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ORIGINAL ARTICLE

A study on the capability of the NCEP-CFS model in simulating the frequency and intensity of high-intensity rainfall events over Indian region in the high and low resolutions

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Abstract

In the current perception of an increase in extreme precipitation events in a developing and densely populated country like India and the demands of high resolution forecast runs are high, the present study compares the statistical skill of free runs from an operational climate model run in two horizontal resolutions in simulating the frequency and intensity of extreme rainfall events over Indian region. The operational climate model is a version of the National Center for Environmental Prediction (NCEP, USA) Climate Forecast System (CFS) version 2. It is run at two horizontal resolutions: CFST126 and CFST382, which is used for seasonal and extended range prediction in real-time in the India Meteorological Department's (IMD) operational forecast framework. From the analysis of departure and bias of both the components of the model with respect to India Meteorological Department's (IMD) observation, it is observed that marked dissimilarity in simulating high-intensity rain events exists between this two versions of the same model which should be hypothetically same. Both the models capture intensity and frequency differently. The main conclusions are (a) CFST126 free run gives better estimates of the frequency of rainfall events compared to CFST382, (b) CFST382 free run gives better estimates of the intensity of rainfall events compared to CFST126. These discrepancies indicate the resolution dependence of the statistics of extreme event, which should be statistically corrected and a multi-resolution ensemble version runs of CFSv2 has to be used for operational outlooks of the extreme events.

Keywords Indian monsoon · Extreme event · NCEP CFS · High resolution · Monsoon simulation

Introduction

High-intensity rainfall events during summer monsoon season over the Indian subcontinent on different spatial scales shows an increasing trend (Goswami et al. 2006; Pattanaik and Rajeevan 2010; Roxy et al. 2017) and are known to cause large-scale flooding and disaster over Indian region (Guhathakurta et al. 2011). Such high intensity rainfall events could be extreme events of highly localized nature with rainfall exceeding well above 100 mm/day, or a larger spatial scale low to moderate intensity rainfall events (50–100 mm/day) whose cumulative rainfall activity exceeds the threshold in a particular region in a short span of time virtually providing enough excess water to cause flooding and inundation. With the risk of increasing trend in high-intensity rainfall events, it is essential that the current generation operational climate models should be geared to simulate as well as effectively predict such events.

For the monsoon season, there is enough evidence that the large-scale environment can assist the formation of convective clouds which can organize as well as mature in clusters and can give large rainfall events of various "shades" (Chattopadhyay et al. 2009; Goswami et al. 2003). In a warming environment, the background moisture supply can be more efficient to favor the extreme events (Min et al. 2011; Mukherjee et al. 2018; Pall et al. 2007). Few studies report that the subseasonal scale planetary waves provide background conditions that are favorable for extreme weather events (Petoukhov et al. 2016; Schubert et al. 2011). For monsoon season over Indian region, subseasonal variability can cluster the synoptic scale disturbances (Goswami et al. 2003). Even though it is highly unlikely that

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Table 1 Number of strong and weak monsoon years

Type of data	Total years	Strong years	Weak years
IMD data (observation)	44	7	11
CFS T 126 (simulated data)	46	9	8
CFS T 382 (simulated data)	38	9	12

Table 2 List of strong and weak monsoon years

IMD (observation data)	
Strong years	1969,1974,1982,1987,1993,2006,2009
Weak years	1967,1971,1978,1981,1985,1986,1991,2000,2001,2003,2008
CFS T 126 (simulated data)	
Strong years	2,3,5,10,11,14,24,33,35
Weak years	13,16,19,20,22,39,42,45
CFS T 382 (simulated data)	
Strong years	2,7,8,11,17,18,20,25,26
Weak years	1,3,5,6,9,12,13,19,22,28,31,35

the extreme rain events could be forecasted with long lead-time more than a day or two, some high-intensity rain events those evolve due to organized convection system may have a better chance of long-lead outlook. The India Meteorological Department (IMD) recently employs such a multi-ensemble subseasonal forecasting system with ensembles derived from a high resolution and a low resolution runs and model forecast skills are based on a forecasting strategy developed for subseasonal multi-model and multi ensemble prediction strategy (Chattopadhyay et al. 2017; Sahai et al. 2015). This IMD operational framework is based on a dynamical model that uses an almost same variant of a state-of-the-art coupled dynamical model (NCEP-CFS, discussed later in "Model data: NCEP CFS v2") with similar physics and dynamics.

Since the simulation of high intensity rainfall events are of paramount importance, the current study will evaluate the statistical skill of the NCEP-CFS model run at T126 (~110 km) and T382 (~38 km) resolutions in capturing the frequency and intensity of high-intensity rainfall events in comparison with observation. This comparison is necessary as a recent study shows a difference in teleconnection pattern of seasonal mean monsoon pattern in the CFST126 and the CFST382 resolutions (Ramu et al. 2016). Studies (Chattopadhyay et al. 2015; Ramu et al. 2016) also show that the seasonal mean background condition is also crucial in determining the moisture supply over Indian region during a particular monsoon year that determines the teleconnection (predictable signal) in the CFS forecast model. In this context, it is important to understand how the high and low resolutions can simulate the extreme rainfall events. Thus the study will aim to look into the question how or whether the horizontal resolution has any role in the statistical distribution of frequency and intensity of extreme events. This is an important aspect for operational forecasters who routinely use global models in various resolutions and this aspect will be studied from long "free runs" of CFS model run at T126 and T382 resolutions. Since virtually the two resolutions are different variants of CFS model, it is hypothesized that the frequency and intensity of the rainfall events in these two models would have identical spatial distribution. Since frequency and intensity of extreme events over Indian region is well studied in the backdrop of global warming (Krishnamurthy et al. 2009; Roxy et al. 2017), the subsequent analysis would help in evaluating the suitability of the operational coupled models in real-time applications.

Data

Observation data

This study utilizes high resolution (1° × 1° lat/lon) gridded daily rainfall dataset over Indian region during the

Table 3 Classification of rainfall events based on 1 day rainfall amount over a location/grid

No rain	Rainfall amount realized in a day is 0.0 mm
Trace rain	Rainfall amount realized in a day is between 0.01 and 0.04 mm
Very light rain	Rainfall amount realized in a day is between 0.1 and 2.4 mm
Light rain	Rainfall amount realized in a day is between 2.5 and 7.5 mm
Moderate rain	Rainfall amount realized in a day is between 7.6 and 35.5 mm
Rather heavy	Rainfall amount realized in a day is between 35.6 and 64.4 mm
Heavy rain	Rainfall amount realized in a day is between 64.5 and 124.4 mm
Very heavy rain	Rainfall amount realized in a day is between 124.5 and 244.4 mm
Extremely heavy rainfall	Rainfall amount realised in a day is more than or equal to 244.5 mm
Exceptionally heavy rainfall	This term is used when the amount realised in a day is a value near about the highest recorded rainfall at or near the station for the month or season. However, this term will be used only when the actual rainfall amount exceeds 12 cm
Rainy day	Rainfall amount realised in a day is 2.5 mm or more

monsoon season (June–September or JJAS) for 44 years from 1967 to 2010. The gridded data is based on over 2100 stations, which is prepared by National Climate Centre (NCC) at the India Meteorological Department (IMD), Pune (Rajeevan et al. 2006). The length of the IMD data is so chosen so as to compare the results with model free runs which are available for an almost similar number of years (discussed next).

Model data: NCEP CFS v2

The model free runs are based on the Climate Forecast System (CFS) version 2 model developed at the National Centre for Environmental Prediction (NCEP), US. CFS is a state-of-the-art ocean–atmosphere coupled climate model with a reasonable simulation of monsoon and is adopted as an operational model at IMD for forecasting in different time scale (Saha et al. 2013). Advanced feature of CFS is that it is a fully coupled ocean–land–atmosphere dynamical operational prediction model representing the interaction between the Earth's atmosphere and oceans and large-scale teleconnection in a realistic manner depicted by several studies (Abhilash et al. 2015; Chattopadhyay et al. 2015, 2017; Liu et al. 2014; Pattanaik and Rajeevan 2010). The model includes modules for land and sea ice, with advanced physics, increased resolution and refined initialization (Saha et al. 2013). It has been run with the help of Prithvi high-performance computer (HPC) at Indian Institute of Tropical Meteorology (IITM), Pune with support from the Monsoon Mission Project of Ministry of Earth Science, Govt. of India. CFS model runs at two horizontal resolution, T126 (CFST 126–100 km) and T382 (CFST 382–35 km) with 64 vertical levels. Free run data of NCEP CFSv2 is employed in this study. 46 and 38 years of free run datasets are used from CFS T126 and CFS T382 respectively.

Table 4 Classification of rainfall events based on seasonal SD over all India region for this study

Extreme rainfall event	Rf > 1.5 SD (135 mm)
Heavy rainfall event	1 SD < Rf < 1.5 SD (90–135 mm)
Moderate rainfall event	Rf < 1 SD (90 mm)

Area of study

The extreme events over Indian subcontinent require operational forewarning. Based on the availability of data and other resources, our study area is the Indian region spanning over latitude 5°N–30°N, longitude 70°E–95°E.

Method

Throughout this study, we have applied the bias calculations for relating CFS model with observation data. Free run model forecasts are compared to observations over an extended period of time to quantify expected errors and biases. The comparison is made between CFST126 and CFST382, and both models are compared with respect to observation.

