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Proportional Trends of Continuous Rainfall in Indian Summer Monsoon

Vinay Kumar [1,*], K. Sunilkumar [2] and Tushar Sinha [1]

[1] Department of Environmental Engineering, Texas A&M University, Kingsville, TX 78363, USA; tushar.sinha@tamuk.edu
[2] Indian Institute of Tropical Meteorology (IITM), Ministry of Earth Sciences, Pune 411008, India; sunil.khadgarai@tropmet.res.in
* Correspondence: vinay.kumar@tamuk.edu

Abstract: A comprehensive study on the Indian summer monsoonal rainfall (ISMR) is performed in the light of decadal changes in the continuous rainfall events and the number of rainy days using 68 years (1951–2018) of gridded rain gauge data. Non-parametric Mann–Kendall's test is applied on total rainfall amount, the number of rainy days, number of continuous rainfall events, and rainfall magnitude to find trends over different climatic zones of India for the two periods, 1951–1984 and 1985–2018. Our results found a decreasing trend for more than 4-days of continuous rainfall events during the recent 34 years (1985–2018) compared to 1951–1984. The rate of increase/decrease in extreme/continuous rainfall events does not follow a similar trend in number of continuous rainfall events and magnitude. Moreover, the rainfall is shifted towards a lesser number of continuous rainfall days with higher magnitudes during 1985–2018. During the crop's sow season (i.e., the first 45 days from the onset date of Indian monsoon), the total number of rainy days decreased by a half day during the last 34 years. Over the Central and North East regions of India, the number of rainfall days decreased by ~0.1 days/yr and ~0.3 days/yr, respectively, during 1985–2018. Overall, the decreasing trends in continuous rainfall days may escalate water scarcity and lead to lower soil moisture over rain-fed irrigated land. Additionally, an upsurge in heavy rainfall episodes will lead to an unexpected floods. On a daily scale, rainfall correlates with soil moisture and evaporation up to 0.87 over various land cover and land use regions of India. Continuous light-moderate rainfall seems to be a controlling factor for replenishing soil moisture in upper levels. A change in rainfall characteristics may force the monsoon-fed rice cultivation period to adopt changing rainfall patterns.

Keywords: monsoon; Mann–Kendall test; rainy days trend; ISMR; LCLU; rice crop

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1. Introduction

The summer monsoonal rainfall variability over different regions in India directly affects the growth of rain-fed crops and socio-economic structure [1]. However, summer (June to September, JJAS) is the only season that brings plentiful rainfall to most parts of India. India receives about 75% to 80% of the total annual rainfall during JJAS, which is vital for the irrigation of *kharif crops* (Crops that are sown in summer in the Indian subcontinent), especially rice [2,3]. Every year, the plantation of the staple crop (rice) starts from May to July in several parts of India. This plantation almost follows the climatological isochrones of rainfall [3,4]. However, in fewer cases, the plantation of rice could be delayed up to August. The germination and planting time of the summer crops mostly depend on the arrival of the very first spell of monsoonal rainfall. Hence, the Indian Meteorological Department (IMD) prioritized the daily rainfall prediction at the district level since 2000 [5]. Every year, IMD issues rainfall prediction on vast spatial (all-India) scale and coarse temporal scales (JJAS). However, the accuracy of rainfall prediction remains poor [6]. On a seasonal scale, ISMR is declared normal or deficient/excess only by the end of each summer season. Additionally, rainfall forecast at the district level, which is five days in advance, carries a

very low accuracy [6]. There is a need to predict rainfall a week to ten days in advance at the district level, which is useful in agricultural and other sectors.

Monsoonal rainfall exhibits great spatial and temporal variability in total amount, intensity, and duration. Every summer rainfall is compared to the long-term normal rainfall (30-year climatological averages) and then declares as normal, drought, and flood year based on total seasonal rainfall received. For instance, on a seasonal scale, the standard deviation of $\pm$10% from the climatological rainfall determines if a year is to be declared a flood or a drought year over India [7]. Both floods and droughts can significantly affect the food production and gross domestic growth of a region and country [1,8]. In addition to floods and droughts, extreme in spatio-temporal variability in rainfall characteristics can also deteriorate crop production, predominantly over rain-fed agricultural regions. To quantify such variability, a widely used metric, "active/break" is used in the summer monsoonal rainfall. Active/break spell is declared when the daily rainfall is higher/lower than climatological values for $\geq$3 consecutive days over Central India [9].

The Indian subcontinent has experienced several flood events in recent decades (e.g., 26 July 2010; 16 June 2013, 5 September 2014). These events highlighted the need to better understand the nature of heavy/extreme rainfall events and their frequency/duration [10]. Despite the advancements in computational resources and meteorological modeling, the prediction of the Indian summer monsoonal rainfall (ISMR) is highly uncertain, particularly for extreme rainfall events and their duration [6]. The understanding of trends/characteristics in continuous rainfall days and extreme events will certainly help the modeling community to better forecast such events.

