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Unraveling Intricacies of Monsoon Attributes in Homogenous Monsoon Regions of India

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India observes the summer monsoon in June–July–August–September (JJAS) season, and the livelihood security of a huge population depends on it. The impact of the monsoon onset timing, length of monsoon season, rainfall amount, and related extreme events is huge on the Indian economy. Therefore, understanding the inherent intricacies needed a detailed investigation. In five homogenous monsoon regions of India, the trend of monsoon onset and the length of monsoon season are examined. The association between 1) monsoon onset ~ rainfall amount, 2) length of monsoon season ~ rainfall amount, and 3) monsoon onset ~ length of monsoon season is investigated. Subsequently, the behavior of rainfall and extreme excess days in the ±1 standard deviation (SD) length of monsoon season is also examined in detail. The trend for monsoon onset shows late onset in all the homogenous monsoon regions except the northeast region. The length of monsoon season is found increasing significantly with high magnitude in west central and northwest regions. A significantly strong negative correlation (~−0.6) for monsoon onset timing ~ length of monsoon season is observed. Therefore, the change in rainfall anomaly, extreme excess days, and rainy days is done concerning the length of the monsoon season. In the cases of the −1 SD (+1 SD) length of monsoon season, rainfall anomaly and extreme excess days are low (high) in most parts of the homogenous monsoon regions. Extreme excess days showed a significant association with rainy days, which indicates a high possibility of rainy days converting into extreme excess days. However, the increase in extreme excess days in the +1 SD length of monsoon season is limited to a great extent in JJAS and June only. Morlet wavelet power spectrum shows the delay (advance) of power in −1SD (+1 SD) length of monsoon season.

Keywords: monsoon onset, monsoon withdrawal, monsoon season, extreme rainfall, homogenous region, monsoon length, rainfall pattern

INTRODUCTION

The onset of monsoon has always been an important phenomenon for any region with a monsoon climate across the globe. India is a tropical country with the summer monsoon season in June–July–August–September (hereafter JJAS). JJAS is generally defined as the monsoon season in India because the major chunk of the summer monsoon rainfall amount is obtained during this period of the year (Sahu et al., 2020; Saini et al., 2020; Saini and Sahu, 2021). India has a huge dependence on the behavior of the monsoon system from its onset to withdrawal (Prasad and Hayashi, 2005; Wang et al., 2021). It is also an agriculturally dominant country with large size of its population engaged in agriculture-based activities for livelihood and food security (Pingali et al., 2019; Kaur et al., 2021). Therefore, early or late monsoon has always been a point of discussion among agronomists, meteorologists, economists, and policymakers.

The timely onset of the monsoon with the appropriate length of the monsoon season (number of days between monsoon onset and withdrawal) and a good amount of rainfall makes the economic environment viable for the smooth progression of the developmental process (Mishra et al., 2020). Many agricultural practices depend on the onset of the monsoon and most of the farmers in India follow the Gregorian calendar for the sowing of the crop. Very early or late onset affects such practices harshly because a large part of India is not irrigated (Zaveri et al., 2016). The mutual influence of the monsoon onset and the length of monsoon season on the monsoon rainfall pattern also remains unexplored in India. Therefore, the whole environment of the agricultural sector in India is always at risk of the change in the monsoon onset timing, length of the monsoon season, and resultant pattern of the monsoon rainfall (Krishna Kumar et al., 2004).

Knowing the importance of the monsoon on many sectors in India, it should also be noted that the onset of monsoon is a very dynamic phenomenon and it depends on many factors (Loo et al., 2015). Significant prediction of the Indian summer monsoon onset and withdrawal is still very difficult (Bombardi et al., 2017). The first onset of the monsoon is generally observed around June 1 over the Kerala coast of India. The monsoon onset in some parts of southern and northeastern India takes place a little earlier than other parts and, sometimes, it may occur in the second half of May (Misra et al., 2018). Several factors are responsible for influencing the first onset in Kerala and the successive progress of the monsoon in India.

Therefore, considering the dynamics involved in the progress of monsoon, many methods were introduced for the determination of the monsoon onset and withdrawal to get the accurate onset and withdrawal of monsoon (Fasullo and Webster, 2003; Cook and Buckley, 2009; Joseph et al., 2015; Noska and Misra, 2016; Walker and Bordoni, 2016; Misra et al., 2018; Pai et al., 2020). Results of many of these methods were compared with the observations of the India Meteorological Department (hereafter IMD) for accuracy estimation and many of them performed well. Hence, knowing IMD as the official authority to release the most accurate monsoon onset and withdrawal for India, we used the observations of IMD on monsoon onset and withdrawal in this study.

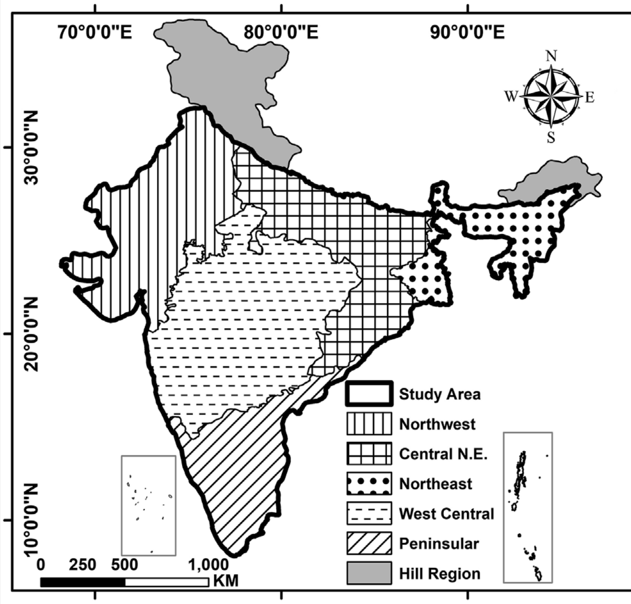

FIGURE 1 | Homogenous monsoon regions in India as delineated and mentioned by Kothawale and Rajeevan (2017) and Parthasarathy et al. (1995). The whole study area in the present study is covered within the emboldened black solid line.

In the recent past, the onset of monsoon and its characteristics at regional and sub-regional scales have been studied (Zhang et al., 2002; Raju et al., 2005; Misra et al., 2018; Pai et al., 2020). However, time passage has made it necessary to understand the early and late monsoon onset and its association with monsoon rainfall events. Early or late monsoon onsets may not be directly visible on the ground in all cases. Nevertheless, consequences of early and late monsoon onsets can cause variation in the length of monsoon season, amount of the total rainfall obtained in a region, number of extreme excess days, etc. In many cases, the short (long) length of monsoon seasons is found responsible for the deficit (excess) of rainfall received (Dhar et al., 1980; Bansod et al., 1991; Patwardhan et al., 2014). However, the long/short length of the monsoon season is not always a guarantee for the expected amount of rainfall. Study on the relationship between the onset of monsoon and the length of monsoon season (Goswami and Xavier, 2005) is one very interesting aspect of the monsoon research and needs in-depth study in Indian case also. The available literature shows that a simultaneous parallel connection between the monsoon onset, the length of the monsoon season, and the rainfall-related events at the pan-India scale has not yet been analyzed comprehensively and remain unknown. Deficit and surplus rainfall impact food grain production. Drought has relatively more impact on the Indian economy (Ha et al., 2020).

Therefore, it is necessary to investigate the intricacies of monsoon from its onset to the resultant events. The present study aims to understand the pattern and intricacies of monsoon onset, the length of monsoon season, and the consequent rainfall events along with their interrelation. In this study, an in-depth investigation was done with the following objectives: 1) to assess the dependency between rainfall and different characteristics of monsoon season (e.g., the monsoon onset and the length of monsoon season) and 2) to evaluate changes in the patterns of rainfall concentration using wavelet analysis. The methodology followed to achieve these objectives is discussed in detail in *Methods section*.

DATA AND METHODS

Study Area

India is a vast country and has the second-largest population in the world. It has high mountains, i.e., "The Himalayas" in the north and "Indian Ocean" in the south. It has the arid and semi-arid region in its western parts, whereas the northeastern part is the biodiversity hotspot with the place having the highest rainfall in the world "Mawsynram". The tropic of cancer passes almost from the middle of the country. Five homogenous monsoon regions (Kothawale and Rajeevan, 2017) exist in India (**Figure 1**) and are mentioned in the research reports, i.e., RR-065 and RR-138 of Indian Institute of Tropical Meteorology (hereafter IITM) (Parthasarathy et al., 1995; Kothawale and Rajeevan, 2017). The hill region as shown in **Figure 1** has a comparatively low density of rain gauge stations. Moreover, the onset and withdrawal maps released by IMD have less or no information available for the hill region. The similarity in rainfall characteristics and association of sub-divisional monsoon rainfall with regional/global circulation parameters led to classify the whole of India into five homogenous regions and, to do so, the rainfall data of various rain gauge stations for the period 1871–1994 were used (Parthasarathy et al., 1995). In the updated version of the research report (RR-138) of IITM by (Kothawale and Rajeevan, 2017), the rain gauge data of the period 1871–2016 were used to delineate the homogenous regions. In the study area, the peninsular region (especially Western Ghats hill) observes the first wave of monsoon onset. Peninsular and west central regions cover the Deccan plateau region of India. West central region has the central highlands and the central northeast (hereafter central N.E.) region is mainly the plain region with a good network of rivers, which makes the ground available for intense agriculture in the fertile land. The northwest region is mainly comprised of arid and semi-arid lands of serious environmental concerns in the global warming scenarios.

