection scheme, the domain size matters in case of rainfall bias over the Indian landmass. On the other hand, while using single convection scheme, the domain size doesn't affect the rainfall bias to that extent.

4.2 Interdecadal variation of ISMR

The interdecadal variation of ISMR is shown in Fig. 5. There are three decades in the whole period of study namely 1976–1985, 1986–1995 and 1996–2005. The rainfall values in all the three rainfall datasets represent the area weighted mean values over the Indian land points in each of the decades. Comparison shows that ISMR obtained from the SA domain simulation is close to the respective IMD observed values in all the three decades examined here. Decadal mean ISMR in the first two decades (1976–1985) and (1986–1995) are about 6.6 mm/day in both IMD observation and SA domain simulation. In the third decade (1996–2005), ISMR has been slightly underestimated by the model in the SA domain simulation. However, ISMR in the Indian domain simulation is underestimated in all the three decades. The value of ISMR in the Indian domain simulation is as low as 60 % of that of IMD in all the three decades. Based on this analysis, it may be interpreted that the ISMR obtained in the SA domain simulation is closer to the observation than that in the smaller Indian domain.

4.3 Skills of simulated rainfall categories

In this section, the skills of simulations over seasonal time scale are measured using Root Mean Square Error (RMSE)

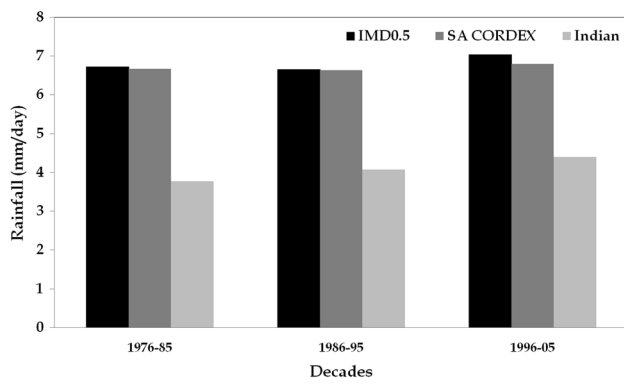


Fig. 5 Inter-decadal variations of ISMR based on IMD0.5 (black bars) and RegCM4.2 simulations over SA domain (dark grey bar) and Indian domain (light grey bar) during 1975–2005

and ETS. The RMSE and ETS have been calculated by taking the area weighted averages of daily precipitation during JJAS over Indian land for the period 1975–2005. The RMSE of daily rainfall over the period of study is 3.69 mm/day in SA domain simulation and 6.13 mm/day in Indian domain simulation. ETS measures the fraction of observed and/or simulated events that were correctly simulated and adjusted for hits associated with random chance. For example, it is easier to correctly simulate rain occurrence in a wet climate than in a dry climate. It is most suited for verification of rainfall in Numerical Weather Prediction (NWP) models because its “equitability” allows scores to be compared more fairly across different regimes. This score is sensitive to hits. Because it penalizes both misses and false alarms in the same way, it does not distinguish the source

of simulated error. Higher value of ETS indicates the model simulation is more capable of capturing the observed rainfall pattern at a certain rainfall threshold. The ETS is defined as

$$ETS = (H - Hr)/(H + M + F - Hr) \quad (1)$$

where $Hr = (H + M) \times (H + F)/T$.

Here H, M and F are Hits, Misses and False alarms for each category respectively. Hr is the hits due to random chance and T is the total number of events. Value of ETS ranges between -0.33 and 1. When ETS equals to 0 there is no skill in the model simulation. In this study, ETS has been calculated for three categories of rainfall which are very light, light and moderate in strength. According to IMD, very light, light and moderate rain events are those when daily rainfall ranges between 0.1–2.4, 2.5–7.4 and 7.6–35.5 mm respectively. Figure 6 shows the ETS values of each rainfall category for the period of study. ETS has been calculated using the daily rainfall simulated in both the experiments and the IMD observed rainfall. Computed ETS for each of the categories indicate that the score is higher in SA domain simulation than that in the Indian domain simulation. The threat scores for all categories of rainfall are less than 0.1 in the Indian domain simulation. In case of very light rain, the ETS are calculated to be 0.27 and 0.04 in SA and Indian domain simulations respectively. The ETS for light rainfall category is 0.12 in the Indian domain simulation. ETS in moderate category of rainfall are 0.24 and 0.03 in the SA and Indian domain simulations respectively. Thus, the ETS in all the rainfall categories indicate that the SA domain simulation yields higher skills than those in the Indian domain simulation.

