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Assessment of Lead-Lag and Spatial Changes in simulating different epochs of the Indian summer monsoon using RegCM4

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ABSTRACT

The present study examines the efficacy of the regional climate model RegCM4 in depicting the onset, active, and break phases of the Indian summer monsoon (ISM). The model is driven by National Centers for Environmental Prediction (NCEP)/NCAR Reanalysis 1 project (NNRP1) data of 28 years (1981–2008) for each monsoon separately. High-resolution gridded rainfall analysis dataset of India Meteorological Department (IMD) and the monsoon epochal report from National Climate Center (NCC) are used for verification. Besides assessment of model performance using qualitative methods, several standard statistical techniques are used to understand the capability of the model in representing monsoonal epochs.

A relationship between the SST changes over the Niño-3.4 region and the ISM over all India and the monsoon core region (MCR) is established where a strong dependency in the rainfall variation over the MCR with the SST variation is found than all India rainfall. The performance of the model is satisfactory in portraying the spatial and temporal intraseasonal variability (ISV) of monsoon over MCR and all India regions. It is found that the model performance is higher in simulating the onset and break phases (dry days) than the active phases. The limited skill of the RegCM4 model in representing the active phase is due to the model simulated low temperature and weak pressure gradient over the MCR which prevents the convection and given rise to small and weak active phases over the region. The mechanism from the pre-onset to onset of monsoon, and the monsoon advance between the onset and the monsoon ISV is also well captured by the RegCM4. Weak tropospheric temperature gradient over the Indian subcontinent during the pre-onset period causes delay onset over the Indian subcontinent and the subsequent high tropospheric temperature gradient during the mid of June causes a faster progression of the active/break phases of monsoon. At the same time, simulation of the monsoon phase by the model is heavily regulated by the changes of SST over the Niño-3.4 region. The signal of ENSO variability, forces to the model through the ICBC, modulates the capability of the regional model in identifying the interannual and ISV of monsoon over the MCR region.

1. Introduction

The southwest (SW) monsoon is one of the most dominant and complex circulation systems in the general circulation of the atmosphere during the months of June to September (JJAS). The India and its neighboring countries receive the about 80% of annual rainfall (Turner and Annamalai, 2012) that heavily regulates the Indian agriculture (Bollasina, 2014). It is reported that 49% of total employments are directly or indirectly dependent on the Indian Summer Monsoon (ISM) Rainfall (ISMR) and ISMR contributes16% of gross domestic product (GDP) (Bollasina, 2014; Economy Survey, 2017–18, Govt. of India). Therefore, development of a suitable modeling framework for advanced intimation of summer monsoon, particularly different epochs such as active and break phases is highly crucial and is the area of research interest by several scientists for beneficial of the farming community.

The ISMR has shown large spatial and temporal variabilities (Sahai et al., 2003; Naidu et al., 2015). The Himalayan foothills in the north and the steep orography in the western coast of the country influence the

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spatial rainfall distribution over India (Sinha et al., 2014). Several scientists have studied that the characteristics of inter-annual and intra-seasonal variability (ISV) of ISMR (Goswami and Mohan, 2001; Bhatla et al., 2018) which is not uniform at any point, and altogether indicate that the ISMR doesn't show any persistent behavior over space. ISMR exhibits a wide range of rainfall variability on daily, intra-seasonal, inter-annual, decadal, and centennial time scales (Rajeevan et al., 2010). As a result, the accurate prediction/simulation of spatial and temporal distribution of ISM rainfall is rather challenging. A more accurate forecast system to simulate the spatio-temporal rainfall pattern is not only crucial for the extended range prediction of ISV but also for the long-range prediction of seasonal mean monsoon rainfall. The occurrence of rainfall or drying conditions for several days in the peak monsoon months of July–August over the monsoon core region (MCR; 18^0N—28^0N and 65°E–88°E) is called active or break in monsoon, respectively (Raghavan, 1973; Krishnamurti and Bhalme, 1976). However, there are several other criteria to define the active and break phases identified over the Indian region (Krishnan et al., 2000; Annamalai and Slingo, 2001; Rajeevan et al., 2006; Taraphdar et al., 2010). Over MCR, the active phases are more frequent (almost 80%) than the break phases (40%) when short span events are considered, while occurrence of active phases (only 9%) is lesser than the occurrence of break phases (32%) for the events having a week or longer time span (Rajeevan et al., 2010). The long and intense active/break phases have a major impact on the seasonal rainfall (Gadgil and Joseph, 2003), and a small fluctuation in the period of wet (active) and dry (break) phases may cause extreme wet and dry climatic conditions over the region (Rakhecha, 2002; Schiermeier, 2006) which have an adverse impact on livelihood (Annamalai and Slingo, 2001). The occurrence of severe monsoon droughts or a prolonged dry phase adversely affects the agrarian society, causes the livestock mortality and damages natural ecosystems (Sivakumar and Stefanski, 2010). Therefore, study of the monsoon epochs (onset, active, and break phases) in modeling framework is very crucial. An early warning system on epochal behavior of ISM will be helpful to different sectors, particularly agriculture sector.

Several modeling studies have investigated the intra-seasonal variability (ISV) associated with the ISMR using Global Climate Model (GCM) (Fu et al., 2002; ParthSarthi et al. 2015, 2016; Prasanna et al., 2020) and Coupled GCM (Goswami et al., 2012; Ramu et al., 2016) but the number of simulations of the spatial features during ISMR by a GCM is still limited (IPCC, 2007). In the recent decades, the GCM is able to capture the large-scale climate features but representing the fine-scale climatic processes such as climate extremes are still very challenging to simulate (Duffy et al., 2003). These fine-scale features can be resolved through the high-resolution regional climate models (RCMs) (Tugba et al., 2017, 2018) and the regional models have enhanced the skills reasonably well in simulating the seasonal monsoon rainfall variability (Bao, 2013; Halder et al., 2015; Maity et al., 2017; Bhatla et al., 2018, 2020a, 2020b; Sinha et al., 2019, Verma et al., 2021) over India and its regions. The RegCM of the Abdus Salam International Center for Theoretical Physics (ICTP) is one of such regional models that has high success rate in studying the ISMR features (Bhatla et al., 2016; Pattnayak et al., 2019, 2016; Maity et al., 2017; Maurya et al., 2018; Ghosh et al., 2019) and capable of downscaling GCM with higher skills than its driven force to study the ISV of ISMR on the regional level (Sinha et al., 2013; Shahi et al., 2021).The developer group has evaluated the fourth version of RegCM4 and found a greater skill compared to the previous versions in simulating the temperature and precipitation variability (Giorgi et al., 2012) over the Indian region. Although, monsoonal epochs (e.g. onset, active and break phases) are the most important phenomena during the summer monsoon, a limited effort is made to predict those phenomena using a dynamical modeling framework. Bhatla et al. (2016) and Pattnayak et al. (2019) showed the sensitivity of RegCM4 in simulating monsoon onset that varies with different convection parameterization schemes (CPSs). The performance of the RegCM4 is sensitive over the land-sea continental region (Bhatla et al., 2016; Mishra and Dwivedi, 2018) and over the MCR, convection plays a major role in monsoon dynamics during the onset, active/break phases of monsoon (Bhatla et al., 2019a; Ghosh et al., 2019, Shahi et al., 2021). It is also reported that the degree of accuracy in the RegCM4 model performance varies from region-to-region with different CPSs (Bao, 2013; Maity et al., 2017; Sinha et al., 2013, 2019). It is evident from previous studies that the RegCM4 model has the efficacy to delineate the ISM at monthly and seasonal scale, but still a lot of effort is needed to find out suitable combination of physics parameterization schemes in RegCM4 model in simulating the monsoon epochs. An extensive diagnosis of RegCM4 products on these issues is indeed one of the imperative issues for the policy planning and management over different subdivisions, especially for the agricultural sectors.

Table 1
Model configuration of RegCM4.

Dynamics	Hydrostatics
Model domain	South Asia CORDEX domain (15° S- 45° N; 10°E–130° E)
Domain cartographic projection	NORMER
Version	4.3
Resolution	50 km horizontal
Vertical level	18 sigma vertical levels
Initial and boundary conditions	NNRP1
SST	ERSST – 6 hourly 1.5°x1.5° SST
Land surface parameterization Radiation	Modified CCM3
Parameterization PBL	Modified Holtslag
Convective parameterization	Emanuel over ocean and Grell over land
Grell Closure Scheme	Arakawa & Schubert (1974)

Ongoing research topic is designed on the following major issues behind the regional level study on ISMR. Primarily it has been tried to focus how the evolution of onset and ISV (active and break phase) of summer monsoon is captured using the RegCM4. Further, authors have diagnosed the NNRP1 forced RegCM4 performance in representing the monsoonal epochs during ISM, and tried to find out the skills and limitations in the RegCM4 to study different phases of monsoon.

2. Data and methodology

2.1. RegCM4 configuration

The RegCM was developed in 1980–1981 at the National Center for Atmospheric Research (NCAR), USA. The introduction of first version of RegCM was introduced by Giorgi and Bates (1989) and Dickinson et al. (1989) where the dynamical core of mesoscale model MM4 has been used. The RegCM4 with sigma-p vertical coordinate system has the capability to run over a large range of regional climate modeling systems (Giorgi et al., 2012). For the urban and suburban environments representation a new land surface physics with two types of land-use, planetary boundary layer and air-sea flux schemes are incorporated in Biosphere-Atmosphere Transfer Scheme (BATS) (Elguindi et al., 2013) in the recent RegCM4 (version 4.3). The surface conditions are altered using the surface energy balance and surface albedo for the development of the urban region. This version of RegCM4 has four CPSs such as Kuo (Anthes et al., 1987), Tiedtke (Tiedtke, 1996), Emanuel (Emanuel, 1991; Emanuel and Živković-Rothman, 1999) and Grell (Grell, 1993). Among the four core CPSs, the mixed convection scheme has been coded using one CPS over land and other CPS over ocean to boost model flexibility and capability. It is reported that these mix convection schemes are the better choices to improve model performance over complex topography region (Giorgi et al., 2012) and has been confirmed in several studies in simulating the ISMR (Raju et al., 2015; Bhatla et al., 2018; Sinha et al., 2019). The model configuration used in the present study is provided in Table 1.

Table 2
Monsoon phase detection criteria as prescribed by the India Meteorological Department (IMD):

Onset Criteria (Pai and Rajeevan, 2007):	
Criterion #1	60% of rainfall stations are found in the Kerala (total 14 stations namely Minicoy, Amini, Thiruvananthapuram, Punalur, Kollam, Allapuzha, Kottayam, Kochi, Trissur, Kozhikode, Talassery, Cannur, Kasargode, and Mangalore) with minimum rainfall of 2.5 mm/day for the two consecutive days (after 10th May) is considered as the onset of monsoon
Criterion #2	Depth of westerly will have to be maintained at 600 hPa over 0^{o}N -10^{o}N and 55°E -80°E region.
Criterion #3	Zonal wind will have to be blown at a speed of 15–20 knots at 925 hPa over the Lat 5°N-10°N and Lon 70°E -80°E.
Criterion #4	INSAT OLR should be less than 200Wm-2 over Lat 5^{o}N -10^{o}N and Lon 70°E -75°E.
Active & Break Phase Criteria (Rajeevan et al., 2010):	
Active and break phase has been identified by standardized rainfall anomaly of greater than +1 and less than -1 for minimum three consecutive days respectively which has been obtained by averaging the daily rainfall over the core monsoon region and by standardizing the daily rainfall data by subtracting from its long term normal and dividing by its daily standard deviation.	

2.2. Data used

For the ongoing study, the model initial condition and boundary condition (ICBC) are prescribed from the National Centers for Environmental Prediction (NCEP)/NCAR Reanalysis 1 project (NNRP1) (Kalnay et al., 1996) 6-h interval forcing at 2.5° × 2.5° horizontal resolutions during 1981–2008. The 6 hourly Sea Surface Temperature (SST) of Extended Reconstructed SST (ERSST) data obtained from National Climatic Data Center (NCDC) is used as model lower boundary condition (Huang et al., 2017). Further, the model simulation has been validated using the high-resolution (0.25° × 0.25°) daily gridded rainfall analysis data of Indian Meteorological Department (IMD) (Pai et al., 2014). Reanalysis outgoing longwave radiation (OLR) data from National Oceanic and Atmospheric Administration (NOAA) (Liebmann and Smith, 1996), upper-air data from the ERA-Interim (EIN15) (Dee et al., 2011) are used as verification analysis to measure the performance of the RegCM4 model.