Data

Rainfall grid data (0.25° × 0.25°) for India were obtained from the IMD (Pai et al., 2014) (https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html). Standard quality control measures were adopted by IMD before the final release of the high-resolution gridded rainfall dataset. Quality control measures used by IMD were the checking of the extreme value existence and homogenization, checking of the existence of the duplicate station and missing data, checking and removal of the typing error in the station data, coding error removal, etc. Interpolation of rain gauge data of 6955 stations was done by IMD using the Inverse Distance Weighted method (Shepard, 1984). As per the assumption in the Inverse Distance Weighted method, the interpolating surface is influenced most by the nearby points rather than the distant points.

Monsoon onset and withdrawal dates for India were obtained from the monsoon onset (1960–2019) and withdrawal (1975–2019) maps released by IMD (https://www.imdpune.gov.in/Weather/weatherforecast.html). Considering the availability of the monsoon onset and monsoon withdrawal data in this study, the length of the monsoon season was calculated for the period 1975–2019. All the monsoon onset and withdrawal date isochrone lines were digitized and converted into the point features, covering the whole path covered by each isochrone in the map. The onset and withdrawal day of the monsoon for all the different homogenous monsoon regions were obtained using the spline interpolation method on the digitized onset and withdrawal isochrones. For ease of calculation and to run various algorithms, all the obtained onset and withdrawal dates were converted to the *N*th day (Julian day) of the year. The scheme followed for the conversion of the date to the *N*th day is shown in **Supplementary Table S1**. The representation of the interpolated result through the spline interpolation is shown in **Supplementary Figure S1**.

Methods

The flow diagram shown in **Supplementary Figure S2** is a glimpse of the methodology followed in the present study. To obtain the trend of the monsoon onset and the length of monsoon season along with the association between 1) monsoon onset ~ rainfall amount, 2) length of monsoon season ~ rainfall amount, and 3) monsoon onset ~ length of monsoon season; the simple linear regression, Pearson's product–moment correlation (hereafter PPMC), and Spearman's rank correlation (hereafter SRC) statistical techniques were used. Subsequently, the behavior of rainfall and extreme excess days in the ± 1 standard deviation (hereafter SD) length of monsoon season was also examined. The SD threshold value of ± 1.5 was also tested for its suitability for extraction of the length of monsoon season cases, and, consequently, no or few cases were found. Therefore, to avoid such a situation, ± 1 SD value is used for the extraction of cases concerning the length of monsoon season.

Interpolation for Monsoon Onset/Withdrawal Date

Among many available interpolation methods, we selected the regularized spline interpolation method (Mitášová and Mitáš, 1993). The spline method is highly acceptable to generate surfaces related to natural aspects (Hofierka et al., 2002; Mariani and Basu, 2015). It provides an estimated value between two or more points (Franke, 1982). The assumption in the method is that the two supporting points are nearly linear (Perperoglou et al., 2019; Skjelbred and Kong, 2019). It is used to obtain the gradually changing very smooth surface showing monsoon onset and withdrawal dates for India at 0.25° × 0.25° spatial resolution. Here, 0.25° × 0.25° resolution was selected to match with the resolution of the rainfall data used in the study. Concerning the present study, the advantage of executing the homogenous monsoon region-wise interpolation of the monsoon onset and

TABLE 1 | Extracted event years based on ± 1 SD anomalous length of monsoon season for the period 1975–2019.

Peninsular		Northeast		West Central		Central N.E.		Northwest	
−1 SD	+1 SD	−1 SD	+1 SD	−1 SD	+1 SD	−1 SD	+1 SD	−1 SD	+1 SD
1979	1975	1981	1975	1978	1990	1976	1975	1981	1996
1980	1986	1982	1993	1979	2008	1979	1989	1982	2008
1983	1990	1984	2004	1980	2010	1981	1999	1985	2013
1984	2000	1997	2006	1982	2011	1982	2000	1987	—
1997	2009	2005	2009	1984	2013	1997	2008	1991	—
2003	2010	2019	2010	1987	—	2005	2013	1995	—
2005	2011	—	—	2005	—	2018		2002	—
—	—	—	—	2014	—	—	—	—	—

withdrawal is that it prevents erroneous or non-satisfactory results.

Identification of Extreme Excess Days and Rainy Days

Generally, extreme excess year in India is the year with + 1 SD excess of all India rainfall in summer monsoon season from the mean of all India summer monsoon rainfall (Kothawale and Munot, 1998; Deka et al., 2016). Whereas, extreme excess days in the present study are based on the +2 SD of daily rainfall data from the calculated daily mean. Rainy days were considered on the basis of the criteria of 2.5 mm or more rainfall as per IMD's definition (Nandargi and Mulye, 2012). ±1 SD threshold was used for extracting the cases of large/small length of monsoon season (**Table 1**) to understand the change in rainfall anomaly, extreme excess days, and rainy days and to obtain wavelet results concerning the length of monsoon season.

Wavelet Analysis

Wavelet analysis is an important method to study and analyze the localized variation of power during a certain period. This method provides the transformation of the unidimensional time series spectrum to the bidimensional visualization (time–frequency visuals). This method has been used in geophysics to attain different objectives, and its conceptual elaboration is provided in some important research articles (Lau and Weng, 1995; Torrence and Compo, 1998). Knowing the advantages of the Morlet wavelet to better localize the time–frequency, we used the Morlet wavelet rather than Daubechies wavelet and Mexican Hat wavelet. The period starting from June 1 to September 30 was selected for the analysis because the majority of rainfall in India occurs during this time only and consideration of the period beyond that would result in the edge effect influencing the true representation of the rainfall wavelet analysis. The area outside the cone of influence excludes the edge effect and is therefore not considered the true result representation.

RESULTS

Monsoon Onset (1960–2019)

Monsoon Onset Trend

On the basis of available data on monsoon onset, i.e., 1960–2019, the anomalous onset of monsoon has a positive trend in all the homogenous monsoon regions except in the case of the northeast region (**Figures 2A–E**). However, the trend is not highly significant in any of the homogenous monsoon regions. Peninsular, west central, and central N.E. regions have the trend of late monsoon onset (80% level of significance). The northeast region is the only homogenous monsoon region with an early-onset trend. Arranging the homogenous monsoon regions with their positive magnitude of trend, the highest positive slope value (0.59 days/decade) is found in peninsular, which is followed by central N.E., west central, and northwest, respectively.

Thus, monsoon onset in the majority of homogenous monsoon regions is found with a late onset. SD values of the anomalous monsoon onsets in peninsular, northeast, west central, central N.E., and northwest are 6.05, 6.00, 5.19, 5.34, and 6.86, respectively. The number of events with +1 (−1) SD onset in peninsular, northeast, west central, central N.E., and northwest are 11, 11, 10, 10, and 13 (7, 7, 9, 11, and 3), respectively. Among all the homogenous monsoon regions, west central and central N.E. regions are in a balanced state with an almost equal number of ±1 SD events and comparatively low SD values.

Linear Association Between Monsoon Onset and Rainfall

Association between monsoon onset and the total rainfall amount in monsoon season and its constituent months was analyzed for the period 1960–2019 using the linear regression model (**Figure 3**). Monsoon onset shows a strong association with rainfall amount in most of the cases (significant at 90% level), such as the case of August for northeast (**Figure 3I**); JJAS and June for west central (**Figures 3K,L**); JJAS, June, and August for central N.E. (**Figures 3P,Q,S**); and JJAS, June, July, and September for northwest (**Figures 3U,V,W,Y**). Interestingly, in the peninsular region, where monsoon onset occurs first in India, no significant results are found on the association of monsoon onset with seasonal rainfall. The onset of monsoon over each homogenous monsoon region is different due to the pulsatory nature (Cadet and Daniel, 1988) of the monsoon onset, and, therefore, the association between rainfall amount and the monsoon onset is different for each homogenous monsoon region.