Identification of strong and weak monsoon years

The Indian summer monsoon typically lasts from June–September (JJAS), with large areas of western, eastern and

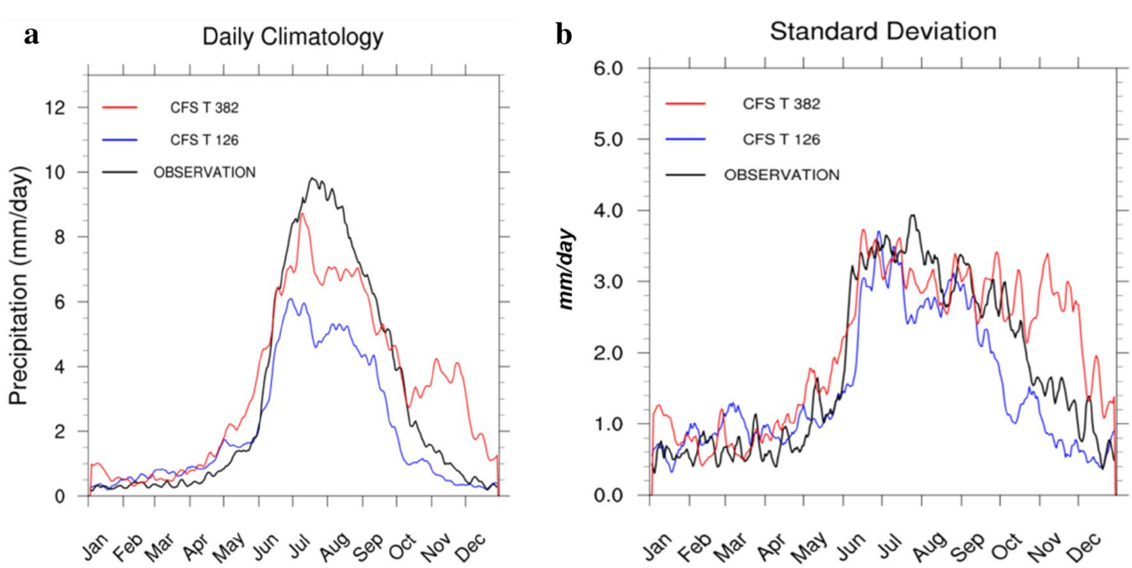

Fig. 1 **a** Daily climatology and **b** standard deviation (SD) of IMD observation data, CFST 126 and CFST 382 for all the years

central India receiving more than 90% of their total annual precipitation during the period, and southern and northwestern India receiving 50–75% of their total annual rainfall. Daily climatology of precipitation is about 7 mm/day in Indian land region during JJAS with 0.77 mm/day (10%) as the daily standard deviation (SD). Monsoon has both intraseasonal and inter-annual variability. This variability determines whether it is a strong, weak or normal monsoon year in the subseasonal to seasonal scale.

In this study we classify strong and weak monsoon years from all the years of sample data (defined as all years). The classification for both the model and observation data is based on standardized anomalies (> 1 SD is classified as a strong year; < −1 SD as a weak year). Standardized anomalies are calculated based on seasonally (JJAS) and regionally (5°N–30°N, 70°E–95°E) averaged data over Indian region. The threshold value of 0.8 is for classification of years as strong and weak years. It is so chosen so that the number of strong and weak monsoon years in observational data, CFST126 and CFST382 simulation runs are comparable (i.e., similar sample size). If the standardized anomaly of a particular year is greater than 0.8, then we sort it into strong

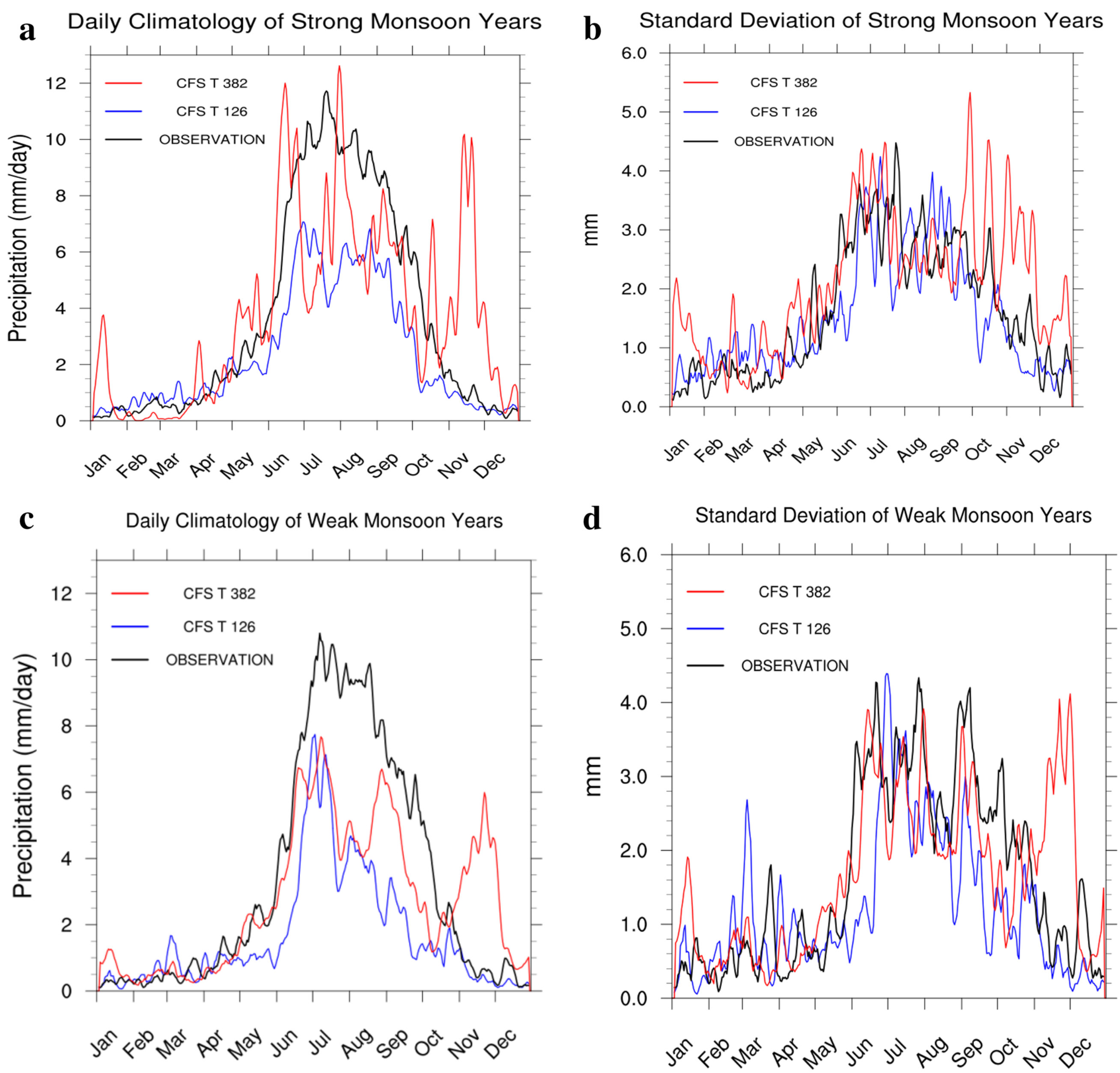

Fig. 2 Daily Climatology and standard deviation for the selected years over the Indian land region

monsoon year. If the standardized anomaly of rainfall is less than −0.8, then we consider the year as a weak monsoon year. Tables 1 and 2 show the statistics of estimated strong and weak monsoon years.

Classification of rainfall events

Daily rainfall at each and every grid point is classified into mainly three classes, which are moderate rainfall events, heavy rainfall events, and extreme rainfall events. Classification of rainfall events based on 1-day accumulated rainfall amount over a grid according to Indian Meteorological Department (IMD) is given in Table 3. In this study, we define a simplified three category method of classification based on seasonal (JJAS) standard deviation (SD) for comparison of model simulations with IMD observation. The seasonal standard deviation is already used for classification of years (i.e. all, strong and weak years in "Identification of strong and weak monsoon years"). Taking the area weighted "all India" seasonal mean as 837 mm and the coefficient of variability ~ 11% (Rajeevan et al. 2006), the seasonal standard deviation is ~ 90 mm. This statistics could vary if we consider smaller homogeneous region like eastern, western, central India. However for purpose of model comparison, we use "all India" mean and standard deviation for uniform comparison. The rainfall at each grid above 1.5 SD is taken as an extreme event; between 1 and 1.5 SD as taken as heavy event and below 1 SD is defined as a moderate event at each grid (given in Table 4). The values given in Table 3 can be used for event classifications over a location. But when the land points over all over India are to be considered, the simple three cluster category based on area weighted seasonal standard deviation is a realistic measure of extreme event for intermodel comparison. This method is employed for comparison between two models, CFST126 and CFST382 and between IMD observation data and models, in which all the three of them are having different daily climatology and SD. For each grid point, seasonal mean and SD is calculated, and rainfall events at each grid point over Indian region are sorted into three categories based on values given in Table 4.