2.3. Experimental design

The complex characteristic of different phases of monsoon over the Indian region has been extensively studied using RegCM4. Bhatla et al. (2018) and Ghosh et al. (2019) have reported that the performance of Mix99 CPS (Emanuel over the Ocean and the Grell over the Land) showed good agreement in simulating monsoon phases (onset, active, and break). The model developer group also found better simulation using mixed-scheme over the complex topographic region (Giorgi et al., 2012). Studies by Ghosh et al. (2019) have shown that the sensitivity in Mix99 CPS over land-ocean and have warned to take some specific precautions before its use. Further, those precautions motivate the authors to check the spatio-temporal performance using Mix99 CPS by forcing NNRP1 initial and boundary conditions. The model is integrated from the May 1st to the October 1st for each of the 28 years' time period (1981–2008) over the South-Asia Co-Ordinated Regional Climate Downscaling EXperiment (SA-CORDEX) domain. In order to identify the ISM onset simulation by the model, IMD's onset criteria have been followed (Pai and Rajeevan, 2007; Rajeevan et al., 2010). Simulations of the active/break phases are considered over the MCR using the criteria given by Rajeevan et al. (2010) (Table 2).

2.4. Methodology

The application of all India seasonal rainfall standardized anomaly index (SAI) is one of the most popular and widely accepted method to monitor drought/wet periods over the subcontinent. Besides, authors have considered the SAI for the MCR seasonal rainfall to monitor the drought/wet period status over the region. Classification of SAI can be classified from McKee et al. (1993) in which the SAI values with −0.99 to 0.99 are categorized as near-normal and the values i.e. +/- with 1.0 to 1.49, 1.5 to 1.99 and >/< 2.0 are classified as Moderate, Very and Extreme wet/dry period, respectively. For the onset condition, the criterion 2.5 mm/day rainfall over 14 rainfall stations (mentioned in Table 2) over Kerala for at least 2 consecutive days is followed. Also, three other criteria based on depth of westerlies (must maintain upto 600 hPa over 10°N and 55–80°E), wind speed (15–20 kts. at 925 hPa over 5–10°N and 70–80°E) and OLR (less than 200 Wm^{-2} at 5–10°N and 70–75°E) also need to be satisfied at the same time. The RegCM4 hindcast performance is evaluated by comparing the deviation from the actual onset date over Kerala. IMD considers a deviation of 4 days for their prediction; therefore, RegCM4 performance for onset declaration has been based on the deviation of ±4 days. The deviation value (D) has been calculated using

$$D = \frac{1}{n}\sum_{i=1}^{n} X_i$$

where, n is the number of deviation and x is the deviation from the actual onset.

The actual active/break phases are obtained from NCC Research Report (2013), where active and break phases are identified by normalized rainfall anomaly of greater than +1 and less than −1 for minimum 3 consecutive days over the MCR respectively (Rajeevan et al., 2010). Throughout the study, Lead 1 (Lag 1) considers the mean of 3 previous consecutive days i.e. -4 to −2 days (post consecutive days i.e. +1 to +3 days) before (after) the onset. The Lead 2 (Lag 2) represents the next three previous consecutive days i.e., −7 to −5 days (post consecutive days i.e., +4 to +6 days) of Lead 1 (Lag 1) where the Lag 0 stands for the mean of the onset (0 day) and the previous day of onset (−1 day). The Lead and Lag periods are stepped to determine the pre- and post-epochal patterns of monsoon circulation in RegCM4 simulation. Along with that the 3 consecutive stride-legged is considered to keep the consistency based on Rajeevan et al. (2010) criteria which further will diminish the daily data simulation noise in the RegCM4. The RegCM4 performance in simulating active and break phases are diagnosed by the contingency table which is one of the widely used statistical methods to diagnose the model verification before forecast/hindcast (Jolliffe and Stephenson, 2003). The contingency table is prepared using the model simulated events in comparison to actual events. The data accuracy (ACCUR), Bias frequency (BIAS), probability of detection (POD), false alarm ratio (FAR) and success ratio (SR) are computed to evaluate RegCM4 performance in simulating active/break phases of monsoon.

Further, for a close look at the model simulated rainfall distribution pattern over MCR during the active and break phases, the MCR is divided into four regions. The region is divided through the latitude 22.5°N and the longitude 78.5°E which is almost at the central location of the MCR and latitude-longitude lines through this point divide the MCR in 4 sectors named Region I, Region II, Region III and Region IV. These sectors will help the reader to understand whether the model has a systematic spatial bias in representing the active/break phases. Further model simulated temperature (850 hPa), mean sea level pressure (mslp) and wind (u & v at 850 hPa) is considered for the different phases of monsoon where the tropospheric temperature gradient is explained between 600 to 850 hPa for the study period.

3. Results

The results have been considered from the seasonal point of view and are focused on different phases of monsoon. Categorical skill score has been considered to validate model performances for epoch simulations. Further, we have tried to show the dependencies of RegCM4 performance during El-Niño Southern Oscillation (ENSO) and have drawn the

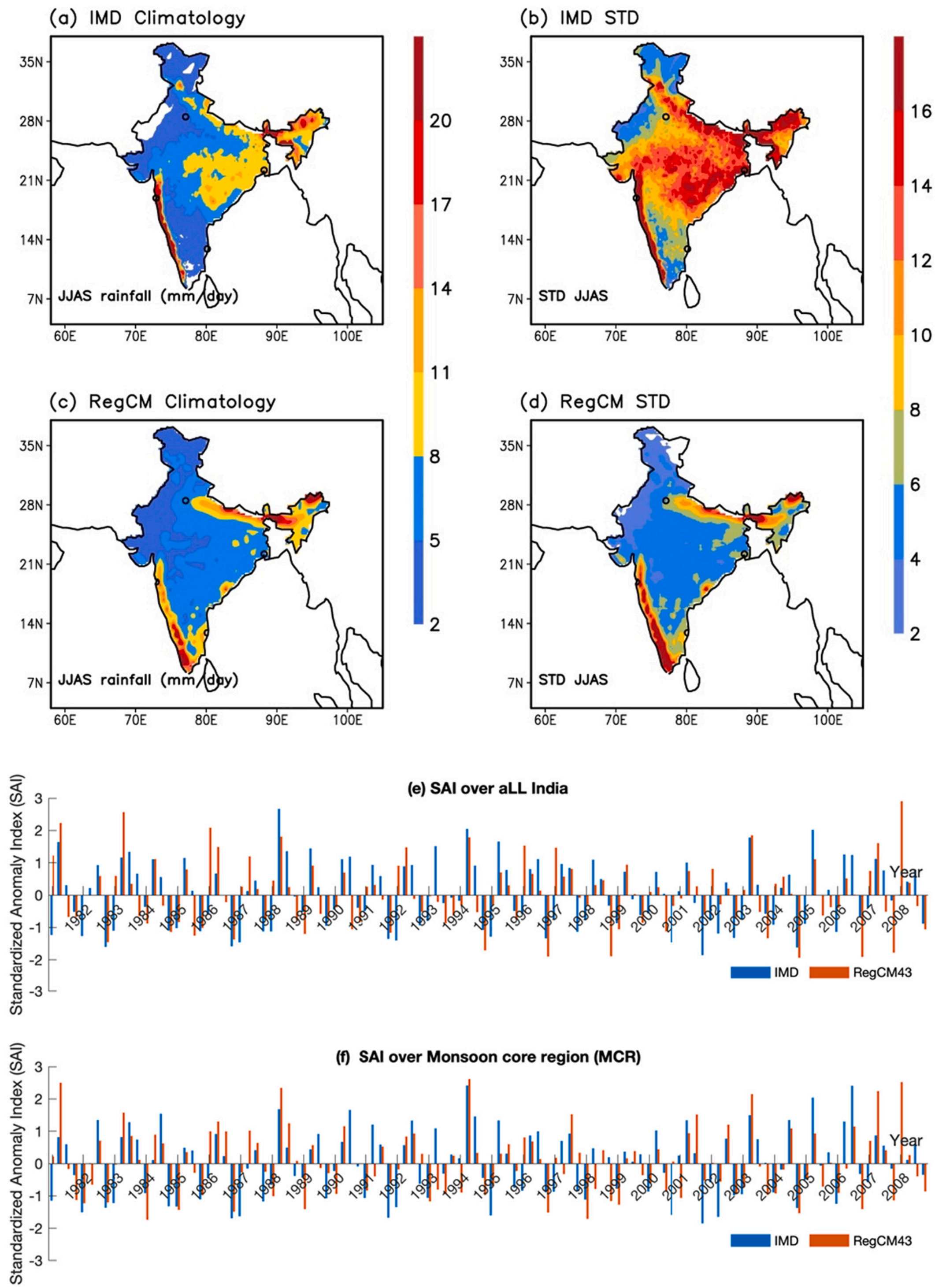


Fig. 1. a-e: Rainfall climatology (mm/day) and standard deviation (STD; mm/day)) of observations in (a) and (b) computed for the period of 28 years; (a) and (d) are same as (a) and (b), respectively but for RegCM model simulation. Panel (e) is representing standardized anomaly index (SAI) of all India and (f) represents the SAI of summer monsoon rainfall over MCR during 1981–2008.

conclusion in different sections.

3.1. Seasonal rainfall distribution:

The seasonal rainfall distribution (mm/day) and the standard deviation (STD, mm/day) are shown in Fig. 1a-d. The spatial distribution of seasonal mean rainfall climatology in RegCM4 (Fig. 1c) is in well agreement with the observed climatology of IMD (Fig. 1a). The model rainfall distribution is closely commensurate with the IMD observations over the area of MCR, Gangetic Plains (GP), Western Ghats, and northeast India (Fig. 1c). However, RegCM4 underestimates the rainfall over the northwest part of India and over the northwest part of MCR (Fig. 1c). The MCR is one of the most important regions for determining the salient features of active and break phases of monsoon and the observed STD of rainfall over that region is 10 mm/day or more (Fig. 1b). The STD of observed rainfall over southern peninsula, northeast India, Himalaya

Table 3
Model performance validation with IMD rainfall over MCZ during 1981–2008.

CC	BIAS	RMSE
0.72	0.74	0.89

foothills and the MCR lies between 10 and 16 mm/day where the RegCM4 performance over the Himalaya foothills, southern peninsula and the northeast India is found to be reasonable (Fig. 1d) as the simulated STD is comparable with the observed STD (Fig. 1b). The STD delineates that the variability of rainfall over the MCR is high which in turn indicates the occurrence of rainfall ranging from low to extreme rainfall categories. The spatial pattern of model simulated STD underestimates over the MCR region.

Fig. 1e-f illustrate the coherencies between the RegCM4 simulated SAI with the observed SAI over all India and MCR region respectively. For both regions, the level of coherencies are more accurate during moderate and above-normal Wet/Dry years. The SAI of the RegCM4 simulation slightly differs from observed SAI when the very frequencies are detected over all India regions. The difference is noticeable when extreme frequencies are considered in all India SAI. Though, the model simulated SAI over the MCR region differs much from the observation pattern in simulating very to extreme frequencies when compared with all India SAI. But, it can be concluded that the model simulated SAI over all India and the MCR show satisfactory during the near normal years.

To have some solid performance validation authors further have considered a statistical table containing correlation coefficient (CC), model performance BIAS and the root mean square error (RMSE) in Table 3. The model simulated rainfall performance over the MCR has been verified with the IMD rainfall over the respective region for the entire period. From the table, it can be stated that the performance of RegCM4 has enough skill to simulate the monsoon variation over the MCR by showing CC of 0.72, BIAS 0.74 mm RMSE of 0.89. Based on the above discussion and the statistical score it can be stated that the NNRP1 forced dynamical downscaled RegCM4 has an excellent capacity to simulate the monsoon variability over Indian region.

3.2. Rainfall distribution during monsoonal epochs (Onset, Active and Break phases):

3.2.1. Model performance in simulating monsoonal epochs

3.2.1.1. Onset. The study of ISM onset has been restricted using IMD onset criteria which are based on rainfall, wind, and OLR parameters. The model simulated onset date is considered when it satisfies the threshold values as defined in Table 2. The Table 4 illustrates that the years 1981, 1988, 1992, 1998, 1999, 2000, and 2001 agree with the actual onset dates, where the simulation date is deviated by 1 day. A good agreement with the actual onset dates is also noticed during the

Table 4
Actual onset dates and RegCM4 simulation onset based on IMD onset criteria as defined in Table 5.