Over the Indian region, extreme rainfall events, linked from local to remote climatic conditions [11–13]. The inter-seasonal variability of the ISMR is associated with El Niño southern oscillation (ENSO), the meridional gradient of temperature, European snow cover, the Indian Ocean dipole (IOD), and the internal dynamics of monsoon itself [14]. Model simulations and observational datasets showed wet bias in the rainfall over North East India during 1971–2005 [15]. However, ISMR predictions from several global climate models show a dry bias, which underscores the need to understand better linkages between local and exogenous climatic conditions [16].

Roxy et al. [2012] showed an increase in extreme rainfall events while a decrease in annual rainfall over Central India from 1950 to 2015 [17]. The increase in moisture supply from the Arabian Sea is the prime reason for an increase in extreme rainfall events over Central India. The reduction in annual rainfall is attributed to the weakening of monsoon circulation and decreasing low-pressure systems over the Indian region [17]. Another study found a decreasing trend in annual ISMR amount by 2.6% (significant trend only over 3 stations out of 45 stations) over Central India based on 102 years (1901–2002) of rainfall dataset [18]. A significant increase in the frequency of heavy rainfall days was found over the northeast Indian region [15]. They further showed an increase in heavy rainfall over the Indian region and a decrease in the duration of light to moderate rainfall during 1953–2002. India witnessed below-normal to normal ISMR, most of the years during 1953–2002 [15]. A good correlation is found between rainfall and the number of rainfall days over in Konkan catchment area of India [19]. Though several studies exist in the literature regarding ISMR rainfall trends, there is a gap in the trends of rainy days, continuous rainfall events and their relation to the regional hydrology and crops. Although fewer studies have analyzed trends in the ISMR over different regions of India, none of the studies have extensively analyzed trends in continuous rainfall days over different climatic zones in India to the best of the author's knowledge. Low to moderate but continuous rainfall is particularly crucial for enhancement of infiltration, which is critical for rain-fed agricultural regions of India.

The objectives of this study are (a) Compare rainfall variability in the light of the number of rainfall days, the number of continuous rainfall events and rainfall magnitude in two periods of 34 years, 1951–1984 and 1995–2018, (b) Analyze spatial-temporal trends and variability of continuous rainfall days over different climatic regions of India, (c)

Understanding the connection between continuous rainfall intensity to other hydrological variables (e.g., soil moisture, evaporation), (d) Usefulness of June to mid-July rainfall for the plantation of rice crop. Such information will be useful in developing adaptive agricultural practices (e.g., planting and harvesting of crops), which needs to be updated under changing climatic conditions and non-stationary climate.

2. Dataset and Methods

2.1. Datasets

Daily gridded rainfall data are obtained from the Indian Meteorological Department (IMD) during 1951–2018. This dataset is generated based on the varying network of 6955 rain-gauges that collected consistent daily rainfall data over a longer period. They used the spatial interpolation method (Shepard 1969) to create gridded datasets and applied standard quality control e.g., missing data, duplicate station check, and extreme value check. The gridded rainfall from the IMD is available at $0.25^\circ \times 0.25^\circ$ spatial resolution [20]. However, for a shorter duration (~20 years), rainfall datasets are available from other sources as well, e.g., satellites, rain-gauges, and reanalysis products. We analyzed 68 years of rainfall data for light to heavy rainfall and continuous rainfall days for different climatic regions in India. In this study, we divided India into 5 homogenous climate regions because of the complex variability of summer rainfall over various regions. We divided the total period (1951–2018) into two equal durations 1951–1984 (referred to as Early, E, E-period, hereafter), and 1985–2018 (referred to as Late, L, L-period hereafter) for comparison as previous studies concluded that the long term trend of the ISMR is stable [21]. We found that the two periods of 34-years are not biased towards drought or wet years and the mean of the two periods are 759.01 mm and 749.53 mm respectively. On other possibilities of the division of ISMR into two equal periods, we applied the abrupt trend change point method [22]. This method divided the series of 68 years (1951–2018) into two periods of 37 years and 31 years. The mean of these two periods is 750.63 mm and 758.62 mm, respectively, while the mean of the total time series is 754.23 mm. The absolute difference between parts of the two-time series and total remain ~4.4 mm, which is very small and insignificant on a climate scale. Hydrological variables e.g., evaporation, soil moisture, and total precipitation were obtained from ECMWF reanalysis on $0.25^\circ \times 0.25^\circ$ spatial resolution [23]. TRMM dataset [24] was also used here from 2009 to 2018 to compare against IMD rainfall.

2.2. Study Region

Monsoonal rainfall over India is spatially quite diverse [25]. We selected 5 regions in Indian to perform regional-scale analysis. These selected regions almost represent the climatological homogenous regions of India. Figure 1a displays different climatic zones: North West (NW, 70–77°E, 23–32°N), West Coast (WC, 72–77°E, 10–20°N), South East (SE, 77–81°E, 9–15°N), North East (NE, 87–97°E, 21–30°N), and Central India (CI, 77–86°E, 20–27°N). The annual mean rainfall approximately around 900 mm in India. The mean summer rainfall peaks over topographic regions such as WC and NE, while ISMR is moderate over CI. Dry regions such as NE and SE are less influenced by monsoon rainfall bearing systems. In addition to large scale monsoon system, India also receives rainfall from cyclones, thunderstorms and western disturbances.

