Comprehensive assessment of RegCM4 towards interannual variability of Indian Summer Monsoon using multi-year simulations

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Abstract

In this study, the Interannual variability (IAV) of Indian Summer Monsoon (ISM) is investigated using multi-year (1982–2016) seasonal scale simulations (May–September) of the regional climate model RegCM4 developed by International Center for Theoretical Physics, Italy. Model simulated fields such as surface temperature, wind and rainfall are validated initially to testify the climatological behaviour of ISM. Subsequently, different aspects of IAV associated with ISM are discussed primarily focusing on model simulated rainfall and are verified against high resolution rainfall analysis from India Meteorological Department (IMD). Empirical Orthogonal Function (EOF) analysis technique is also applied to identify the leading modes of IAV.

Analysis indicated that RegCM4 shows reasonable accuracy in simulating major large scale features, however, has cold bias over entire India and wet (dry) bias over northwest and peninsular (central) India. Easterly (westerly) bias is noticed in the model simulated low (upper) level wind that affects regional Hadley circulation. The model bias is found to be associated with the feedback cycle of land-atmosphere interaction. Surface evaporative cooling likely affects the instability in the atmospheric column, thereby limiting the convection and thus reducing rainfall. While categorizing, it is noticed that the deficit, normal and excess rainfall years in the model simulation agrees well with the IMD observation for about half of the study period, however, the normal years are relatively better reproduced by the model than the extreme years (deficit and excess). EOF analysis revealed that first two leading modes of IMD rainfall are linked with large scale variabilities viz., El-Nino southern oscillation and Indian ocean dipole respectively but RegCM4 could not well reproduce these relationships. Eventhough, the model showed spectral peaks for 2–7 years periodicity, these peaks are very close to the red noise spectrum due to their weak power which indicated the model's limitation in capturing large scale variability. Overall, this study suggests that the

RegCM4 could capture the climatological features of ISM fairly well, but needs further improvement in representing the IAV more accurately.
Keywords: Indian Summer Monsoon, RegCM, Interannual variability, EOF analysis, regional climate model.

1. Introduction:

Indian Summer Monsoon (ISM) is one of the most pronounced monsoon systems of the world, which mainly affects the Indian subcontinents. It is reported in earlier studies (e.g., Srinivas et al., 2013; Raju et al., 2015) that the country receives significant volume (nearly 80%) of its total annual rainfall during the monsoon season (June - September) which primarily used in agricultural sectors, hydrological planning, power generation etc. (Webster and Yang, 1992; Guhathakurta and Rajeevan, 2008). Importantly, the rainfall during ISM (ISMR) exhibits large variation at different temporal scales such as interdecadal (decade to decade: Malik et al., 2017), interannual (year to year: Halder at al., 2015; Umakanth and Kesarkar, 2019), intraseasonal/subseasonal (within the season; Chaudhari et al., 2013; Mishra et al., 2018) and diurnal (within a day: Ganai et al., 2016; Bhate and Kesarkar, 2019). Even a small fluctuation in ISMR may affect the country's economy to a considerable extent. For example, the year 2002 with only 19% deficit of ISMR was considered as the biggest drought year in the recent past and estimated loss was accounted in the order of billions of dollars (Gadgil et al., 2004). Therefore, reliable prediction of ISMR always remains a critical concern (Wang et al., 2015).

The interannual variability (IAV) of ISMR was extensively studied for many years from the observation/reanalysis datasets (Gadgil et al., 2004; Suhas et al., 2012; Chaudhari et al., 2015; Shukla and Huang, 2016) and multi-year Global Climate Model (GCM) simulations (Ajayamohan, 2007; Ratna et al., 2011; Mishra et al., 2012; Sinha et al., 2013; Shukla and Huang, 2016). However, the Regional Climate Model (RCM) has not been comprehensively used for the purpose although many studies were conducted with various RCMs over Indian region (Ratnam et al., 2009; Mukhopadhyay et al., 2010; Polanski et al., 2010; Dasari et al., 2011; Srinivas et al., 2013; Haldar et al., 2015; Umakanth and Kesarkar, 2019). In the recent past, RCM has become more sophisticated in regional-scale studies compared to GCMs because of their better ability in representing the regional-scale terrain, land surface heterogeneity (Nayak H. et al., 2018) and subgrid scale physical processes (Maity et al., 2017a). Among the various available RCMs, regional climate modelling system which is commonly abbreviated as RegCM of International Center for Theoretical Physics (ICTP, Italy) becomes remarkably popular due to its successful application towards numerous scientific studies those investigates climate change, climate sensitivity, climate diagnostic etc. (Tchotchou and Kamga, 2010; Octaviani and Manomaiphiboon, 2011; Gianotti et al., 2012; Huang et al., 2013; Haldar et al., 2015; Almazroui, 2016; Pieczka et al., 2017; Nayak et al., 2017; Maity et al., 2017a; Maity et al., 2017b; Nayak S. et al., 2018; Nayak et al., 2019; Umakanth and Kesarkar, 2019). Moreover, it is reported in Umakanth et al., 2015 that RegCM4 is one of the state-of-the-art RCM members in COordinated Regional climate Downscaling Experiment (CORDEX). Although many numerical experiments using RCMs were conducted, they are primarily discussed about ISM in continuous simulation mode. RCMs were not extensively used for seasonal scale simulation (SSS) of ISM for June-July-August-September (JJAS). Very few studies were there based on SSS of RCM of less 10–15 years or less (Samala et al., 2013; Maity et al. 2017; Maurya et al. 2020) but they are mostly focused on ISM features. However, studies on IAV of ISMR are not well documented particularly in multi-decadal scale. Moreover, It is also worth to mention that before applying an RCM for long term simulation over any geographical region, skill assessment of the corresponding RCM is required.