Year	Actual Onset	RegCM4	DEVIATION (in Days)
1981	30M	29M	-1
1982*	28M	3J	+6
1983	13J	--	--
1984	30M	3J	+4
1985#	28M	2J	+4
1986	4J	11J	+7
1987*	2J	10J	+8
1988#	26M	27M	+1
1989	3J	29M	-4
1990	19M	22M	+3
1991*	2J	18J	+16
1992	5J	4J	-1
1993	28M	--	--
1994	28M	3J	+5
1995	5J	--	--
1996	3J	31M	-3
1997*	9J	3J	-6
1998#	2J	1J	-1
1999#	25M	26M	+1
2000#	1J	2J	+1
2001	23M	22M	-1
2002*	29M	6J	+8
2003	8J	2 J	-6
2004*	18M	12M	-6
2005	5J	12J	+7
2006	26M	31M	+5
2007#	28M	--	--
2008	31M	--	--

-- Represents non simulation of onset dates by not fulfilling the criteria.
* El-Niño year & # La-Niña year
M=May & J=June

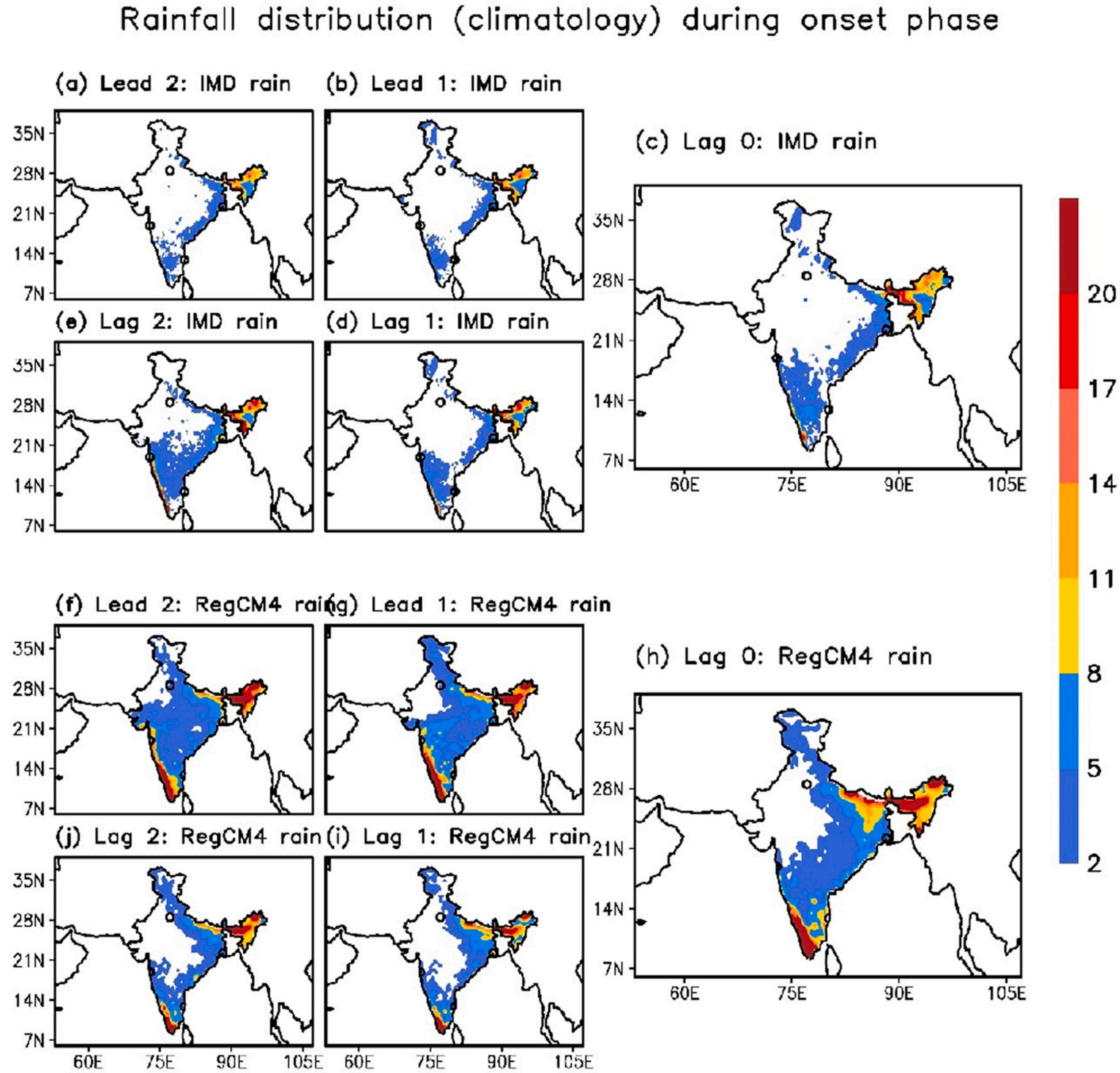


Fig. 2. a-j: Spatial distribution of IMD (a-e) and RegCM simulated (f-j) rainfall climatology (mm/day) during onset phase where Lead means before onset days [Lead 1 (−4 to −2 day), Lead 2 (−7 to −5 day)], Lag 0 stands for mean of −1 day and Onset date; and Lag is the post days of onset [Lag 1 (+1 to +3 days) and Lag 2 (+4 to +6 days)].

years 1984, 1985, 1989, 1990, 1994, 1996, and 2006 where the model deviation is only by 5 days from the actual date of onset. Deviation of more than 5 days is noticed during a few years e.g., 1982, 1986, 1987, 1991, 1997, 2002, 2004, and 2005.

Fig. 2 shows the spatial distribution of IMD observed (Fig. 2a-e) and the RegCM4 simulated (Fig. 2f-j) rainfall during onset over the Indian subcontinent. The before-onset and after-onset periods are termed as Lead period and Lag period, respectively. From the observed rainfall, it is found that the Kerala region receives more than 2.5 mm/day rainfall for two consecutive days and the average of those two consecutive days are termed as the date of onset (in Lag 0: Fig. 2c). The mean rainfall distribution during two Lead periods before onset (Lead 2 & 1) are shown in Fig. 2a-b. Once the monsoon hits over Kerala, the rainfall distribution is increased over the southern peninsula and spreads over the surrounded region (Lag 1 & 2: Fig. 2d-e). The rainfall pattern over the areas of northeast India and the adjoining regions of the Bay of Bengal (BoB) are close to the observation pattern during the onset days and the rainfall progression spreads over these regions during the Lag days of onset. Areas of the Himalayan foothills receive a negligible amount of rainfall before onset as the rainfall advancement over the space does not cover the central India and the Himalayan foothills at that time (Bhatla et al., 2016). The RegCM4 simulated rainfall distribution during the onset and post onset phases closely follows the observed rainfall pattern over Kerala (Fig. 2f-j). During onset period (Lag 0), the model simulates more widespread and higher amount of precipitation compared to IMD observation over southern peninsula, especially over Kerala and adjoining regions. At the same time, the rainfall distribution is widely spread over central India during the Lag period (Fig. 2i-j). However, RegCM4 overestimates the rainfall distribution over the MCR during Lead 1 and Lead2 (Fig. 2f-g). Except these regions, the model simulated rainfall pattern agrees well with the observed one over most of the areas during the Lag 1 & 2 (Fig. 2i-j). It can be summed up that the RegCM4 predicts early arrival of onset phase which actually hits the Kerala during Lead period instead of Lag 0, and the RegCM4 rainfall simulation is showing overestimation over a larger area compared to IMD observations during the onset phase (Lag 0: Fig. 2c).

3.2.1.2. Active/break. The RegCM4 simulated active and break phases are described in Table 5 where the actual active and break phases are considered from NCC Research Report (2013). The RegCM4 is simulating the break phases approximately 4.76% less in numbers than the

Table 5
Active/Break spells obtained from observations and RegCM4 simulations. Observed active/break phases are based on the NCC Research Report (2013).

Years	Active phases		Break phases	
	RegCM4	Actual	RegCM4	Actual
1981	1-10J, 15-23J, 28-30J	7-10J	23-31A	24-27A
1982*	14-22A	21-23A, 12-14A	1-14J, 26-31A	1-8J
1983	14-25J, 12-14A, 31J-2A	18-20A	6-12J	14-16J
1984	15-20J, 16-18A	1-3A, 9-11A, 16-19A	27-29J	28-30J
1985#	15-20J, 30J-1A	15-17J, 30J-2A, 6-8A	1-10J, 20-31A	23-25A
1986	17J-12A	21-24J, 13-15A	23-31A , 1-5J	23-31A
1987*	6-13J	24-29A	18-22J	23-25J, 30J-4A,9-13A
1988#	1-7J, 12-19J, 3-11A	26-28J	26-31A	14-17A
1989	12-15J	--	1-4J, 31J-3A	18-20J, 30J-3A
1990	2-5J	2-4J, 21-24A, 29-31A	20-22A	--
1991*	18-24A	21-24J, 29-31J, 22-24A	1-6J, 10-15A	1-3J
1992	26J-4A	27-29J, 16-21A	1-6J	4-10J
1993	--	7-11J, 15-17J	1-7J ,20J-2A, 8-27A	20-23J, 8-13A, 22-28A
1994	2-4J, 8-18J, 28J-2A	2-4J, 9-16J, 30J-2A, 18-20A, 25-27A, 29-31A	--	--
1995	18-26J	18-20J, 22-25J	1-9J	3-7J, 11-17A
1996	10-15J	24-28J, 19-21A	4-8J, 26-31A	11-13A
1997*	29J-2A, 19-25A	30J-1A, 21-25A	11-18J	11-15J, 9-17A
1998#	--	30J-1A, 21-25A	20-28J, 9-14A	21-26J, 16-21A
1999#	5-9J	7-9A	1-4J, 12-14J, 22-24J, 29-31A	1-5J, 12-18A, 22-24A
2000#	2-7J	12-14J, 17-20J	19J-21A, 26-31A	29J-8A
2001	9-13J, 2-10A	9-12J	23-28A	31J-2A, 27-29A
2002*	1-4A, 11-15A	23-25A	1-17J, 25-27J	4-16J, 22-31J
2003	6-11J, 21-28A	23-28J, 27-29A	15-17A	--
2004*	13-15J, 30J-3A, 8-13A	8-13A, 21-23A	1-3J, 18-27J, 26-31A	10-13J, 19-22J, 26-31A
2005	21-25J	1-5J, 25-29J, 31J-2A	7-15A, 20-31A	7-14A, 24-31A
2006	26J-9A, 14-16A	3-6J, 27J-7A, 13-15A, 17-20A	16-21J	--
2007#	1-7J, 21-31J	1-9J, 6-9A	--	18-23J, 15-17A
2008	--	10-12A	14-20J, 17-31A	16-21J, 21-24A, 28-30A

-- Represents non simulation of onset dates by not fulfilling the criteria.
* El-Niño year &# La-Niña year

actual break events, while the model simulates 24.5% more active phases when compared with the actual active events. It is also observed that most of the model simulated active phases are less intense than the actual phases and sometimes a group of simulated active phases in RegCM4 are representing a single actual phase. The RegCM4 model reduces the surface temperature due to higher cloud cover which in turn downplays the convective instability (Betts et al., 2014); and as a result, the model's efficiency decreases in representing the strong convective activities. The performance of RegCM4 in simulating the ISV has shown a good agreement with the actual active/break phases and was previously described by Maharana and Dimri (2016) using different version model setup.

Fig. 3a-j illustrates the spatial pattern of active and break phases of IMD and NNRP1 forced RegCM4 output based on Table 5. The rainfall advancement over the MCR during pre-active phase is discussed using Lead 2 to Lead 1. Afterward, the post-active phase rainfall circulations are accomplished through the Lag 1 & 2 followed by the Lag 0. An obvious picture of the rainfall progress before and after the active phase can be shown using Fig. 3a-e, where the rainfall amount over the MCR is showing a pattern of increasing rainfall from Lead 2 to Lag 0 and the amount is reduced with the drift of time (Lead 1 and Lead 2). The maximum areas of the MCR have received a minimum of 6–10 mm/day rainfall during pre-active phase (Lead 2 and Lead 1) which peaked to 14 mm/day during active phase (Lag 0). The area of the southeast region of MCR is showing a large amount of rainfall of 22 mm/day during lag 0 (Fig. 3c) and in the Lag 1, the rainfall amount is decreased (Fig. 3d). The Lag 2 span is not following the usual pattern and an overestimation in rainfall simulation over the area is observed (Fig. 3e). The justification behind this unusual behavior is the occurrence of another active phase after 3 consecutive days of Lag 0 (difference between Lag 0 and Lag 2 i.e., Lag 1). The RegCM4 simulated active phases are considered in Fig. 3f-j and are compared with the observed pre-definite and post rainfall circulation of active phases. The utmost region of the MCR has received 6 mm/day of rainfall during Lead 2 and Lead 1 (Fig. 3f-g). During that period, the areas of the GP are receiving an amount of 10 mm/day rainfall where a large amount of rainfall is simulated in the Himalayan foothills. However, the area of GP and the Himalayan foothill are not considered under MCR. On the arrival of model simulated