The trends in mean rainfall do not provide exact information on spatio-temporal variability of the ISMR in changing climatic conditions. We investigated how the magnitude and number of continuous rainfall events changed in different climatic regions of India in the past 68 years. However, the cases of extreme events over Indian regions came into the focus in the last 20 years or so [10].

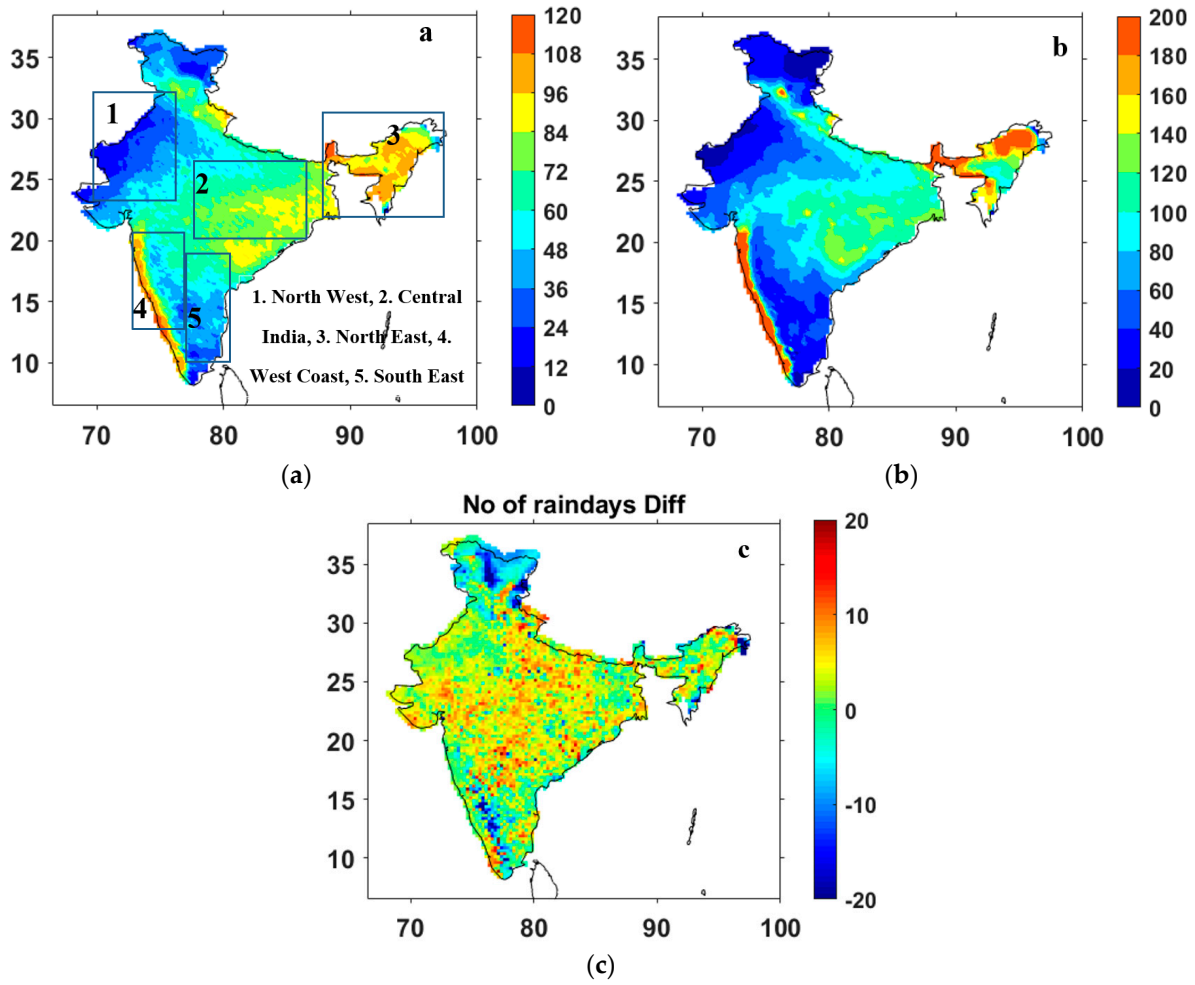


Figure 1. India Meteorological Department (IMD) gridded summer rainfall from 1951–2018 (**a**) Climatology of the number of rainy days (where rainfall > 0.5 mm/day on each grid), (**b**) Rainfall climatology (cm), (**c**) Difference between the number of rainy days from E-Period and L-Period. Black boxes numbered from 1 to 5 represent five homogenous regions of India [1 North West (NW), 2 Central India (CI), 3 North East (NE), 4 West Coast (WC), 5 South East (SE)].

2.3. Methodology

Non-parametric based Mann–Kendal (MK) test with Sen's slope estimator was used to compute trends for several qualitative and quantitative rainfall characteristics that were derived using the daily gridded rainfall data. MK test and Sen's Slope are insensitive to missing data and data distribution since this test considers the median of all slopes and rank of the data. Therefore, the MK test is robust and performs better than linear regression, particularly when data has outliers. MK trend statistic and Sen's slope were estimated using the equations described in earlier studies [26].