Keeping these aspects in background, present study attempts to assess the skill of RegCM specifically in examining the IAV of ISMR in a long term simulation. In order to achieve that, 35 years SSS of RegCM for the period 1982–2016 is carried out and various aspects of IAV, especially the temporal variation of seasonal rainfall, excess/deficit year identification and leading modes of IAV are carefully examined against the India Meteorological Department (IMD) rainfall analysis as well as forcing data. The manuscript is organized as follows. Model description, forcing and validation data and experimental design are described in the next three subsequent sections (Sections 2, 3, 4). Section 5 having multiple subsections represents results and analysis while the summary and concluding remarks are provided in Section 6.

2. Model description

RegCM version 4.4.5 (RegCM4 henceforth), used in the present study, is an improved version of its previous version [RegCM3 (Pal et al., 2007)]. It is a compressible, hydrostatic, terrain-following, finite difference, limited area model having similar dynamical core to that of RegCM3. The model offers a variety of parameterization schemes to represent different physical processes. Cumulus convection is represented using five major schemes such as Kuo (Anthes 1977), Grell (Grell 1993), MIT (Emanuel 1991), Tiedke (Tiedke 1989) and Kain-Fritsch (Kain and Fritsch 1993; Kain 2004). In addition to that land surface processes are described by means of Biosphere Atmosphere Transfer Scheme (Dickinson et al. 1993), Community Land Model version 3.5 (Oleson et al., 2008; Tawfik and Steiner 2011) and version 4.5 [CLM4.5 hereafter: Bonan et al., 2013; Oleson et al., 2013]. Radiative transfer calculations follow Kiehl et al., 1996 while planetary boundary layer scheme follows Holtslag et al., 1990 and Bretherton et al., 2004. Detailed description of all other available physics schemes viz., ocean fluxes, interactive lake models, atmospheric chemistry and aerosol etc. are available in earlier reported literature (Giorgi et al., 2012; Maity et al. 2017a, b; Maity, 2019).

3. Forcing and validation data

In our study, the model is forced with six hourly ERA Interim reanalysis (EIN75; Dee et al., 2011) at 0.75°x 0.75° resolution. Topography and land use data are obtained from United States Geological Survey and Global Land Cover Characterization (Loveland et al., 2000) global data at 10 minutes resolution. The model uses optimum interpolation weekly mean sea surface temperature (SST henceforth; Reynolds et al., 2002) at 1°x1° resolution from National Oceanic and Atmospheric Administration (NOAA). Additional datasets including land cover, soil texture, soil colour, leaf area index, plant functional type, emission factors, snow data etc. required for CLM4.5 is obtained from http://clima-dods.ictp.it/Data/RegCM_Data/CLM45/.

For the evaluation of the model performance, gridded daily temperature at 1°x1° spatial resolution (Srivastava et al., 2009) and daily rainfall data at 0.25°x0.25° spatial resolution (Pai et al., 2014, 2015, 2016) from IMD are considered as reference which is available for the spatial domain of 6.5°N to 38.5°N and 66.5°E to 100°E covering the mainland region of India. The IMD daily rainfall analysis is generated using large number rain gauge network well distributed over Indian landmass and found to be finest data source so far for the analysis and therefore used in various observational as well as model validation/evaluation studies (Pai et al., 2015; Vinnarasi and Dhanya, 2016; Moron et al., 2017; Tiwari et al., 2017). In addition to EIN75, very high resolution (31km x 31km) reanalysis ERA5 (Hersbach et al. 2020) is also used while required. Before model comparison, each dataset is bi-linearly interpolated to the model grid (~30 km resolution) to get rid of mathematical errors.

4. Experimental Design

SSS (00UTC 1 May–18UTC 30 September) of ISM is conducted for a period 35 years (1982–2016) using RegCM4 encompassing the geographical area covering 30°E–120°E, 15°S–45°N (Fig. 1) at 30 km horizontal resolution. Different components of the model set up are demonstrated in Maity (2019) and mentioned in Table 1. The model uses mixed convection scheme (Grell over Ocean and MIT over land) as convection scheme and CLM4.5 model to parameterize land surface processes. In each of the simulations, the month of May is considered as spin up (Maity et al., 2017a; Maity et al., 2017b) and the results from June, July, August and September are analyzed. The Model uses buffer zone of 12 grid points inside the lateral boundary (Seth and Giorgi, 1998; Wang et al., 2003; Giorgi et al., 2011).