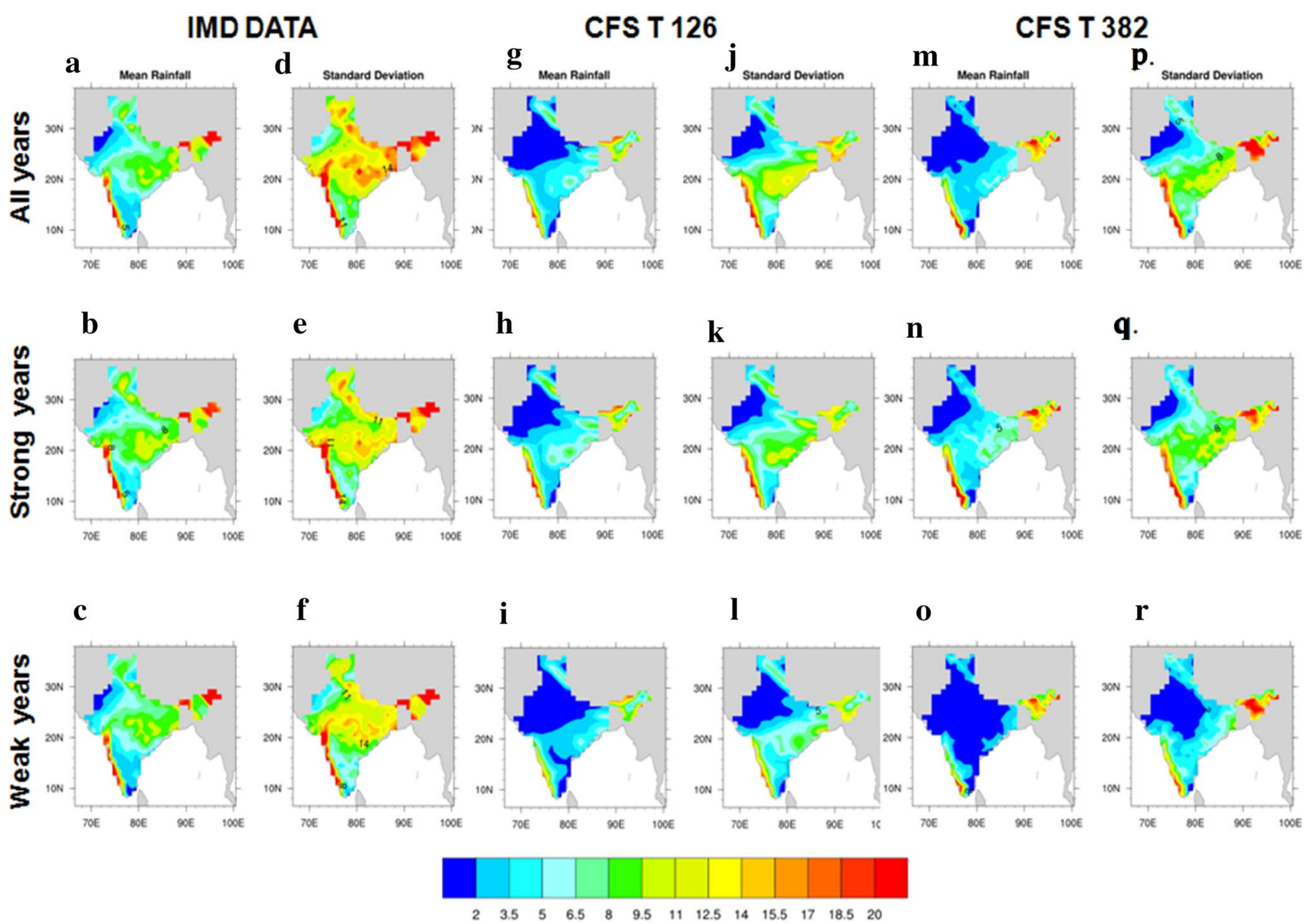

Fig. 3 Comparison of spatial patterns of rainfall for different years (mm/day)

Analysis of the bias of model-simulated rainfall events

Every model simulation shows non-rainy days and the number of non-rainy days is not same in different model versions as well as the number is different in observation for a JJAS rainy season. To calculate the bias, we normalize the frequency count with respect to the number of rainy days. The ratio of rainfall events of a particular category (moderate, heavy or extreme) to a total number of rainy days is calculated. Then a measure of the bias (in percentage) for the selected set of days is estimated using the following equation.

$$bias = \left(\frac{m}{m0} - \frac{ref}{ref0} \right) * 100 \tag{1}$$

where *m*—count of rainfall events in any one category say for CFST126 or CFST382, < 1 SD, *m*0—total number of rainy days from the model (CFST126 or CFST382); *ref*—count from a reference data for the same category as that of the model selected as *m; ref*0—total number of rainy days from reference data. The reference data could be IMD observation data or the alternate model data that is not used as *m*. In the latter case the bias of one model with respect to other

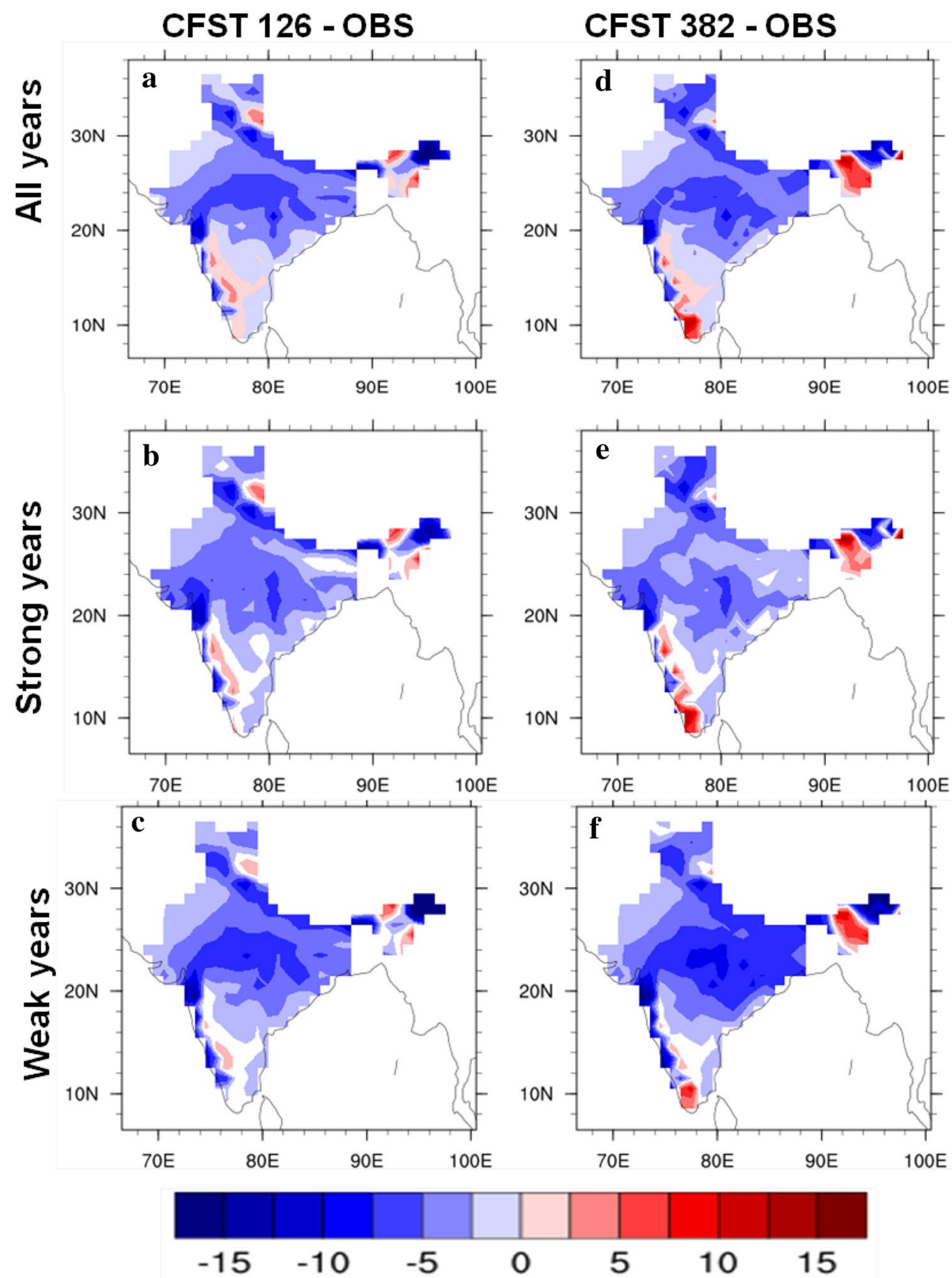

Fig. 4 Bias of mean rainfall of CFST126 and CFST382 with respect to observation (OBS) for different clustered years (mm/day)

could be calculated. For example bias of CFST382 (*m382*) with respect to CFST126 (*m126*) is calculated as:

$$Bias_{model} = \left(\frac{m382}{m382_0} - \frac{m126}{m126_0}\right) * 100 \quad (1a)$$

Here the total number of rainy days ($m0$ or $ob0$) is used as the normalization factor. Comparison is also shown for the relative count of model (m) and observation (obs) with respect to a particular category (extreme, heavy and moderate) for different categories of years (all, strong and weak).

Calculation of mean rainfall intensity at each grid point for each category

Estimating the total cumulative rainfall in the each and every grid point for a particular category, say > 1.5 SD, shows a clear picture of the intensity of rainfall at that point for any category. We next show a comparison of cumulative intensity of rainfall in all the categories as defined earlier. While estimating cumulative rainfall in this study, only the precipitation greater than 1 mm/day is considered in every grid point. Average intensity of precipitation in a grid in a particular category is calculated as:

$$avg\_rf = \frac{sum\ of\ rainfall\ for\ all\ the\ days\ in\ the\ grid\ clustered\ in\ a\ particular\ category}{total\ count\ of\ rainy\ days\ in\ the\ grid\ for\ the\ days\ those\ exceed\ threshold\ (1\ \mathrm{mm}\ per\ day)} \quad (2)$$

A comparison of this average rainfall intensity will be made in this study for different clusters and for different models to quantify the bias in intensity.