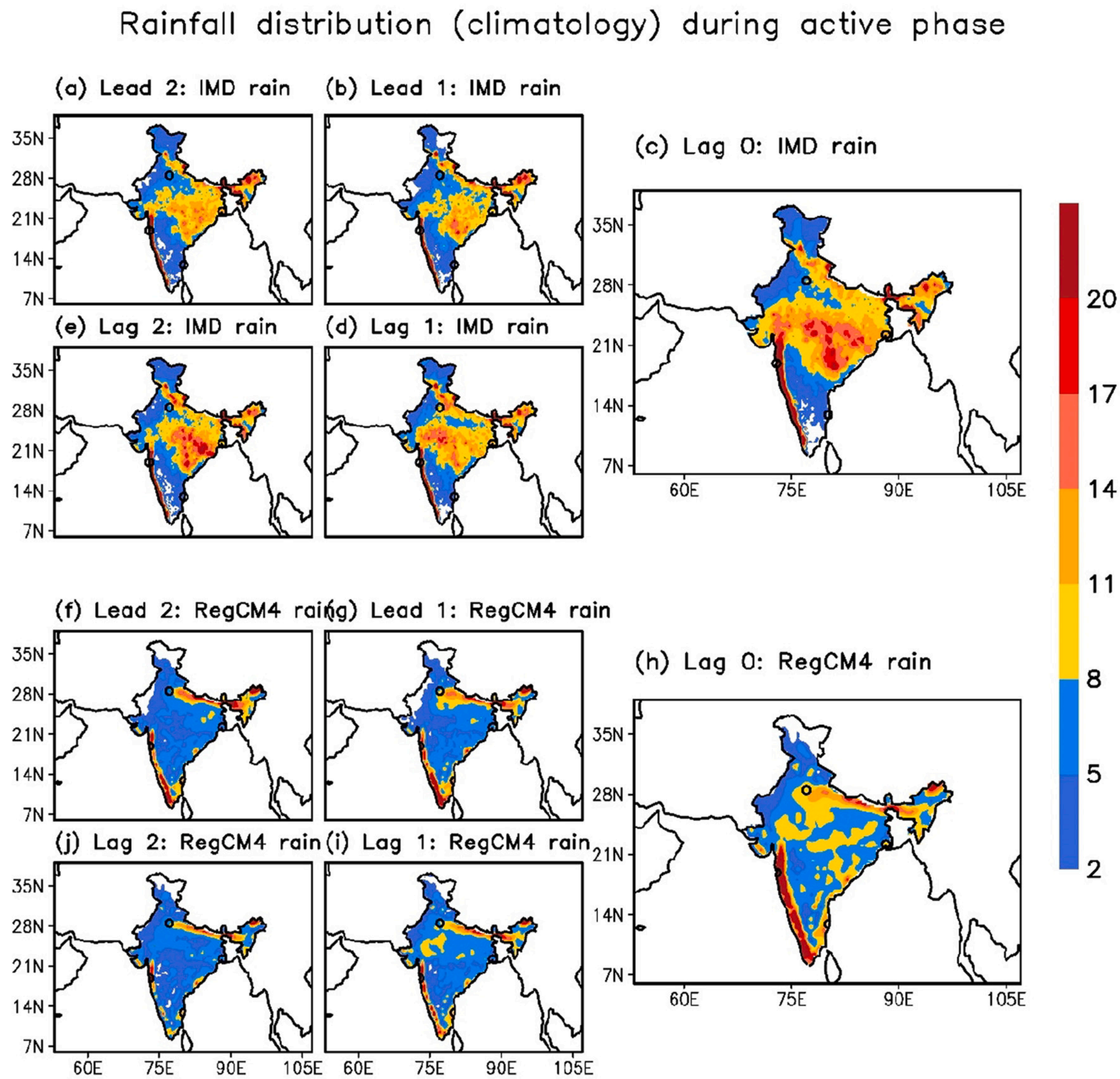


Fig. 3. a-j: Spatial distribution of IMD (a-e) and RegCM4 simulated (f-j) rainfall climatology (mm/day) of active phase where Lead (Lead 2 and Lead 1) means previous days of active spells [Lead 1 (−3 to −1 day), Lead 2 (−6 to −4 day)], Lag 0 stands for mean of active spells; and Lag (Lag 1 and Lag 2) means post days of active spells [Lag 1 (+1 to +3 days) and Lag 2 (+4 to +6 days)].

active phase (Lag 0) the entire MCR has received a minimum of 10 mm/day of rainfall (Fig. 3 h) which is disappeared in Lag 1 and Lag 2 (Fig. 3i-j), and follows the trends of observed rainfall pattern over the region. The model simulated active phase in Lag 2 is drier than the observed.

The spatial rainfall distribution during break phases can be found in Fig. 4a-j, where the observed and the model simulated break phases are shown inFig. 4a-eand Fig. 4f-j respectively. The rainfall progression from the active/normal phase towards the break phase is shown in Fig. 4a-e. Fig. 4c shows that the rainfall amount is drastically reduced over the region in Lag 0 (break phase) which is comparatively very less than the Lead and Lag periods of the break phases. During the break condition a shifting of rainfall distribution from the northwest and SW towards the northeast and southeast region of MCR has also been noticed (Fig. 4c). A large part of MCR receives rainfall up to 6 mm/day. The northeast and southeast MCR have received up to 10 mm/day rainfall during this phase. The model simulated rainfall during the break phase (Fig. 4f-j) is less than the observed rainfall. The rainfall during the Lead and Lag phases in model simulation is about 6 mm/day over the MCR (Fig. 4f-g, i-j). During Lag 0, the rainfall amount is reduced by 2 mm/day over the northwest and SW parts of MCR, and the northeast and southeast parts of MCR have received 6 mm/day of rainfall during this phase (Fig. 4 h). From the figure it is also noticed that the northeast and southeast MCR are the high intense rainfall zone during all monsoonal conditions (Fig. 3: active and Fig. 4: break condition) and throughout the monsoon season (Fig. 1) which is observed in IMD and well simulated by the RegCM4.

The mechanism behind different epochs of monsoon has justified further. Therefore, the anomaly pattern of model simulated temperature (at 850 hPa), mslp and the wind circulation pattern at 850 hPa for the different phases (ref to Lag-0 in Fig. 2–4) of monsoon are considered in Fig. 5a-f. The anomaly is considered from the climatology pattern of the model simulated parameters (temperature, mslp and wind) using the criteria as discussed before. The temperature gradient over the Indian region, specially over the north-west region is very crucial for the monsoon onset over India. From Fig. 5a-b, a temperature gradient is noticeable all over India except the top north region of India. A high temperature gradient is captured over the north-west region where a deep low-pressure belt is also formed and together supports the best climatic condition for monsoon onset over India. During the onset condition, wind direction is divided in two different directions, one is directed towards the west part of India where the low-pressure belt is formed through Kerala and another bypasses Srilanka region and hits

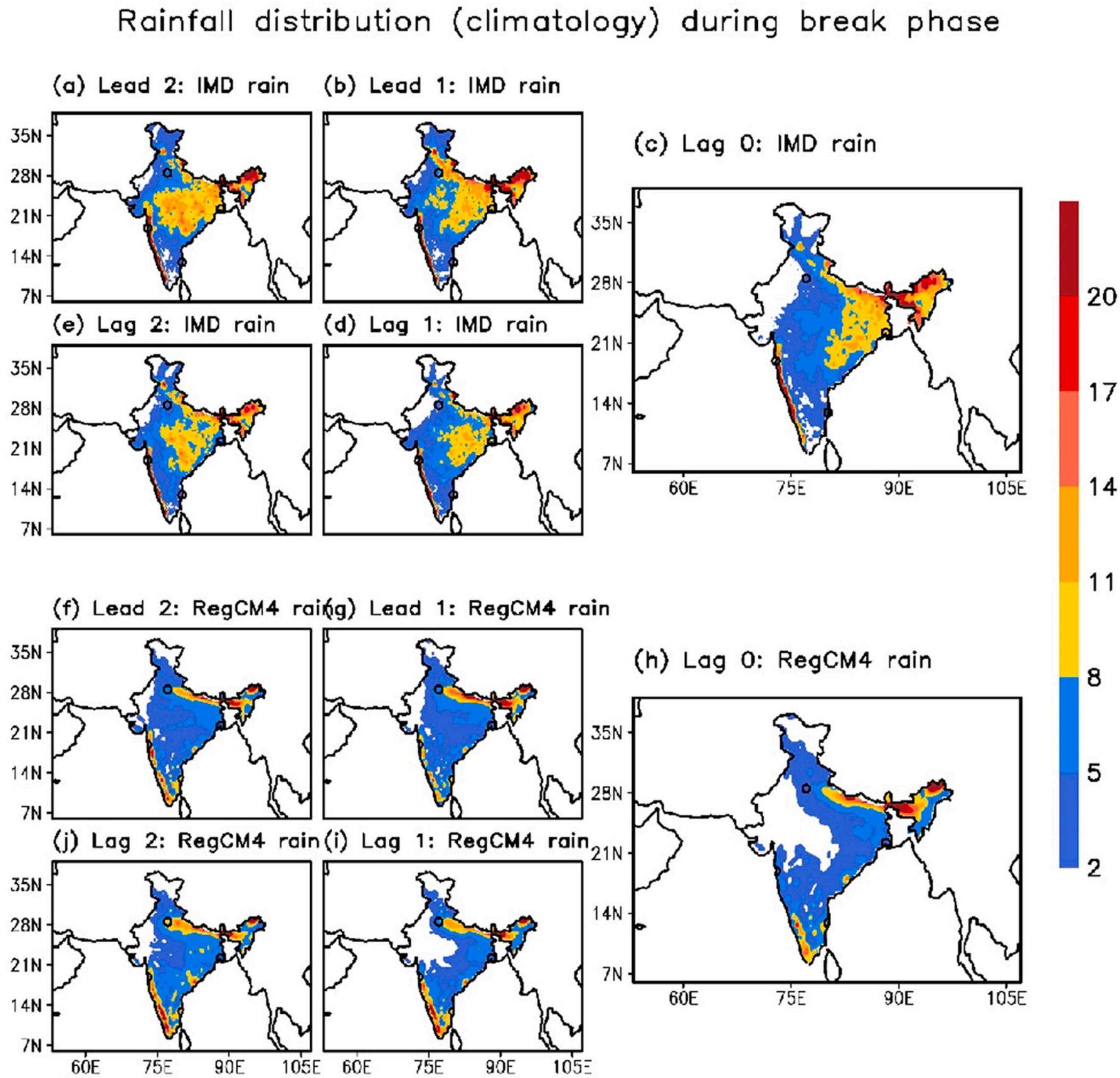


Fig. 4. a-j: Same as Fig. 3 but for break phase.

top of the BoB. The active/break phases start during the peak monsoon months of monsoon i.e., July and August. During the active phases of monsoon (Fig. 5c-d), A high temperature gradient over the northern part of India and a comparatively low gradient is formed over the MCR region (Nayak et al., 2019). A strong monsoon trough is extended over the western, northern and some western art of the central India. Though, a comparatively weak monsoon trough is noticed over rest of the part of the MCR. The positive temperature gradient and the low-pressure belt over the MCR together boost the monsoon propagation to the MCR and the MCR receives the reasonable amount of rainfall depends upon the strength of those parameters which are partially weak in the model simulated active phases. Therefore, the rainfall distribution over the MCR region suffers during the period. In the other hand, the break phases circulation pattern is well captured by the RegCM4. In Fig. 5e-f, the positive temperature gradient is very well distributed over the MCR and the monsoon trough, which shifted over the Himalayan foothills, regulates the wind circulation towards the foothills. During these phases the MCR stays dry, and Himalaya and the hoot hills region receives heavy amount rainfall, and the mechanism is well represented in the model simulation.

3.3. Categorical skill scores of RegCM4 in simulating intra-seasonal monsoon phase

Further, the study is focused on verification of model performance in simulating the intra-seasonal monsoon variability over the Indian subcontinent. The contingency table is one of the standard tools to diagnose the model simulated intra-seasonal summer monsoon variability using a statistical approach (Klein and Meissner, 2017). Two different tables have been considered to diagnose two different phases of monsoon in model simulation: one is for active phases (Table 6a) and the other for the break phases (Table 6b). Model simulated 24 active phase events are correctly matched with the actual phases (H_n). The model is unable to simulate 31 (M_n)phases which actually occurred. Along with it, the model simulates 23 more active phases which did not actually occur (FA_n). The model could not simulate the correct negative active phases (CN_n) throughout the simulation. On the other hand, the model has successfully simulated the break phases 27 times (i.e. $H_n = 27$) and failed for 15 times ($M_n = 15$). The $FA_n$and CN_n values for break phases are 19 and 1, respectively.

