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RESEARCH ARTICLE

How good is regional climate model version 4 in simulating the monsoon onset over Kerala?

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This study assesses the performance of regional climate model version 4 (RegCM4) in simulating the monsoon onset over Kerala (MOK). It also examines any possible relationship between the onset dates with the summer monsoon rainfall over India as whole as well as each grid points of the India land points and also the moisture inflow into Indian subcontinent. A 30-year long simulation starting from 1979 till 2008 was carried out with the lateral boundary forcings provided by European Centre for Medium Range Weather Forecasts Reanalysis (ERA-interim) at 25 km horizontal resolution. The simulated climatological MOK date is found to be 28th May, while as per the India Meteorological Department, climatological normal onset date is 1st June. The model has performed well in simulating the inter-annual variation of MOK during the study period. The correlation coefficient between model simulated and observed MOK is 0.83 significant at 95% confidence level. In both model and observations, the MOK is weakly correlated with All India Summer Monsoon Rainfall. Again, the model skill was examined through equitable threat score (ETS). The ETS score is high for normal (0.48) and delayed (0.42) onset years, while the score is very low in early onset years. The spatial patterns of rainfall over central India are very similar in early and normal onset years. The model has performed well in reproducing the moisture inflow in to the Indian subcontinent from all the directions in most of the years, but there is no one-to-one relation between different categories of MOK years with total rainfall and net moisture inflow. Based on this study, it is found that RegCM4 reproduces different aspects of MOK reasonably well.

KEYWORDS

equitable threat score, ERA-interim, monsoon onset over Kerala, moisture Inflow, RegCM4

1 | INTRODUCTION

Monsoon onset over Kerala (MOK) is one of the key features of Indian summer monsoon; it marks the commencement of the rainy season over India. It is well known that the climatological date of MOK is 1st June; however, it varies by a few days from year to year with a standard deviation of 8 to 9 days (Ananthakrishnan and Soman, 1991; Joseph *et al.,* 1994). The variations in the timing of MOK can have a significant influence on agricultural productivity. A delay in the onset of the monsoon by a few days can affect the initiation of agricultural activity while an early onset might not be utilized to its full advantage without an advanced forecast. India's agricultural output, economy, and societal well-being depend significantly on the timing of the MOK. Thus, the monitoring and forecasting of MOK are essential for the economy of the country.

During the onset phase (mainly in the month of May and June), sudden changes in the surface and upper air parameters are observed over the Arabian Sea and southern part of the Indian peninsula. Considering these sudden changes, it is a difficult task for the researchers to predict the monsoon onset over Kerala (Kar *et al.,* 2014). Several scientific papers have given a lot of attention to the prediction of onset of south west monsoon over India (Ananthakrishnan *et al.,* 1983; Ananthakrishnan and Soman, 1988; Soman and Kumar, 1993; Joseph *et al.,* 1994; Joseph *et al.,* 2006; Sahu *et al.,* 2008; Pai and Nair, 2009; Ratna *et al.,* 2011; Dodla *et al.,* 2013; Sharma and Babel, 2013). The MOK is associated with changes in the large-scale dynamical parameters as well as local moisture parameters (Ananthakrishnan *et al.,* 1983; Ananthakrishnan and Soman, 1988; Soman and Kumar, 1993; Joseph *et al.,* 1994; Joseph *et al.,* 2006; Pai and Nair, 2009). During the onset time, significant changes in the large-scale atmospheric and oceanic circulations is observed in the Indo-Pacific region. Monsoon onset also comprises steady accumulation of moisture (Pearce and Mohanty, 1984; Soman and Kumar, 1993) and kinetic energy (Ananthakrishnan *et al.,* 1983) over the Arabian Sea. Prior to the monsoon onset, strengthening of south westerlies, enhancement of moisture transport and growth of strong convection over the equatorial Bay of Bengal are observed (Wang and Fan, 1999; Flatau *et al.,* 2001; Sahu *et al.,* 2017). During the onset phase, Joseph *et al.* (1994) found that there is a band of deep convection in the east–west direction across Kerala, a maximum cloud zone. They found that this cloud band passing through Kerala had genesis over the Indian Ocean, three to four pentads before MOK and during the following pentads steadily increased in area and intensity. The axis of deep convection moved northwards bringing monsoon rains to Kerala.

There are many definitions available for identifying the MOK dates (Ananthakrishnan and Soman, 1988; Fasullo and Webster, 2003; Joseph *et al.,* 2006; Xavier *et al.,* 2007; Pai and Nair, 2009; Wang *et al.,* 2009). According to Ananthakrishnan and Soman (1988), onset dates reflect the temporal variation of rainfall, but it could be affected by local variability and not correctly represent the large-scale variation. Fasullo and Webster (2003) included the effect of large-scale circulation, but representativeness in terms of the actual precipitation was not discussed. In other studies, criteria directly related to rainfall or convective clouds were used (Yin, 1949; Murakami *et al.,* 1984; Joseph *et al.,* 1994). However, strong low-level westerly winds, deep convection and its abrupt formation are also principal features of the Indian Summer Monsoon (Joseph *et al.,* 2006). Therefore, India Meteorological Department (IMD) is currently using the MOK criteria (Flatau *et al.,* 2001; Pai and Nair, 2009), which takes account of the rainfall, wind field, and outgoing longwave radiation (OLR). Since the MOK criteria used by IMD consider the rainfall amount, circulation pattern and convective processes, it is the most robust technique to identify the onset (Joseph *et al.,* 2006; Pai and Nair, 2009). The variations in the timing of onset and withdrawal of the MOK might influence the length of the summer monsoon season over India. Therefore, the variation in the length of summer monsoon season may affect the seasonal mean rainfall (Fasullo and Webster, 2003; Taniguchi and Koike, 2006; Pattnayak *et al.,* 2013).

Ji and Vernekar (1997) simulated the summer monsoons of 1987 and 1988 by using the NCEP Eta model nested in the Center for Ocean-Land-Atmosphere (COLA) GCM and their results indicate improvements in the onset and progress of monsoon and associated rainfall distribution with respect to the COLA GCM, when the NCEP Eta nested model was used. Pattnayak *et al.* (2017) made a short simulation of 7 years from 1997 till 2003 and shown that RegCM has successfully simulated the monsoon onset over India. The onset criteria of Fasullo and Webster (2003) were adopted in their study.