Result

Comparison of climatology and standard deviation of CFS

The skill and expertise of CFS model components (CFST126 and CFST382) are analyzed by comparing the model free runs with IMD observation data. So as to understand the general structure and characteristics of precipitation, spatially averaged or area-averaged daily climatology and standard deviation (SD) for all years, strong years and weak years are plotted for CFST126, CFST382, and IMD observation data and are compared in Fig. 1. From Fig. 1a it is seen that both the models have dry bias compared to observation. Daily climatology of CFST126 is the least. October, November and December months show high climatology in the case of CFST382. It also shows high and varying SD (Fig. 1b).

Figure 2a, b show daily climatology and SD respectively of all the strong years. CFST382 has a highly fluctuating

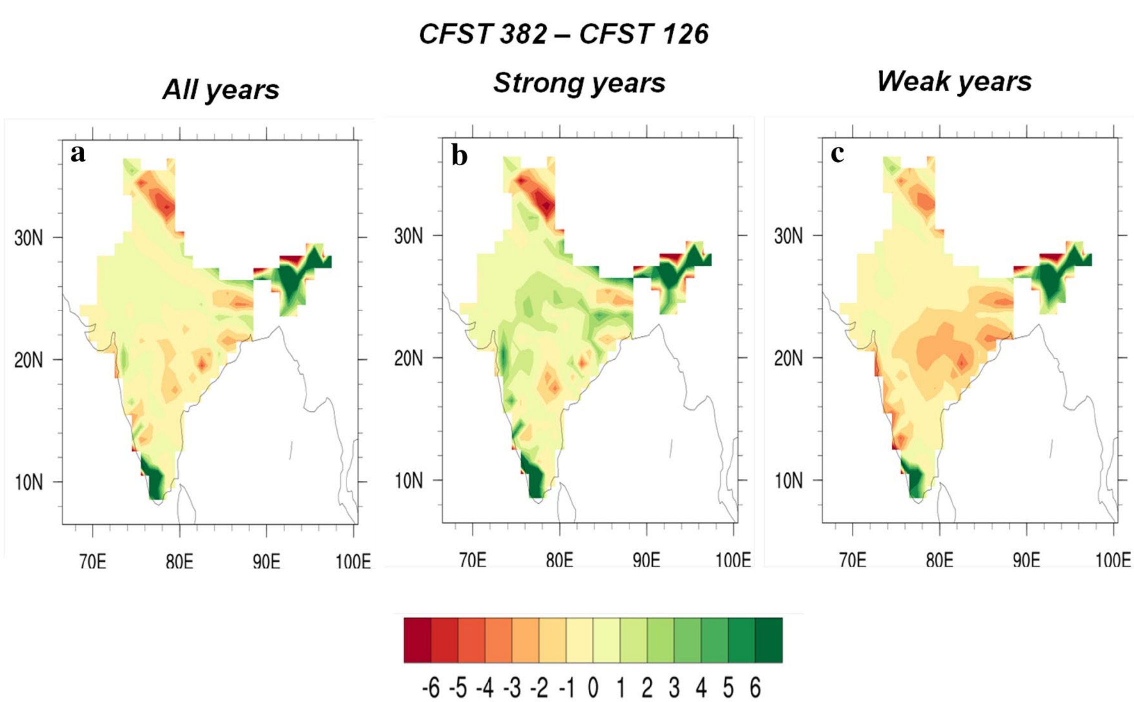

Fig. 5 Inter comparison of mean rainfall of CFST126 and CFST382 models (mm/day)

daily climatology. Many peaks and dips can be seen throughout indicating high variability in rainfall in these years. Mean climatology of strong monsoon year has higher values comparing to all years (Fig. 1a) for all the three cases, i.e., two components of model and observation data. Taking into account the SD, both the models are highly fluctuating. High spurious values of mean climatology and SD are observed for CFST382 from September to December which is more realistic in CFST126.

Figure 2c, d show the same but for weak years. As in the case of all years, in weak monsoon years also models show dry bias. CFST382 has extraordinary large spurious climatological values during the month of November and December same as strong monsoon years (Fig. 2a, b). From all the three cases it is seen that CFST382 has greater SD than CFST126.

Comparison of the spatial pattern of mean rainfall

Similar to Figs. 1 and 2, which is showing spatially averaged annual cycle, yearly and seasonally (June–September or JJAS) averaged climatology and SD are plotted to look into the spatial distribution of precipitation all over India. Figure 3a–f is the spatial plots of IMD observation data averaged during the JJAS for the years 1967–2010. Both mean rainfall (Fig. 3a–c) and SD (Fig. 3d–f) in each grid point over Indian region can be analyzed from the figure. The figures represent the well-known features summarized for the sake of completeness: (i) it is seen that rainfall distribution in India is highly uneven which is due to geographical and climatic distribution, i.e., the tropical and coastal regions and plains receive more rainfall than the plateau and desert regions in the interior, windward side of mountains and hills receive more rainfall than leeward side

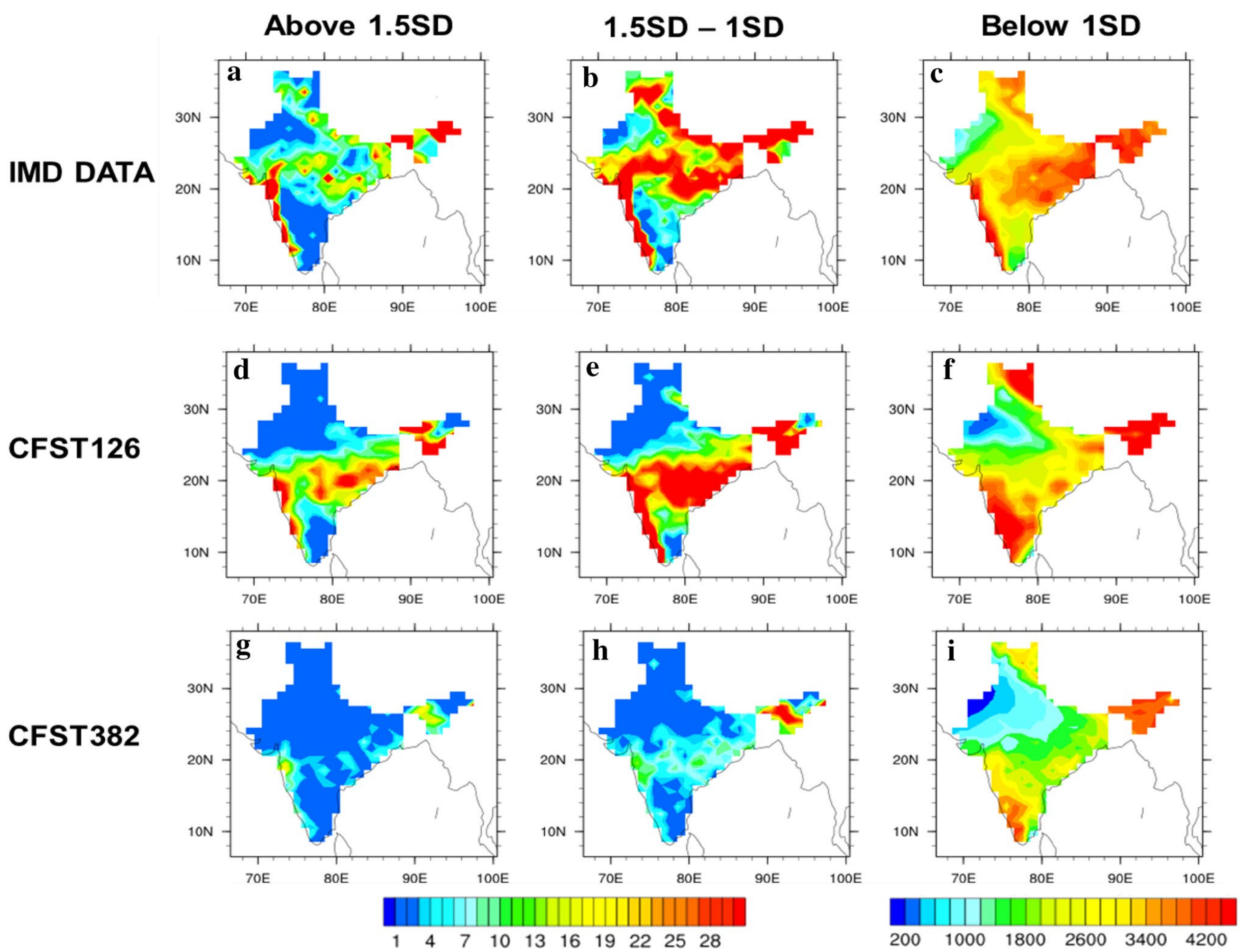

Fig. 6 Relative count of rainfall events of all years for the categories above 1.5 SD, between 1.5 and 1 SD and below 1SD for IMD data, CFS T 126 and CFS T 382. Each column represents cluster categories (> 1.5 SD, 1–1.5 SD and < 1 SD) and each row represent IMD observation, or the CFST126 and CFST382 models as mentioned in the top or left side of the panels. Similar convention is followed in other plots

and the monsoon troughs and depressions. (ii) The western coast which is the Western Ghats or Konkan region and North East India receive the maximum amount of rainfall in the Indian subcontinent. Least amount of rainfall is observed in western Rajasthan and adjoining parts of Gujarat, Haryana, and Punjab. Similarly, rainfall is low in the interior of the Deccan Plateau and east of Western Ghats. Leh in Jammu and Kashmir is also an area of low precipitation. SD is high in regions of heavy rainfall and low in regions of less rainfall.