Length of Monsoon Season (1975–2019)

Length of Monsoon Season Trend

The observed positive trend in the anomalous length of the monsoon season (**Figures 2F–J**) indicates enlargement of the monsoon season. However, the significant results are found only

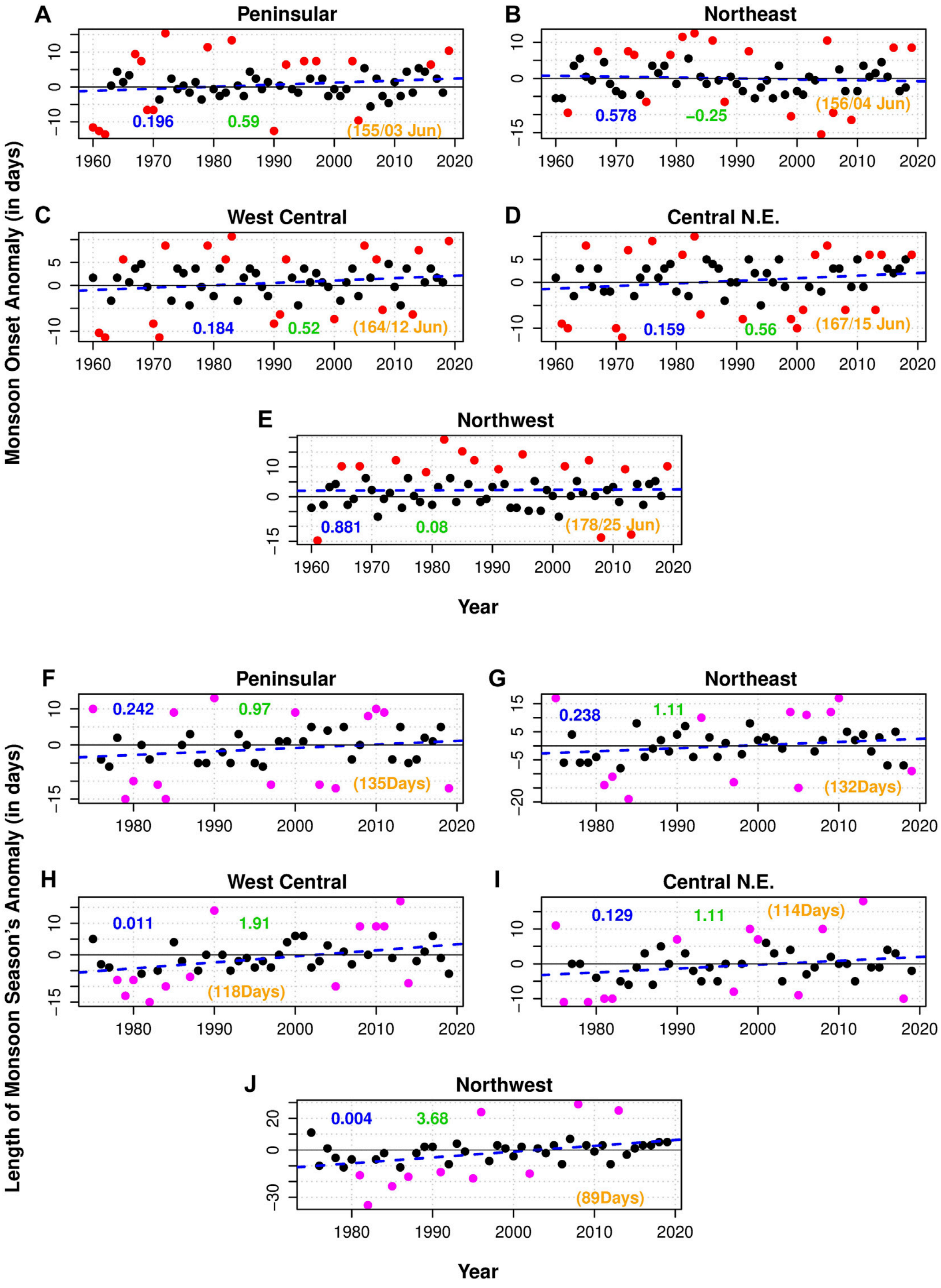

FIGURE 2 | (A–E) Anomalous onset of the monsoon in India and different homogenous monsoon regions. Red dots show the anomalous onset with +1 (−1) SD. **(F–J)** Anomalous onset of the monsoon season's length in India and different homogenous monsoon regions. Pink dots show the anomalous monsoon season's length with +1 (−1) SD. Blue dashed line shows the linear trend in each panel. Blue (green) color value is representative of the *p*-value (slope) of the anomalous monsoon onset data. Slope value shows the change per decade. Whereas yellow color in **(A–E)** shows the mean calculated value of the *N*th day of the monsoon onset, and, in **(F–J)**, it shows the mean number of days of the monsoon season's length.

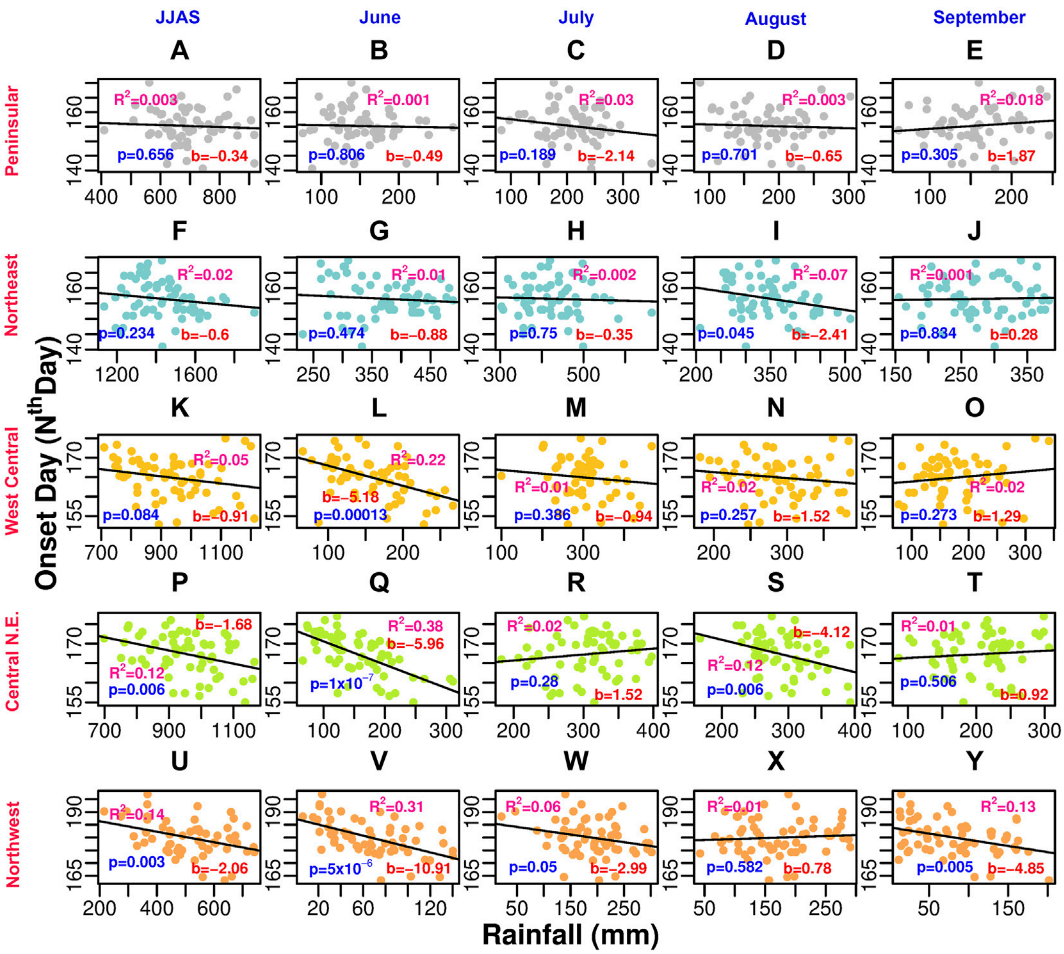

FIGURE 3 | The linear tendency of monsoon onset with rainfall amount for the period 1960–2019. Black solid line represents the linear trend. *p*-value (slope) in the panels is represented by blue (red) color. Slope value shows the change in onset (in days) per hundred millimeter (10 cm) rainfall.

for west central and northwest regions (significant at 99%). Both the homogenous monsoon regions with a significant length of monsoon season trend shows the high positive magnitude, indicating the enlargement of the length of monsoon season by 1.91 days/decade and 3.68 days/decade in west central and northwest regions, respectively. In addition, the analysis related to the change point existence in the trend of the length of monsoon season was also adopted and the significant change point is identified only in west central (year 1988) and northwest (year 1995) regions. However, no significant trend is found before and after the existing change point in west central and northwest region.

Linear Association Between Length of Monsoon Season and Rainfall

Results on the association of the length of monsoon season with the rainfall amount (**Supplementary Figure S3**) show that west central, central N.E., and northwest regions have a significant association in June, and northwest region shows significant association in September also. Therefore, in the case of a longer length of monsoon season in the homogenous monsoon regions with significant results, there is a high possibility of the occurrence of a large amount of rainfall.