Fig. 6 ETS estimated for three different rainfall categories namely very light rain (0.1–2.4 mm/day), light rain (2.5–7.5 mm/day) and moderate rain (7.6–35.5 mm/day) obtained from RegCM4.2 simulations over both domains with respect to IMD observed rainfall during 1975–2005. Dark grey bar SA domain and light grey bar Indian domain simulations

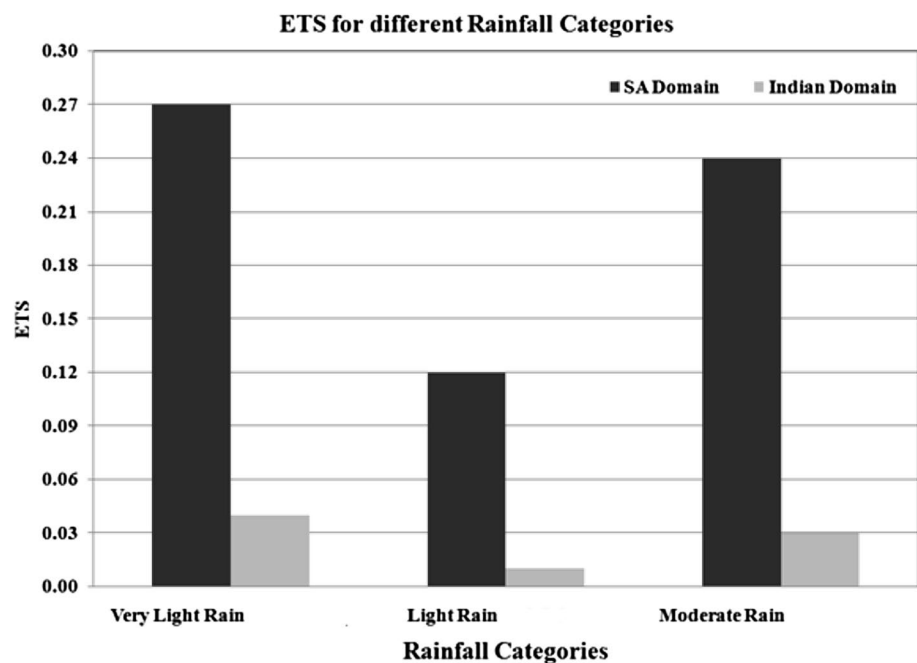
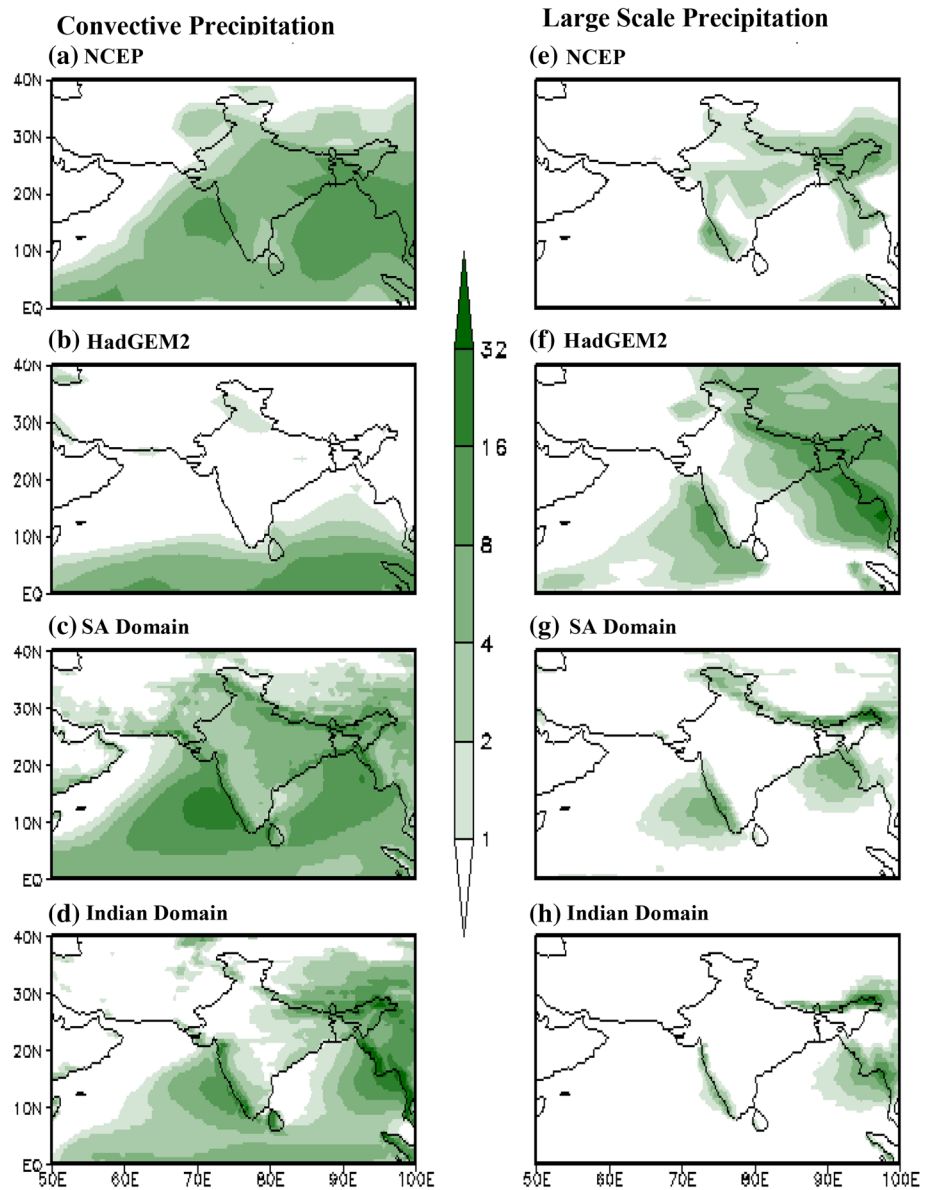