The statistics of the MK test and Sen's slope for a time series is given by

$$S = \sum_{k=1}^{n-1} \cdot \sum_{j=k+1}^{n} \cdot \text{sign}\left(x_j - x_k\right) \quad (1)$$

$$\text{Where } x_j - x_k = \begin{cases} 1 \text{ if } x_j - x_k > 0 \\ 0 \text{ if } x_j - x_k = 0 \\ -1 \text{ if } x_j - x_k < 0 \end{cases} \text{ and j and k are numbers in series} \quad (2)$$

We applied the MK test and computed Sen's slope on daily rainfall data during ISMR at a confidence level of 95%. This study analyzed the trends in the number of rainy days and continuous rainfall events ranging from 1 day to 11 days. Hereafter, in the manuscript

we referred continuous rainfall of 1 day, 2 days, 3 days, 4 days and N days as 1DAY, 2DAY, 3DAY and NDAY respectively. A day is considered as rainy day when the daily rainfall exceeds or equal to 0.5 mm [25,27], while a light/heavy intensity rainfall is estimated when the daily rainfall is below/above, 10th/90th percentile over each grid. IMD defines a rainy day when the daily rainfall exceeds 2.5 mm over central India. However, we considered a threshold of 0.5 mm in the present study since dry regions such as NW and SE often might not meet the criteria of 2.5 mm. A continuous X-rainfall event is defined as an event when the daily rainfall exceeds 0.5 mm over X consecutive day/s (where X = 1DAY, 3DAY, 5DAY, and more than 10DAY). For example, a 3DAY continuous rainfall event should have >0.5 mm of rain over a grid, while a day preceding and following that event should have less than 0.5 mm of rainfall over that grid. It is noted that the rainfall may be discontinuous on an hourly basis. However, it was still considered as a continuous rainy day in this study if the daily rainfall were higher than 0.5 mm for many days. However, consideration of rainy days based on rainfall $\geq$ 0.5 mm or rainfall $\geq$ 2.5 mm does not influence the rainfall trends shown in this manuscript but only the magnitude of rainfall (Figure S1). The general formulae of rainfall frequency and fraction calculation are mentioned below. *X_event* frequency over each grid is estimated by normalizing the total number of *X_events* by the total period of ISMR, which is 122 days long from June 1 to September 30. Similarly, the *X_event* intensity fraction was estimated by the ratio of total rainfall contributed from *X_event* to total ISMR rainfall.

$$X_Event\ frequency = \frac{Total\ number\ of\ X_events}{122} \quad (3)$$

$$X_Event\ fraction = \frac{Rainfall\ contributed\ from\ X_events}{Total\ amount\ of\ ISMR} \quad (4)$$

where X = 1DAY, 2DAY, 3DAY, 4DAY, 5DAY up to 11DAY

3. Results

3.1. Trends in Number of Rainy Days and Rainfall

It is expected that the number of rainy days is higher over the regions that receive excessive rainfall than the areas with relatively low rainfall or drought-prone areas. Figure 1a shows the climatology of the number of rainy days (where rainfall > 0.5 mm/day on each grid) over five selected climatic regions of India, e.g., NW, CI, NE, WC, and SE, which almost replicates the spatial pattern of the ISMR climatology (Figure 1b). WC and NE regions show the highest number of rainy days (Figure 1a), which resembles spatial patterns with the composite of active-spells (Continuous rainfall of $\geq$3 days over central India of standard deviation > 0.7) of the ISMR. Hot-spot regions of maximum rainfall and a higher number of rainy days, in general, experienced an increase in the number of floods [12]. Additionally, NW and SE regions are drought-prone areas, particularly during the summer monsoon season. Notably, the standard deviation of rainfall in regions that receive low rainfall is higher than excessive rainfall [28]. Few studies have highlighted the usefulness of rain harvesting, particularly in regions that receive moderate to low rainfall so that the stored water could locally be utilized during monsoon breaks and droughts [29]. The decrease in rainfall trend can force people to preserve the water during active spells of rainfall.

We calculate the difference between the number of rainy days for the E-period (1951–1984) and the L-period (1985–2018) (Figure 1c). In the L-period, the number of rainy days is higher over central India, while lesser over the Western Ghats. However, a decrease in rainy days over the southern Western Ghats is unusual. The changes in the number of rainfall days have implications for rain-fed agriculture, industries and socio-economics of locals.

Total rainfall and its duration are an essential aspect of rainfall over a given region. Significant differences are seen in the monthly mean rainfall trends during the two different periods (Figure 2). All the summer months display an increasing trend of rainfall during

the E-period (Figure 2a–d). In contrast, June, July, and September months show a decreasing trend during L-period (Figure 2e–h). The rainfall contributions from the summer months are as follows: July (~24%), August (~21%), September (~14%), and June (~14%), respectively, to the annual rainfall [30]. In the recent 34 years, the decreasing trends of rainfall in July and September months are much steeper than the other months (Figure 2). Overall, the ISMR displays a clear contrast in the monthly rainfall trends in the two periods.