The ACCUR of model categorical output depends on fractional correction statistics. The performance of RegCM4 is 31% accurate in simulating the active phase whereas for break phase the ACCUR is 45%. The above analysis indicates that the accuracy of RegCM4 simulation for

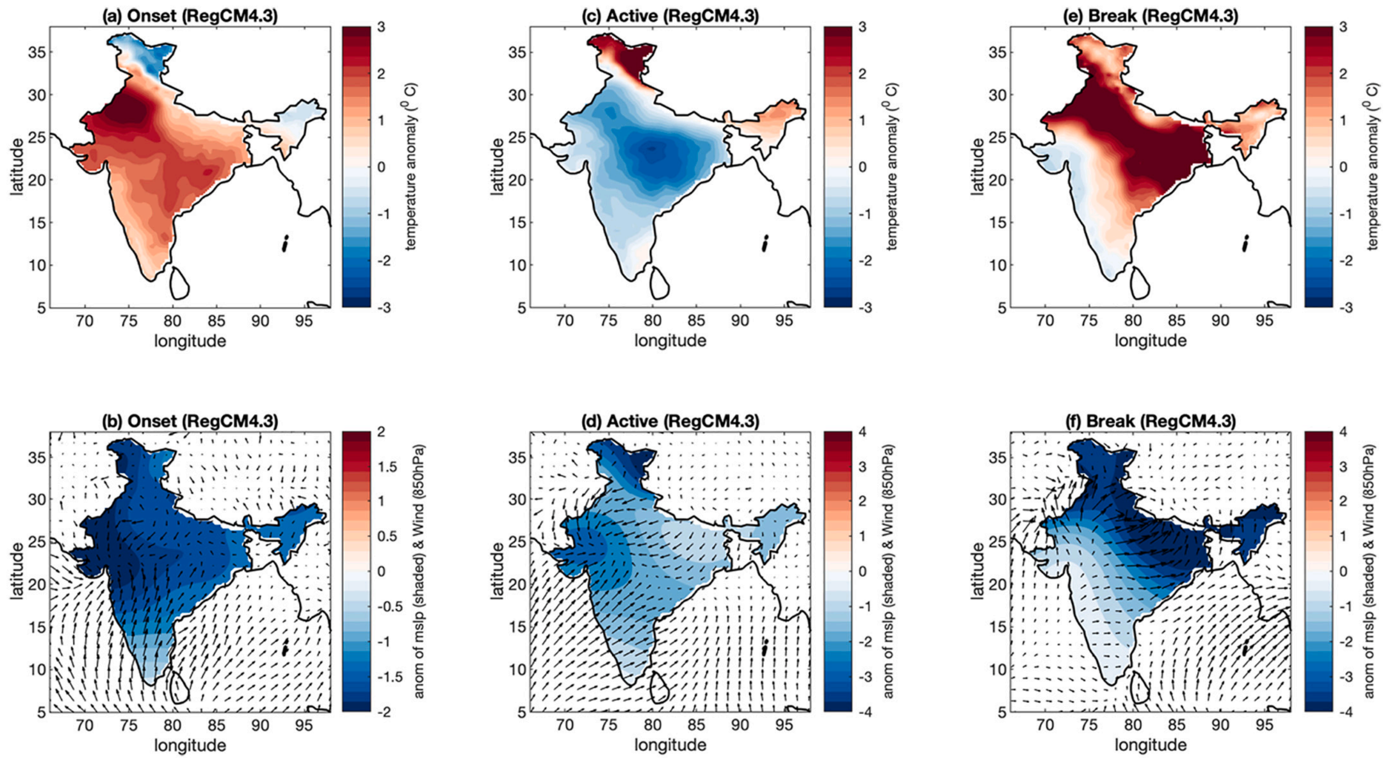


Fig. 5. a-f: Variability of temperature (850hPa; unit in ^{0}C), mslp (unit in hPa) and wind (850hPa) during (a-b) onset, (c-d) active and (e-f) break phases of monsoon during 1981–2008. The anomaly has considered from the climatology pattern of the respective phases.

Table 6
Contingency table of RegCM4 simulated active and break phase distribution.

(a) Active Phase

Model	Actual dates: Yes	No	Total
yes	24	23	47
No	31	0	31
Total	55	23	78

(b) Break Phase

Model	Actual dates: Yes	No	Total
yes	27	19	46
No	15	1	16
Total	42	20	62

Categorical statistics		Active	Break
Accuracy (fraction correct) - Equation for accuracy	(ACCUR):	0.31	0.45
Bias score (frequency bias)	(BIAS):	0.85	1.10
Probability of detection (hit rate)	(POD):	0.44	0.64
False alarm ratio	(FAR):	0.49	0.41
Success ratio	(SR):	0.51	0.59

the break phase is higher than the active phase. The BIAS is another standard skill score that represents the model proficiency in active and break phase simulations. The analysis indicates that the BIAS of RegCM4 is 0.85 during active phase while the BIAS is 1.1 during break phases. These values indicate a slight under-estimation of active phase and a minor over-estimation of break phase frequency in RegCM4 simulation. The POD indicates that about ½ of the active phases (0.44) and about 2/3rd of break phases (0.64) are correctly simulated by RegCM4 and the model performance during the break condition is significantly higher than the model performance during active phase simulations. The FAR is roughly ½ (0.49) during the active phases whereas during break events the FAR reaches 0.41. The rate of success (SR) of the model in simulating rain events during active phases is 51% and during break phases is 59%. The above discussion accomplishes that the RegCM4 has the capability to simulate the monsoonal epochs, however, the skill is higher during break phases compared to active phases. The possible cause behind the high statistical agreement of RegCM4 performances during the break phase might be the dry bias in RegCM4 simulation (Halder et al., 2015).

3.4. Simulation stretches between the phases:

This section is designed to verify the stretches between the phases in

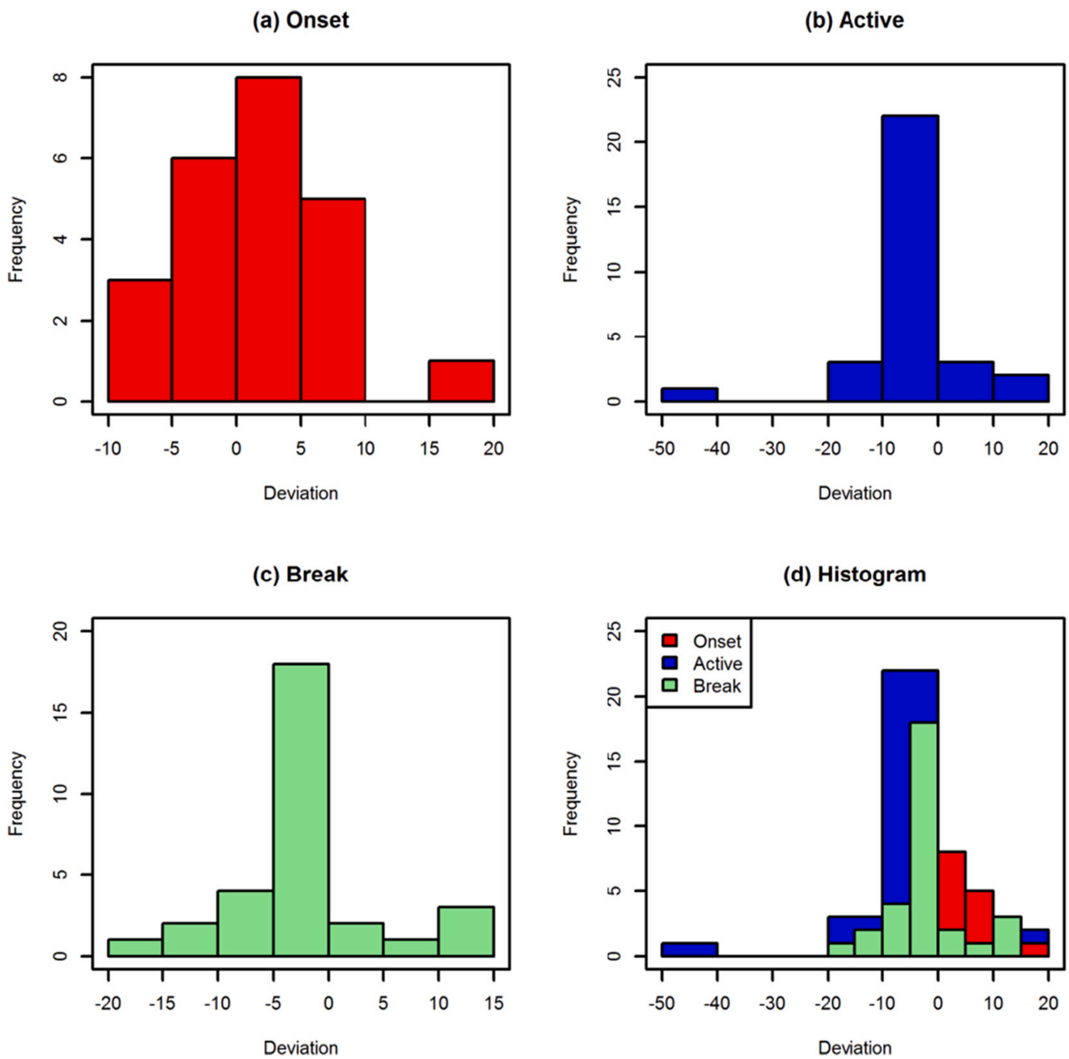


Fig. 6. a-d: Frequency distribution in the advancement and delayed occurrence of onset, active, and break epochs in the panels (a), (b), and (82a) respectively in the RegCM4 model as compared to observations. Panel (d) is representing advancement and delayed occurrence of all the epochs in RegCM4 compared to the observations.

RegCM4 simulation. Fig. 6a-d represents the frequency of model deviation from the actual onset date (Fig. 6a), active (Fig. 6b) and break (Fig. 6c) events whereas a combined model performance is shown in Fig. 6d for the ease of comparison with the observation. Throughout the analysis the model simulated frequency between +4 to −4 has been treated as normal as described in the earlier sections. From the figure it is observed that the frequency of onset events is maximum for the deviation of +5 to +10 days and sometimes the deviation reaches +20 days (Fig. 6a). In other words, it shows the late occurrence of the maximum numbers of model simulated onset events with respect to the actual onset. A number of active events are simulated between −10 to 0 days in model simulation followed by a few of positive frequencies during the phases (Fig. 6b) of monsoon. The model deviation between −10 to −20 days is as less as the positive deviation during the phases. It indicates the early arrival of active phases in RegCM4 simulation compared with the actual active phases. During break phase, 10 times higher frequencies are found for −5 to 0 days deviation than 0 to 5 days. The frequencies are nearly tripled in −10 to −5 days than the frequencies of 5 to 10 days (Fig. 6c). This analysis portrays the early occurrence of break events in model simulation. A clear representation for comparison between phases occurrence can be obtained from Fig. 6d in which the frequencies of the events during the phases (onset, active, and break) are superimposed to visually gauge the simulation stretches between the monsoon phases.

3.4.1. Model sensitivity and rainfall distribution:

The data distribution and model sensitivity are other important requirements for a good simulation of ISMR over complex Indian landscape (Sinha et al., 2014; Caccamo et al., 2017; Tiwari et al., 2017; Devanand et al., 2018; Abish and Arun, 2019). The model simulated rainfall distribution and the model sensitivity over the MCR is shown in Fig. 7a-d. The MCR has been divided in 4 sectors (yellow shaded region; Fig. 7a). A scatter plot of region wise rainfall distribution for active and break phases is shown in Fig. 7b-82a, and Fig. 7d represents the contribution of total rainfall in IMD and RegCM4 simulation during the phases over the 4 sectors. Fig. 7b shows a large variation in rainfall amount and number of events and the rainfall magnitude is lesser in RegCM4 model over all regions except over the Region II, where the observed rainfall is about half of the model simulated rainfall during the active phases. It is noticed that the observed rainfall (mean of each active phase) is almost half in Region II compared to the other regions, while it is in reverse in the RegCM4 simulations, which is troubling in representing the sectorial rainfall amount over MCR during the active phase. RegCM4 simulated average active rainfall phases are between5 − 10 mm in each of the regions except Region II. The RegCM4 simulated rainfall variation over the Region II is nearly double of the values over