Besides that, the relationship between the onset and the length of monsoon season shows a significantly very strong correlation value for all the homogenous monsoon regions except central N.E. having −0.5814 (PPMC) and −0.5879 (SRC) values (**Table 2**). In different homogenous monsoon regions, the significant strong negative correlation (~−0.6) between the monsoon onset and the length of monsoon season reveals that the early (late) onset leads to a large (short) length of monsoon season. Knowing this fact, it is pertinent to decipher the character and pattern of the rainfall and extreme excess days in large (+1 SD) and short (−1 SD) length of monsoon seasons in different homogenous monsoon regions.

Rainfall Pattern and Extreme Excess Days in the ±1 SD Length of Monsoon Season

Rainfall

The majority of areas of all the panels are covered with negative anomalies in the −1 SD length of monsoon season (**Figure 4**). It

TABLE 2 | Pearson's product–moment correlation (PPMC) and Spearman's rank correlation (SRC) for the period 1975–2019. Correlation coefficient is calculated between the *N*th onset day and the length of monsoon season. All the correlation coefficient values are significant at the 99% level.

Peninsular		Northeast		West Central		Central N.E.		Northwest	
PPMC	SRC	PPMC	SRC	PPMC	SRC	PPMC	SRC	PPMC	SRC
−0.677	−0.645	−0.724	−0.730	−0.623	−0.567	−0.581	−0.587	−0.828	−0.694

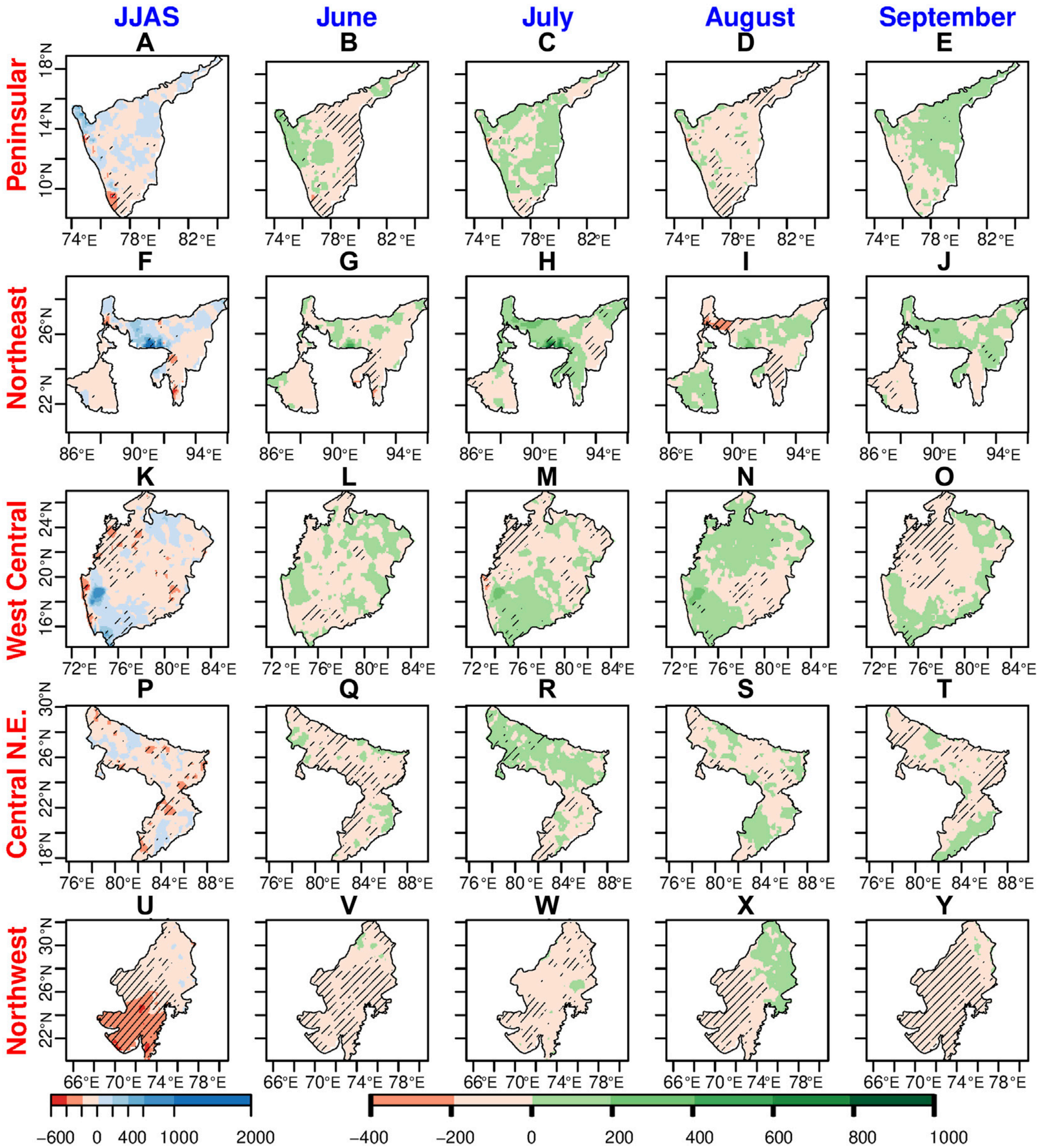

FIGURE 4 | Anomalous rainfall distribution in homogenous monsoon regions in the events of the −1 SD length of monsoon season (as given in **Table 1**). The calculated anomaly of rainfall in monsoon season is based on the normal years (years excluding the ±1 SD monsoon length), whereas the level of significance (>90%) is based on the Mann–Whitney–Wilcoxon test and represented by the 45° line pattern. The unit of the anomalous rainfall is millimeter.

shows that the smaller length of the monsoon season receives less amount of rainfall. In the peninsular region, a dark red spot signifying a whole province of India, i.e., Kerala, shows the highest negative anomaly. Given this fact, the harsh impact will be directly faced by this region as it observes one of the highest rainfalls in India (Saini et al., 2020) and it also observes

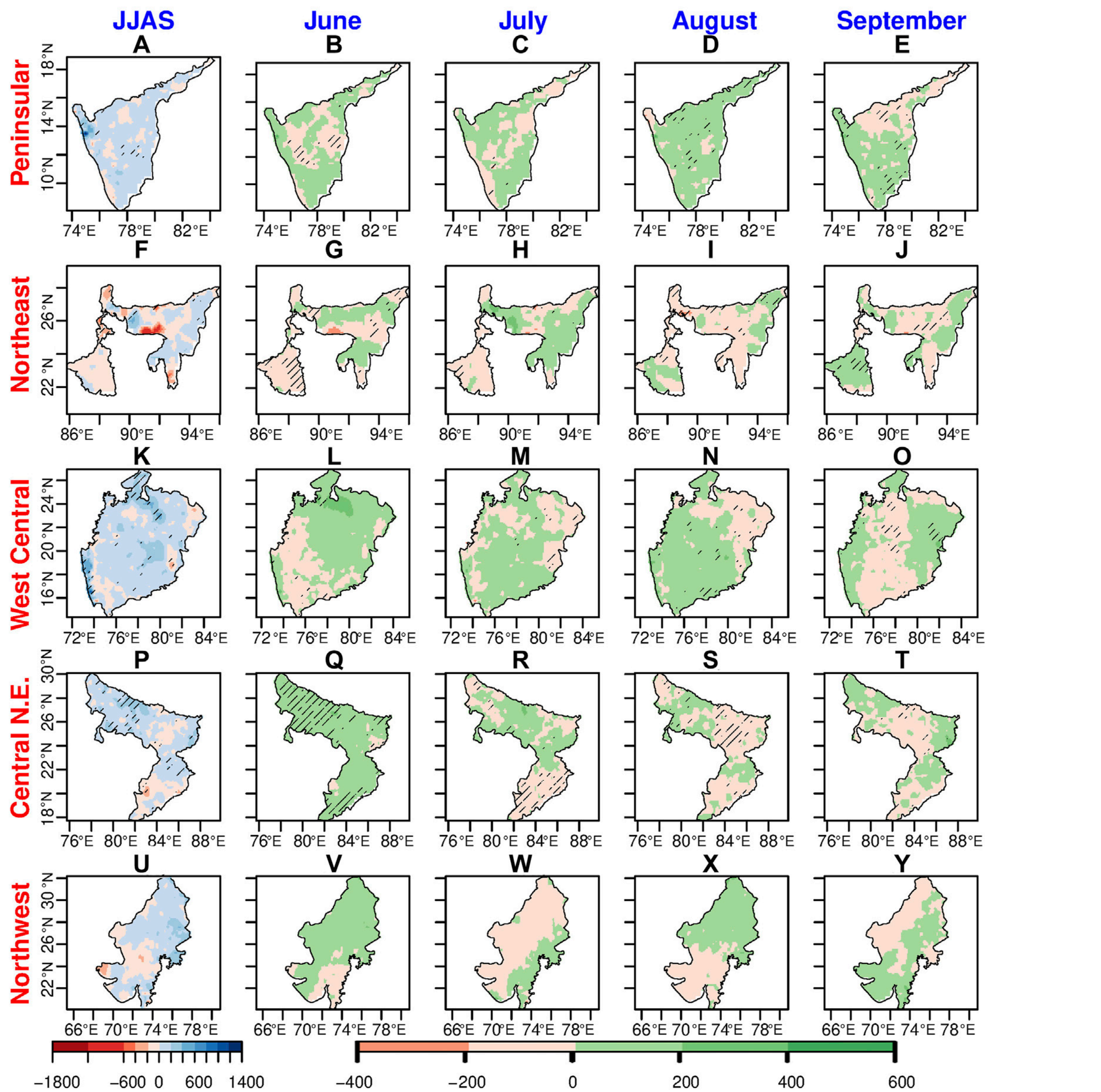

FIGURE 5 | Anomalous rainfall (same as in **Figure 4**) and, here, it is for the case of the +1 SD length of monsoon season.

the first monsoon onset in India. However, significantly widespread areas under negative anomaly are found in June and August in this homogenous monsoon region.