Fig. 7 Climatological JJAS mean precipitation (mm/day) for the period 1975 to 2005 in NCEP/NCAR reanalysis (a, e), HadGEM2 (b, f) and RegCM4.2 simulations over SA (c, g) and Indian (d, h) domains. *Left panels (a–d)* represent convective precipitation (mm/day) and the *right panels (e–h)* show the large scale precipitation (mm/day)

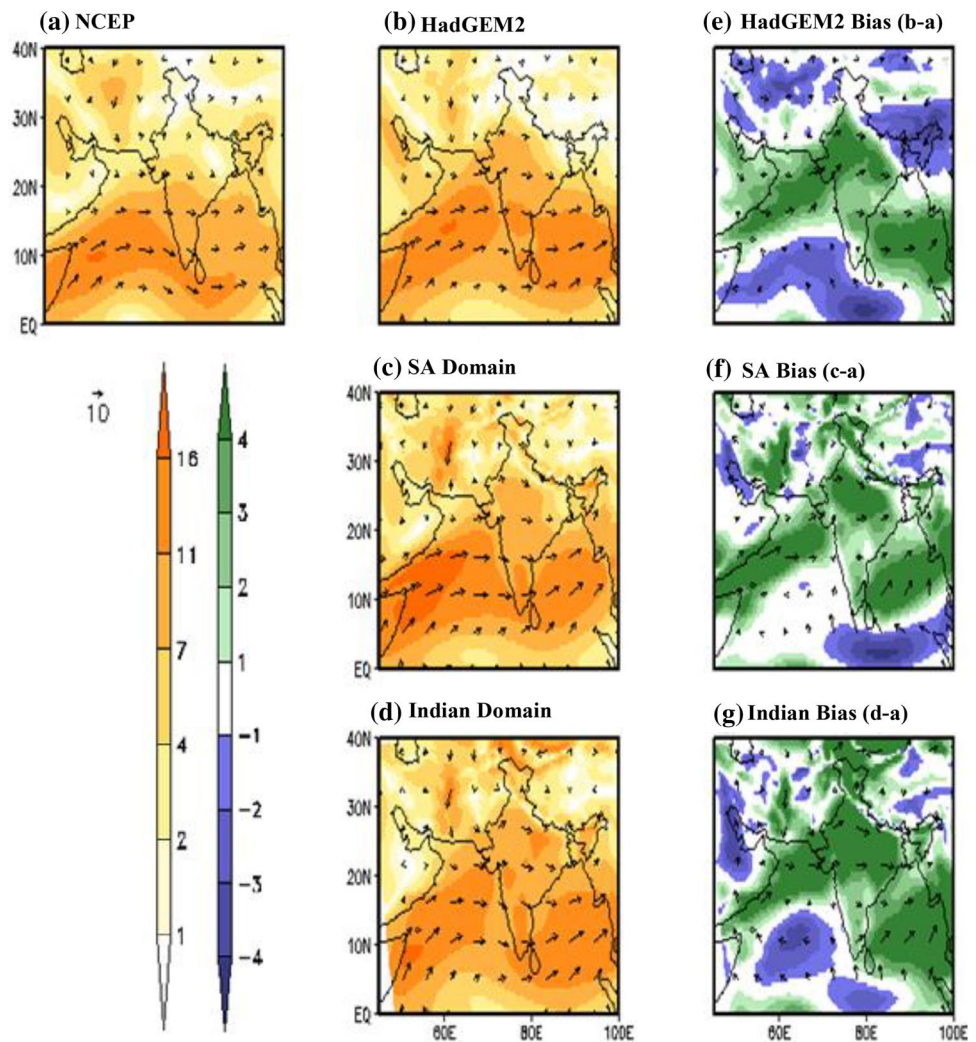


4.4 Convective and large scale precipitation

Figure 7 shows the two components of the precipitation, i.e., convective and large scale precipitation from NCEP reanalysis data, the global model HadGEM2 and RegCM4.2 in both the SA and Indian domain simulations. As the summer monsoon is primarily driven by the atmospheric convection, Fig. (7a–d) depict the dominance of convective precipitation in both the domain simulations. However, the convective precipitation decreases (Fig. 7c, d) considerably as the domain size reduced from larger SA domain to smaller Indian domain. There is a change of about 4 mm/day over the Kerala coast, about 3 mm/day along the foothills of the Himalayas, around 4–8 mm/