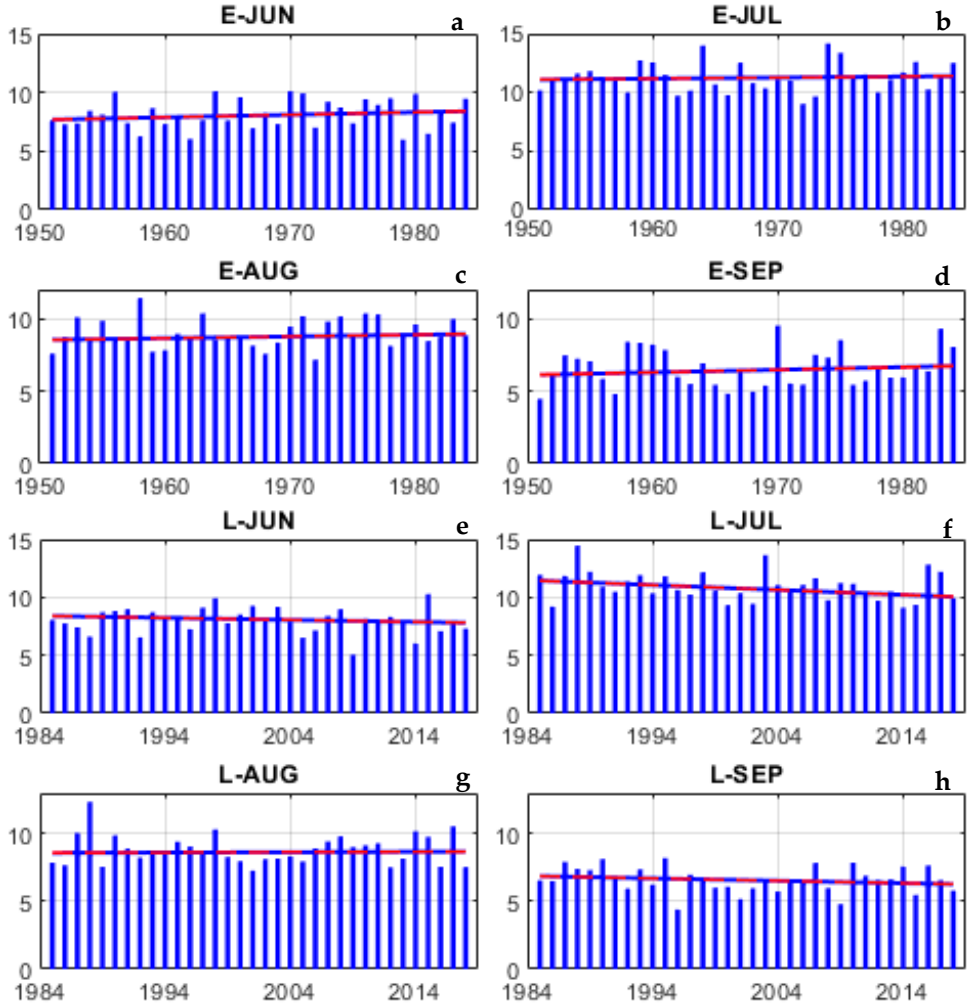


Figure 2. MK test and trends of rainfall (mm/month) over India for summer months for E-Period (**a**) June, (**b**) July, (**c**) August, (**d**) September, and for L-Period (L) (**e**) June, (**f**) July, (**g**) August, (**h**) September. On each panel prefix, "E" means, data considered from 1951 to 1984, while prefix "L" means, data consideration from 1985 to 2018 in this figure and the following figures. The blue line shows the trend, while the red dotted lines show confidence at a 95% significance level here. The same nomenclature is followed in all the figures.

Figure 3 displays the trends of summer monsoonal rainfall days over various regions in India (see Figure 1a). The number of rainfall days are notably declined over NE in L-period as compare to E-period. Such a strange shift is observed over the NE region, which is known for its dense forest region and the world's wettest point, Cherrapunji. Over CI the rainfall days are continuously decreasing (Figure 3). However, the regions, e.g., NW, SE, and WC, show an increasing trend for the L-Period (Figure 3 right column). In contrast, for the E-Period, NW displays a decreasing trend, while SE and WC show no trend (Figure 3 left column). The number of rainy days over different climatic zones demonstrates a remarkable difference in trends during E-period and L-periods. Overall, the number of rainfall days, as well as rainfall quantity, declined over CI and NE India

during JJAS (Figures 2 and 3) during L-period. It is interesting to note that the number of rainfall days decreased over the southern region of WC (Figure 1c), while over total WC number of rainfall days increased in L-period (Figure 3, bottom right). These results do not dilute the fact that the cases of extreme rainfall events are increasing over Central India [10]. From Figures 2 and 3, it seems the total number of rainfall days used to be linearly related to the total rainfall during the E-Period, but this does not hold during L-Period. Figure S1 shows similar trends for two periods as in Figure 3, where we consider the IMD definitions of rainy days (rainfall on each grid > 2.5 mm). Such criteria do not affect our analysis even if we consider rainfall over a grid > 0.5 mm or 2.5 mm to define a rainy day.