Significant negative anomalies are seen for some parts in the northeast region in June, July, and August (**Figures 4G–I**). In the case of the west central region, the majority of the area with the negative anomaly is found significant. A large part of this homogenous monsoon region observes positive anomaly in July, August, and September (**Figures 4M,O**); however, it is not significant. JJAS season for the west central region shows that its northwestern part is highly vulnerable to negative rainfall. One very important homogenous monsoon region concerning fertile plain land and high agricultural productivity is central N.E., and most of its areas are covered with a significant negative anomaly in June. In the northwest region, a very large area has a widespread significant negative anomaly. The southern part of the northwest region shows a severely negative anomaly in the JJAS season (**Figure 4U**). Interestingly, we found that some parts of the northwest region also have positive rainfall anomalies in August, but it is not statistically significant. Widespread negative anomaly in the −1 SD length of monsoon season in almost every part of the homogenous monsoon regions in one or the other time frame is highly notable and needs the attention of the policymakers for mitigation measures.

Comparing the cases of the −1 SD length of monsoon season (**Figure 4**) with the +1 SD length of monsoon season (**Figure 5**) shows that longer seasons generally have excess rainfall amount. **Figure 5F** shows the central part of the northeast region is against

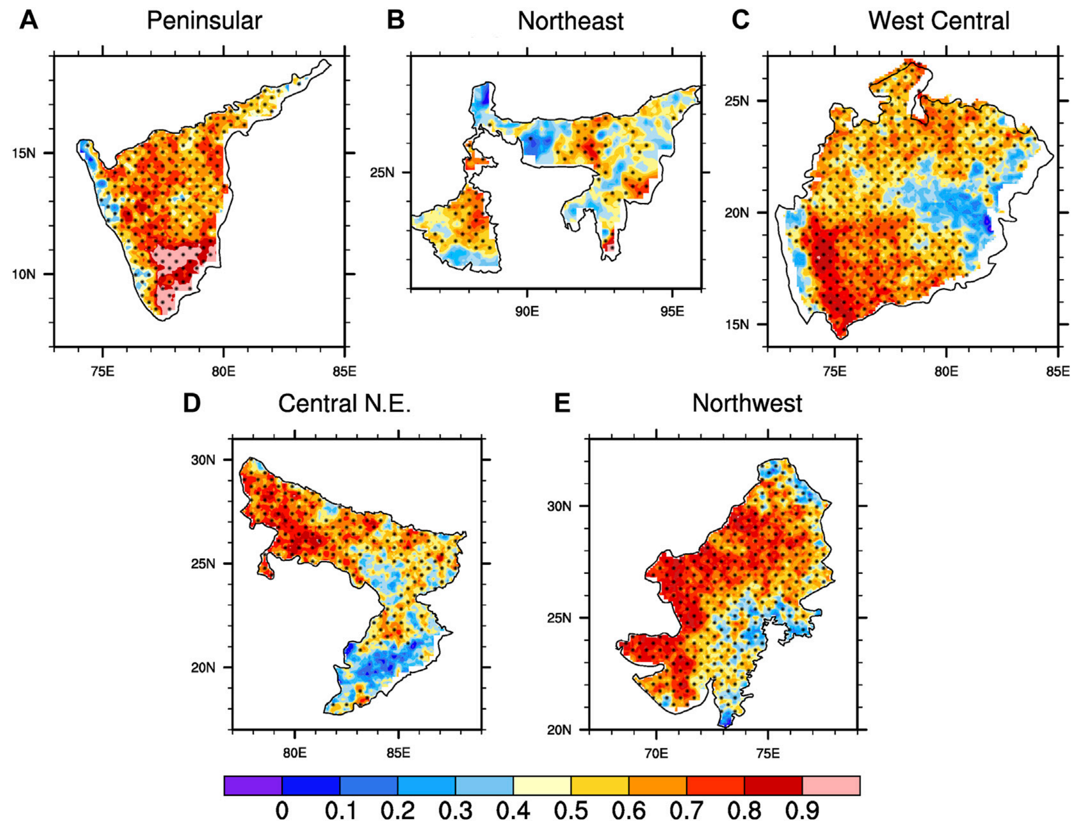

FIGURE 6 | Pearson's product–moment correlation of extreme excess days with rainy days in JJAS for the period 1975–2019. Dots in the map refer to region with correlation coefficient value significant at >90% level.

the general pattern of a positive anomaly in the +1 SD length of monsoon season and a similar independent pattern is also seen in **Figure 4F** in the case of the −1 SD length of monsoon season. A significant positive anomaly is seen for the western part of central N.E. in the JJAS season and June month (**Figures 5P,Q**). It should be noted that the results for the +1 SD length of monsoon season are not highly significant for most parts, and, therefore, the results are highly predictive only in the −1 SD length of monsoon season cases.

Obtained results for the rainfall in the ±1 SD length of monsoon season are further investigated using the wavelet analysis in *Wavelet Analysis of Rainfall section* because the change in the spatial pattern of the rainfall shows a unidimensional picture of the phenomena on the ground and wavelet analysis has the potential to produce the bidimensional picture for exploration of the shift in the aggregated power and discontinuities.

Extreme Excess Days

Generally, extreme excess days have an instant damaging effect on the ground, and, therefore, its estimation is highly important for the society and natural ecosystem. The spatial correlation between the rainy days and extreme excess days was calculated for the JJAS season from 1960 to 2019 to see the possibility of conversion to extreme excess days. The results clearly show (**Figures 6A–E**) the presence of significantly high correlation in large parts of homogenous monsoon regions except for some parts such as eastern parts of the west central region, the southern central N.E. region, and the northeast region.

The spatial pattern of the rainy days in the ±1 SD length of monsoon season (**Supplementary Figures S4, S5**) and the extreme excess days in the ±1 SD length of monsoon season (**Figures 7**, **8**) are found similar to each other. In both cases, it should be noted that the constituent months being representative of a small period compared to the JJAS season suggest the low magnitude of the anomalous extreme excess days.

In the case of the −1 SD length of monsoon season (**Figure 7**), the widespread negative anomaly is found for extreme excess days, and it is similar to the anomalous rainfall distribution in the −1 SD length of monsoon season (**Figure 4**). Southern parts of the peninsular region are highly vulnerable to the decrease in the extreme excess days (**Figure 7A**). Moreover, **Figures 7B–E** show the cases of all four constituent months with the varying spatial pattern of the anomalous extreme excess days. Some parts covering the southeastern part of the northeast region show a significant negative anomaly of >4 days (**Figure 7F**). Parts of the western edge of the west central region show a significant increase in the extreme excess days that suggests flood-like conditions there. However, the rest of the area in the homogenous monsoon region observe significant negative anomalies in JJAS