day over North Bay of Bengal and 1–2 mm/day over east coast of India. However, there is no significant change in the large scale precipitation (Fig. 7g, h) over the main land due to the reduction in domain size. The convective precipitation over the Western Ghats and head Bay of Bengal have been better captured in SA domain simulation than the respective ones in the Indian domain simulation. But the large scale precipitation over the central India has not been captured in any of the simulations. It is seen that the convective precipitation from the parent global model HadGEM2 is not close to the respective value obtained from NCEP reanalysis data. However, both the regional model simulations after downscaling have improved upon the parent value and become more realistic.

Fig. 8 Climatological JJAS wind (m/s) at 850 hPa in NCEP/NCAR (a), HadGEM2 simulation (b) and RegCM4.2 simulation over South Asia (SA) domain (c) and Indian domain (d). The respective differences from the reanalyzed fields are given in (e–g)



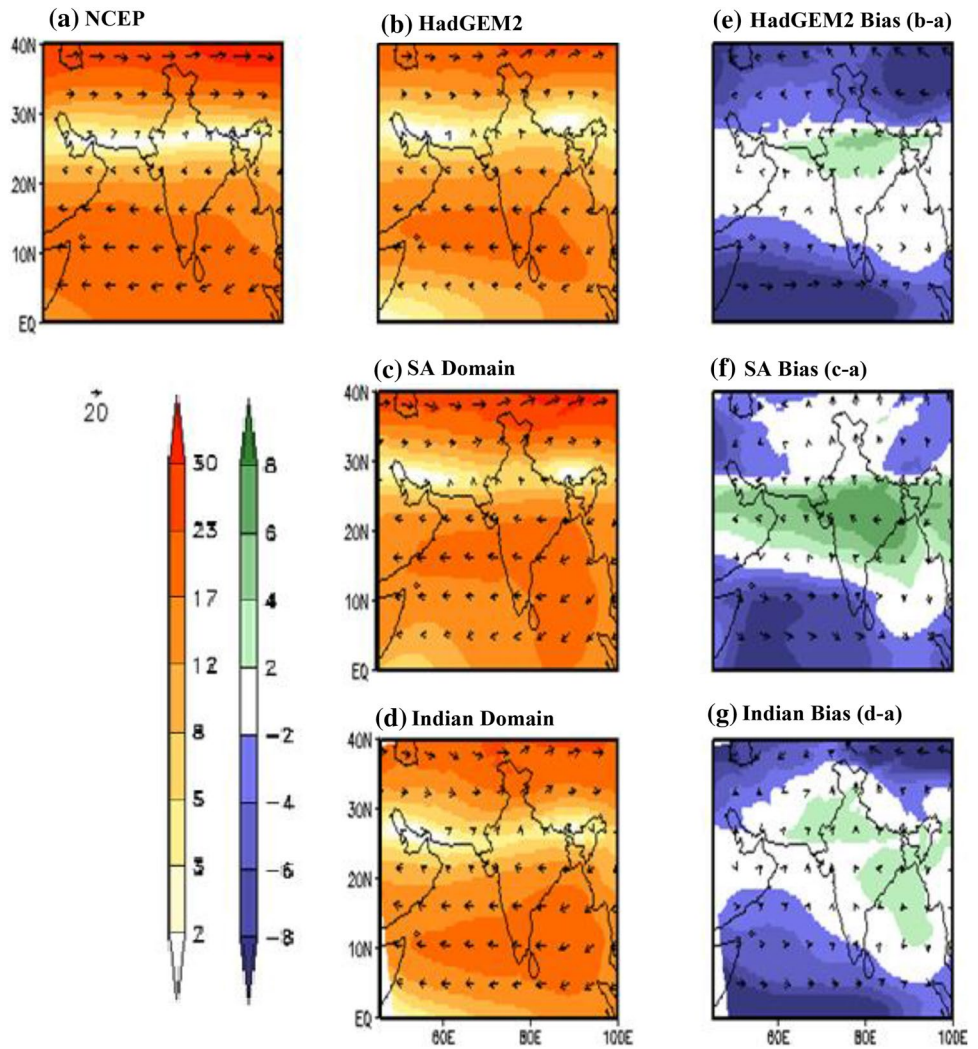
5 Model simulated circulation features

Study of Sperber and Palmer (1996) shows that a model which can represent the climatic circulation features realistically could simulate the interannual variation more accurately. This section deals with the JJAS mean winds at 850 and 200 hPa obtained in both the domain simulations of RegCM4.2 for the period 1975–2005. These variables have been plotted in Figs. 8 and 9. These figures show the climatological winds from NCEP/NCAR reanalysis, HadGEM2 simulation and RegCM4.2 simulations over the SA domain and Indian domain respectively.