Forecasting the exact timing of the MOK still poses a key research challenge with significant implications on water resources and management policies (Mall *et al.*, 2006; Archer *et al.,* 2010; Kar *et al.,* 2012; Kar *et al.,* 2014; Tiwari *et al.,* 2016). Very few monsoon onset studies have been done using regional models (Jyoti *et* al., 2012; Bhatla *et al.,* 2016; Pattnayak *et al.,* 2017). Therefore, the primary goal of this study is to quantify the ability of regional climate model version 4 (RegCM4) in simulating the monsoon onset and associated mechanisms. This study will also examine the spatial distribution of rainfall during different categories of monsoon onset years. Furthermore, an attempt has been made to find the possible relationship between the monsoon onset and total moisture flux inflow in to the Indian subcontinent. A brief discussion of the data, experimental design and methods used in this study are given in Section 2. Section 3 provides the capability of RegCM4 in simulating the MOK and other aspects during the onset. The important results obtained in this study are summarized in the concluding Section 4.

2 | DATA, EXPERIMENTAL DESIGN AND METHODOLOGY

2.1 | Data

The initial and boundary conditions for the simulation were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-interim) reanalysis $0.75^\circ \times 0.75^\circ$ gridded reanalysis (Dee *et al.,* 2011), which is the third generation ECMWF reanalysis product. The elevation data used are obtained from the United States Geological Survey (USGS). Global Land Cover Characterization (Brown *et al.,* 1999) dataset at 10 min resolution is used to create vegetation and land-use files. The simulated rainfall has been compared with observational data from IMD at $0.5^\circ \times 0.5^\circ$ resolution by (Rajeevan and Bhate, 2009). The IMD gridded rainfall dataset was developed using quality-controlled rainfall data from more than 3,000 rain gauge stations over India for the period 1971–2005. This data set is prepared at regular grids using observed data at stations which are not at the same grids. Thus, interpolation and statistical methods are involved in gridded data preparation. In the process there may be some smoothing effect and differences exist with respect to the station data. The wind field has been validated against the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay *et al.,* 1996), whereas the model simulated OLR has been compared with National Oceanic and Atmospheric Administration (NOAA) dataset (Liebmann and Smith, 1996). For model evaluation, the simulated fields have been interpolated to the respective observed or reanalysis data grids.

2.2 | Experimental design

To study the ability of regional climate model in simulating monsoon onset over Kerala, the fourth version of regional climate model of International Centre for Theoretical Physics RegCM4 (Giorgi *et al.,* 2012) over South Asia domain (Figure 1a) has been chosen. RegCM4 is the outcome of a new step in recoding (Giorgi *et al.,* 2012) of the RegCM3 (Giorgi *et al.,* 1993a; Giorgi *et al.,* 1993b; Pal *et al.,* 2007). The model is hydrostatic and includes a number of options for physical parameterizations (Giorgi *et al.,* 2012). This domain over South Asia has been adopted from the framework of World Climate Research Programme (WCRP) organized experiment known as the COordinated Regional Climate Downscaling EXperiment (CORDEX) (Giorgi *et al.,* 2008). Dash *et al.* (2014) showed that South Asia CORDEX domain is the ideal domain for studying Indian summer monsoon using RegCM4. The domain covers the region 10°–130°E and 22°S–49°N at 25 km resolutions in both latitudinal and longitudinal direction (Figure 1a).

A simulation of 30 years starting from 1st January 1979 up to the end of December 2008 has been carried out using RegCM4. The choice of the physical parameterization schemes has been made based on the study carried out by Dash *et al.* (2014) over the same South Asia CORDEX domain. The physical parameterization schemes used in these experiments are radiation scheme and planetary boundary layer scheme of Kiehl *et a*l. (1996) and Holtslag *et al*. (1990), respectively. Different cumulus parameterization schemes were used over land and ocean such as MIT Emanuel scheme (Emanuel, 1991; Emanuel and Živković-Rothman, 1999) over land and Grell scheme (Grell, 1993) with Fritsch and Chappell (1980) convective closure scheme over the ocean. SUBEX scheme of Sundqvist *et al.* (1989) have been used for large-scale precipitation scheme and Zeng's ocean flux parameterization (Zeng *et al.,* 1998) have been used for this study. Diurnal cycle sea surface temperature scheme of Zeng and Beljaars (2005) has been enabled and model desert seasonal albedo variability has been disabled in this simulation.

2.3 | Methodology

In order to evaluate RegCM4 in simulating MOK, the climatological and inter-annual variation of onset has been calculated. Further, the model skill has been evaluated through equitable threat score. This study also discusses the moisture flux inflow and outflow across the Indian subcontinent. All of these methodologies adopted in this study have been discussed in the following subsections.

2.3.1 | Monsoon onset criteria

For identifying the onset of monsoon over Kerala, IMD's latest definition suggested by (Joseph *et al.,* 2006) has been adopted for this study. The criteria are as follows:

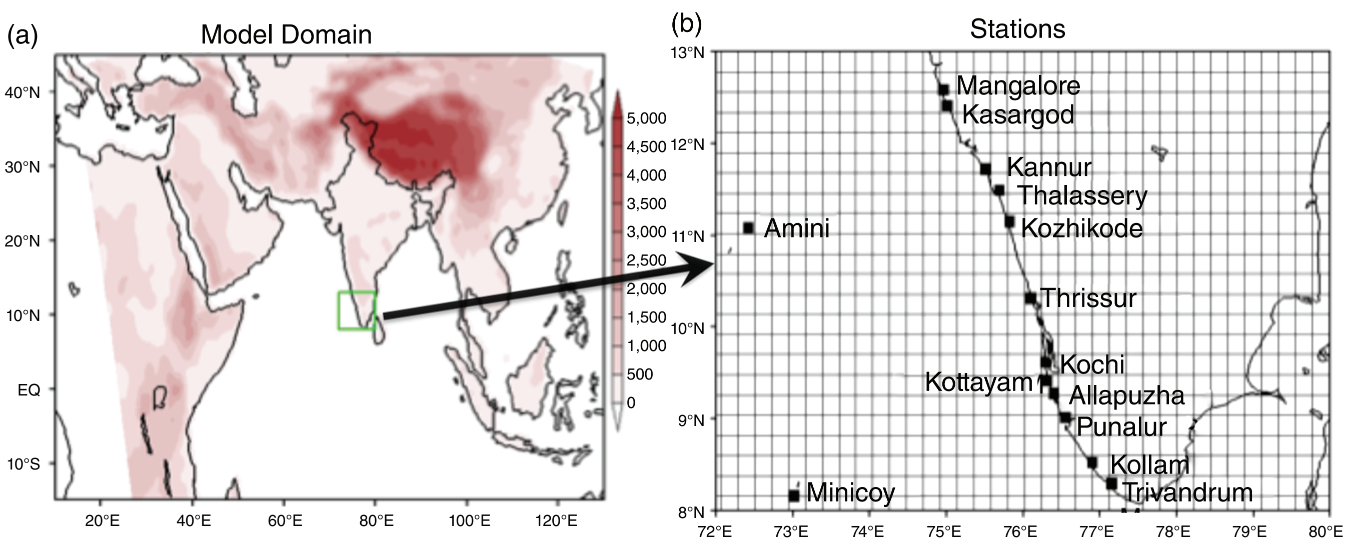

FIGURE 1 (a) Topography of model domain (in meters) over which RegCM4 has been integrated. (b) Location of 14 stations over which the model simulated rainfall has been compared with the IMD 0.5 gridded rainfall to identify the monsoon onset over Kerala

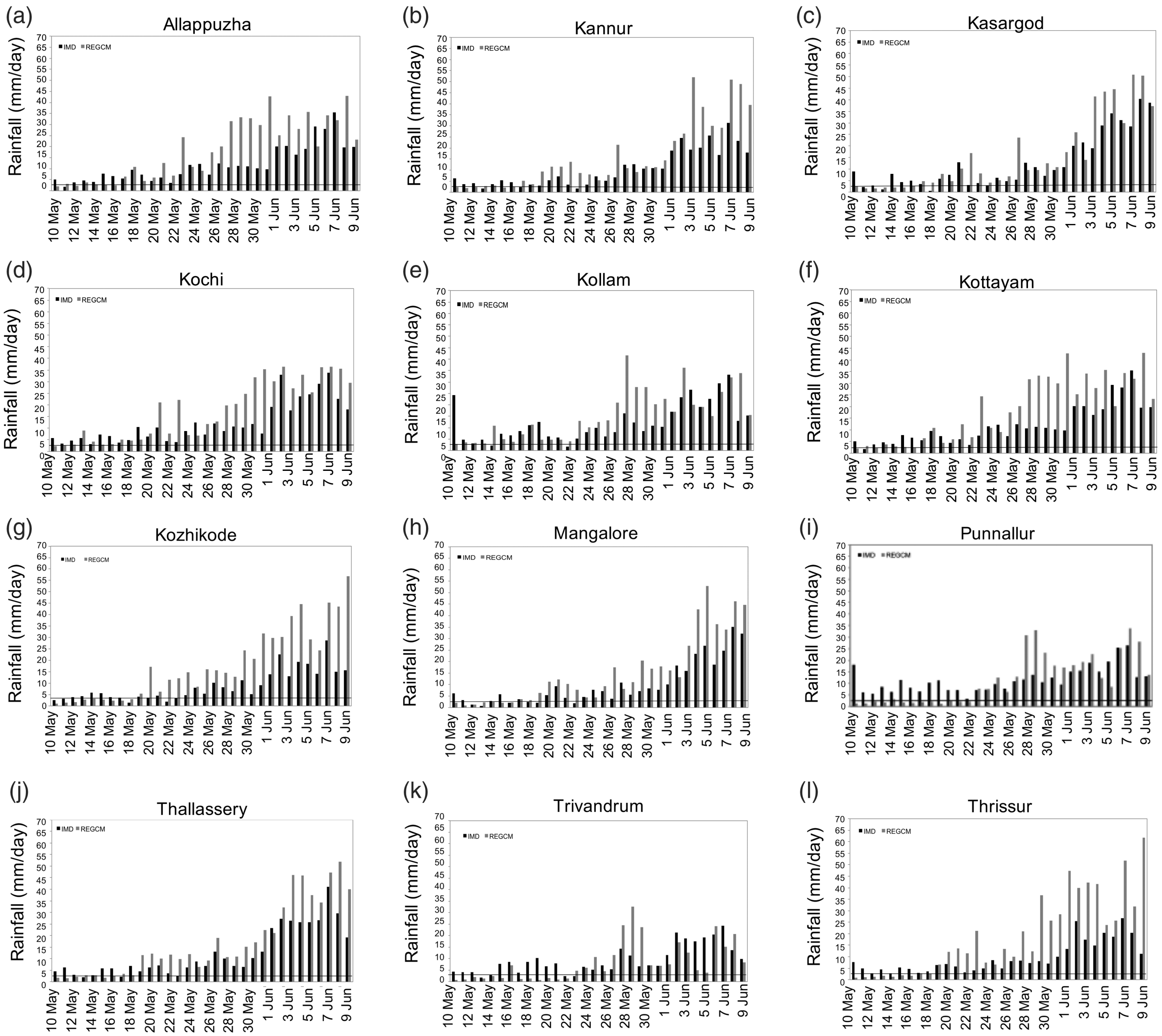

FIGURE 2 (a–f) Climatological daily mean rainfall from 10th May till 9th June as recorded in IMD (*black bars*) and simulated by RegCM4 (*grey bar*) for the period 1979–2008 over (a) Allappuzha, (b) Kannur, (c) Kasargod, (d) Kochi, (e) Kollam and (f) Kottayam. (g–l) Climatological daily mean rainfall from 10th May till 9th June as recorded in IMD (*black bars*) and simulated by RegCM4 (*grey bar*) for the period 1979–2008 over (g) Kozhikode, (h) Mangalore, (i) Punnallur, (j) Thallassery, (k) Trivandrum and (l) Thrissur

i. If after 10th May 60% of the available 14 stations (Figure 1b) enlisted, viz. Minicoy, Amini, Trivandrum, Punnalur, Kollam, Allapuzha, Kottayam, Kochi, Thrissur, Kozhikode, Thalassery, Kannur, Kasargod and Mangalore report rainfall of 2.5 mm or more for two consecutive days, the onset over Kerala will be declared on the 2nd day, provided the other two criteria are also in concurrence.
ii. The depth of westerlies should be maintained up to 600 hPa, in the box equator to latitude 10°N and longitude 55°–80°E. The zonal wind speed over the area bounded by latitude 5°–10°N, longitude 70°–80°E should be of the order of 15–20 knots (~7–10 m/s) at 925 hPa.
iii. INSAT derived OLR value should be below 200 wm^{-2} in the box confined by latitude 5°–10°N and longitude 70°–75°E.