The spatial distribution of climatological rainfall and SD for the CFST126 and the CFS T382 model is also shown in subsequent panels for the "all" year, "strong" year and the "weak" year case. It is evident from Fig. 3 that observation data has stronger amplitudes of climatology and SD than both the models (indicating a dry bias for both the models) which support the conclusions from Figs. 1, 2 is consistent with earlier results (Chattopadhyay et al. 2015; Ramu et al. 2016). For both strong and weak monsoon years in CFST382 and CFST126, they have very less precipitation climatology in almost all parts of India except parts of northeastern India and parts of Kerala in the west coastal southern tip of peninsular India.

To compare CFST126 and CFST382 with the observation we plot the difference as shown in Fig. 4. For "all" year case, CFST382 is showing a positive bias in rainfall amplitude than CFST126 as many places over peninsular India show a positive bias in rainfall in Fig. 4a. This is clearer in strong year plot in Fig. 4b. Over central India, all plots show negative bias irrespective of the type of years. In order to compare CFST126 with CFST382, we plot the difference plots in Fig. 5. An interesting fact is that the weak monsoon year

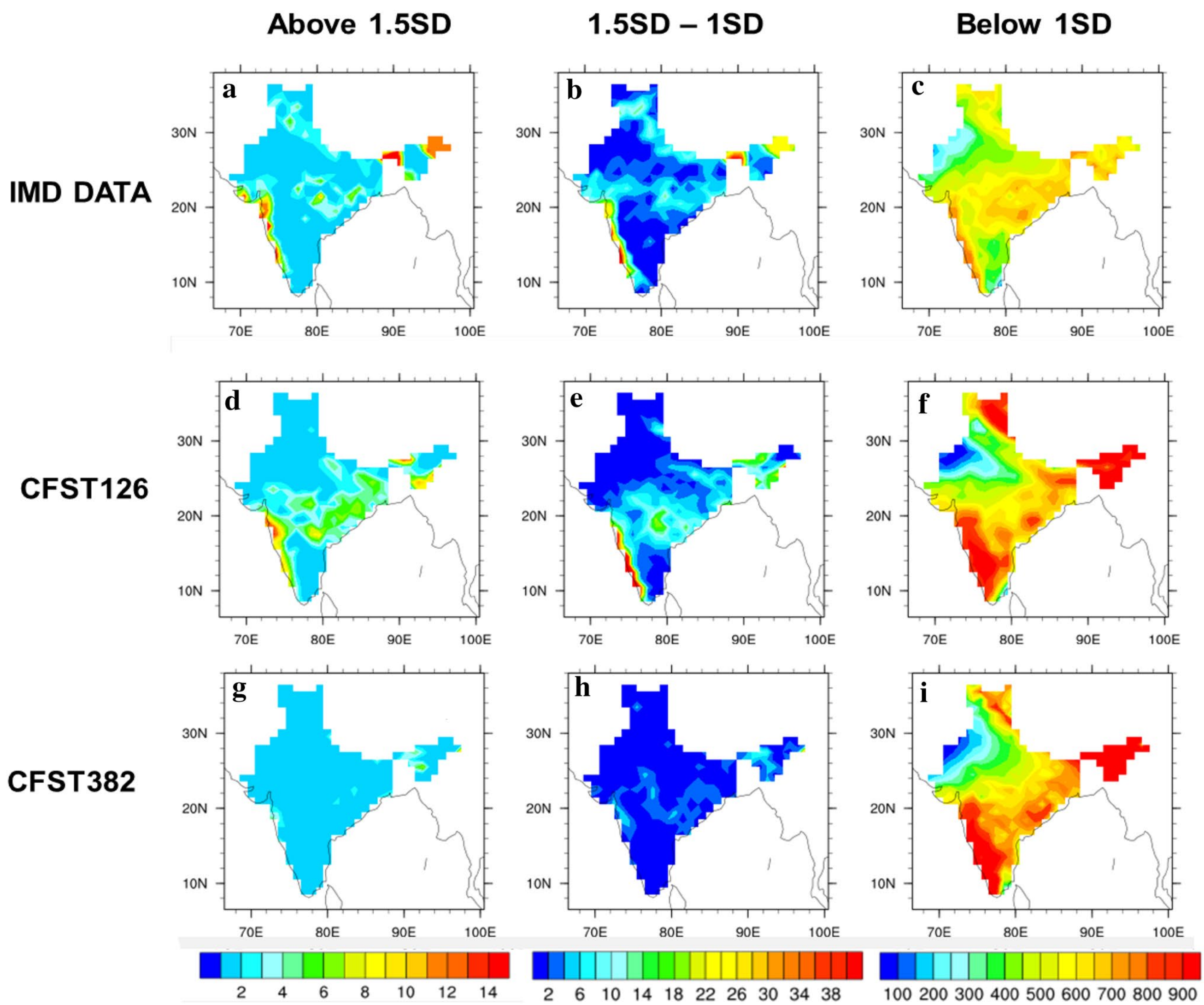

Fig. 7 Relative count of rainfall events same as Fig. 6, but for strong monsoon years (Table 4)

CFST382 shows dry bias with respect to CFST126 while in strong monsoon year CFST126 shows wet bias with respect CFST126 for a major part of India. It is also to be noted that high positive values are seen in the western coast and north-eastern parts of India irrespective of classification of years or not. Figures 4 and 5 plots may give a sense that as compared to CFST126, CFST382 is positively (negatively) biased in rainfall amplitudes towards strong (weak) extreme years.

Relative counts of rain events

Relative counts of rainfall events (cf. "Analysis of the bias of model-simulated rainfall events") with respect to a particular category of classification (Rf > 1.5 *SD*, 1 SD < Rf < 1.5 SD and Rf < 1 SD) is shown in the following plots. Rainfall events from total years of models and observation are counted and plotted in Fig. 6. Similarly, for strong monsoon years and weak monsoon years, results are shown in Figs. 7 and 8. From Fig. 6, for all years, it is observed that in above 1.5 SD categories, CFST126 shows more counts of precipitation events. In the 2nd category (between 1.5 and 1 SD) classified as moderate rainfall events, CFST126 shows much more number of events than that of CFST382 especially over the central parts of India. Over the Himalayan foothills region, however, it underestimates the counts of the moderate rainfall events. Also in the 3rd category which is below 1 SD, IMD observation has captured more counts of events especially over north and central India. Over peninsular India, both the CFST126 and CFST382 capture excess low rainfall events. Overall the skill of estimating counts of events seems to be less for CFST382 in the core Monsoon Zone over central India in all the categories compared to IMD data and CFST 126.

Considering Fig. 7, strong monsoon year's precipitation counts show the almost same trend as that of all years. In the 1st (> 1.5 SD) and 2nd (1.5–1 SD) category CFST126 has

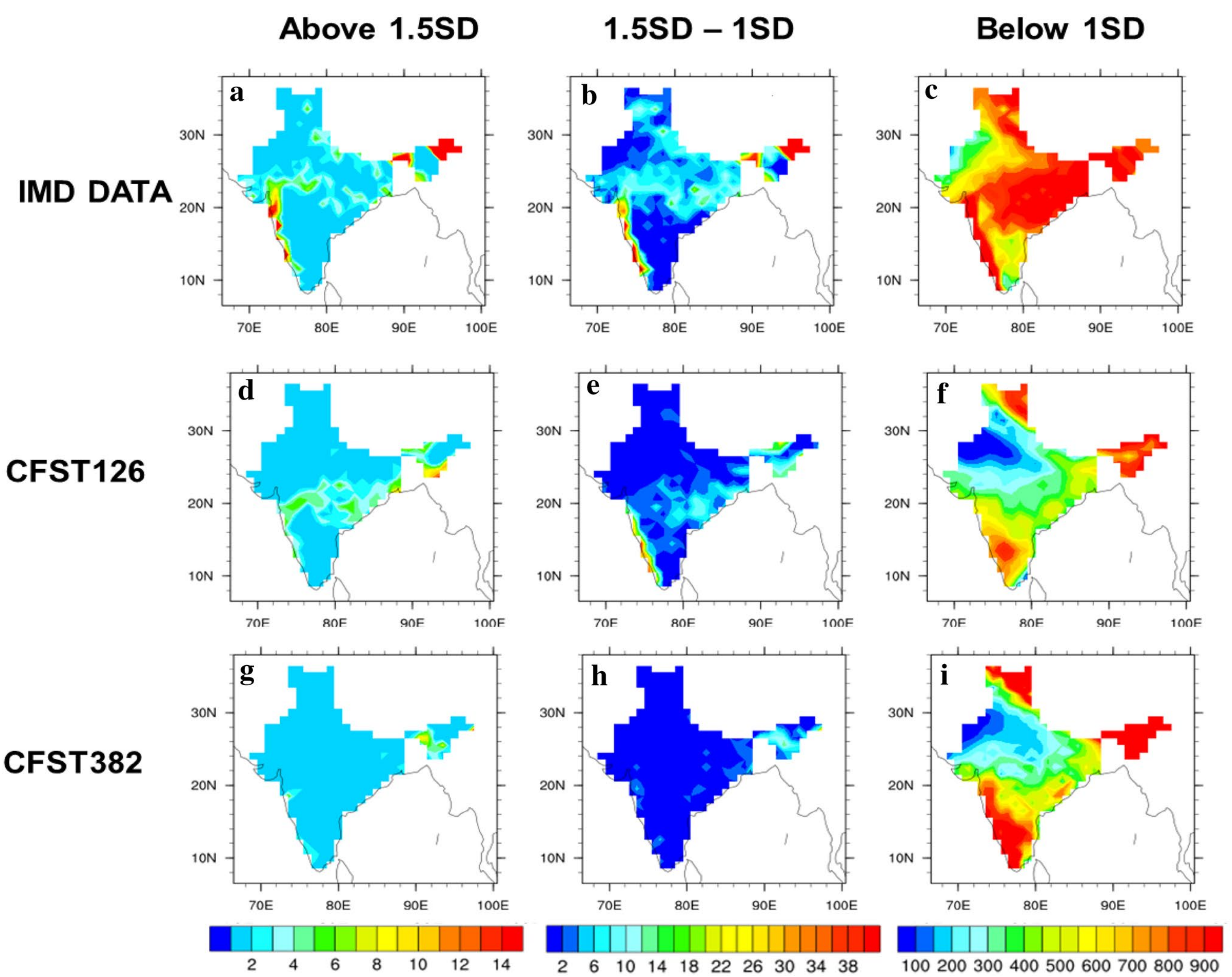

Fig. 8 Relative count rainfall events same as Fig. 6, but for weak monsoon years (Table 4)