The comparison of RegCM4.2 simulated seasonal wind with HadGEM2 and NCEP/NCAR winds at 850 hPa has been shown in Fig. 8a–g. The magnitudes of the Somali jet over the Arabian Sea and the southernmost India during summer monsoon are in the range of 7–16 m/s in both the SA domain simulation and reanalysis. However, the core of the Somali Jet in the SA domain simulation has larger

spatial extent than that in the reanalysis. The Somali jet and the westerlies over the south Arabian Sea are weaker in HadGEM2 than in the reanalysis. From the difference plot (Fig. 8f), it is seen that the wind over the southern Arabian Sea in the SA domain simulation has bias in the range of –1 to 1 m/s whereas in the northern Arabian Sea, wind is overestimated by 3–4 m/s. In the Indian domain simulation, the southwesterly wind over Arabian Sea is underestimated by 2–3 m/s. In both the simulations, the wind is stronger over the northern Arabian Sea, Northern India and Bay of Bengal by 2–3 m/s. In the SA domain simulation, the model has reproduced the cross-equatorial flow and south equatorial easterlies in the lower troposphere closer to the NCEP/NCAR reanalysis than in the Indian domain simulation. The upper level wind at 200 hPa is shown in Fig. 9a–g. The simulated Tibetan anticyclone and the position of the tropical easterly jet are similar in both the simulations. The magnitude of the core of the easterly jet in reanalysis and in both simulations is around 23 m/s, but the reanalysis has larger

Fig. 9 Climatological JJAS wind (m/s) at 200 hPa in NCEP/NCAR (a), HadGEM2 simulation (b) and RegCM4.2 simulation over South Asia (SA) domain (c) and Indian domain (d). The respective differences from the reanalyzed fields are given in (e–g)



spatial extent than the model simulations. The simulated easterly jet is weaker by 4–6 m/s over the equatorial Indian Ocean and 2 m/s over Arabian Sea in both the simulations than the NCEP/NCAR value. The model yields stronger Tibetan anticyclone in the SA domain simulation than in the Indian domain run. Easterly wind is stronger by 2–4 m/s over Central India in the SA domain simulation. This bias has originated from the Thailand region and extended up to the western part of Arabian Sea. The westerly jet stream has been underestimated in both the simulations. The simulated upper level easterly and westerly jet streams are weaker as compared to NCEP/NCAR reanalysis.

6 Model simulated moisture flux

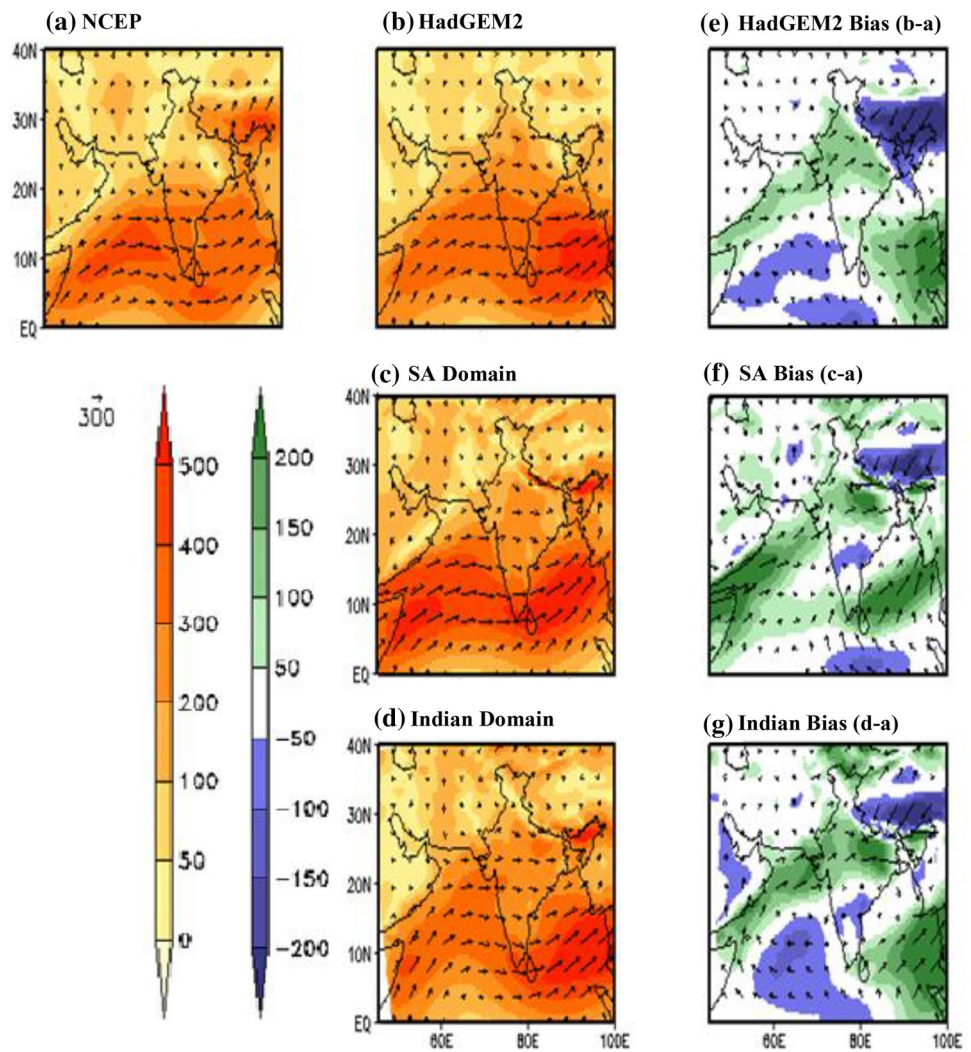
The summer monsoon rainfall is mostly linked to the amount of moisture transported from the oceanic part to