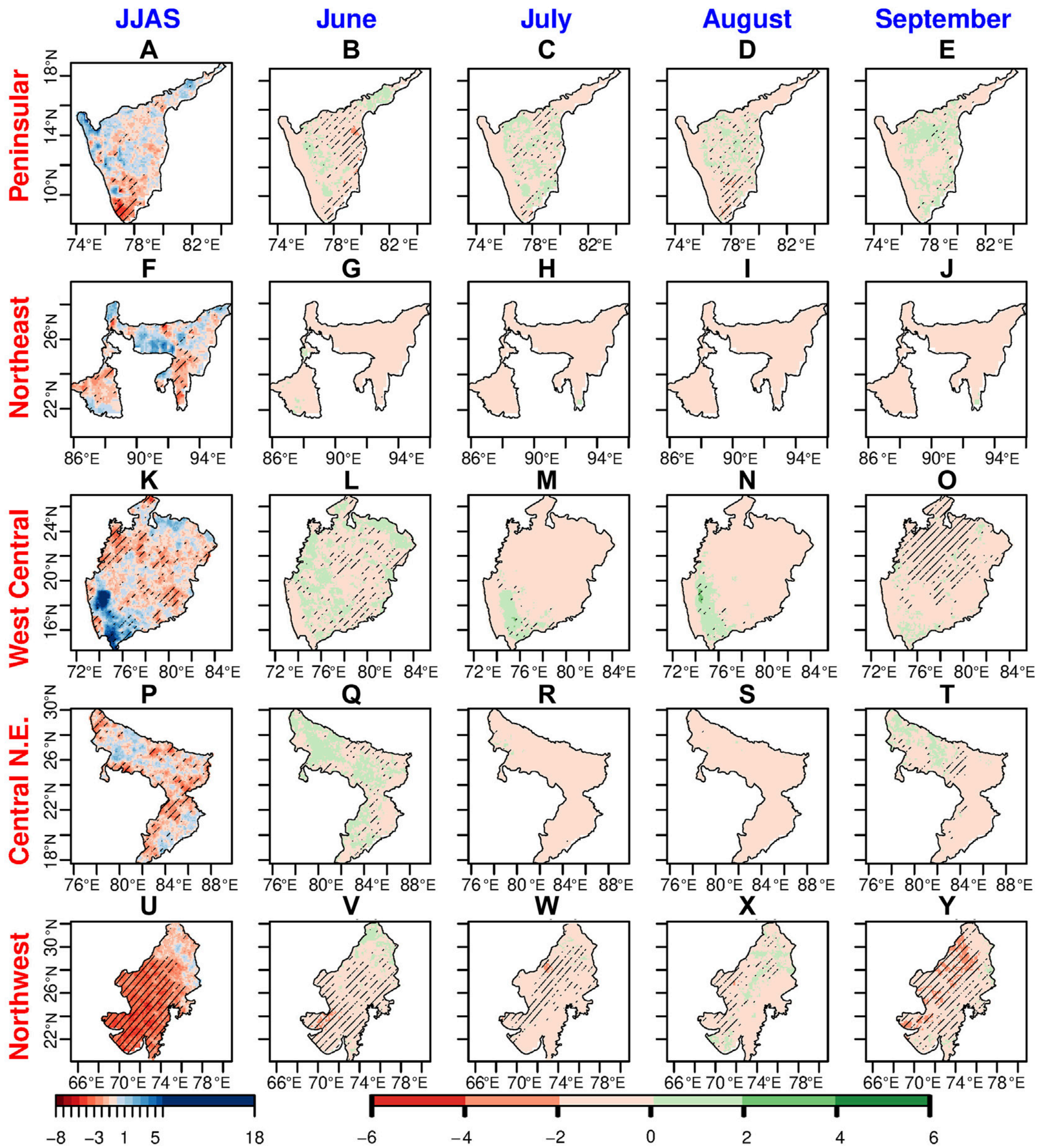

FIGURE 7 | Anomalous extreme excess days distribution in homogenous monsoon regions in the events of the −1 SD length of monsoon season (as given in **Table 1**). The calculated anomaly of extreme excess days is based on the normal years (years excluding the ±1 SD monsoon length), whereas the level of significance (>90%) is based on the Mann–Whitney–Wilcoxon test represented by the 45° line pattern.

(**Figure 7K**), June (**Figure 7L**), and September (**Figure 7O**). The highly fertile central N.E. region also shows a significantly negative anomaly as shown in **Figures 7P,T**. The northwest region is an arid/semi-arid region and receives very low rainfall. A significant decrease can be seen in large parts of this homogenous monsoon region (**Figures 7U,Y**). Overall, the widespread negative anomaly is the clear representation of the fall in extreme excess days during the −1 SD length of monsoon season.

Interestingly, a large part of all the homogenous monsoon regions as shown in the case of the +1 SD length of monsoon season for JJAS (**Figure 8**) is found with the increase in the number of extreme excess days. JJAS season and June month have a considerable distribution of positive anomaly, and the months succeeding June show the dominance of negative anomaly. This suggests a high probability of extreme excess days in June month or JJAS season as a whole. The negative anomaly in the months succeeded by June is insignificant and does not show a high magnitude of decrease. Some parts of homogenous monsoon regions such as northern parts of peninsular, west central, and central N.E. show a significant increase in the occurrence of extreme excess days. An increase of the extreme excess days in the western part of central N.E. (**Figures 8P,Q,T**) is of high concern for the intense agriculture and high population in the area. It can

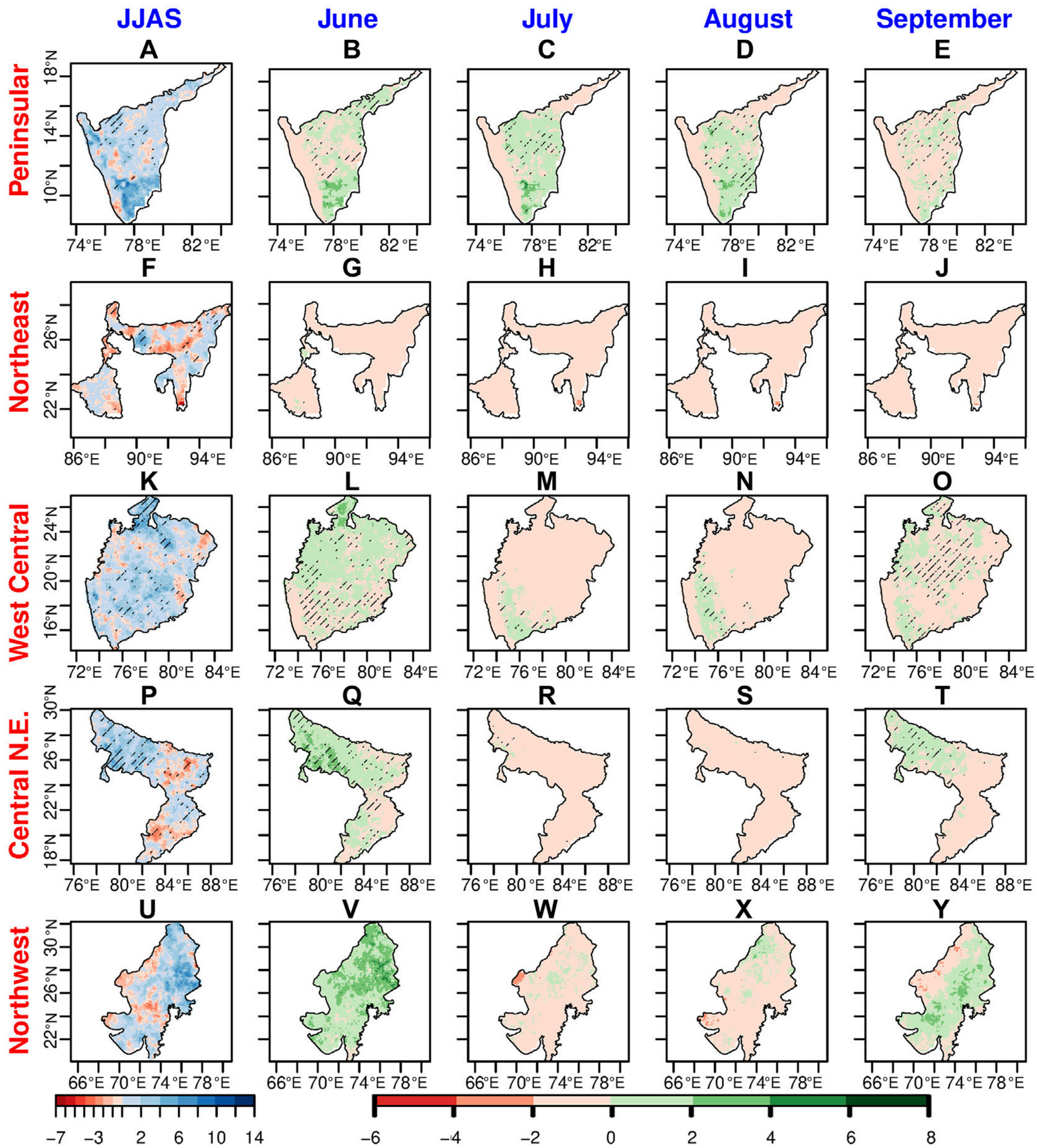

FIGURE 8 | Anomalous extreme excess days (same as in **Figure 7**) and, here, it is for the case of the +1 SD length of monsoon season.

be summarized that the year with the +1 SD length of the monsoon season has high chances of a large number of extreme excess days in June month and JJAS season as a whole. The northeast region does not show any significant impact in this case.

Wavelet Analysis of Rainfall

The wavelet analysis method was used to analyze the rhythm and concentration of the power of the rainfall during the normal, −1 SD, and +1SD length of monsoon seasons (**Figure 9**). It assisted in understanding the significant daily rainfall activity in the JJAS season.