When all the above criteria are satisfied, then the monsoon onset over Kerala is declared. For the first MOK criteria, the IMD grid point closest to the 14 stations presented in Figure 1b were selected. In order to identify the MOK simulated in the model, the simulated daily rainfall, wind and OLR have been calculated based on the above criteria and compared with MOK computed from the IMD0.5 gridded daily rainfall, NCEP/NCAR wind and NOAA OLR datasets.

2.3.2 | Equitable threat score

Skill of RegCM4 in simulating MOK over the inter-annual time scale is measured using equitable threat score (ETS). ETS measures the fraction of observed and/or simulated events that were correctly simulated and adjusted for hits associated with random chance. A higher value of ETS indicates the better skills of the model in simulating the particular event. The ETS is defined as

$$\mathrm{ETS} = \frac{H - H_r}{H + M + F - H_r}, \quad (1)$$

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

Here, H, M and F are Hits, Misses and False alarms for each category, respectively. H_r is the hits due to random chance and T is the total number of events. The value of ETS ranges between −0.33 and 1. When ETS equals to 0 there is no skill in the model simulation.

2.3.3 | Moisture flux inflow and outflow

To conduct an analysis of large-scale moisture transport into and out of the Indian subcontinent, wind fields from surface to top of the atmosphere were averaged and used to identify the dominant atmospheric transport patterns for the inflow and basin outflow transects (Figure 8). Column-integrated northward and eastward water vapour fluxes were used to estimate average moisture flow across these transects for the period of 1979–2008. The moisture flux transport is by definition the product of the precipitable water and an equivalent velocity integrated over the height of the atmosphere, that is, the depth-averaged wind velocity weighted by humidity (Liu and Tang, 2005). The moisture flux transport (Q) is calculated as

$$Q = \int_{\mathrm{Surface}}^{\mathrm{Top}} \rho q V dz, \quad (2)$$

where ρ is atmospheric air density, q is specific humidity, z is height and V is horizontal wind. Total moisture transport (Q) into (inflow) or out of (outflow) the Indian subcontinent (Figure 8) has been calculated by multiplying the length of the boundary each side. The sign of the net moisture flux (Q) indicates the inflow (positive sign) or outflow (negative sign).

3 | RESULTS AND DISCUSSION

This section deals with the study of climatological and interannual variation of MOK in observations and simulated by RegCM4 for the period 1979 to 2008. For identifying the climatological MOK, the climatic fields from the model and observations have been calculated by averaging the daily fields for the entire period of study, that is, 1979 to 2008 and plotted in Figures 2–4.

3.1 | Climatological MOK

As per the first criteria of MOK, the long-term daily means of precipitation over 12 stations for the period 10th May till 9th June has been plotted in Figure 2a–l. In this study, only 12 stations out of 14 stations have been considered as the two stations Amini and Minicoy lies outside the Indian landmass where IMD0.5 gridded observed rainfall is not available. The rainfall over the 12 stations (Figure 1b) has been interpolated from the nearest grid point. All the 12 stations are in the radius of less than 10 km from its nearest IMD grid points, therefore, it is fair to interpolate from the model grids to IMD observations. Similar nearest grid point interpolation approach has been used in Dash *et al*. (2012). It can be seen that the rainfall is less than 2.5 mm/day in most of the stations till 25th May in both model simulations as well as in the IMD observation. Then, the rainfall has increased suddenly in all the stations. All other stations received more than 2.5 mm/day of rainfall. The model shows a consistent increase in rainfall after 22nd May. In most of the stations, the model simulated rainfall matches well with the IMD0.5 observed rainfall. The rainfall is more than 2.5 mm/day in model simulations and observations after 26th May and 28th May, respectively, in more than 75% of the stations. According to the criteria I of MOK, the onset date will be 27th May and 29th May in RegCM4 and IMD0.5 gridded observed rainfall provided the other two criteria will be satisfied.

To assess the second criteria for MOK, the zonal components of the wind from the model simulation and NCEP/NCAR reanalysis have been averaged over the box bounded by equator to latitude 10°N and longitude 55–80°E for each of the standard pressure levels from starting from 1,000 to 600 hPa viz. 1,000, 925, 850, 700, and 500 hPa. The climatological daily mean of the zonal component of the wind over box from 10th May till 9th June has been shown in Figure 3. It can be clearly observed that the value of the zonal component of the wind is positive, which indicates that the southwesterly wind already sets in the box explained above after 10th of May in both model and reanalysis datasets. In RegCM4, the zonal wind speed reached 7 m/s on 26th May but again it dropped below 7 m/s on very next day and then after 28th May, the wind speed is consistently more than the threshold value. In case of the NCEP/NCAR reanalysis dataset, the zonal wind speed reached the threshold value on 28th May but again it dropped below 7 m/s and after 1st June the wind speed increased and crossed the threshold value. Based on the second criteria, 28th May and 1st June are the dates when the model and reanalysis datasets, respectively, satisfy the criterion of MOK. It can be noticed from Figure 3 that the westerlies were stronger in the RegCM4 simulation at all the levels (Figure 3). Probably, this might be the reason why more moisture was advected in to the Kerala region during the onset phase. In order to assess the ability of the model in simulating the third criteria of MOK, the climatological daily mean of OLR from the NOAA and RegCM4 have been averaged over latitude 5°–10°N and longitude 70°–75°E. The time series of the long-term daily mean of OLR from 10th May till 9th June from both model and observations have been depicted in Figure 4. It can be observed that the OLR from NOAA has dropped