the Indian subcontinent during the summer monsoon months (Pisharoty 1965; Saha and Bavadekar 1973; Murakami et al. 1984). Therefore, vertically integrated moisture flux (VIMF) has been computed in both the simulations and compared with that in the NCEP/NCAR reanalysis in this section. Also the time-latitude diagram of VIMF averaged over the longitudes 62.5°E–75°E is examined here. It may be noted that in the above mentioned longitudinal region over Arabian sea, there is rapid VIMF fluctuations during the summer monsoon season (Fasullo and Webster 2003). The VIMF has been calculated using the following relation:

$$VIMT = \int_{Surface}^{300\text{mb}} qUdp \tag{2}$$

Here, q is specific humidity and U is the wind vector.

Fig. 10 Climatological JJAS vertically integrated moisture flux ($\text{kg m}^{-2} \text{s}^{-1}$) in NCEP/NCAR (a), HadGEM2 simulation (b) and RegCM4.2 simulations over South Asia (SA) domain (c) and Indian domain (d). The respective differences from the reanalyzed fields are given in (e–g)

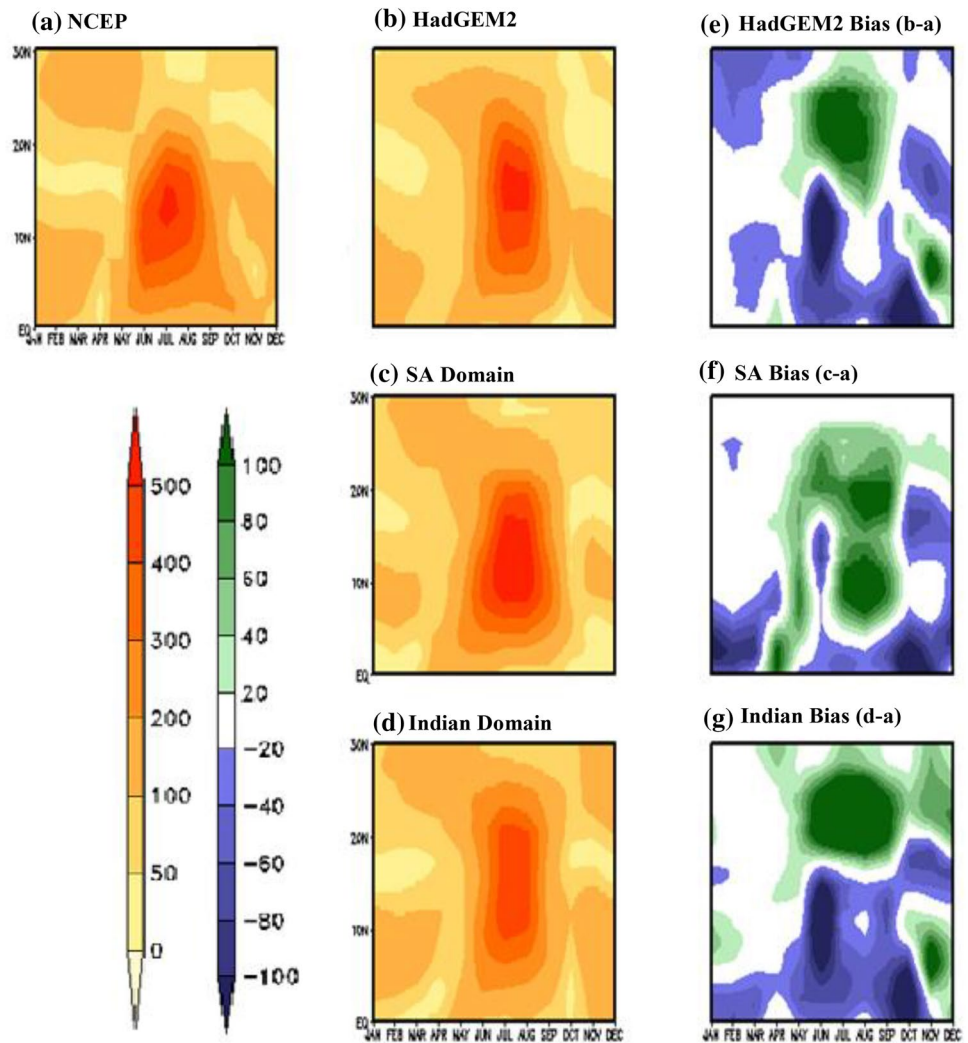


6.1 Role of vertically integrated moisture flux

The climatological JJAS mean VIMF obtained from NCEP/NCAR reanalysis dataset, HadGEM2 and in both the simulations in RegCM4.2 are shown in Fig. 10. In HadGEM2, the VIMF is weaker than that in the NCEP/NCAR reanalysis over the south Arabian Sea and central equatorial Indian Ocean. In the SA domain simulation, the amount of moisture flux during summer monsoon season over the Arabian Sea is about $400\text{--}500 \text{ kg m}^{-2} \text{ s}^{-1}$ against the NCEP/NCAR value of about $300\text{--}400 \text{ kg m}^{-2} \text{ s}^{-1}$. The moisture flux obtained from NCEP/NCAR and SA domain simulations are in good agreement over most parts of the Arabian Sea. However, the moisture flux in SA domain simulation is overestimated by $50\text{--}100 \text{ kg m}^{-2} \text{ s}^{-1}$ over the northern Arabian Sea. Such overestimation is initiated from the north Somalia and extended up to the Gujarat coast. The amount of moisture flux over the Arabian Sea is about $200\text{--}300 \text{ kg m}^{-2} \text{ s}^{-1}$ in the Indian domain simulation. The