In the −1 SD length of monsoon season (**Figure 9B**), wavelet power is concentrated between July 1 and August 30 in the peninsular region, but, in the case of +1 SD, it is highly scattered (**Figure 9C**). In the normal phase (**Figure 9A**), the scattered pattern of the power concentration is observed and initialization in early June is observed. In the −1 SD case, the concentration is maximum in July (between 6 and 16 days period). Compared to the −1 SD length of monsoon season, the +1 SD length of monsoon season usually have initialization in early June and the overall scattered pattern indicates episodes of breaks.

Similar to the peninsular region, the northeast region's normal length of monsoon season (**Figure 9D)** shows a scattered pattern and early start in mid-June. Whereas, in the −1 SD length of monsoon season, power remains concentrated between 4 and 7 days period with a similar scattered pattern as in normal case (**Figure 9E)** but has late start compared to the normal and +1 SD

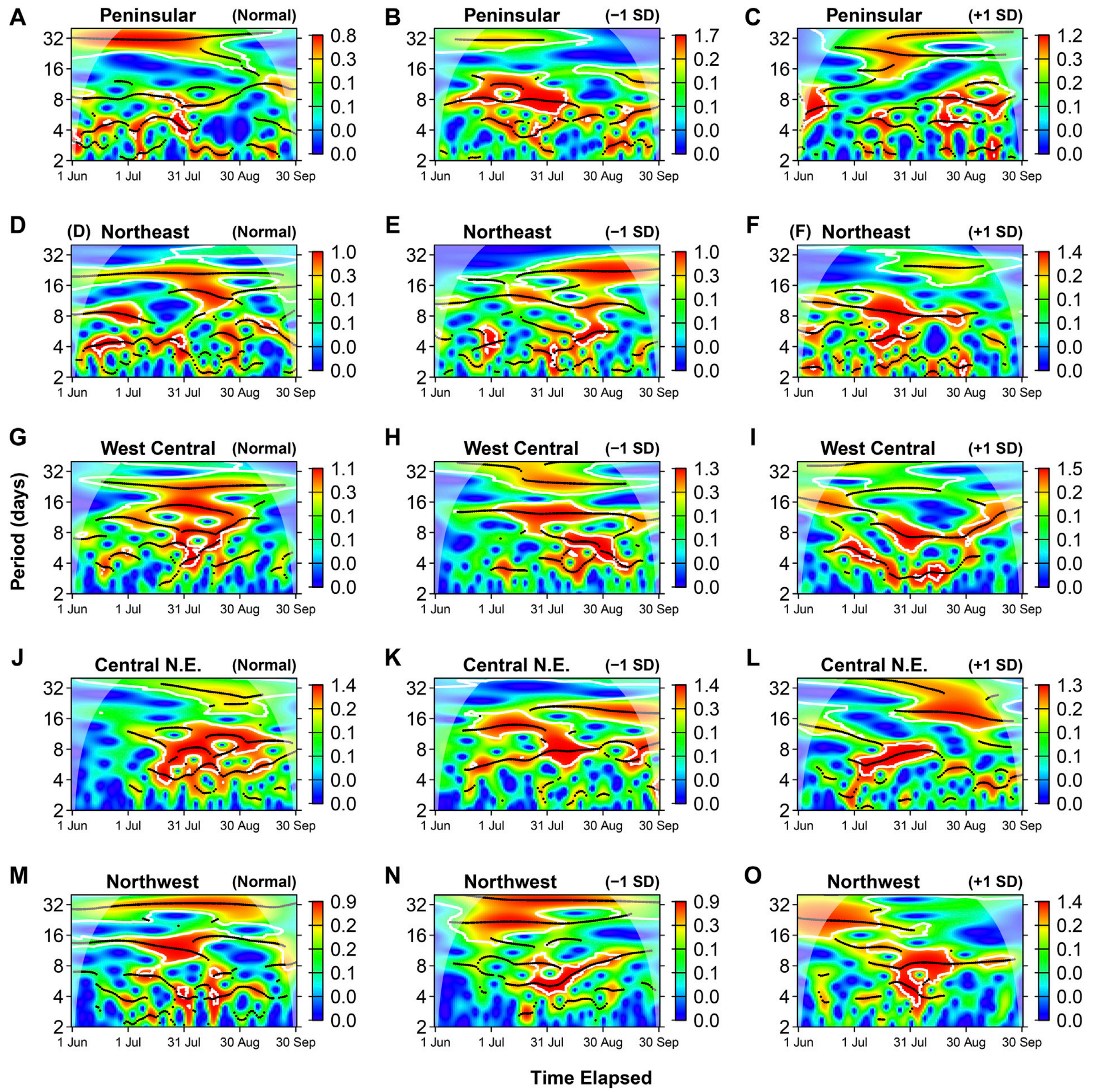

FIGURE 9 | Wavelet power spectrum using continuous wavelet transform based on Morlet wavelet. The *x*-axis represents the location of the wavelet in time and the *y*-axis shows the period of the wavelet. Legend on the right side of each panel indicates the level of the wavelet power. In each panel, red area shows the occurrence of high intensity of the rainfall activity. The area shown with higher clarity in the panels inside the cone of influence (curved white shadow on left and right edge of each panel marks the cone of influence) excludes the edge effect.

length of monsoon seasons. It is interesting to note in the +1 SD length of the monsoon season that significant power starts comparatively earlier than the −1 SD length of monsoon, the area of high-power concentration is also very large with a 4 to 16 days period.

In the case of the west central region (**Figures 9G–I**), the power spectrum clearly shows that the rainfall activity is present with the embarkment of June month in the +1 SD length of monsoon season and lasts until the end of September. However, it is comparatively late in the normal and −1 SD cases of the length of monsoon season. The normal case of central N.E. (**Figure 9J**). shows the start of high power in the second half of July in the normal length of monsoon, whereas it occurs early in the −1 SD and +1 SD length of monsoon seasons. It starts with a high period in the −1 SD case (**Figure 9K)** compared to +1 SD ((**Figure 9L)** which is under 8 days. Heavy accumulation of rainfall activity is seen in the −1 SD case of the northwest region since the start of the monsoon season and high intensity of power is concentrated between mid-July to mid-August (**Figure 9N**). Similar is the case of +1 SD (**Figure 9O)** with a high concentration of power in

August, though the concentration of the power is not prevalent with the starting of June and hence delayed in the case of the +1 SD length of monsoon season.

DISCUSSION

India being a country with a large population size and majority rainfall occurring in a particular season (JJAS) cannot afford the changes in the monsoon onset, length of monsoon season and the associated rainfall amount. "How does the monsoon onset is connected with the rainfall amount; monsoon onset with the length of monsoon season; length of monsoon season with rainfall amount and extreme excess days?" were some important questions that needed to be answered. The highest (~±7 days) and lowest (~±5 days) variability of monsoon onset is found in the northwest and west central regions, respectively. Interestingly, the variability of monsoon withdrawal is highest (~±7 days) and lowest (~±5 days) in the same regions as found in monsoon onset. The mean variability of onset and withdrawal in India is found almost the same, i.e., ~ ± 6 days. The pattern of the variability of the monsoon onset and withdrawal is found similar to the spatial pattern discussed by Pai et al. (2020) in their study. Only the magnitude of variability in monsoon withdrawal is found higher by ~1 day in some parts of India. Many factors influence the onset of monsoon in India and major factors among many are: 1) depression in the Bay of Bengal formed in the last week of May or the first week of June (Dash et al., 2004), 2) similar low pressure or depression in the Arabian Sea (Vinayachandran et al., 2007), 3) the cyclonic vortex associated with the cloud mass and it is marked much closer off the Kerala coast than the usual cyclonic circulation (Hari et al., 2021), 4) the trough along the west coast (Murakami et al., 2017), and 5) cross-equatorial winds are another major factor (Pérez-Hernández et al., 2012). The process of the withdrawal of monsoon from India is comparatively much faster than the monsoon onset and factors influencing the monsoon withdrawal can be the El Niño–Southern Oscillation, Rossby waves, the interannual variations in upper and lower level atmospheric temperature, etc. (Syroka and Toumi, 2004).