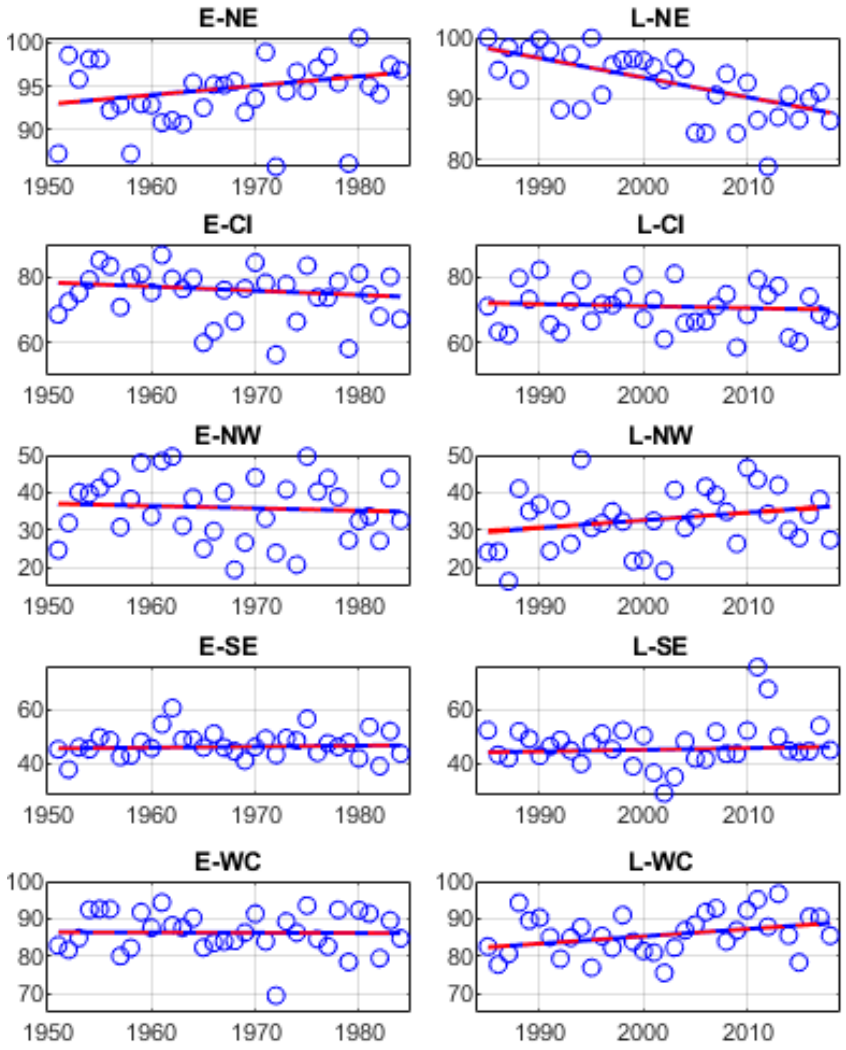


Figure 3. MK test for the number of rainy days over five homogenous regions of India North West (NW), Central India (CI), North East (NE), West Coast (WC), South East (SE)]. On each panel prefix, "E" means, data considered from 1951 to 1984, while prefix "L" means, data consideration from 1985 to 2018. The blue line shows the trend, while the red dotted lines show confidence at a 95% significance level here.

Such declines in the ISMR will adversely affect soil moisture and irrigation in the early summer period over India. Several earlier studies also reported similar trends in rainy days over homogeneous regions. For example, annual rainfall from 1881 to 1970 showed an increasing trend over North India and Central India while decreasing trend over the North-Eastern region of India [31]. Over Central India, the decreasing trend of rainfall may be due to the weakened relationship between the ISMR and the ENSO and a decrease in

the meridional temperature gradient across the Indian landmass and the Indian Ocean [32]. A significant decreasing trend is observed over NE and CI regions [33]. Few other studies have reported mixed trends in rainfall (i.e., either increase or decrease) based on station datasets [34], river basin scales [35], and regional levels [30]. The results in the current study are in agreement with the previous findings on rainfall intensity and rainfall days. However, the present study deals with different rainfall periods than other studies [31,32].

The overall trend of the number of rainy days in each month and over each climatic zone are shown in Table 1 for L-period. The number of rainfall days shows a decline during July over all regions of India. Overall, the number of rainfall days exhibits a decreasing trend in the summer season and months except for June over India. CI and NE exhibit a decreasing trend in the number of rainy days for the summer season. August also experienced a reduced number of rainy days over all regions, except for SE. The number of rainy days decreased over NE and increased over WC in the L-period. The trends in rainy days are significant at 95% e.g., an increasing trend over all India in June, increasing trend over SE in August, and decreasing trend over WC in JJAS.

Table 1. Trends in the number of rainy days from 1985 to 2018, where "*" shows the significant trends at 95%. The up/down arrows show increasing/decreasing trends.

	Number of Rainy Days				
	June	**July**	**August**	**September**	**JJAS**
Northwest	↑	↓	↓	↓	↓
Central India	↓	↓	↓	↓	↓
Northeast	↓	↓	↓	↓	↓
West coast	↑	↓	↓	↑	↓*
Southeast	↑	↓	↑*	↑	↓
All India	↑	↓	↓	↓	↓

Table 2 shows the monthly and seasonal rainfall trends over selected climatic regions of India for the L-period. There is an increasing rainfall trend in June over all regions except over NE, a decreasing rainfall trend in July over all regions except over NW, a mixed trend of rainfall in August over various regions, and an increasing rainfall trend in September over all regions except over CI (Table 2). Decreasing rainfall in July and increasing rainfall in August over CI and NE, respectively, are significant trends at 95%. The Central India region is being addressed in many studies, here, except in June, all the months show decreasing rainfall trend. It seems that the number of rainfall days and monthly mean rainfall are linearly varying over CI for the summer season. The decrease in July rainfall will bring hardship to the farmers to irrigate their crop, a time of crop sustainability.