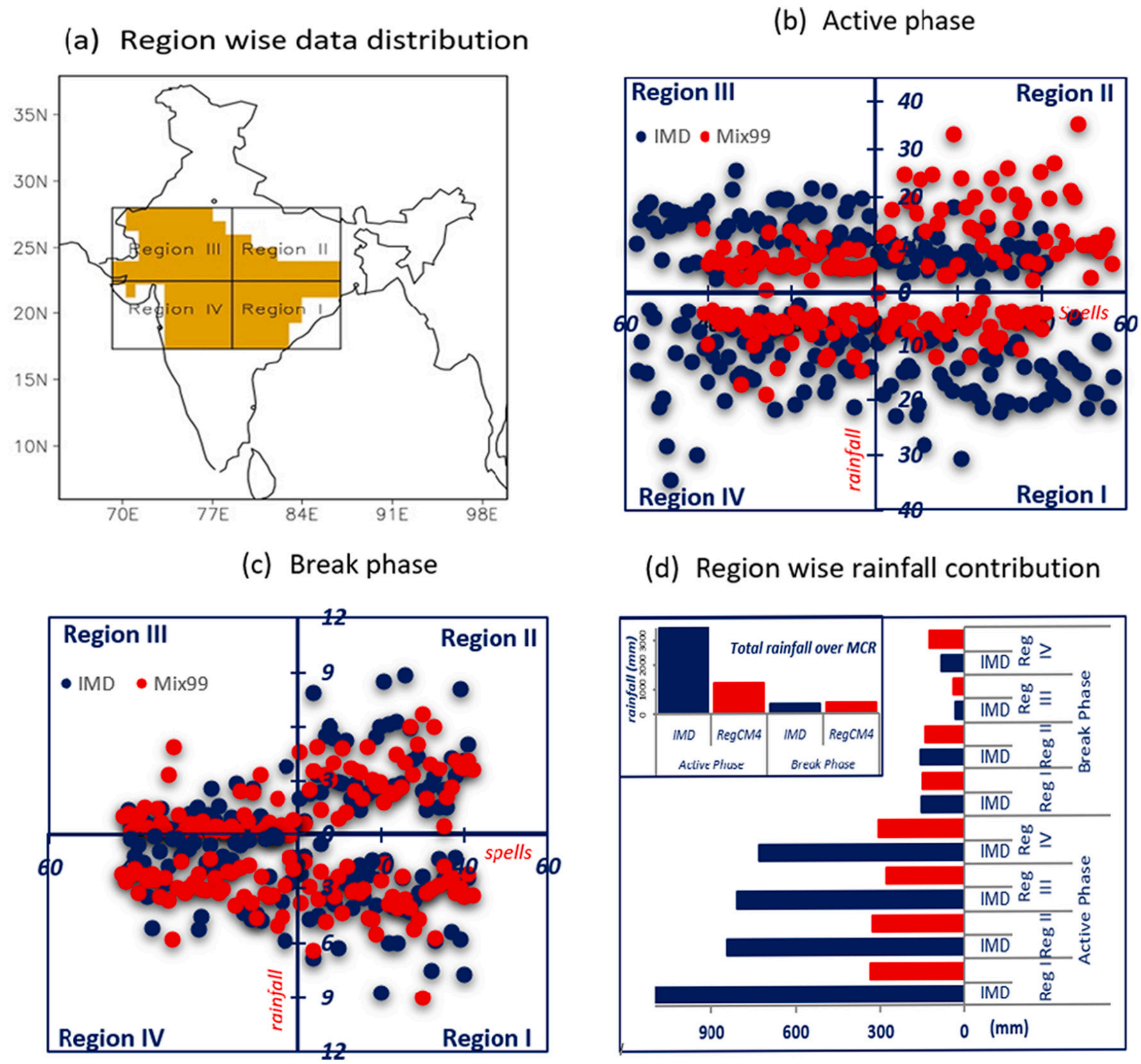


Fig. 7. a-d: Rainfall data distribution over monsoon core region (MCR) (yellow shading) and four subdivisions divided through the latitude 22.5 and the Longitude 78.5 centered in the MCR (a). Where, Region I is the South-East, Region II is the North-East, Region III is the North-West and Region IV is the South-West part of the MCR. The region wise rainfall data distribution during active and break spells are placed in panel (b) and panel (82a), respectively, and the region wise rainfall contribution in IMD and RegCM4 simulation during active and break phases is shown in panel (d). The blue and red colors are indicating IMD and RegCM4 simulated rainfall, respectively.

other regions (Region I, III & IV) during the active phase. During break phases (Fig. 7c), the RegCM4 model simulation is in close agreement with the IMD rainfall pattern except Region IV, where a little over-estimation is noticed compared to the observations. The region wise total rainfall contribution in observed and RegCM4 simulated active and break phases can be obtained from Fig. 7d. The figure illustrates that the Indian subcontinent receives a maximum amount of rainfall during active phases where the rainfall contribution is very less during the break phase over India as well as over the MCR (top left corner of Fig. 7d). The RegCM4 simulated rainfall is approximately three times lesser compared to IMD total rainfall over the MCR during active phase, whereas an equal amount of rainfall contribution is observed in model simulation during the break phase over the same region. In each region, the rainfall amount simulated by RegCM4 is about half of the observed rainfall over the respective region. The RegCM4 simulation during break phase is quite remarkable as the rainfall amount simulation by RegCM4 is very accurate over the sectors of MCR. It is also observed that the Region I and Region IV are high rainfall and less rainfall regions of MCR during active phases, respectively. On the other hand, the observed and model simulated rainfall amounts are very close during the break phases for each of the regions, and the Region III receives least amount of rainfall during the break phase in observed and RegCM4 simulation.

Sensitivity of rainfall frequency and rainfall intensity are considered by evaluating the RegCM4 performance during intra-seasonal time scale over MCR (Fig. 8a-b). The frequency-intensity histogram during active phase (Fig. 8a) represents a small value of rainfall frequency in early days of the season which has increased in later days. The IMD observation shows a frequency of an average to very heavy rainfall which is obtained either from long active phases or from the extreme events during the active period. It is seen that rainfall events with an amount 20 mm/day to 60 mm/day with an interval 5 mm/day occur more than 5 times, which is absent in the RegCM4 model simulations. Figures also indicates that the model can simulate a maximum amount of 20 mm/day rainfall for 10–20 days. The frequency of 5–10 mm/day rainfall amount during the active phases is quite large in the model compared to the observations. The RegCM4 model has a tendency to simulate low to moderate rainfall intensity during the early days and is limited to simulate the moderate-to-heavy rainfall intensity during the phases. The rainfall frequency and intensity during break condition is shown in Fig. 8b. This figure demonstrates that the model simulated rainfall intensity-frequency performance is reasonably good during the break phase, and the lesser rainfall intensity (dry) is comparatively

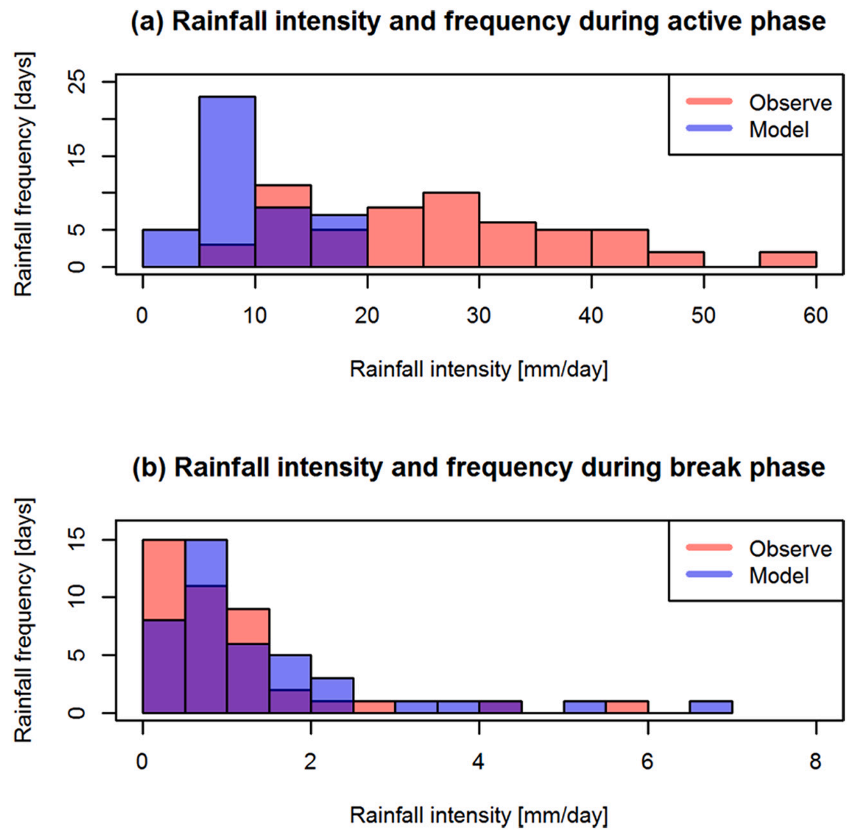


Fig. 8. a-b: Rainfall intensity vs. frequency distribution during active and break phases of rainfall.

represented better. The discussion suggests that the rainfall intensity during the active phase is simulated up to a limit by the model and the model is suffering from lack of simulating intense rainfall during the active phase; in contrast the RegCM4 has a prospective skill for break phase simulations. In other words, this version of RegCM4 has adequate skill to simulate the break phase or dry conditions, while it has very limited skill to simulate the heavy rainfall events during the monsoon season.

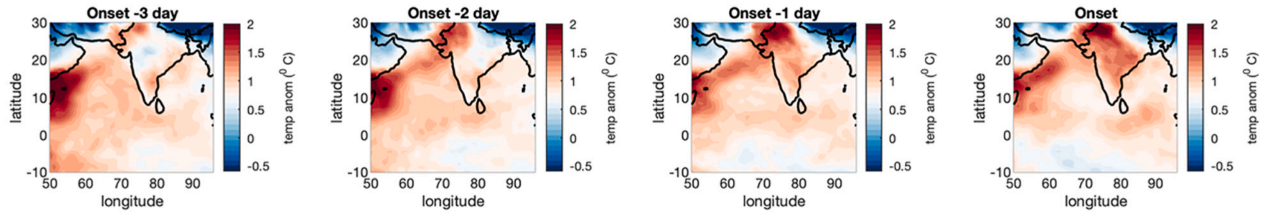
3.5. Tropospheric temperature gradient and monsoon propagation:

Tropospheric temperature gradient plays a crucial role for monsoon propagation. It holds the mechanism behind the onset propagation to the Indian subcontinent and monsoon advance over the Indian land mass. Fig. 9a-b represents the monsoon propagation a bit advance from the date of onset to the peak monsoon months of July. To see the monsoon propagation before the onset (Fig. 9a) and the advance of monsoon till the formation of the active/break phases (Fig. 9b), the data from 3 days before the onset to the first few days of July is considered. From the Fig. 9a it is noticed that a positive anomaly over the Indian ocean (IO) (5 ^{0}N-15 ^{0}S) changes the sign to negative and is covering the IO very fast from 3 days before onset (Li and Yanai, 1996; Pradhan et al., 2017). By the date of onset negative sign covers almost the region over the IO and the sign is changed completely. One transition effect from the east to the India subcontinent through the IO is also depicted which further extends to the Arabian sea (AS) and the BoB region. At the same time, the temperature gradient is started rising over the south-west and the southern part on India from few days before of onset and a warm gradient is covers all over the region. A subsequent warmer condition can also be noticed over the Indian subcontinent 3 days before the onset and on the day of onset (Pradhan et al., 2017).

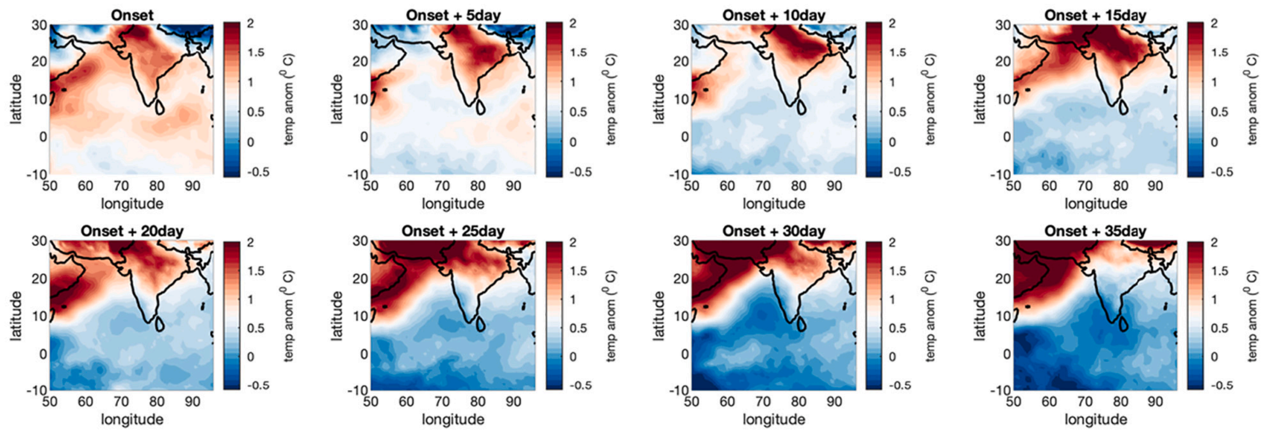
After the onset on monsoon when it further progresses to the central India (Fig. 9b), the change of sign shows very prominent over the IO and other oceanic region. Regions of AS and BoB started changing the sign. The warm condition over the monsoon trough region is showing warmer during the mid of June (Onset +15 days to Onset +20 days). This high temperature gradient over the monsoon trough region pulls the moisture loaded air towards the central India and advance of monsoon start progressing through the IGP and is the possible reason behind the early arrival of active/break phases of monsoon for this study. A deep negative anomaly is started forming over the AS and IO by the end of June (from Onset +25 days to Onset +30 days) or starting of July (Onset +30 days to Onset +35 days). Though, by the starting of the July, the warm condition over the central India is started diminishing as the ISV over the MCR region is activated and the region is started receiving the monsoon rainfall.