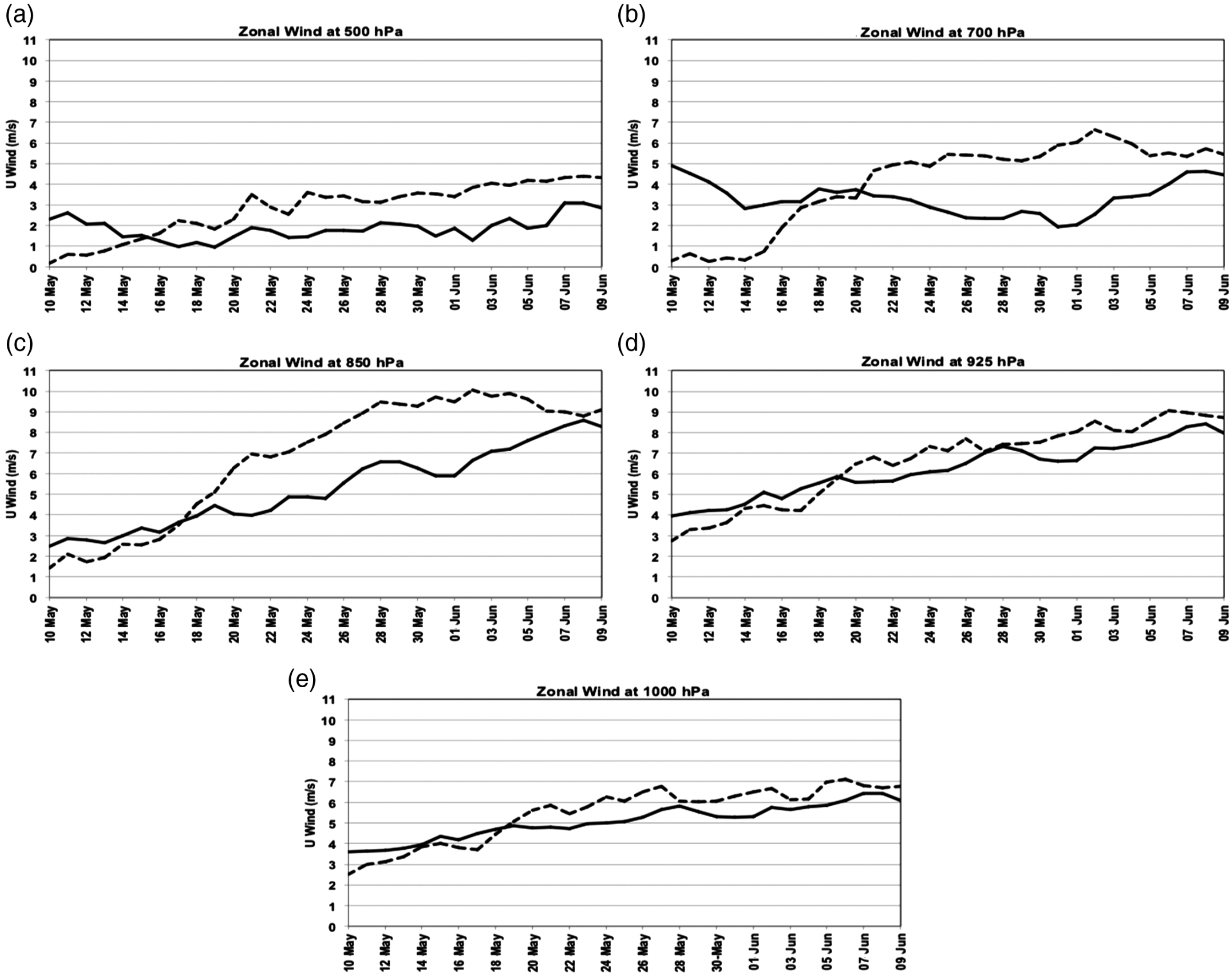

FIGURE 3 Climatological daily time series of zonal component of wind (m/s) from RegCM4 (dashed curve) and NCEP/NCAR reanalysis (solid curve) at (a) 500 hPa, (b) 700 hPa, (c) 850 hPa, (d) 925 hPa and (e) 1,000 hPa for the period 1979–2008. The average has been calculated over the region bounded by 5°–10°N and 70°–80°E

below 200 w/m^2 on 26th May, while the model simulated OLR has reached below 200 w/m^2 on 29th of May.

Based on the analysis discussed above, RegCM4 and the observations satisfy all the three criteria on 28th May and 1st June, respectively. Thus, the simulated climatological MOK is 28th May, which is 3 days prior to the observed date of onset. From this analysis, it is observed that RegCM4 has performed reasonably well in simulating the climatological MOK.

3.2 | Relationship between MOK and all India summer monsoon rainfall

This section deals with the inter-annual variability of MOK and its possible relationship with all India summer monsoon rainfall. The MOK has been calculated based on the criteria provided in Section 2 for each of the years starting from 1979 to 2008 is shown in Table 1. The mean onset date calculated by taking the average for the period 1979 to 2008 is 2nd June in both model and observation. For calculating the inter-annual variations of all India summer monsoon rainfall, the rainfall values have been averaged and weighted over the Indian land points in each of the years starting from 1979 to 2008. Figure 5 shows the inter-annual variations of MOK (line curve) and rainfall over whole India (bar graph) observation and model simulations for the period 1979 to 2008. It is found that the onset dates in simulated in RegCM4 follow a similar pattern as in the gridded observations in all the years (Figure 5a). The correlation coefficient between the simulated and observed MOK is 0.83, which is significant at 95% confidence level. In 24 years out of the 30 years, the bias is less than 2 days. In the summer monsoon rainfall contrasting years such as 1982 and 1983, 1987 and 1988, 2002 and 2003 (Pattnayak *et al.*, 2013; Pattnayak *et al.*, 2015), the onset dates simulated by RegCM4 are close to observed onset dates. The aim of presenting the MOK and all India summer monsoon rainfall on the same plot (Figure 5a) is to show the relation between these two. The correlation between MOK and all India summer monsoon

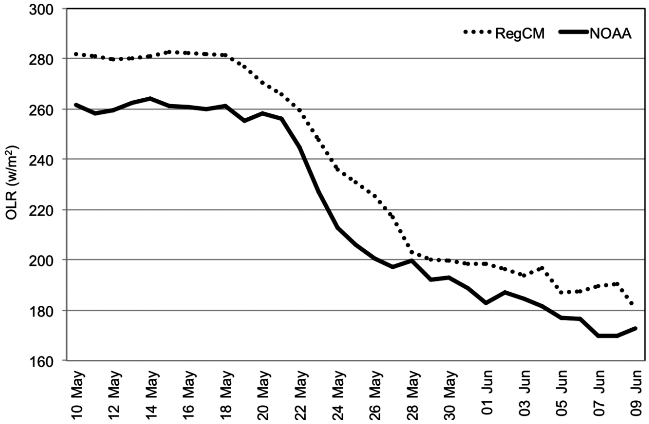

FIGURE 4 Climatological daily time series of outgoing longwave radiation (w/m^2) in RegCM4 (dotted line) and NOAA (solid line) for the period 1979–2008. The average has been calculated over the region bounded by 5°–10°N and 70°–75°E

rainfall is 0.02 in the observation and 0.1 in the model. Thus, the relation between the monsoon onset dates and all India summer monsoon rainfall is not significant.