Model's fidelity associated with reproducibility of IAV mostly depends on the reasonable representation of mean ISM features as good as possible. Earlier studies (DelSole and Shukla, 2010; Chaudhari et al., 2013) reported that models which replicate the mean climatology closely to the observed data, are relatively more skilful in producing IAV. Therefore, JJAS mean climatology of surface temperature (T2m), low level wind (850 hPa) and upper level wind (200 hPa) and rainfall are computed and validated with observed/reanalysis datasets. Various statistics such as spatial correlation (SC), root mean square error (RMSE), temporal correlation (TC) etc. are also computed as and when required for the validation.

To investigate IAV of ISM, JJAS average rainfall anomaly from both the model simulation and IMD is computed based on area averaged rainfall over all India and five homogeneous regions viz. North west India, West central India, Central and north east India, South peninsular India and North east India [AI, NWI, WCI, CNEI, SPI, NEI] as described in Parthasarathy et al., 1994. In continuation with these, each of the 35 years (1982–2016) are categorized as excess, normal and deficit monsoon year and compared with that of IMD data using standardized precipitation index [(Rajeevan et al., 2010; Maharana and Dimri, 2014].

Finally, Empirical Orthogonal Function (EOF) analysis technique (Pai et al., 2011; Brankovic et al., 2012; Shukla, 2014; Roundy, 2015; Shrivastava et al., 2017) is employed on seasonal rainfall for further assessment of the model skill in analysing the leading modes of IAV. EOF analysis is a mathematical technique (Eigen analysis) which distributes the total variability of a meteorological datasets in terms of few spatial modes known as EOF and their temporal evolution referred as principal component (PC)].

We focused only on those EOF patterns which are well separated by North's rule of thumb (North et al., 1982) and dominant, rather considering all of the EOFs. To avoid confusions, it is noteworthy to mention here that physical interpretation of the EOFs are attempted disregarding the sign of it. For the physical interpretation of the leading modes of IAV, some of the well-known large scale variability over the tropics viz., El-Nino Southern Oscillation (ENSO) and Indian ocean dipole (IOD) are considered. For that purpose, NINO 3.4 index [SST anomaly over NINO 3.4 region (5°N–5°S, 120°W–170°W)] and dipole mode index [DMI; SST gradient between (50°E–70°E, 10°S–10°N) and (90°E–110°E, 10°S–0°N)] are used to compute TC with different PCs while analyzing. Both the indices are calculated based on NOAA optimum interpolation SST version 2 (Banzon et al., 2016).

5. Results and Discussion

Firstly, 35 years JJAS mean climatology (1982–2016) of T2m, wind and rainfall are analyzed and verified against observed/reanalysis data. Further analyses are carried towards identification of excess/deficit years, IAV of ISMR using EOF analysis etc.

5.1 Seasonal/monthly Climatology (1982–2016)

5.1.1 Surface Temperature

As reported in earlier ISM studies (Maity et al. 2017a, b; Maity, 2019), T2m plays vital role in the establishment of ISM by setting up continental-maritime temperature gradient which finally determines the strength of ISM. Seasonal mean T2m is usually characterized by high temperature zone over NWI (Rajasthan, Pakistan and neighbouring region) referred as heat low (22.5°N–32.5°N; 65°E–75°E). Relatively low temperature region is observed over north India (Punjab, Haryana, Himachal Pradesh, Uttarakhand and Uttar Pradesh) and is further extended up to West Bengal as well as east coast of India (Odisha and some part of Andhra Pradesh). Seasonal mean climatology of T2m (°C) from IMD and RegCM4 are depicted in the Fig. 2 alongwith the model bias (RegCM4–IMD) and TC. The black dots in bias and TC plot (Fig. 2c, 2d) denote statistically significant point at 95% significance level. It is observed that the simulated pattern of T2m climatology is fairly close to IMD. Simulated heat low is well marked over NWI but appears to be slightly warmer. North India temperate zone (28–32°C) along Indo Gangetic plain is quite sensibly simulated but compared to IMD, this region is not further widened along the east coast in the model simulation. It is also noticed that simulated T2m is temporally correlated at 95% significance level over rain fed regions (Fig. 2d) of ISM which infers that IAV is well produced over those regions.

The model shows statistically significant cold bias (~2°C) over most parts of India except over heat low region at NWI where warm bias is noticed. Interestingly, cold bias is largest over Jammu and Kashmir and peak of NEI which is predominantly high topography region. Therefore, the model tendency of generating cold bias over high mountainous region viz., Hindukush and Himalayan range is likely to be attributed due to the smoothed topography as observed in earlier reported studies (Haldar et al., 2015; Fuentes-Franco et al., 2014). It is also mentioned in Coppola et al., 2014 that this strong bias might be related to the treatment of cloud radiative processes in RegCM4. Hence, further investigation is necessary for an accurate explanation. It is noteworthy to mention here that EIN75 (boundary forcing data considered here) has similar amount of significant and systematic cold bias over those mentioned regions (see Fig. 4). Spatial statistics viz., mean, correlation and RMSE of T2m climatology over India and its five homogeneous regions are shown in Table 2 which specifies that T2m is well distributed over NWI, WCI, CNEI and India with higher correlation and lower RMSE. However, higher RMSE is noticed over SPI and NEI indicating discrepancies over those areas.