3.6. Model dependency on ENSO

Several studies have shown the limitations of RegCM4 under different climatic conditions (Zhong, 2006; Wang et al., 2015; Yang et al., 2018; Ghosh et al., 2019; Abish and Arun, 2019). A number of articles have pointed the dependency of ISMR simulation over India and its subregions with the ENSO and the SST variability over Niño regions (Sahai et al., 2003; Azad and Rajeevan, 2016; Raj Deepak et al., 2019; Verma and Bhatla, 2021). This kind of large-scale global circulation can be identified in global datasets. But the dynamical downscale model domain is limited over the south Asia CORDEX domain and respective domain does not cover the Niño regions. In the other side, the regional climate models are completely depended on the ICBC which is a global dataset. Therefore, there is a possibility that the signal of ENSO variability over the Niño regions forces into the model domain through the ICBC and can modulate the capability of the regional model in identifying the interannual and ISV of monsoon over the MCR region. Verification of the RegCM4 sensitivity during ENSO years has been designed with 4-time spans to address the model performance due to the ENSO



(a) : Tropospheric temperature gradient and ISM onset propagation from 3 days before the date onset over India.



(b) : Tropospheric temperature gradient from the date of monsoon onset and monsoon advance until the peak monsoon month of July.

Fig. 9. a-b: Climatology pattern of tropospheric temperature gradient (a) 3 days before (i.e. figure caption with *Onset -3 day*) the hits of onset over Indian region and (b) the advance of monsoon from the day of Onset (figure caption with *Onset*) till the start of the ISV in July (figure caption with *Onset* + *30 days* and *Onset* + *35 days*).

climate modes (Table 7). The rainfall patterns for the climatology period, Normal period, El-Niño period, and La-Niña period have been considered in the present study. Further, we have also considered two more climatic conditions i.e., warm and cold conditions. The warm/cold condition has been identified by +/− SST anomaly over Niño-3.4 region for JJAS period.

3.6.1. *SST anomaly and rainfall during different time span of ISM*

The association of all-India observed rainfall during different time span of ISM and SST anomaly over Niño-3.4 region can be analyzed from Table 7. The rainfall departure for the year 1982 is below normal (B) which is also an El-Niño year and the entire time span is indicating Weak El-Niño (WE). On the other side, in 1983, only JJA and JAS are indicating normal SST anomaly, and the rainfall departure of this particular year is representing above normal (A) condition. It is observed that most of the 'B' rainfall departure occurs during the El-Niño years, and the Indian subcontinent has received a good amount of rainfall either in La-Niña year or in cold conditions during the year span. CC between all India and MCR rainfall with the SST anomaly over Niño-3.4 region show the dependency of seasonal rainfall for different ISM span (JJA, JAS, JJAS) on SST anomalies during MAM, AMJ, MJJ, JJA and JAS (Table 8). The highest association (CC up to 0.44 for all region and 0.45 for MCR) during JAS and JJAS rainfall with JJA and JAS SST anomaly is also observed. From the table it can be stated that the MCR region is more impacted on the SST changes over the Niño-3.4 region along with all India regions. The negative CC between ISMR and SST over Niño-3.4 illustrates that the rise of SST over the region is the cause behind weakening of monsoon over the Indian subcontinent and vice-versa.

3.6.2. *Impact of ENSO conditions on Monsoon epochs*

The RegCM4 performance in simulating onset is presented in Table 4. For normal years, the model is able to simulate the date with a deviation of ±3 days. The model performance is quite well during this condition and can be considered as standard performance. During El-Niño years, the model performance deteriorates due to simulation of the onset dates with a deviation of ±8 days or more. This deviation in monsoon onset simulation simply explains the model's limitation to simulate the dates during those years and climatic condition (El-Niño) (Chevuturi et al., 2018). It may also be inferred that the model is strongly influenced by the large-scale events such as ENSO which may have affected onset simulation and hence a higher bias in the model simulation is noticed. On the other side, the model shows a much improved performance during the La-Niña years by simulating the deviation of ±1.5 days. The performance of the model in simulating the onset phase is not only much depends on the ENSO condition, but a similar tendency of the model performance in simulating active and break phases of monsoon has also been noticed during the similar climatic condition. Table 5 shows a tendency of higher deviation in active phases and less deviation during break phases under El-Niño climatic condition. A detailed explanation can be obtained from Fig. 10a-i.

The rainfall frequency and the deviation of model performance from the actual events show the nonconformity in model performance during the phases for Normal, El-Niño and La-Niña conditions (Fig. 10a-i).An average of ±7 days of deviation from actual onset date is observed during normal years (Fig. 10a) and the deviation is quite extended during El-Niño years (Fig. 10b) where some frequencies have reached its deviation to +15 days. During La-Niña years, the deviations in rainfall frequencies are very close to the actual onset (Fig. 10c). The RegCM4 simulated active phases are indicating a large frequency where a tendency of negative deviation (−10 to 0) is noticed (Fig. 10d). Although, most of the events occurred between −5 to 0 days and some of frequencies have been observed between +15 to +20 days. Identification of

Table 7
SST anomaly influence for El-Niño and La-Niño during 1981–2010 for three consecutive months March–April-May (MAM), April–May-June (AMJ), May–June-July (MJJ), June–July-August (JJA), July–August-September (JAS).

	MAM	AMJ	MJJ	JJA	JAS	Rainfall Departure
1981	> - 0.5	> - 0.5	> - 0.5	> - 0.5	> - 0.5	3.05 (N)
1982	WE	WE	WE	WE	WE	-11.09 (B)
1983	ME	WE	WE	< 0.5	< 0.5	15.57 (A)
1984	> - 0.5	> - 0.5	> - 0.5	> - 0.5	> - 0.5	1.16 (N)
1985	WL	WL	WL	> - 0.5	> - 0.5	-8.12 (N)
1986	> - 0.5	> - 0.5	< 0.5	< 0.5	< 0.5	-10.15 (B)
1987	ME	ME	ME	ME	SE	-15.70 (B)
1988	> - 0.5	WL	ML	ML	ML	16.27 (A)
1989	ML	WL	> - 0.5	> - 0.5	> - 0.5	4.79 (N)
1990	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	9.86 (N)
1991	< 0.5	< 0.5	WE	WE	WE	-5.03 (N)
1992	ME	ME	WE	WE	< 0.5	-5.08 (N)
1993	WL	WL	WE	< 0.5	< 0.5	4.80 (N)
1994	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	15.22 (A)
1995	< 0.5	< 0.5	< 0.5	> - 0.5	WL	-3.22 (N)
1996	> - 0.5	> - 0.5	> - 0.5	> - 0.5	> - 0.5	3.84 (N)
1997	< 0.5	WL	WL	ME	SE	5.39 (N)
1998	ME	WL	> - 0.5	WL	WL	3.92 (N)
1999	ML	ML	ML	WL	WL	-0.59 (N)
2000	ML	ML	WL	WL	WL	-5.88 (N)
2001	> - 0.5	> - 0.5	> - 0.5	< 0.5	> - 0.5	-4.04 (N)
2002	< 0.5	< 0.5	WE	WE	WE	-19.95 (B)
2003	< 0.5	> - 0.5	> - 0.5	< 0.5	< 0.5	2.74 (N)
2004	< 0.5	< 0.5	< 0.5	WE	WE	-9.94 (N)
2005	WL	< 0.5	< 0.5	< 0.5	< 0.5	3.62 (N)
2006	> - 0.5	< 0.5	< 0.5	< 0.5	< 0.5	5.21 (N)
2007	> - 0.5	> - 0.5	> - 0.5	> - 0.5	WL	13.08 (A)
2008	ML	WL	WL	> - 0.5	> - 0.5	7.27 (N)
2009	> - 0.5	< 0.5	< 0.5	WE	WE	-19.26 (B)
2010	WL	< 0.5	> - 0.5	ML	ML	2.27 (N)

SST Anomaly terms

0.5°C to 0.9°C	Weak El-Niño (WE).	-0.5°C to -0.9°C	Weak La-Niña(WL)
1.0°C to 1.4°C	Moderate El-Niño (ME)	-1.0°C to -1.4°C	Moderate La-Niña(ML)
Greater than 1.5°C	Strong El-Niño (SE).	less than -1.5°C	Strong La-Niña(SL)

Rainfall departure criteria (in % of long-term average)

> +10 = Above Normal (A) -10 to +10 = Normal (N) < -10 = Below Normal (B)

Table 8
Correlation between SST over Niño-3.4 region and Indian monsoon rainfall over all India and MCR.

		Sea surface temperature (SST)				
All India Rainfall		MAM	AMJ	MJJ	JJA	JAS
	JJA	−0.17	−0.23	−0.29	−0.31	−0.31
	JAS	0.18	0.00	−0.22	−0.37	−0.43
	JJAS	−0.02	−0.14	−0.30	−0.40	−0.44
MCR rainfall	JJA	−0.09	−0.19	−0.29	−0.35	−0.37
	JAS	0.22	0.05	−0.17	−0.33	−0.40
	JJAS	0.09	−0.07	−0.25	−0.35	−0.45

active days during El-Niño years are representing an earlier hit with a large negative deviation compared to the total number of active phases during El-Niño years (Fig. 10e). Simulation of active phases during La-Niña years show an opposite state where an earlier hit in model simulated phases along with a large positive deviation are observed during the phases (Fig. 10f). The NNRP1 downscaled RegCM4 simulation shows an earlier hit in break phase simulation which primarily occurred (maximum cases) between −5 to 0 days under normal climatic condition (Fig. 10 g). The maximum frequency is also observed between −10 to 0 days during El-Niño and La-Niña years (Fig. 10 h-i). The figure also illustrates that due to the lack of rainfall representation in model simulation during El-Niño years the break phases have increased, and model simulation has peaked the frequency of rainfall during the respective climatic conditions (Fig. 10 h). On the other side, the MCR region has received reasonable amount of rainfall during La-Niña which is the reason behind fewer frequencies in RegCM4 simulated break phases (Fig. 10i). In another direction, during El-Niño years the model simulated active phases are less than the actual number of rainy phases (Fig. 10e) and surplus the dry phases during the break periods (Fig. 10 h). At the same time, the RegCM4 simulates larger number of active days (Fig. 10f) and a lower number of dry days (Fig. 10i). Thus, it follows the general mechanism during La-Niña years.

Further, The warm/cold phases have been identified by positive (+)

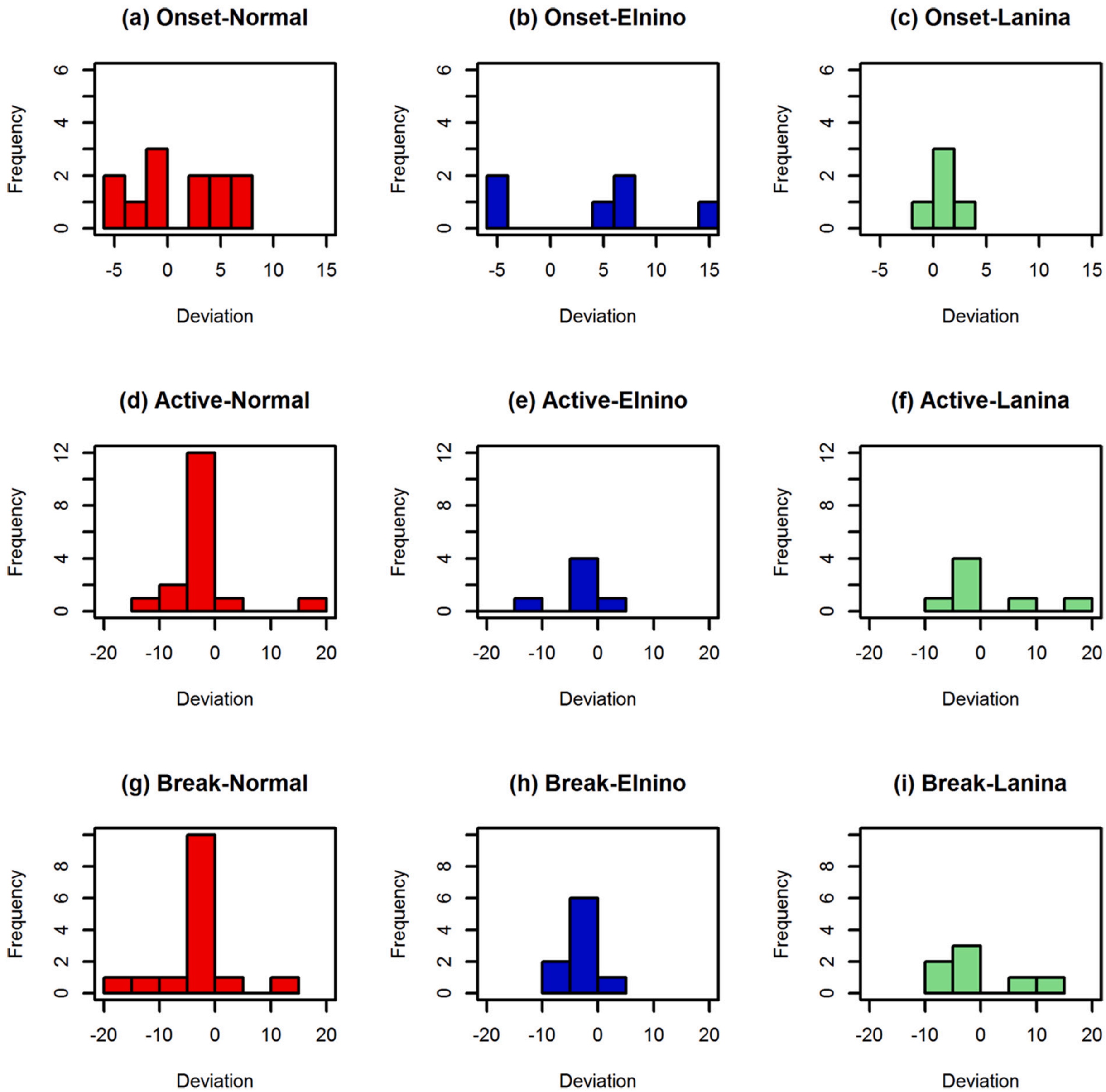


Fig. 10. a-i: Frequency in model deviation (in days) of onset, active and break events during Normal, El-Niño and La-Niña years.