Further, the relationship between the MOK and seasonal rainfall over the whole of India has been analysed. The correlation of MOK date with each of the grid points in the Indian subcontinent has been calculated and shown in Figure 5b,c. It is inferred that neither in the model simulation nor in observations, there is any region in India where the rainfall is strongly correlated with MOK. The correlation value ranges from −0.4 to 0.4 but it is not significant. Over the central India and northeast India, the MOK is found to be negatively correlated, while rest of the India is positively correlated with seasonal rainfall in both IMD observation and RegCM4 simulation. From observations, the correlation value ranges from −0.2 to −0.4 over central India and − 0.2 to −0.3 over northeast India. In the Peninsular India, the correlation values are very low (0.05 to 0.2) and over northwest and north India, it is 0.2 to 0.3. The correlation values are quite similar in the RegCM4 simulations; however, the spatial patterns are slightly different in IMD gridded observations. Since the correlation values of MOK with rainfall over India as whole and with different regions is not significant, the total summer monsoon rainfall over India is not dependent on the timing of monsoon onset over Kerala.

3.3 | Skill of RegCM4 in simulating different MOK categories

In this section, the skill of RegCM4 in simulating MOK over the inter-annual time scale is measured using ETS. MOK is considered as early if it has occurred 8 days or more before 1st June, normal if it has occurred within ±7 days of 1st June, and if MOK is 8 days or more after 1st June, it is defined as delayed (Pai and Nair, 2009; Preenu *et al.*, 2017). These three categories of onset years in observations and RegCM4 simulations are shown in Table 2 and the ETS has been calculated for these three categories of onsets. Figure 6 shows the ETS values of each onset categories for the period of study. ETS has been calculated using the onset dates of each of the years simulated by RegCM4 and observation. Computed ETS for each of the categories indicates that the score is very small for early onset category (0.04). In case of normal and delayed onset years, the ETS is calculated to be 0.48 and 0.42, respectively. The model has a higher score in simulating the normal and delayed onset than the early onset years. Thus, the model yields higher skills in normal and delayed onset years.

3.4 | Spatial distribution of climatic fields during the composites of early, normal and delayed onset years

The spatial distribution of rainfall during different categories of onset years is presented in this section. Therefore, the composite of early, normal and delayed onset years has been computed for rainfall in the observations and model

TABLE 1 MOK dates for the study period based on the observations and RegCM4 simulation

Years	IMD Onset date	RegCM4 Onset date	Type of onset	
			Observation	Model
1979	12-June	10-June	D	D
1980	03-June	01-June	N	N
1981	30-May	29-May	N	N
1982	30-May	28-May	N	N
1983	12-June	09-June	D	D
1984	01-June	01-June	N	N
1985	24-May	29-May	E	N
1986	12-June	06-June	D	N
1987	01-June	30-May	N	N
1988	02-June	05-June	N	N
1989	04-June	04-June	N	N
1990	18-May	31-May	E	N
1991	02-June	04-June	N	N
1992	05-June	04-June	N	N
1993	03-June	02-June	N	N
1994	28-May	25-May	N	E
1995	10-June	06-June	D	N
1996	09-June	07-June	D	N
1997	12-June	15-June	D	D
1998	03-June	31-May	N	N
1999	22-May	27-May	E	N
2000	01-June	30-May	N	N
2001	26-May	28-May	N	N
2002	09-June	05-June	D	N
2003	13-June	08-June	D	D
2004	03-June	03-June	N	N
2005	07-June	05-June	N	N
2006	26-May	29-May	N	N
2007	28-May	25-May	N	E
2008	31-May	29-May	N	N

Note. Different categories of onset i. Early (E) ii. Normal (N) and iii. Delayed (D) onsets.