more counts of extreme event than IMD observation data. On the contrary, CFST382 has very fewer counts of extreme rain events especially over Western Ghats. Whereas in the below 1 SD category, both CFST126 and CFST382 has more counts than IMD observation. Now while analyzing the weak monsoon years count from Fig. 8, it is seen that in the weak monsoon category both the models have overall fewer counts compared to the IMD observation. In all the categories, i.e. extreme (Rf > 1.5 SD), strong (1 SD < Rf < 1.5 SD) and normal (Rf < 1 SD) both the models fail to capture the frequency of rainfall events. The Figs. 6, 7 and 8 identifies one key bias in the model: in the moderate and heavy rainfall category, both CFST126 and CFST382 fares worst in peninsular India in terms of frequency of events. Both models need improvement in terms of representation of rain event in this region.

Bias in the count of rainfall events

In order to understand the bias of the model, the counts of the frequency of rainfall events are evaluated by subtracting the CFST126 and CFST382 model from observation and also by comparing the components of the model with each other (Eq. 1). Figure 9 shows the bias of CFST126 with respect to observation. All of the three rainfall categories in all years, strong monsoon years and weak monsoon years are analyzed. It is observed that extreme rainfall events (> 1.5 SD category) are more prominent in this model than observation, showing a positive bias in most of the grid points. In the heavy rainfall category (1–1.5 SD) shows positive and negative bias in the all year category. Large positive and negative biases are equally and strongly indicated in the western, northern and north East Indian region in the strong and weak monsoon years. For

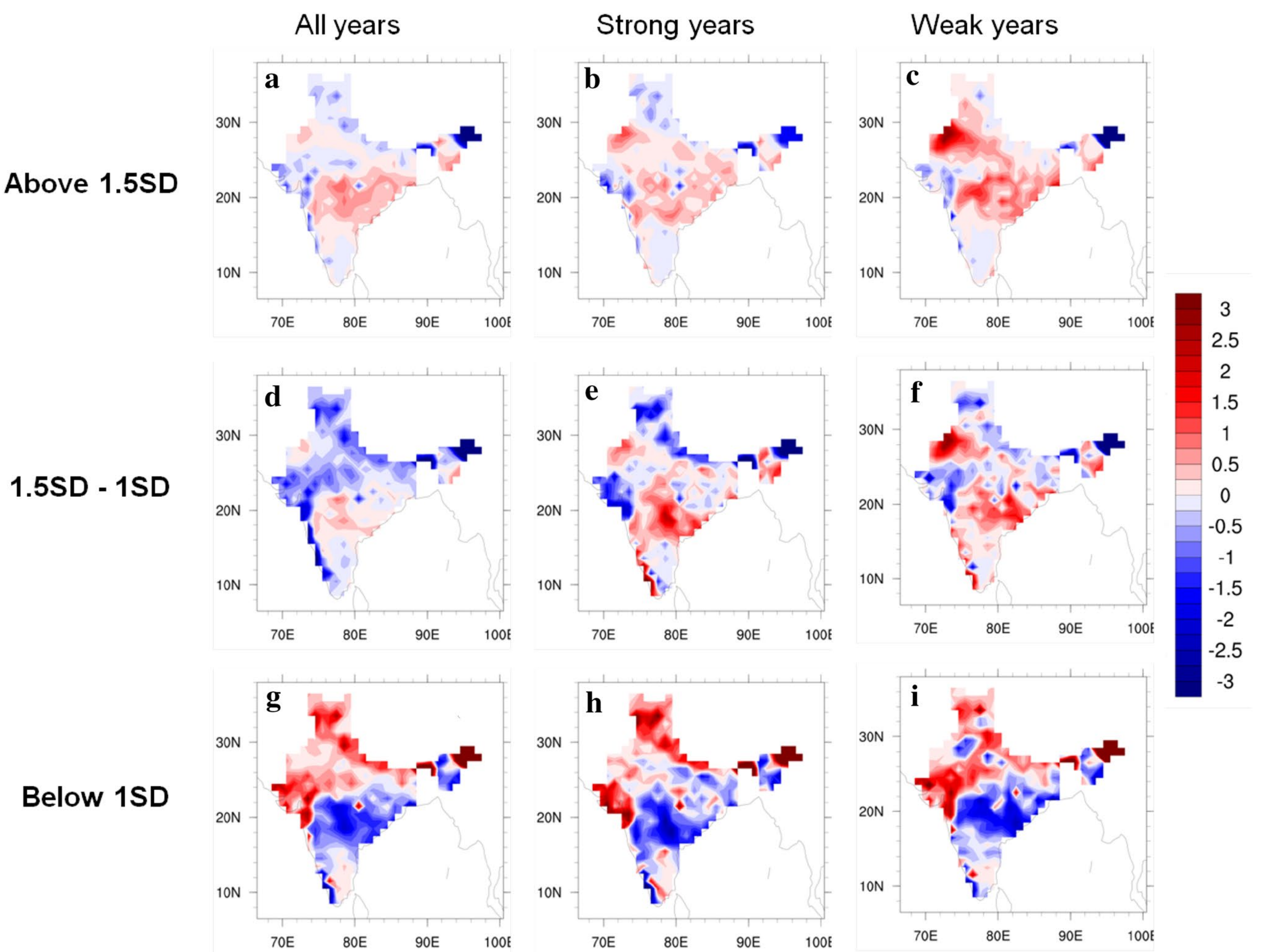

Fig. 9 Bias (in percentage) of CFST126 with respect to observation (i.e. normalized CFST126 minus IMD observation) for all years, strong monsoon years and weak monsoon years. (cf. Equation 1). Columns show year categories as mentioned in the top of panels. Rows show cluster categories as mentioned in the left hand side of the panels

the moderate category (i.e., rainfall below 1 SD) strong positive bias is seen in upper central and western India while strong negative bias is seen in lower central and peninsular India. The strong bias gradients in rainfall counts (changing from negative to positive signs) are interesting features and require more careful examination for prediction purpose.

In the case of bias analysis of CFST382 with respect to IMD observation (Fig. 10), it is noted that the CFST382 in the extreme rainfall category (above 1.5 SD) show rain events much weaker than observation in the many grid points except for weak years. Negative bias is observed over central and adjoining regions of India. In the heavy rainfall category (between 1.5 and 1 SD) the CFST382 shows stronger negative bias as compared to the extreme rainfall category. It is much more negatively biased than above 1.5 SD category. On the contrary, in the last category, moderate events (less than 1 SD) are very strongly positively biased in the model than observation. The extreme rainfall category shows lesser (negative) bias than the moderate rainfall category indicating better simulation in this category. This large bias may arise if the rainfall simulation in the model may have a problem in converting rain rate from one to another category due to problems in convective schemes. One other important point is CFST126 shows both positive and negative bias in some categories, while the bias in CFST382 shows the bias of one sign (either positive or negative). Increase in horizontal resolution is thus an essential factor in deciding the frequency of rainfall intensity over a location. Since the rainfall primarily arises through parameterization (convective or large scale), horizontal resolution in models could linked to this biases through altered simulation in vertical velocity in these two versions.