For further quantitative evaluation, Histograms during 1982–2016 are provided in Fig. 3 for India and its homogeneous regions. The bars filled with pattern (plane) demonstrate the frequency of the respective classes for RegCM4 (IMD). It is observed that the frequency of simulated T2m from those respective classes closely match with that of IMD mostly everywhere except SPI and all India. Over those regions (SPI and all India), simulated T2m lies in the range of 24–26°C, while that lies in the range of 26–28°C and 28–30°C in IMD. It seems that RegCM4 exhibits consistent cold bias over SPI and all India which may be corrected using of a suitable bias correction method. Therefore, evaluation of T2m reveals an overall consistency with IMD in terms of distribution and magnitude with some evident exceptions and bias.

5.1.2 Circulation

With the advent of ISM, atmospheric circulation also undergoes with several major changes at lower as well as upper tropospheric level. A conceptual vertical cell referred as regional Hadley circulation usually appears to form mainly across India in tilted north-south direction with its ascending and descending branch over Tibetan plateau and Mascarene high (high pressure zone at about 60°E, 35°S) respectively. As a result, wind appears mainly as westerly/southwesterly (easterly/northeasterly) at low level (upper level) during ISM. Low level jet stream is the main artery through which moisture from the adjoining oceanic regions [Arabian Sea (AS), Indian Ocean (IO) and Bay of Bengal (BOB)] fed into Indian landmass and the upper level wind maintain the return flow for the circulation lively and consequently ISM. Therefore, regional Hadley cell and its associated wind pattern is the main driver of the

ISM circulation and hence its impact is demonstrated in various earlier studies (Freitas et al., 2017) so far as long term simulation of ISM is concerned.

Seasonal mean climatology of wind at lower (850 hPa) and upper (200 hPa) tropospheric level are presented in Fig. 5 and Fig. 6 and validated against EIN75 reanalysis along with model bias. Simulated low level wind is very close to the EIN75 data [Fig. 5a,b]. Several major low level circulation features such as Cross equatorial flow (CEF), Somaly Jet (SJ), south westerly flow over AS, westerly wind over Indian landmass and BOB, monsoon trough etc. are well portrayed by the model. SJ appears to be slightly stronger (~2 ms^{-1} and even more) in the model which is likely to be attributed due to stronger CEF over 10°S–0° belt (Fig. 5a,b). Simulated jet core is well positioned at about 10°N, 52°E with wind speed in the range of 18–20 ms^{-1} in the model which is similar to EIN75 data. Southwesterly/westerly flow over central, northern and eastern AS are pretty close to the reanalysis although seems to be more zonal and hence anticyclonic in direction. Flow pattern over BOB is slightly weaker (stronger) at the head (central) bay. It is important to note that monsoon trough is prominently found as a organised cyclonic flow with wind speed less than 2 ms^{-1} and aligned at northwest-southeast direction but inclined more southwards and positioned far from GWB in the model simulation (Fig. 5b). In general, the model has tendency to strengthen easterly wind (Fig. 5c). As a result, easterly wind at the southern hemisphere (10°S–0°) gets stronger which makes the CEF and SJ further strong (noticed earlier) and westerly biased. On the contrary, this easterly flow intrudes the southwesterlies to advance and thereby force to weaken the low level jet over north AS, entire Indian landmass and BOB except over extreme southern part of peninsula. This might affect formation of regional Hadley circulation and therefore, likely to have major implications in the rainfall simulation. While comparing TC of wind magnitude, simulated wind shows statistical significance at 95% significance level over major windy regions over the ocean viz., coast of Somalia, southern IO, central BOB etc. However, correlation is not significant over the entire Indian landmass.

In a similar way, analysis is further extended by investigating different upper level circulation features associated with ISM viz., subtropical westerly jet (STWJ), tropical easterly jet (TEJ), Tibetan anticyclone (TA) etc. As noticed from Fig. 6, these features are simulated reasonably well however, variation is noticed in wind magnitude. STWJ is located to the north of the Himalaya between 35–40°N with jet core in the range of 28–32 ms^{-1} in both model simulation and EIN75 data (Fig. 6a,b). TA and its associated ridges are nicely captured (25–30°N) by the model but the core moved more westwards as compared to EIN75 data. TEJ in EIN75 data is located as a strong divergent flow (16–24 ms^{-1}) over tropical IO starting from Thailand and Indonesia and is extended up to the east coast of South Africa covering the southern part of Indian landmass. Simulated TEJ is of similar pattern but with noticeable underestimation (~4 ms^{-1} and even more). It exists in a latitudinal belt of 0 - 20°N with maximum wind speed of 20–24 ms^{-1} in EIN75 while that is 16–20 ms^{-1} in the model simulation. Therefore, simulated wind is weaker and shows westerly bias (Fig. 6c) over the entire region. TC (Fig. 6d) is significant over most of the region except some of the pockets such as the peninsula. Furthermore, TEJ core is moved far westwards from its normal position at the southern peak of peninsula in the model simulation. On average sense, eventhough the major wind patterns of ISM circulation at both lower and upper level are simulated quite satisfactorily, it fails to replicate the wind magnitude accurately and therefore shows prominent underestimation.