Table 2. Trends in monthly mean rainfall from 1985 to 2018, where "*" shows a significant trend at 95%. The up/down arrows show increasing/decreasing trends.

	Monthly Mean				
	June	**July**	**August**	**September**	**JJAS**
Northwest	↑	↑	↓	↑	↑
Central India	↑	↓*	↓	↓	↓
Northeast	↓	↓	↑*	↑	↓
West coast	↑	↓	↓	↑	↓*
Southeast	↑	↓	↑	↑	↑
All India	↓	↓	↓	↑	↓

3.2. Frequency of Continuous Rain Events and Their Magnitude

As a matter of fact, monsoon, a large-scale phenomenon where an episode of continuous rainfall lasts for a couple of days to weeks. During active spells, about 70% of the monsoonal rainfall is typically caused by strati-form clouds, which provide widespread

and continuous rainfall as compared to convective rainfall that drives extreme events [36]. Further, the low-pressure systems (e.g., lows, depressions, deep depressions) also retain the rainfall over Central India [37]. Moreover, seasonal rainfall over southwest monsoonal regions happens due to various rainfall bearing systems of different temporal and special scales, e.g., monsoon lows, depressions, cyclones, and mesoscale convective systems (MCS's), and isolated convective systems. Extreme rainfalls due to low-pressure systems are linked to global warming over the Indian subcontinent [10,38]. Considering spatiotemporal rainfall variability over India, such systems depict the asymmetric distribution of rainfall over sub-regions (WC, CI, NE, SE, and NW). That is one of the reasons why rainfall quantity and rainfall days showed quite strange results for two periods (Figures 2 and 3). Thus, it motivates us to find out the trends of continuous rainfall for 1DAY, 2DAY, 3DAY, and more.

We evaluated the continuous rain events and continuous rainfall magnitude over Indian region for two periods. The frequency of continuous rainfall events increased for 1DAY, 4DAY and ≥6DAY for E-period (Figure 4a,d,f). However, it is decreased for day 2 of rainfall (Figure 4b), and almost constant for 3DAY and 5DAY (Figure 4c,e). For, L-period, trends in continuous rain events frequency escalated for 1 to 4DAY (Figure 4g–j), and almost constant for 5DAY (Figure 4k), while decreased for >6DAY (Figure 4l). In recent years, the frequency of continuous rain events de-escalated for a higher number of days (>6DAY). The magnitude of Sens slope in E-period (0.01 for 1DAY and 0.004 for ≥6DAY) is smaller than the L-period (0.04 for 1DAY and −0.01 for ≥6DAY) for rain event frequency. A well-known local name for the frequency of continuous rainfall, *Jhad*, in northern Indian villages, is fading in recent times. Some of the well-known recent flood events (such as 26–28 July 2010; 15–16 June 2013) over India lasted for 1DAY to 3DAY, which is also evident from Figure 4g,i) during L-period.

The Sen's slope calculated for JJAS seasonal and continuous rainfall day's magnitude ranging from 1 to 5DAY and more days (Figure 5), for both the periods. The number of continuous rainfall magnitude remain almost constant for 1DAY, 2DAY, 4DAY, and 5DAY (Figure 5a,b,d,e), while decreasing and increasing trend for 3DAY and ≥6DAY, respectively (Figure 5c,f). In E-period magnitude of continuous rain magnitude with ≥6DAY were increasing (Figure 5f) as compared to L-period (Figure 5l), where they are decreasing. The magnitude of Sen's slope for ≥6DAY is 0.69 and −0.29 respectively for E-and L-period. In the E-periods, the trends of continuous rainfall event and magnitude are quite irregular for 1 to 6DAY, somewhat resembled with Figure 4a–f. In the case of L-period continuous rain day's magnitude increased from 1 to 3DAY, remain constant for 4DAY while decreased for >5DAY. The frequency of continuous rainfall event and magnitude decreased for ≥6DAY for L-period (Figures 4 and 5). It seems that the number of continuous rainy events and corresponding rainfall quantities are in a linear relationship over the Indian region (Figures 4 and 5).

In particular, the magnitude of continuous rainfall is increasing for fewer days (i.e., extreme rainfall for 1 to 3DAY). There is an increase in rainfall magnitude of 1DAY continuous rainfall by 1mm, 2DAY continuous rainfall by 2.7 mm and 3DAY continuous rainfall by 4.9 mm but reduced for ≥6DAY by 10 mm during L-period. A reduction in the number of continuous rainfall episodes for more than 6DAY is consistent with other studies highlighting the influence of global warming over the Indian subcontinent. For example, in a study, it is concluded that for every 1 °C warming, the atmosphere could hold extra 7% moisture. This is one of the possible reasons for the extreme rainfall [39]. Based on Figures 4 and 5, it is inferred that the heavy rainfall for fewer continuous days (≤4) shows an increasing trend as compared to higher numbers of days (≥5).