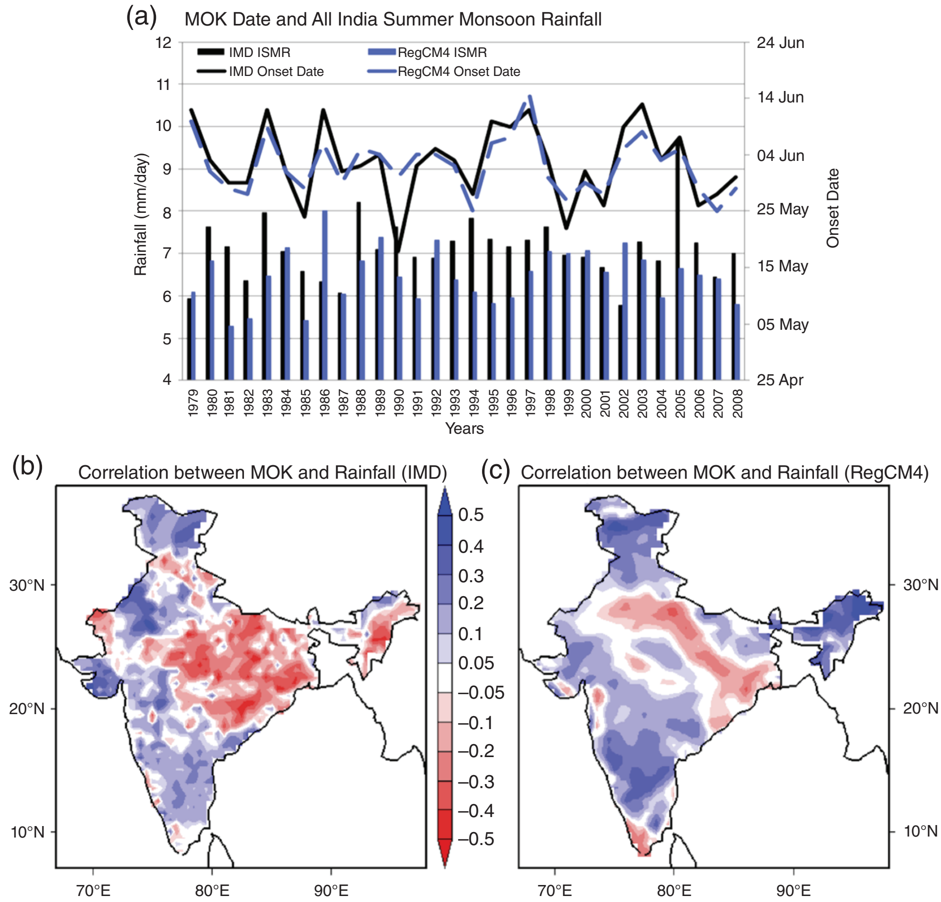

FIGURE 5 (a) Inter-annual variations of monsoon onset over Kerala (line curves) and Indian summer monsoon rainfall averaged over Indian land point (bar graph) for the period 1979 to 2008. Y-axis on the left side corresponds to the ISMR, while right side axis corresponds to monsoon onset dates over Kerala. Black and blue line curve represents to IMD observed and RegCM4 simulated MOK dates. (b) Correlation between the MOK and IMD rainfall over each of the grid points. (c) Same as (b) but for RegCM4

simulation. The model simulation and observations have different years in each of the category. The model composite is calculated based on the 30 years simulations model, while all the observed composite is based on the observed data. Thus, it is not necessary that the specific category is based on similar years in model and IMD0.5 gridded observation. Main aim of such computation is to assess the ability of the model whether it is able to replicate the similar spatial patterns of the climatic fields during specific category of monsoon onset years. Figure 7 shows the JJAS rainfall in the composite of early, normal and delayed onset years. In the IMD observations, the spatial pattern of rainfall over central India in the early and normal categories are similar, both of them being different from the spatial pattern of the delayed onset category. During the early and normal onset years, the observation shows that a major portion of central India receives rainfall of about 8–16 mm/day (Figure 7a,b), while the spatial extension relatively less in the delayed onset years (Figure 7c). But in Peninsular India, the spatial

TABLE 2 Different categories of MOK based on the observations and RegCM4 simulation

Onset categories	Observation (based on IMD0.5 gridded data set)	RegCM4 simulation
Early onset years	1985, 1990, 1999	1994, 2007
Normal onset years	1980, 1981, 1982, 1984, 1987, 1988, 1989, 1991, 1992, 1993, 1994, 1998, 2000, 2001, 2004, 2005, 2006, 2007, 2008	1980, 1981, 1982, 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1995, 1996, 1998, 1999, 2000, 2001, 2002, 2004, 2005, 2006, 2008
Delayed onset years	1979, 1983, 1986, 1995, 1996, 1997, 2002, 2003	1979, 1983, 1997, 2003

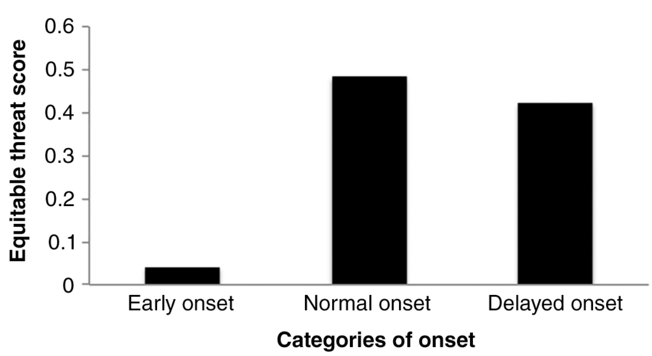

FIGURE 6 ETS estimated for three different onset categories namely, early onset (8 days or more before 1st June), normal onset (within ±7 days of 1st June) and delayed onset (8 days or more after 1st June) obtained from RegCM4 simulations during 1979 to 2008