5.1.3 Precipitation

Comparison of the seasonal rainfall climatology from the model simulation and IMD analysis data is depicted in the Fig. 7 alongwith the bias. From the earlier studies (Sinha et al., 2013; Maity et al, 2017b; Nayak S et al., 2018), it is reported that ISMR shows large spatial inhomogeneity and is generally clustered over few selected convective zones anchored along coastal (viz., Western Ghat (WG), Arakan Yoma and Bilauktong ranges along Myanmar coast) as well as non-coastal mountains at NEI (viz., Garo Khasi range, Purvanchal range and Himalayan range) which is usually recognized as zone of rainfall maxima (Xie et al., 2006; Chaudhari et al., 2013). Least rainfall is generally noticed over NWI and east peninsula (rain shadow region). All these features are replicated fairly well in RegCM4 simulation (Fig. 7a, b). In IMD analysis, rainfall over the WG exceeds 24 mmday^{-1} while it is in the range of 16–24 mmday^{-1} over NEI. Corresponding rainfall in the model varies in the range of 8–12 mmday^{-1} and 12–16 mmday^{-1} which indicates clear underestimation (dry bias~2–6 mmday^{-1}) over those regions (Fig. 7c). Relatively smaller dry is noticed over the entire Gangetic West Bengal and central India (covering Gujarat, Madhya Pradesh, Chhattisgarh, some parts of Orissa). However, ISMR is overestimated mainly over NWI, peninsular India (except WG) and thereby shows wet bias over there. In IMD, climatological rainfall over west and east coast of the peninsula India varies in the range of 22–24 mmday^{-1} and 2–4 mmday^{-1} while that is 14–18 mmday^{-1} and 2–4 mmday^{-1} in the model simulation. Magnitude of temporal correlation (Fig. 7d) is insignificant over most of the Indian landmass which indicates that year to year variation is not well represented by RegCM4.

Details of spatial statistics viz., average, correlation (95% significance level) and RMSE at both monthly and seasonal scale are presented in Table 3. Instead of higher SC at all India level, the model fails to represent the month to month variation of ISMR as in IMD and hence RegCM4 seems to simulate higher (lower) rainfall in the month of June and September (July and August). It indicates that although the model is able to replicate all India patterns of climatological ISMR reasonably, it is not successful in simulating the magnitudes of rainfall accurately. Fig. 8 shows the histograms of seasonal rainfall during 1982–2016 over India and its five homogeneous regions. Eventhough, model behaves similarly with IMD at all India level, disparities are noticed at smaller subdivisions. Over the time, rainfall is significantly underestimated over NEI (Fig. 8f) as the frequency from RegCM4 belongs to lower rain classes while compared with IMD. In addition, it is also observed that RegCM4 generally simulates moderate rainfall (4–8 $mmday^{-1}$) irrespective of year as well as regions which infers model's inability in representing IAV variability accurately. IAV will be broadly discussed in later subsections.

The causes of rainfall and temperature biases are further investigated by examining the role of land surface processes on ISMR. It is observed that net radiation at the surface is sensibly higher (Fig. 9) in the model simulation which is likely due to less cloud cover (Fig. 10a-c). As a result, the land surface in the model contains excess volume of radiant energy which it pumps to the atmosphere in terms of sensible and latent heat flux. In the model simulation, higher soil moisture (Fig. 11d-f) together with excess net radiation causes more latent heat flux (Fig. 11j-l) leading to strengthen evaporative cooling and thereby lowering the sensible heat flux (Fig. 11g-i) and thus cold bias in T2m (Fig. 2a-c) and soil temperature (Fig. 11a-c). Surface cooling causes underestimation of equivalent potential temperature (θ_e) markedly at 1000hPa–850 hPa (Fig. 10g-i) over the entire latitudinal belt which infers underrepresentation of vertical instability at the lower troposphere. Hence, despite of having adequate volume of precipitable water available in the model atmospheric column (Fig. 10d-f), atmospheric convection and thereby cloud formation gets hindered by atmospheric instability. This land-atmosphere interaction works as a feedback mechanism demonstrated in Fig. 12 by which we can partially explain the possibility of having cold and dry bias of t2m and rainfall simulation in the model. It is also reported in recent studies by Mohanty et al. 2019 that default auto-conversion rate in RegCM4 is slightly lower which might restrain the rainfall production. All these may lead to suppress/strengthen the convective activity and consequently underestimation in rainfall.