While comparing the model with model, i.e., the bias of CFST382 relative to CFST126, it is noticed that CFST382 is negatively biased and do not indicate more extreme and strong rainfall than CFST126 in the extreme and heavy category (Fig. 11). Whereas in the below 1 SD category, moderate precipitation events are showing a positive bias in almost all the grid points. Even though CFST382 has higher

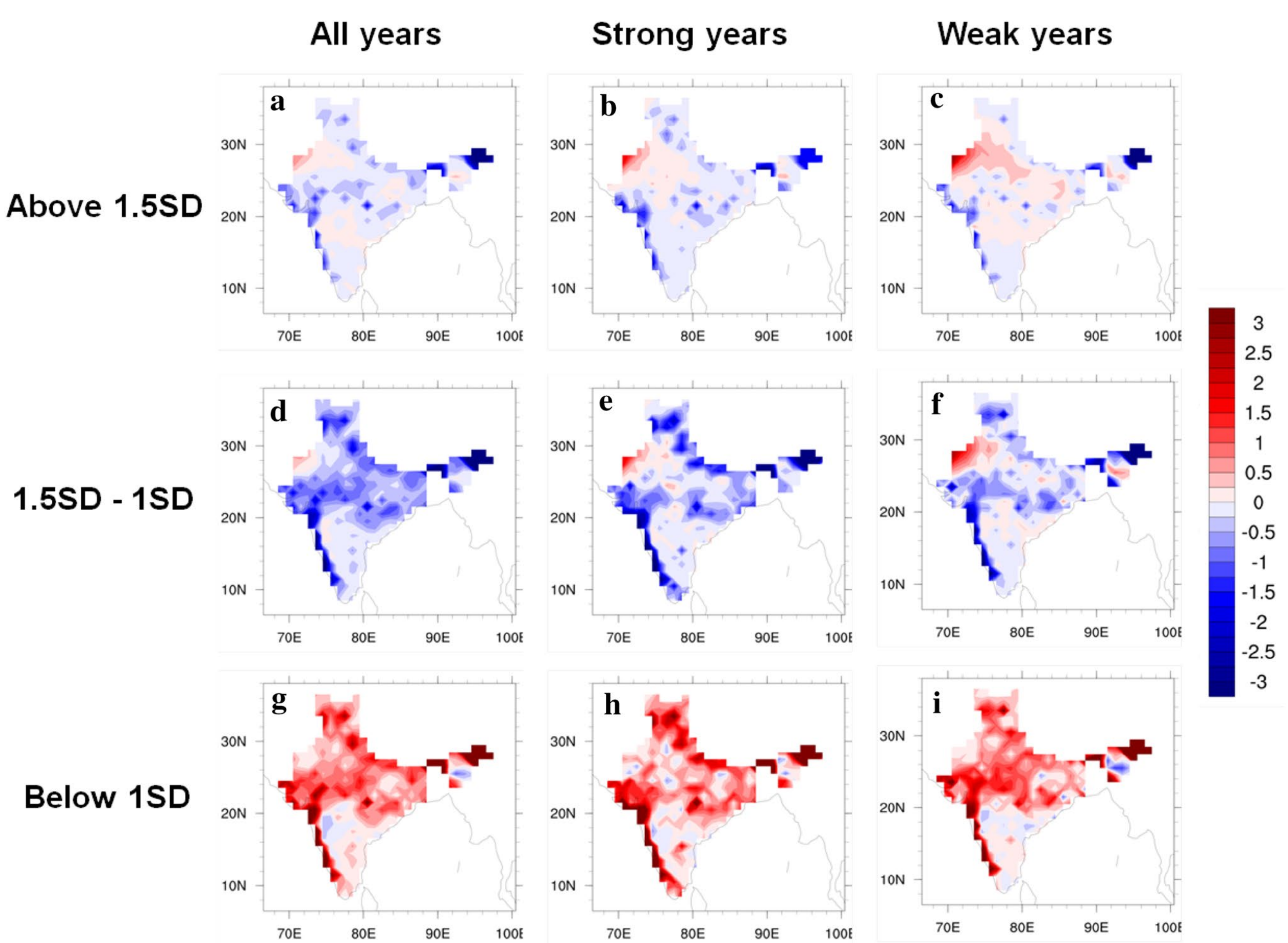

Fig. 10 Similar to Fig. 9 but showing the bias (in percentage) of CFST382 with respect to IMD observation for all years, strong monsoon years and weak monsoon years

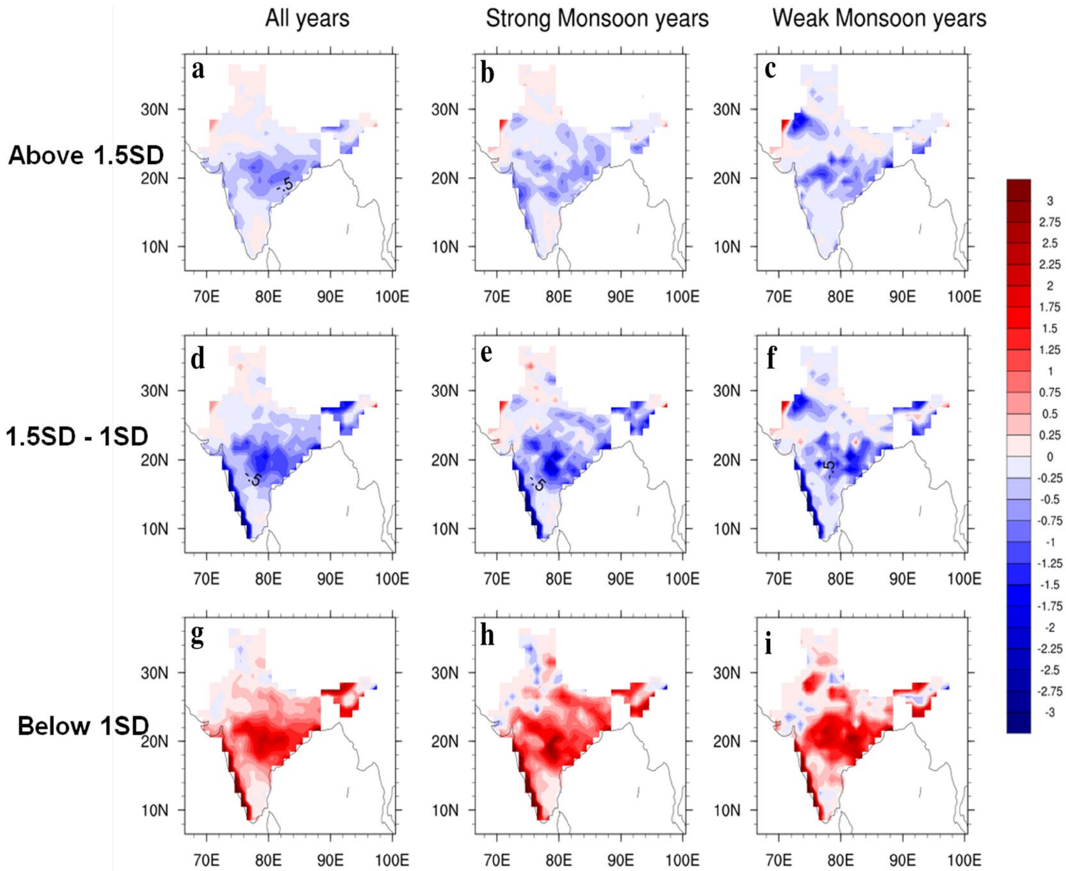

Fig. 11 Similar to Fig. 9 but showing the bias (in percentage) of CFST382 with respect to CFST126 for all years, strong monsoon years and weak monsoon years. Refer Eq. (1a), "Analysis of the bias of model-simulated rainfall events"

climatological annual cycle than CFST126 (refer Fig. 1), it cannot indicate more extreme and strong rainfall events.

Average rainfall intensity over Indian region

In order to understand the spatial pattern of rainfall intensity for different classes [extreme (> 1.5 *SD*) heavy (1–1.5 *SD*) and moderate (< 1 *SD*)], cumulative rainfall or actual intensity of rainfall is calculated for each grid location and for different categories of years (all, strong and weak) based on Eq. (2) ("Calculation of mean rainfall intensity at each grid point for each category") and is plotted next. First, we discuss the all years plot (Fig. 12), where we can see for the extreme category that CFST126 has least intensive rainfall, and CFST382 has most intensive rainfall although spatial distribution is more homogeneous over central India in CFST126 than CFST382. CFST126 gives more rain than CFST382 in the most parts of peninsular India that is predominantly a rain shadow region. Most intensive rainfall occurs in the category—between 1.5 and 1 SD in CFST382. In this category, the CFST382 rainfall intensity shows a wetter bias compared to observation and CFST126. For the normal rainfall (< 1 SD) category both the model shows dry bias compared to observation.

The same trend is observed in the strong monsoon years (Fig. 13), but the spatial spread of precipitation in CFST382 has decreased. In the case of weak monsoon years (Fig. 14), it is seen that the spatial spread of extreme events decreases further. Weak monsoon years have intense rainfall in fewer places or grid points while comparing with strong monsoon years and even lesser while comparing with all years. Overall rainfall has more homogeneous spatial distribution in CFST126 than CFST382.