magnitude of overestimation in VIMF in Indian domain simulation is similar to that in the SA domain simulation, but the zone of overestimation is larger and is extended up to the northern part of India. Major parts of Arabian Sea and equatorial Indian Ocean show underestimation in VIMF by about $50\text{--}100 \text{ kg m}^{-2} \text{ s}^{-1}$ in the Indian domain simulation. During JJAS, a large amount of water vapor is transported to the Indian subcontinent due to the large-scale flows from outside the Indian monsoon region such as the moisture transport from the Southern Hemisphere (Li 1999; Ding 2004). The other source of water vapor is the evaporation when the low-level monsoon wind passes over the oceans. In SA domain simulation, the cross-equatorial moisture flux has a good agreement with the NCEP/NCAR reanalysis whereas it is less in the Indian domain simulation. Since the southern boundary of the Indian domain is along 3.5°S latitude, there is less transport of moisture flux from across the equatorial and southern Indian Ocean. The deficit VIMF provided by HadGEM2 to both the

Fig. 11 Annual cycle of longitudinally averaged (62.5°E to 75°E) vertically integrated moisture flux ($\text{kg m}^{-2} \text{s}^{-1}$) in NCEP/NCAR (a), HadGEM2 simulation (b) and RegCM4.2 simulation over South Asia (SA) domain (c) and Indian domain (d) simulations. The respective differences from the reanalyzed fields are given in (e–g)



simulations has been recovered in SA domain due to the inclusion of equatorial and southern Indian Ocean.

6.2 Monthly variation of VIMF

Monthly variation of VIMF over the Arabian Sea is quite significant during the summer monsoon season. The longitudinal average of monthly VIMF over the Arabian Sea (62.5°E – 75°E) is shown in Fig. 11. The moisture content in the HadGEM2 over the Arabian Sea is less as compared to that in the NCEP/NCAR reanalysis. The pattern of VIMF in SA domain simulation is close to that in NCEP/NCAR reanalysis. The location and time of maximum in the value of VIMF are well captured in both the simulations. In SA domain simulation the maximum magnitude of VIMF is about $500 \text{ kg m}^{-2} \text{ s}^{-1}$ with a larger spatial extent than that in the NCEP/NCAR reanalysis. While it is about $400 \text{ kg m}^{-2} \text{ s}^{-1}$ in the Indian domain simulation. Underestimation of VIMF in the Indian domain simulation (Fig. 11g) up to 15°N might be attributed to the location of the

southern boundary at 3.5°S latitude line. In SA domain simulation, VIMF has started building up in the month of April which more or less follows that in the NCEP/NCAR reanalysis. On the other hand, in the Indian domain simulation, the buildup started in May. In sum, the monthly cycle of VIMF has been well simulated in the SA domain compared to that in the Indian domain simulation.