5.2 Interannual variability

This section deals with the assessment of the model skill in simulating the IAV of ISMR which plays a very crucial role for the long prediction of ISM.

5.2.1 Temporal variation of seasonal rainfall

Temporal variation of seasonal ISMR over AI as well as its five homogeneous regions namely NWI, WCI, CNEI, SPI and NEI both is depicted in Fig. 13 both from RegCM4 and IMD. It is reported that RegCM4 reproduces in phase rainfall signature with IMD at 14 (44%), 12 (38%), 18 (56%), 17 (53%), 19 (59%) and 11 (34%) no. of years over NWI, WCI, CNEI, SPI, NEI and AI respectively which indicates relatively better skill over NEI, CNEI and SPI. TC is found to be negative (positive) at NWI, WCI, SPI, AI (CNEI, NEI). Magnitude of R^2 (coefficient of determination) is undeniably less irrespective of the regions which indicate that the model couldn't accurately explain the observed variance (IMD). Spatial distribution of the interannual standard deviation (ISD) of seasonal rainfall (Fig. 14) is also shows noticeable underestimation over most of the Indian landmass except few pockets viz. WG, Odisha coast and peak of NEI which justifies the inefficiency of the model in capturing IAV over those regions.

5.2.2 Excess/Deficit year identification

Excess and Deficit ISM years are identified from the model simulation and are compared with that of the IMD analysis based on the methodology discussed earlier. Primarily, excess/deficit is defined considering AI rainfall. At the same time, the same criterion is applied over other homogeneous regions to examine temporal coherence with respect to AI level. Details are described in Table 4. Based on rainfall over AI level, 5 excess (1987, 1988, 1991, 2002, 2014), 4 deficit (1994, 1996, 2008 and 2012) and 26 normal years (1982–1986, 1989, 1990, 1992, 1993, 1995, 1997, 1998–2000, 2001, 2003–2007, 2009–2011, 2013, 2015,

2016) are found from RegCM4 while 7 excess (1983, 1988, 1990, 1994, 2005, 2011 and 2013), 8 deficit (1982, 1986, 1987, 2002, 2004, 2009, 2014 and 2015) and 20 normal (1984, 1985, 1989, 1991–1993, 1995–2001, 2003, 2006–2008, 2010, 2012 and 2016) years are identified in IMD data. Interestingly, the model is able to pick most of the normal years rather than the extreme years. In particular, some of the well documented extreme rainfall years such as 1982, 1987, 2002, 2009 etc. are not represented satisfactorily by the model and shows completely opposite signature as that with IMD data. There is no clear inference found between rainfall at AI and other regional level both in IMD and RegCM4. Of course, the model skill varies from region to region but as mentioned earlier, RegCM4 is more efficient in simulating the normal rainfall signature compare to extremes even at regional level. In the composite figure of deficit, normal and excess years (Fig. 15), it is observed from IMD rainfall that CNEI plays a vital role in deficit, normal and excess rainfall year. No such discernible variation was found in the simulated rainfall. Moreover, the rainfall bias (Fig. 7c) still persist in each of the deficit, normal and excess composites which indicates that the model has consistent rainfall bias which could be corrected using suitable bias correction scheme.

5.2.3 EOF analysis of seasonal rainfall

In order to investigate the leading modes of IAV and its simulation by the model, EOF analysis on JJAS mean rainfall is carried out both on IMD and RegCM4 datasets. Based on North's rule, the first three EOFs are reasonably separated and are therefore presented in Fig. 16 (IMD) and Fig. 17 (RegCM4) alongwith their corresponding explained variance (EV). The correlation of PCs with AI rainfall and different climate indices such as DMI and Nino 3.4 index are demonstrated in Table 5. In addition, spectral analysis is also carried out on PCs and the results are specified in Fig. 18. The cumulative EV from IMD and RegCM4 are 32.8% and 39.3% respectively which indicates slightly higher spatial coherence in the model.

From IMD rainfall data, it is noticed that first, second and third EOF (Fig. 16) account for 15.6%, 9.6% and 7.6% of the total spatiotemporal variability respectively. EOF1 exhibits a zonal dipolar structure having negative (positive) loadings over northeast (rest part of India) which suggests an out of phase relationship between them. Interestingly, PC1 accurately identified different normal, deficit and excess monsoon years discussed earlier indicating thereby its association with IAV at all India level which is clear from the strong correlation 0.89 (95% significance, see Table 5). Furthermore, it is also observed that PC1 is negatively correlated with NINO3.4 index (Table 5) which advocates its possible resemblance with ENSO. EOF2 shows a meridional dipolar distribution having negative loading over north India (including foothills) and east coast of peninsula while positive loading over monsoon trough region which indicates its plausible linkage with active-break events connected to intraseasonal variability of ISMR as reported in Chaudhury et al., 2015. In addition, correlation of PC2 with DMI index is significant (Table 5) which shows PC2 might be linked with IOD. It's interesting to note that PC2 is also correlated with the NINO3.4 index but at a lower significance level which suggests that variability corresponding to EOF2 is partly contributed by ENSO events.