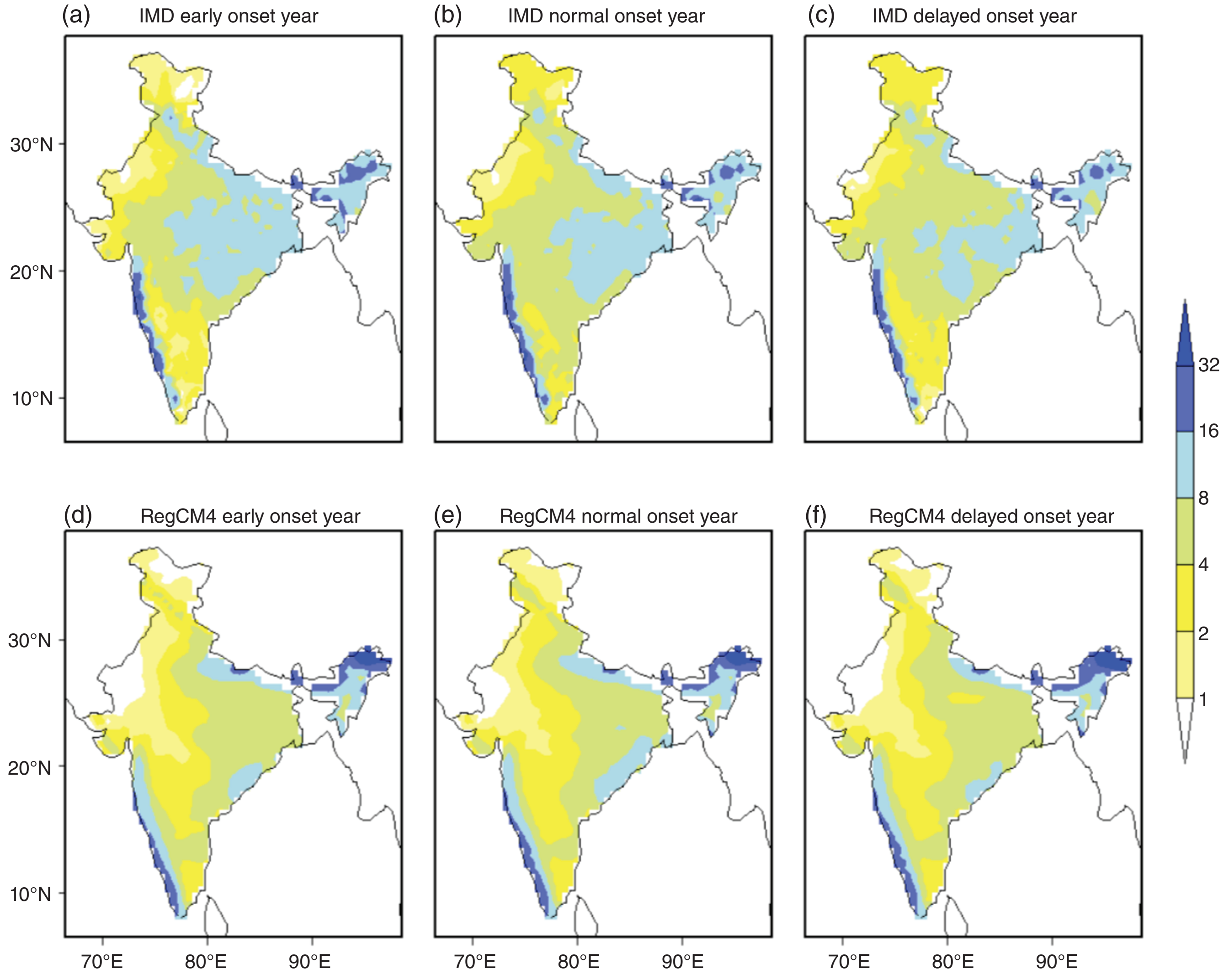

FIGURE 7 JJAS rainfall (mm/day) in the composite of early onset years (left column), normal onset years (centre column) and delayed onset years (right column) during the study period. Top and bottom row represents rainfall from the IMD0.5 gridded observation and RegCM4, respectively

distribution of rainfall in the early onset years resembles with delayed onset years. During normal onset years, Peninsular India receives more rainfall (about 4–8 mm/day) while it is less (2–4 mm/day) in the early and delayed onset years. The spatial distribution is similar in all the three categories over northwest and northeast part of India. Similar inference can be made from the RegCM4 simulations as well over northwest and northeast India. However, the rainfall is underestimated in the model over central India and western India. In this study, no important differences are observed in RegCM4 spatial patterns of precipitation for the three onset categories, which are slightly different from the IMD dataset.

3.5 | Moisture flux inflow into the Indian subcontinent during 1979–2008

The summer monsoon rainfall of India is mostly associated with the amount of moisture transported from the oceanic region to the Indian landmass during the summer monsoon months (Pisharoty, 1965; Saha and Bavadekar, 1973; Murakami *et al.,* 1984; Roxy *et al.,* 2017). Therefore, it is necessary to study the moisture flux transported in the Indian subcontinent and its association with the monsoon onset. The purpose of this section is to examine the moisture inflow into the Indian subcontinent (i.e., moisture contribution from each of the direction) during early, normal and delayed onset years and how the model is responding to each of the scenarios. Here, the time series of moisture inflow (outflow) into (out of) the Indian subcontinent from all the directions have been shown in Figure 8. It is also evident that the major contribution of moisture inflow is from the west and outflow from the east. No significant inflow or outflow is noticed from the north and south directions. These findings are well supported by the model. The net moisture inflow in the model is close to the observation in most of the years. During early and delayed onset years (either observed or simulated), the net moisture flux values in the model simulations are closer to the observed values (except 1999 and 2002).

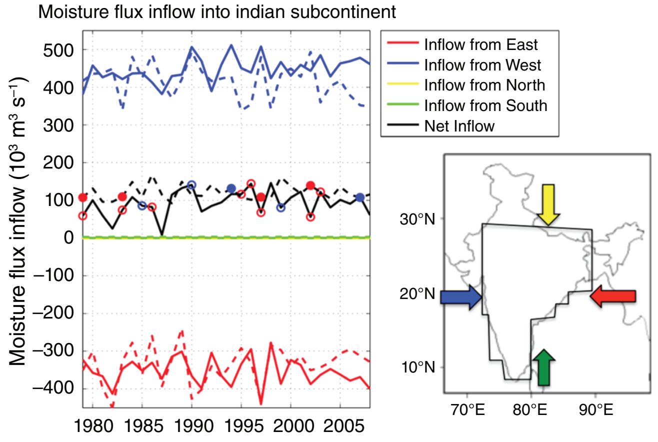

FIGURE 8 Time series of total moisture flux inflow (outflow) into (out of) Indian subcontinent (across the polygon shown in right panel) during summer monsoon for the period 1979 to 2008 based on NCEP/NCAR reanalysis (solid lines) and RegCM4 simulations (dashed line). The moisture flux inflow or outflow has been calculated from each direction in to the polygon shown in right panel. Blue and red circles indicate early and delayed onset years, respectively. The open circles indicate observed onset years while the closed circles indicate model simulated onset years. Positive values of moisture flux indicate inflow in to the Indian subcontinent while the negative values indicate the moisture flux transported out of the marked polygon

Results are very similar in the normal onset years. The model has performed well in reproducing the moisture inflow from all the directions in most of the years. However, this study does not find any one-to-one relationship between the different types of onset years and net moisture inflow.

4 | CONCLUSIONS

The purpose of this study is to assess the performance of RegCM4 in simulating the MOK during Indian summer monsoon. Possible relationship between the onset dates with the all India summer monsoon rainfall is also examined. State-of-the-art regional model RegCM4 has been integrated over south Asia CORDEX domain for 30 years period, that is, 1979 to 2008 with boundary forcing provided from ERA-Interim reanalysis datasets. Results show that the model has performed fairly well in simulating the climatological MOK. The MOK date based on simulated climatology is found to be 28th May, whereas the mean onset date calculated taking the average of onset dates in all the 30 years simulations is 2nd June. The actual climatological MOK date of 1st June lies between these two simulated MOK dates. So far as the inter-annual variation of MOK for the study period 1979 to 2008 is concerned, it follows a similar pattern as in the observations. The correlation coefficient between simulated and observed MOK dates is 0.83 significant at 95% confidence level. The all India summer monsoon rainfall is weakly correlated with the MOK in both the model simulations and observation. Furthermore, the skills of RegCM4 in simulating different categories of onset were examined. The model performed poorly in simulating the early onset years, while it performed fairly well in simulating the normal and delayed onset years. The number of early onset years is small in both the cases, that is, IMD observations (3) and RegCM4 simulations (2). The spatial distribution of rainfall over central India is similar in early and normal onset years. The model simulation agrees well with the observations in representing the spatial distribution of the rainfall in each of the categories. The model has performed well in reproducing the moisture inflow from all the directions in most of the years. But there is no one-to-one relationship between different categories of onset years and the total rainfall and/or net moisture flux inflow into the Indian subcontinent during those years.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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