7 Conclusions

The purpose of this study is to examine the sensitivity of Indian summer monsoon circulation and associated rainfall to the domain size of model integration in case of RegCM4.2 driven by HadGEM2. Here the state-of-the-art RegCM4.2 has been integrated over two selected domains of different sizes. In the SA domain simulation, the model is able to reproduce the major rainfall regions such as those of Northeast, Western Ghats, Gangetic plains and East Coast. On the other hand, in the smaller Indian

domain simulation, rainfall has been underestimated over most of the regions in India as compared to corresponding IMD observations. The climatological mean value of area weighted ISMR in the SA domain simulation is 6.84 mm/day and the corresponding value in the Indian domain simulation is almost half of that at 4.01 mm/day. The respective value based on IMD gridded rainfall dataset is 6.67 mm/day. These values of ISMR clearly indicate that the rainfall decreases considerably when the domain size of model integration reduces from SA domain to the smaller one over India alone. Further, comparison shows that the convective precipitation has contributed to a large extent to the decrease in rainfall when the domain size reduced from SA to the smaller Indian domain, while the corresponding change in the large scale precipitation is insignificant. Values of ETS for the occurrence of very light, light and moderate rainfall events are higher in the SA domain simulation than those in the Indian domain simulation.

The climatological value of Somalia Jet strength at 850 hPa in the SA domain simulation is found closer to that in the NCEP/NCAR reanalysis. In other words, the cross-equatorial flow and the Somali Jet are weaker in the Indian domain simulation as compared to their respective strengths in the SA domain simulation. Thus the weak southwesterly wind over the Arabian Sea and subsequent less moisture transport to the Indian land mass may explain the less value of ISMR in the Indian domain simulation. Similar to the lower level weak wind flow, the easterly wind at 200 hPa is weaker in the Indian domain simulation than that in the SA domain simulation. It is further found that the upper level easterly jet strength in the SA domain simulation is close to that in the NCEP/NCAR reanalysis.

In the SA domain simulation, the amount of VIMF during summer monsoon season over the Arabian Sea is estimated to be about 400–500 kg m⁻² s⁻¹ which is more than the corresponding NCEP/NCAR reanalysis value of about 300–400 kg m⁻² s⁻¹. Similar VIMF in the Indian domain simulation is less at about 200–300 kg m⁻² s⁻¹. Over major parts of the Arabian Sea and equatorial Indian Ocean, the VIMF has been underestimated by about 50–100 kg m⁻² s⁻¹ in the Indian domain simulation whereas it is close to the reanalysis values in the SA domain simulation. Since the southern boundary of the Indian domain over which the model is integrated is close to the equator in the southern hemisphere, there is less transport of VIMF from the equatorial and southern Indian Ocean. The deficit VIMF at the regional model boundary supplied from the global forcing of HadGEM2 to both the simulations has been improved in the SA domain simulation due to the inclusion of equatorial and southern Indian Ocean in the model integration. Comparison shows that VIMF starts building up little late in the Indian domain simulation as compared to the SA domain simulation.

In the SA domain simulation, VIMF built up follows that in the NCEP/NCAR reanalysis to a large extent. On the whole, the Indian domain seems to be too small in size to take care of the effect of the Himalayas in the summer monsoon circulation and in representing adequate moisture transport from the Indian seas.

Acknowledgments The authors are thankful to the organizations from which datasets are obtained for conducting this study. The initial and boundary conditions to integrate RegCM4.2 are obtained from the Abdus Salam International Centre for Theoretical Physics (ICTP) website <http://clima-dods.ictp.it/data/d8/cordex/HadGEM2/>. The gridded rainfall data have been obtained from the India Meteorological Department (IMD). The atmospheric fields are obtained from the NCEP/NCAR reanalyzed dataset. Thanks are due to Dr. Erika Coppola, Mr. Graziano Giuliani and Mr. Ivan Girotto for providing the computing facility at ICTP to conduct the additional simulations suggested by the reviewer. The authors are also thankful to the anonymous reviewers for their valuable suggestions to improve the quality of the paper. This study has been undertaken as part of a research project sponsored by the Department of Science and Technology, Government of India.

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