/ negative (−) SST anomaly over Niño-3.4 region during JJAS period. In Fig. 11, it has been attempted to draw a line on the relationship between the SST variation over Niño-3.4 region and the model simulation of the monsoon epochs. Deviation of the onset period in model simulation from the actual onset date is simply considered same as the earlier discussion. The percentage deviation has been computed during active and break phases by dividing the difference between the number of RegCM4 simulated total active/break days and the mean of actual active/break days with the number of climatology years. The figure represents how closely the RegCM4 simulated deviation during onset, active and break phases are associated with the SST anomaly over Niño-3.4 region. It is observed that in each of the El-Niño years (WE, ME, SE), the model deviation in simulating the onset phase is minimum of 6 days whereas during La-Niña years the deviation is only 1 day. The model simulation during the warm phase shows larger deviation from the actual onset date but during cold phase the model performance is quite good. In warm phases, a large percentage of deviation in days is noticed during the active as well as break phases, and the tendency is high for active phase in comparison to the break phase simulation. Analysis has shown that the model performance degrades during the warm condition and model bias is reduced during the cold phase due to generation of enough rainfall during the active phases.

Fig. 12a-l represents the spatial distribution of ISM epochs during onset, active and break phases and the RegCM4 performance under warm and cold conditions. The figure shows that the model simulation agrees well with the actual rainfall pattern of onset phase during those periods (Fig. 12a-d). The rainfall is overestimated by the model over the Indo-Gangetic plain (IGP) and the southern peninsular region during the onset phases. The overestimation by model over the lower IGP is high during the warm phase. A tendency of heavy rainfall can be noticed in the observation during the active phases over the MCR under warm climatic condition (Fig. 12e-f). A rainband is clearly visible in the IMD observation while model shows rainfall deficit over the region. Though, the rainband over the MCR region is slightly weak during the cold condition, the rainfall tendency over the IGP and the north-east region of India is increased during the active phases and a rainband can be noticed in the IMD observation (Fig. 12 g). This rainband which covers the IGP and extends upto the north-east region during the active phases is well captured by the model simulated rainfall under the cold condition (Fig. 12 h). The lower IGP and the north-east region receive more rain

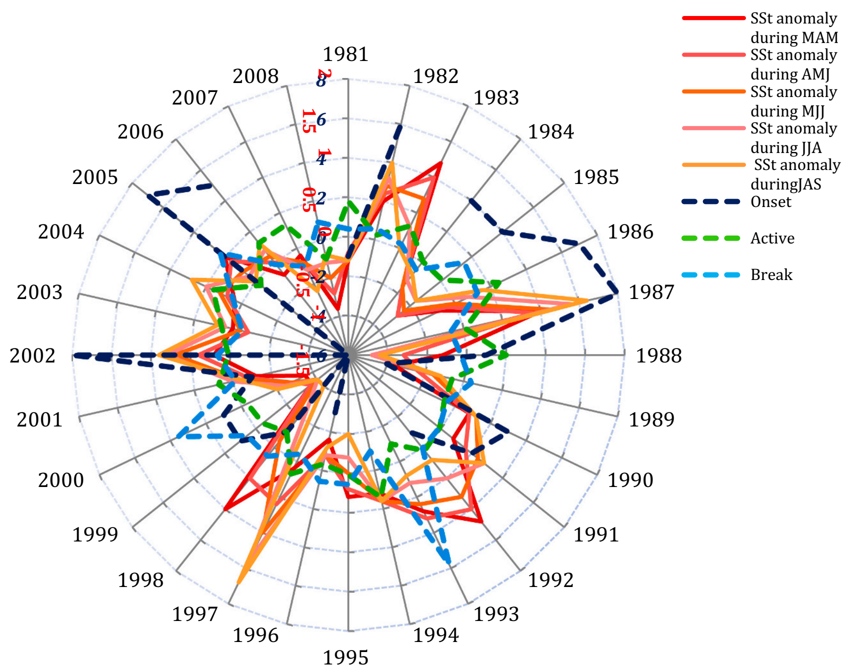


Fig. 11. Dependency of RegCM4 performance during different monsoon phases i.e., onset, active and break on SST anomaly over Niño-3.4 region. Axis with various red colors represents the SST anomaly during MAM, AMJ, MJJ, JJA and JAS and the combinations of blue stands for model deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

under the cold condition than warm condition during the break of monsoon (Fig. 12 k-l). An improved pattern under the cold condition by the model simulated break phase can be noticed over the lower IGP and north-east region. At the same time the deficit of rainfall over the leeward of western ghat region is noticed during active and break phases of monsoon in the IMD observation under the warm condition.

4. Conclusions

RegCM4 has been very popular to the meteorologists, climate modelers, and the policy makers to study the regional phenomena of atmospheric state at short-term climate scale. The authors find this model useful to simulate the different epochs of the ISM because of the flexibility in choosing the boundary and the parameterization schemes and the model performance over the complex topography.

Present study examines the performance of the RegCM4 in portraying three major ISM epochs (onset, active, and break phases). In-between, an opposite relationship is found between the SST changes over Niño-3.4 region and the summer monsoon rainfall over all India and MCR. RegCM4 is found suitable for the study of monsoon epochs by establishing high correlation with the IMD observation. The discussion emphasized that RegCM4 has a satisfactory skill in representing spatial distribution of rainfall during the monsoon season and its epochs. The northeast and southeast MCR are higher intense rainfall zones during the major monsoonal conditions (active and break conditions). The progression of model simulated rainfall indicates a late onset arrival and an early arrival of active and break phases over the MCR. Along with it, the RegCM4 simulated active phases indicate the inadequacy during the extreme events over the most rainfall prone regions of MCR.

The mechanism behind the issue in capturing monsoon phases can be demonstrated from the above results. Study shows that the model simulated temperature gradient and monsoon trough are very weak during the active phases over the MCR, which are very crucial for a strong/normal active phase, is weak in the RegCM4 simulation. Therefore, the MCR regions is experiencing a number of active spells rather than a normal or prolonged active phase. It can be noticed that the mechanism during the onset and break phases of monsoon are well represented in the model simulated rainfall, temperature at 850 hPa, mslp.

At the same time, RegCM4 is very efficient to present the pre-onset and monsoon advance mechanism. The positive and negative tropospheric temperature gradient over the Indian subcontinent and the IO region respectively has a great impact on delay/fast progress of monsoon onset (Li and Yanai, 1996). Low temperature gradient in the RegCM4 simulated temperature over the Indian/MCR (Nayak et al., 2019) reduces the convection during the pre-onset period which further diminishes in tropospheric temperature over the region and causes delay of monsoon onset (Pradhan et al., 2017). The monsoon advance mechanism from the day of onset to the peak monsoon months of July is simulated well in RegCM4 simulation. The high tropospheric temperature gradient over the monsoon trough region during the mid of June pulls (which is a bit early) the moisture loaded air towards the central India and advance of monsoon start progressing through the IGP. The early rise of the tropospheric heat gradient during the mid of June could be the possible reason behind the early arrival of active/break phases of monsoon this study.

Performance of the RegCM4 simulation depends on the SST variation over Niño-3.4 region. RegCM4 shows dry bias during the intra-seasonal and inter-annual monsoon variability simulations. In warm climatic conditions (El-Niño), the Indian subcontinent lacks monsoon rainfall (Raj Deepak et al., 2019). Though, MCR receives more rain during the active phases under warm condition while a special rainband is noticed over the IGP that is extended upto the north-east India during the cold condition. A decent amount of rainfall is also noticed over the lower IGP region during the break phases under cold condition. At the same time the leeward of Western Ghat region deficits of rainfall during the active and break phases of monsoon under the warm condition.

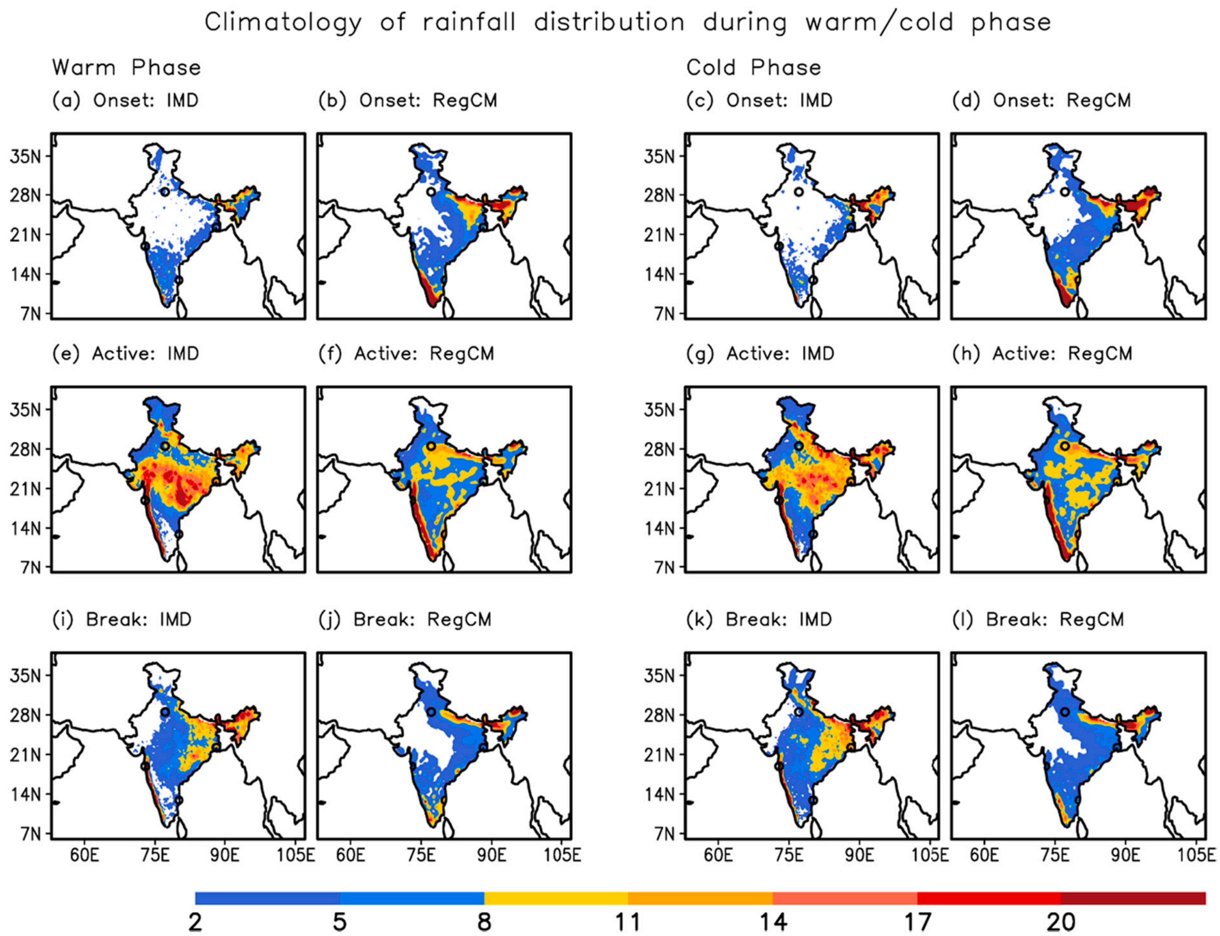


Fig. 12. a-l: Spatial distribution of IMD (a-e) and RegCM4 model simulated (f-j) rainfall climatology (mm/day) during Onset, active and break phases during warm and cold phases of ENSO. SST positive Anomaly over Niño-3.4 region is considered as warm phase and negative value over the same region is considered as cold phases.

Authors contribution

Authors RB and SG conceived the idea of the work. SG setup the model experiment, run the model, carried out the analysis and wrote the paper. PS guided the Lead author during the analysis. PS, RB, RKM and AS provided their expertise to improve the work quality. SG, AS and RB revised the paper. All the authors read the paper and accepted the authors' agreement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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