Concerning the rainfall amount, there can be many natural and anthropogenic factors responsible for the changes in the monsoon rainfall amount (Niyogi et al., 2007; Paul et al., 2016; Roy and Tedeschi, 2016). The influence of monsoon onset and resultant length of monsoon season were examined with different perspectives, i.e., amount of monsoon rainfall and expected number of extreme excess days. There exists no significant trend of monsoon onset in India as a unit and it is in agreement with the earlier study by Saini and Sahu (2020). Three out of five homogenous monsoon regions have the trend showing delay in the monsoon onset (~80% level of significance), which might become more significant and intense. Results with no significant monsoon onset trend in different homogenous monsoon regions are found consistent with the findings of Xavier et al. (2007) for India. The delay in onset is also noted in the majority of the grid point–based analysis at the pan-India level (Pai et al., 2020); however, its relation with the rainfall is discussed here in the present study. Variability of monsoon onset is found similar to the spatial pattern discussed by Pai et al. (2020) in their study. Moreover, the trend of late monsoon onset discussed in *Monsoon Onset Trend section* and the enlargement trend of the length of monsoon season in different homogenous monsoon regions signifies the late withdrawal of the monsoon. Whereas, contrary to the present study, Xavier et al. (2007) found earlier withdrawal for India. Sabeerali et al. (2012) and Xavier et al. (2007) highlighted the shortening of the length of the monsoon season in India and it should be noted that the onset and withdrawal dates in such studies are significant for a particular region and not the homogenous monsoon regions.

A good linear association of monsoon onset with rainfall amount (90% level of significance) is found in the majority of the homogenous monsoon regions. It can be asserted from the obtained results that the timing of the monsoon onset can be used as a predictor for the amount of rainfall to be received in the JJAS season or its constituent months. However, at a finer spatial scale, the situation may be different due to the impact of stochastic and synoptic events (Saha and Saha, 1980). Previously, at a smaller spatial scale, an attempt was made to understand the association of the rainfall over different stations in India with the onset of monsoon in Kerala (Bansod et al., 1991).

A strong positive correlation between the monsoon onset and the length of the monsoon season gives a clue of a good amount of rainfall in the monsoon season because monsoon onset and rainfall have a significant linear association for all the homogenous monsoon regions except the peninsular and northeast region. Dhar et al. (1980) also agree with no clue obtained on the association of early/late monsoon onset and amount of rainfall in the coastal part of the peninsular region.

Analysis of anomalies of rainfall and extreme excess days shows that the northeast region is an exception among all the homogenous monsoon regions due to widespread positive (negative) anomaly of rainfall and extreme excess days in the −1 SD (+1 SD) length of monsoon season. It is the region, where the world's highest rainfall receiving area is located (Murata et al., 2007). It needs further investigation to understand the mechanism of such circumstances in the northeast region. Monsoon dynamics in the northeast region is a little different from other homogenous monsoon regions. Recent studies show an exceptional monotonic decrease in the monsoon rainfall of this homogenous monsoon region (Saini and Sahu, 2021) and a high density of forest cover, which causes transpiration and it controls many atmospheric factors to a great extent (Pradhan et al., 2019). A general increasing monotonic trend of extreme rainfall events in June, July, and August months was reported by Varikoden and Revadekar (2020); however, such occurrence is not found in either the +1 SD or −1 SD length of the monsoon season (**Figures 7**, **8**).

Moreover, the decline (significant at 90%) in the rainfall and number of the extreme excess days is found in −1 SD length of monsoon season for the southern part of the peninsular region (representing Kerala) along with the insignificant rise in the +1 SD length of monsoon season. Therefore, the general trend of decrease (increase) in the moderate (extreme) rainfall events

(Sreelash et al., 2018) in combination with the behavior in the ±1 SD length of monsoon season can be lethal for this part of the peninsular region as it is the part of the Western Ghats biodiversity hotspot. The decreasing rainfall trend in this region is credited to the northward shifting of the low-level jet stream and the warming of the Arabian sea (Varikoden et al., 2019). However, the dynamics behind the change in the number of extreme excess days in the ±1 SD length of monsoon season needs to be investigated.

The number of rainy days shows a positive correlation with the extreme excess days. Therefore, the possibility of the occurrence of extreme excess days is high in all the homogenous monsoon regions in the case of the +1 SD length of monsoon season. An increase in the number of extreme excess days in June month and JJAS season as a whole is notable. Future projections also show the significant rise in the occurrence of extreme precipitation events in the monsoon season in India (Goswami et al., 2006; Menon et al., 2013; Katzenberger et al., 2021). Therefore, it can be asserted that, with the early (late) onset, there are chances of onset leading to the larger (shorter) length of monsoon season with a high (low) amount of rainfall, which results in the larger (smaller) number of the extreme excess days. Available literature shows that this interrelation between rainy days and extreme excess days has not been studied for India considering the different homogenous monsoon regions.

Wavelet analysis shows that the rainfall is well spread across the monsoon season and highly concentrated between July 1 to July 31. In most of the cases of the +1 SD length of monsoon season, the concentration of power is found located comparatively earlier than the cases of the −1 SD length of monsoon season and neutral cases. It also indicates that the rainfall in the larger monsoon season of different homogenous monsoon regions is distributed well in advance. Along with these assertions, the shift in the core of power representing the intensity of the rainfall in the wavelet spectrum also assisted to understand the change in the behavior of rainfall in the ±1 SD length of monsoon season. However, the shifting and pattern of the power in the spectrum sometimes do not present a clear picture. Whereas, the shift could be easily observed while comparing wavelets of ±1 SD length of monsoon season with the wavelets of the normal length of monsoon season.

CONCLUSION

The onset of monsoon, length of the monsoon season, and monsoon rainfall was studied independently in detail and simultaneously in parallel also because, until the most recent, the interrelation between them was still unknown at the pan-India level. The present study was designed mainly to 1) assess the strength of interrelation between the monsoon onset, the rainfall, and the length of the monsoon season that has serious implications on agriculture, water resources management and associated activities in India, and 2) to investigate the behavior of rainfall, and extreme excess days and rainy days in the ±1 SD length of monsoon season. Trend analysis of monsoon onset shows no significant monotonic trend but the length of monsoon season is found monotonically increasing in west central and northwest regions. Homogenous monsoon regions have a significant pattern concerning the monsoon onset and rainfall for either JJAS seasonal rainfall or some monthly rainfalls except for the peninsular region.

A strong and significant (>99% level of significance) negative correlation between the monsoon onset and the length of monsoon season is obtained for all the homogenous monsoon regions and it reveals that the early (late) onset leads to a large (short) length of monsoon season. The observed positive trend in the anomalous length of the monsoon season indicates the enlargement of the monsoon season, especially significant enlargement trend in the west central and northwest regions.

Considering the strong correlation between the monsoon onset and the length of monsoon season, the behavior of rainfall, extreme excess days, and rainy days was studied in detail as its influence is mainly on rainfed agriculture systems and many environmental attributes in India. West central, central N.E., and northwest regions have a significant association between the length of monsoon season and rainfall in June, and northwest region shows significant association in JJAS and September also.

Extreme excess days showed a strong significant positive correlation with the rainy days. In the majority of areas of all the homogenous monsoon regions, extreme excess days are found following a spatial pattern similar to rainy days, and, therefore, the increase in the rainy days has greater chances for the occurrence of the extreme excess days. However, an increase/decrease in the number of rainy days does not guarantee the occurrence of extreme excess days. A large part of all the homogenous monsoon regions as shown in the case of the +1 SD length of monsoon season for June and JJAS is found with the increase in the number of extreme excess days.

The trend of the late monsoon onset, enlargement of the length of monsoon season, a good correlation between monsoon onset ~ rainfall, monsoon onset ~ length of monsoon season, and extreme excess days ~ rainy days are the major highlights of the present research. Through the results of the present study, it can be stated that the early/late onset of monsoon in different homogenous monsoon regions of India (except peninsular and northeast) provides the clue on the performance of monsoon activity. Therefore, it is pertinent to consider early/late onset for the planning and policymaking in the monsoon season to mitigate beforehand the expected impacts of the monsoon onset. Notably, the monsoon onset trend is not found significantly monotonic but the timing of monsoon onset is found helpful to get the estimate of seasonal monsoon rainfall in the homogenous monsoon regions. On the other hand, a trend of the length of monsoon season is significantly monotonic in west central and northwest regions, and both these regions along with the central N.E. region also show a good association between length of monsoon season ~ rainfall, especially in June. Therefore, it can be asserted that in the future, the west central and northwest regions may observe a large amount of rainfall in June. In the larger length of the monsoon season (+1 SD), there are high chances of the transformation of the rainy days into extreme excess rainy days in vast areas of the homogenous monsoon regions. Hence, the west central and northwest regions of India are at high risk due to a significantly monotonic increase in the length of the monsoon season, leading to the huge rainfall and high possibility of the rainfall transformation into extreme excess rainy days. The present findings and further in-depth study based on these results can be helpful to mitigate the impacts of monsoon in India.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found at https://cdsp.imdpune.gov.in/home_gridded_data.php.

AUTHOR CONTRIBUTIONS

AS did the investigation, used software, prepared the original draft, drew all the figures, and did the data curation part. AS and NS conceptualized the central idea, framed the methodology, and completed the formal analysis. NS did the supervision and validation. WD, MK, RA, MM, PK, and RP reviewed and edited the manuscript. SB provided important comments to improve the manuscript and contributed in the validation part of the study.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.794634/full#supplementary-material

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