EOFs from RegCM4 simulation (Fig. 17) explains 15.7%, 14.3%, 9.3% variance by the first, second and third EOF respectively. It is noticed that EOF1 (EOF2) from the model specifies north-south (east-west) dipolar distribution which exhibits similar pattern with EOF2 (EOF1) from IMD. It establishes that either the model couldn't capture the phenomena governed by EOF1 or the amplitude of the phenomena is weak in the model simulation. PC1 shows positive and significant correlation (slightly smaller than IMD) with AI (Table 5) which indicates its association with IAV. Contrarily, PC1 also shows significant and positive correlation with the NINO3.4 index which contradicts the IAV-ENSO mechanism. On the other hand, PC2 and DMI index are significantly correlated which directs towards its relation with IOD as observed in IMD. Therefore it can be concluded that although the model is able to reproduce the IOD-IAV relationship reasonably but it fails to do so for the ENSO-IAV teleconnection.

Moreover, spectral analysis of different PCs of IMD data reflects very clear peaks during 2–7 years period but with varying spectral power which indicates their degree of association with the large-scale features. PC1 shows three peaks (above the red noise spectra) with period 16.66, 5.88 and 2.5 years with the strongest peak at 5.88 years. Based on earlier discussion on EOF1, it may be concluded that PC1 is linked with ENSO signal. In a similar way PC2 has periodicity of 4.35, 2.5 and 2.32 years where the strongest peak is noticed at 2.5 years. Behera et al, 2008 reported that IOD is of quasi-biennial periodicity. Therefore IOD might be connected with PC2. PC3 shows the strongest peak at 4.35 years which is in the range of ENSO periodicity but with very weak power. It is also to be mentioned here that EOF3 from IMD (Fig. 16) doesn't reveal any specific climate pattern and therefore it might be considered as pure noise and consequently excluded from further analysis. In the case of PCs from RegCM4, although the model is able represent the spectral peak during 2–7 years but due to weak spectral power, they are very close to red noise spectrum indicating weakness of the model in capturing large scale variability accurately. PC1 shows signal with periodicity of 2–3 years which is very short for ENSO and PC2 shows a relatively strong peak at 2.17 years. But since the power of each signal is unmistakably underestimated, therefore it will be an unwise attempt to comment on the model skill about large scale variability on an average sense. As observed in IMD, PC3 doesn't reveal any specific periodicity and therefore may be regarded as noise Thus, it might be concluded that the model skill is indeed limited in predicting various features of IAV such as IOD and ENSO and hence further investigation and improvement is needed.

6. Summary and concluding remarks

This study assessed the IAV of Indian Summer Monsoon and associated spatiotemporal features from 35 years (1982–2016) seasonal (May–September) scale simulations using RegCM4. At the first step, the seasonal mean climatology of T2m, wind (at 850 hPa and 200 hPa) and rainfall are analysed form the model simulations, IMD analyses and EIN75/ERA5 for the 35 years and subsequently different aspects and leading modes of IAV of ISMR are discussed for this period. The results inferred that RegCM4 has a reasonable accuracy in depicting several major large scale features associated with ISM including heat low, SJ, monsoon trough, STWJ, TA, TEJ while it has strong biases in reproducing the temporal variability particularly the rainfall. Simulated T2m shows cold bias (~2°C) over entire India except at heat low region. Highest cold bias is noticed over high mountainous regions of Jammu and Kashmir and NEI, perhaps due to the smoothed topography in the model. Wind in the model simulations is found relatively weaker and easterly (westerly) biased over entire Indian landmass at lower (upper) tropospheric level. Model exhibits strong dry bias over large region of central India and wet bias over eastern peninsula and NWI. We found an existence of a feedback mechanism in the coupled land atmosphere system through which we may explain the cold and dry bias in T2m and rainfall simulation respectively (Fig. 12). It is noticed that the model reproduced less cloud cover which in turn resulted higher surface net radiation (Fig. 9, 10). Now, higher soil moisture in the model together with excess net radiation causes more latent heat flux and thus strengthens the evaporative cooling. This led to lower the sensible heat and caused cold bias in T2m and soil temperature. As a consequence, vertical instability at the lower troposphere is underrepresented which obstructs convection and consequently reduces rainfall in the model simulation despite of having adequate volume of precipitable water available in the model atmospheric column.

It is further observed that deficit, normal and excess rainfall years in the model simulation agrees well with the IMD analysis for about half of the study period. The model shows better skill in predicting normal monsoon years compared to extreme years. The first three EOFs based on North's rule of separation, indicated percentage variance explained by first, second and third EOF are15.6%, 9.6% and 7.6% in IMD while that of RegCM4 are 15.7%, 14.3%, 9.3% respectively. The cumulative EVs from IMD and RegCM4 are noticed as 32.8% and 39.3% respectively which indicates slightly higher spatial coherence in the model. From IMD analysis, it is observed that EOF1is directly (inversely) linked with IAV (ENSO) while EOF2 is associated with DMI which corroborates with the earlier studies (Mishra et al., 2012; Chaudhari et al., 2013, 2015). EOF1 (EOF2) from the model simulations also exhibits similar spatial structure associated with EOF2 (EOF1) from IMD which indicates model's limitation to classify the EOFs. Overall, the model fails to reproduce ENSO-IAV teleconnection eventhough it represented IOD-IAV relationship reasonably well.