Discussion and conclusions

The skill of CFST126 and CFST382, the two individual components of CFS model, in simulating frequency and intensity of precipitation is estimated and analyzed throughout this study over the Indian land region. Statistical comparison is made in relating model and observation. Frequency and intensity of precipitation events over Indian region are appraised along with the analysis of bias and

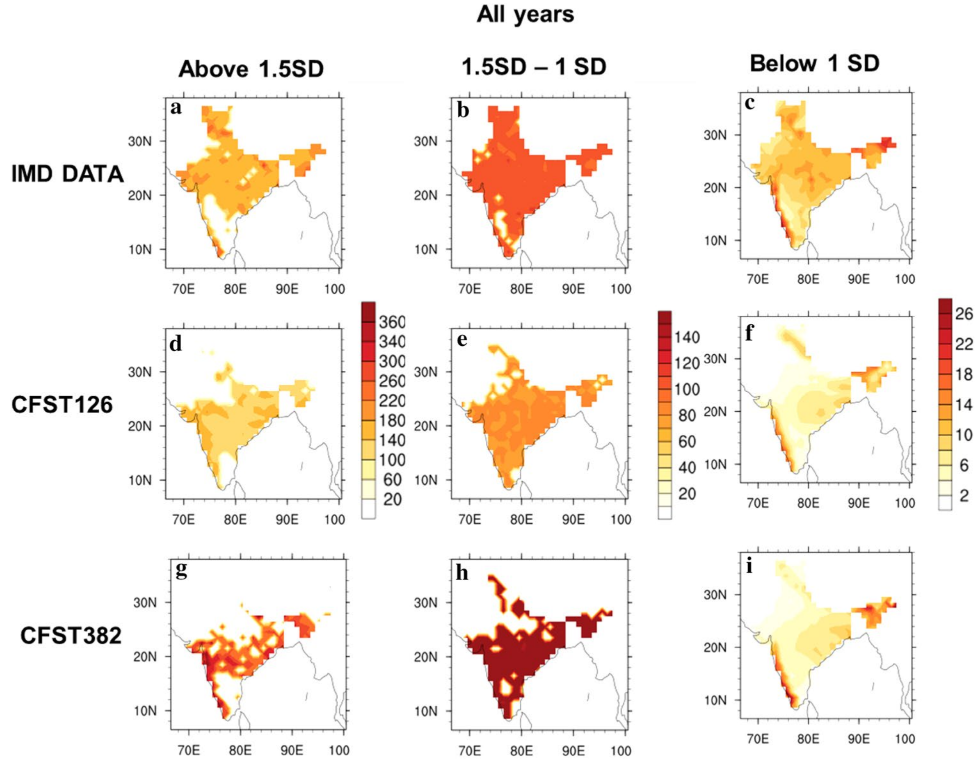

Fig. 12 Average Intensity (mm/day/event) of rainfall of all years for the categories above 1.5 SD, between 1.5 and 1 SD and below 1 SD for IMD data sets, CFST126 and CFST382 free run datasets (cf. Equation 2)

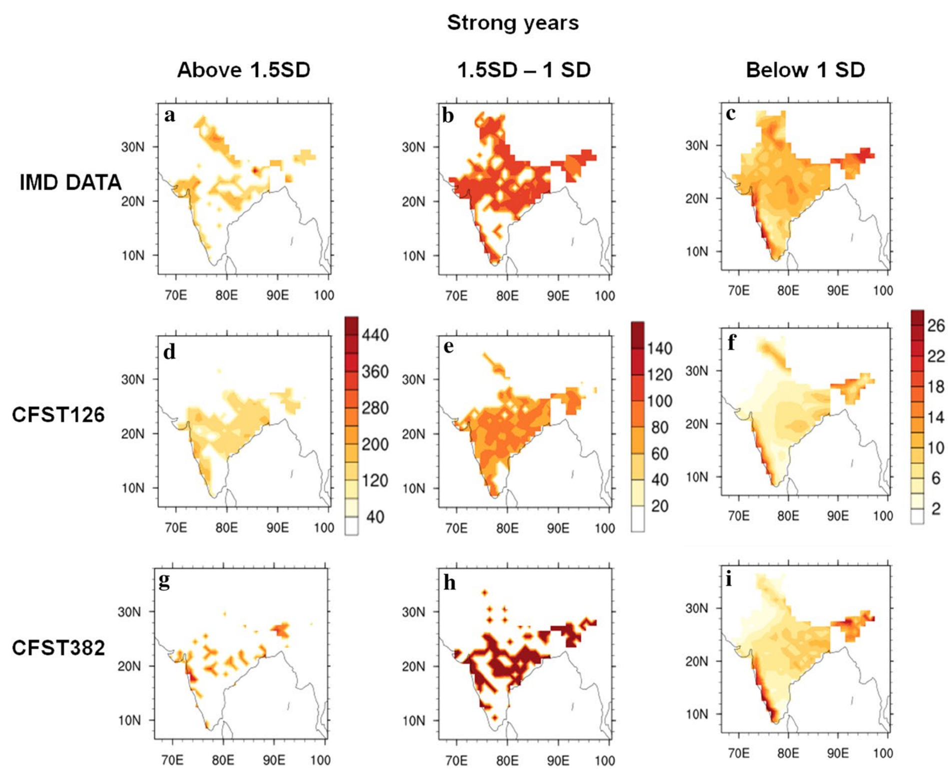

Fig. 13 Average intensity of rainfall same as Fig. 12, but for strong monsoon years

departures of both the components of the model. These are done in two ways, (1) comparing both the components of CFS model with observation, (2) comparing the components of model with each other. $1° \times 1°$ gridded daily rainfall data-set over Indian region prepared by National Climate Centre (NCC) at IMD, Pune and free run data of NCEP CFSv2 with

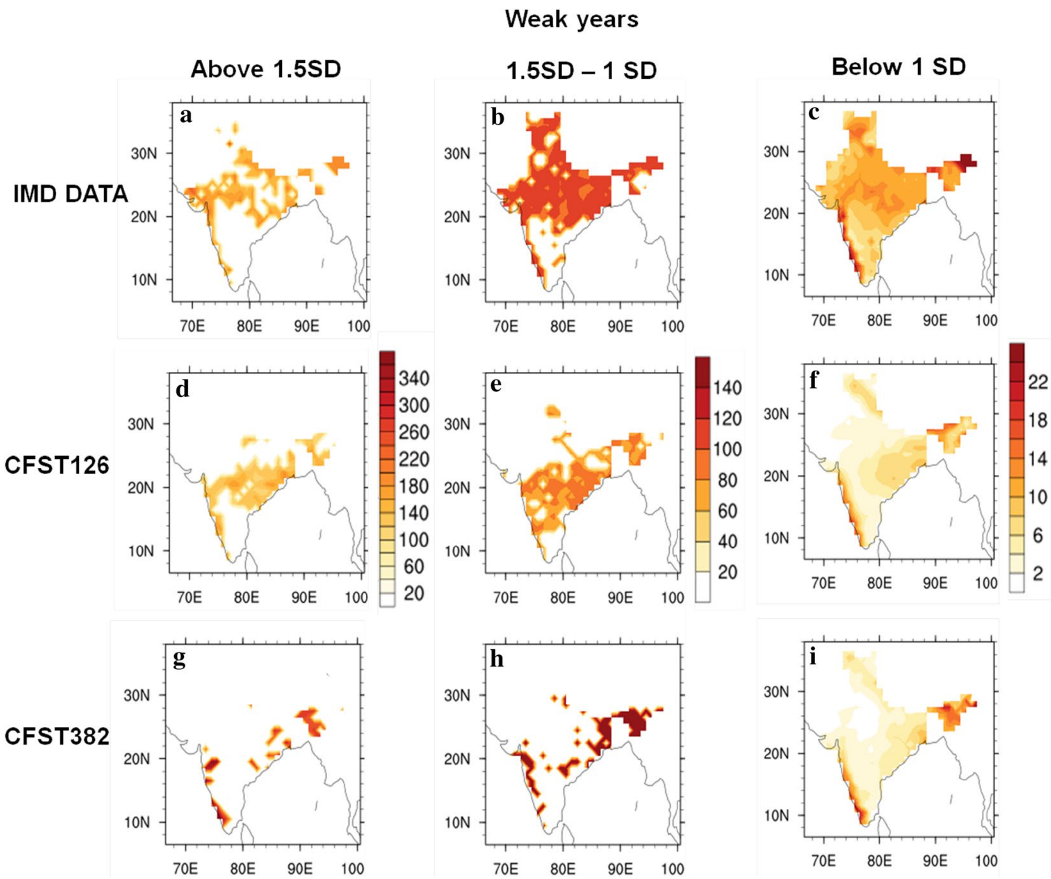

Fig. 14 Average intensity of rainfall same as Fig. 12, but for weak monsoon years

horizontal resolution of CFST126 and CFST382 is utilized in this study.

The results discussed above could be summarized in the following way: it is observed that CFST382 indicates fewer precipitation events (counts) compared to CFST126 (Figs. 6, 7, 8), but the intensity of rainfall events captured is very high especially in the extreme or moderate events (Figs. 12, 13). For CFST382 mean annual cycle is higher in amplitude than CFST126 and SD of similar magnitude during monsoon months (Figs. 2, 3), it indicates the increased intensity of rainfall whenever it precipitates. Also, the resolution of CFST382 is ~35 km whereas that of CFST126 is ~100 km. This difference in resolution leads to better capturing the statistics of the intensity of events by high-resolution model. So from this study conclude that

- CFST126 free run gives better estimates of the frequency (relative counts) of rainfall events compared to CFST382 for all years in all categories and for extreme (> 1.5 SD) categories in strong and week years.
- CFST382 free run gives robust estimates of the average intensity (amplitude) of rainfall events compared to CFS T126 though spatial distribution is more homogeneous in CFST126 at least for some categories.

The reason for the difference in capturing the frequencies of rainfall events by these two components of CFS model is unexplored in this study. Although, from the spatial distribution of rainfall intensity and frequency it looks like parameterization of rainfall and the large-scale dynamical feedback of rainfall to the cumulus routine could be a problem especially in the rain shadow region of peninsular India. Also, it is to be noted that some statistical multi-model ensemble correction formalism has to be formulated so as compare extreme events in a multi-model and multi ensemble formulation which is absent in current generation of operational IMD forecast. This part can be studied in future and along with the problem of difference in intensities of rainfall events. From this study we put forward that (a) to get a reasonable operational skill of high intensity rainfall events in current generation IMD forecast strategy it is necessary to employ both the high (CFST382) and low resolution (CFST126) model and (b) there is a need of bias corrections in the post-processing, which can be done in the model output for improved estimation, predictability, and forecast of rainfall events primarily in the moderate and extreme rainfall categories.

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