Furthermore, spectral analysis of different PCs in IMD data reflects very clear peaks during 2–7 years period. Although, the model shows spectral peak during 2–7 years but due to weak spectral power, they are very close to red noise spectrum indicating weakness of the model in capturing large scale variability accurately. This finding is consistent with several studies reported earlier (Ratna et al., 2011; Srinivas et al., 2013; Cash et al., 2015). Third EOF from both IMD and RegCM4 are not discussed as they don't reveal any specific climate pattern and therefore considered as pure noise. To be precise, our overall results suggest that RegCM4 captured the climatological features reasonably well, while it has some consistent bias towards the IAV of ISMR. Thus we could like to apply a suitable bias correction method in a future research to further improve these results.

In the present study, the major motivation was to explore the IAV of ISMR using regional model as it has pronounced impacts on socioeconomic sectors specifically on agriculture which contributes nearly 14% of the gross domestic product in India. It is also noteworthy that RCM plays major role in improving weather/climate studies at regional levels due to its sophisticated treatment of subgrid scale physical processes. Thus we believe, this study will assist further model improvement efforts and we propose to conduct research on similar objective in the near future.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table captions

Table 1: Overview of the model considered for this study.

Table 2: Spatial statistics of seasonal climatology of T2m (°C) over Indian landmass and five homogeneous regions. mod: RegCM4; obs: IMD. ! Not significant ; * Significant.

Table 3: Spatial statistics of monthly and seasonal climatology of rainfall (mmday^{-1}) over masked India (Indian landmass only). mod: RegCM4; obs: IMD. ! Not significant; * Significant.

Table 4: Excess/Normal/Deficit years by RegCM4 and IMD based on rainfall during 1982–2016. mod: RegCM4, obs: IMD. E: Excess, N: Normal, D: Deficit.

Table 5: Correlation of PC1 and PC2 with AI (All India rainfall), DMI (Dipole Mode Index) and NINO3.4 (ENSO Index over Nino 3.4 region). *, ^ Significant at 95%, 90% significance level. † Not significant at 95% significance level.

Figure Captions

Fig. 1: Map of the simulation domain used in the study. The domain encompasses 30°E–120°E, 15°S–45°N over Lambert Conformal map projection. Different colour shades specifies the topographical height above sea level (in meters).

Fig. 2: Seasonal climatology (1982–2016) of T2m (°C). a: IMD, b: RegCM4, c: bias, d: temporal correlation. Black dots denote 95% significance level.

Fig. 3: Histogram of seasonal T2m (°C) during 1982-2016 over AI and five homogeneous region.

Fig. 4: Temporal variation of T2m (°C) over Jammu and Kashmir (33°N–37°N, 73°E–80°E) during 35 years (1982–2016).

Fig. 5: Same as Fig. 2 but for low level wind [850 hPa (ms^{-1})]. EIN75 is considered as reference.

Fig. 6: Same as Fig. 2 but for upper level wind [200 hPa (ms^{-1})]. EIN75 is considered as reference.

Fig. 7: Same as Fig. 2 but for rainfall ($mmday^{-1}$). IMD rainfall is regarded as ground truth.

Fig. 8: Same as Fig. 3 but for rainfall ($mmday^{-1}$).

Fig. 9: JJAS mean climatology of net shortwave radiation (Wm^{-2}) from a) ERA5, b) RegCM4 and c) bias. Similarly, for net longwave radiation (Wm^{-2}; d, e, f) and net radiation (Wm^{-2}; g, h, i).

Fig. 10: Same as Fig. 9 but for cloud cover (a, b, c) bias, precipitable water (kgm^{-2}; d, e, f) and equivalent potential temperature (°C; g, h, i).

Fig. 11: Same as Fig. 9 but for soil temperature (°C; a, b, c), soil moisture (m^3m^{-3}; d, e, f), sensible heat flux (Wm^{-2}; g, h, i) and latent heat flux (Wm^{-2}; j, k, l).

Fig. 12: Pictorial representation of feedback mechanism between land and atmosphere.

Fig. 13: Interannual variation of seasonal rainfall over all India and five homogeneous regions.

Fig. 14: Interannual standard deviation of seasonal rainfall ($mmday^{-1}$) during 35 years (1982–2016).

Fig. 15: Composite of seasonal rainfall ($mmday^{-1}$) during Deficit, Normal and Excess years.

Fig. 16: First three EOFs and their corresponding PCs of seasonal rainfall from IMD.

Fig. 17: First three EOFs and their corresponding PCs of seasonal rainfall from RegCM4.

Fig. 18: Spectral analysis of different PCs. IMD (a, b, c) and RegCM4 (d, e, f). The highlighted no. indicates the frequency of the corresponding peak.