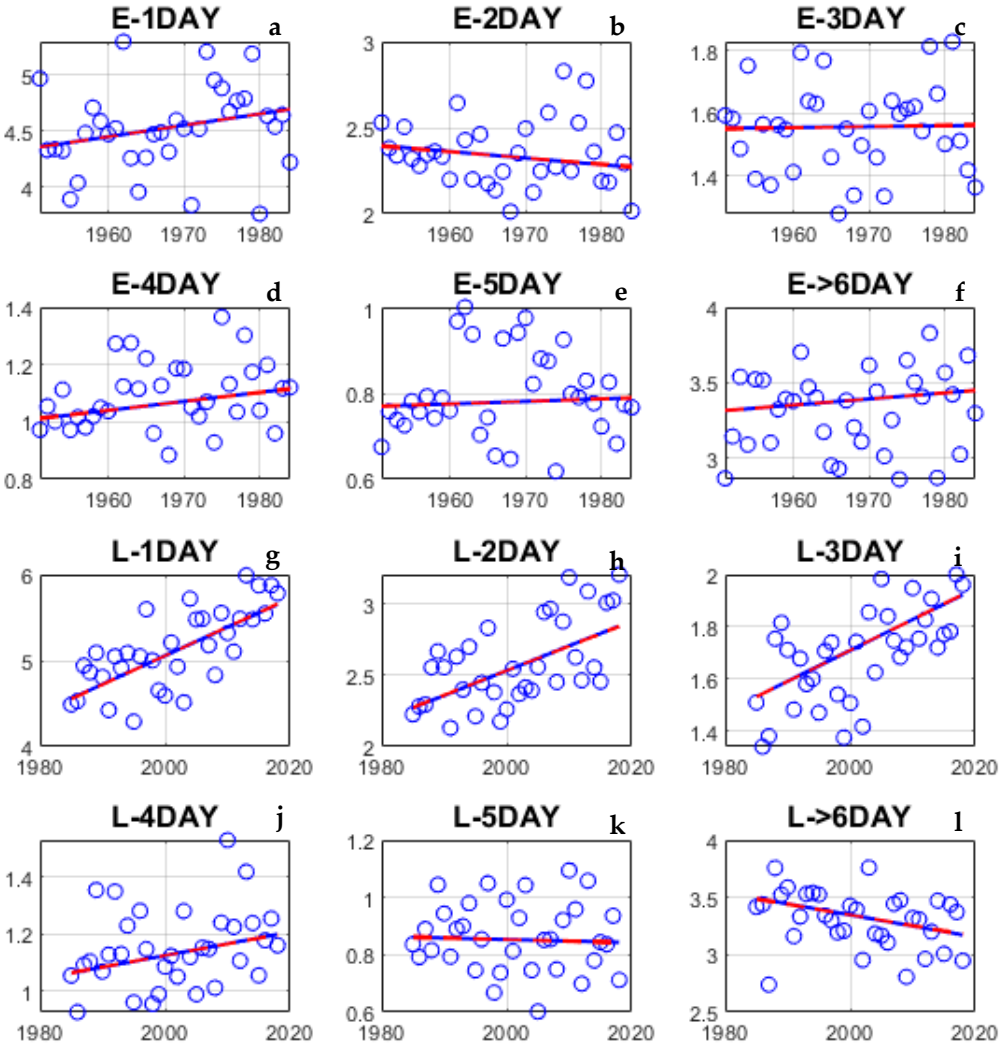


Figure 4. MK test for continuous rainfall events over India for 1 DAY to 5 DAY and more, (**a**–**f**) E-period, (**g**–**l**) L-Period. On each panel prefix, "E" means, data considered from 1951 to 1984, while prefix "L" means, data consideration from 1985 to 2018. Continuous rainfall of 1 day, 2 days, 3 days, 4 days and N days are referred as 1DAY, 2DAY, 3DAY and NDAY respectively. The blue line shows the trend, while the red dotted lines show confidence at a 95% significance level here.

3.3. Variability of Light and Heavy Rainfall

Numerous studies showed that signatures of climate change are reflected in the extreme side (heavy and low rainfall episodes) rather than in mean rainfall over the various regions of the Indian domain [40]. Thus, we evaluated the possible changes in rainfall magnitude, likely for heavy and light rainfall events. Figure 6a–d displays the trend in heavy (greater than or equal to top 90th percentile) and light rainfall event's magnitude (less than or equal to lowest 10th percentile). The heavy rainfall events magnitude shows an increasing marginal trend over India, while light rainfall events magnitude shows a remarkable decreasing trend over India in L-period (Figure 6c,d). It is to be noted that the cases of extreme rainfall events are influenced by the cyclonic systems, cloud bursts, regional water bodies, and atmospheric rivers [41]. The heavy rainfall grows at the expense of light rainfall, thus neutralizing such kind of trends in ISMR for 100 years [10]. During an extreme rainfall event, an excessive quantity of rainfall is poured in a short period. In contrast, a moderate to light rainfall event occur when almost a similar rainfall amount is spread over a longer time. The regions NW and SE typically receive light rainfall while the regions WC and NE receive relatively heavy rainfall (Figure 1b).

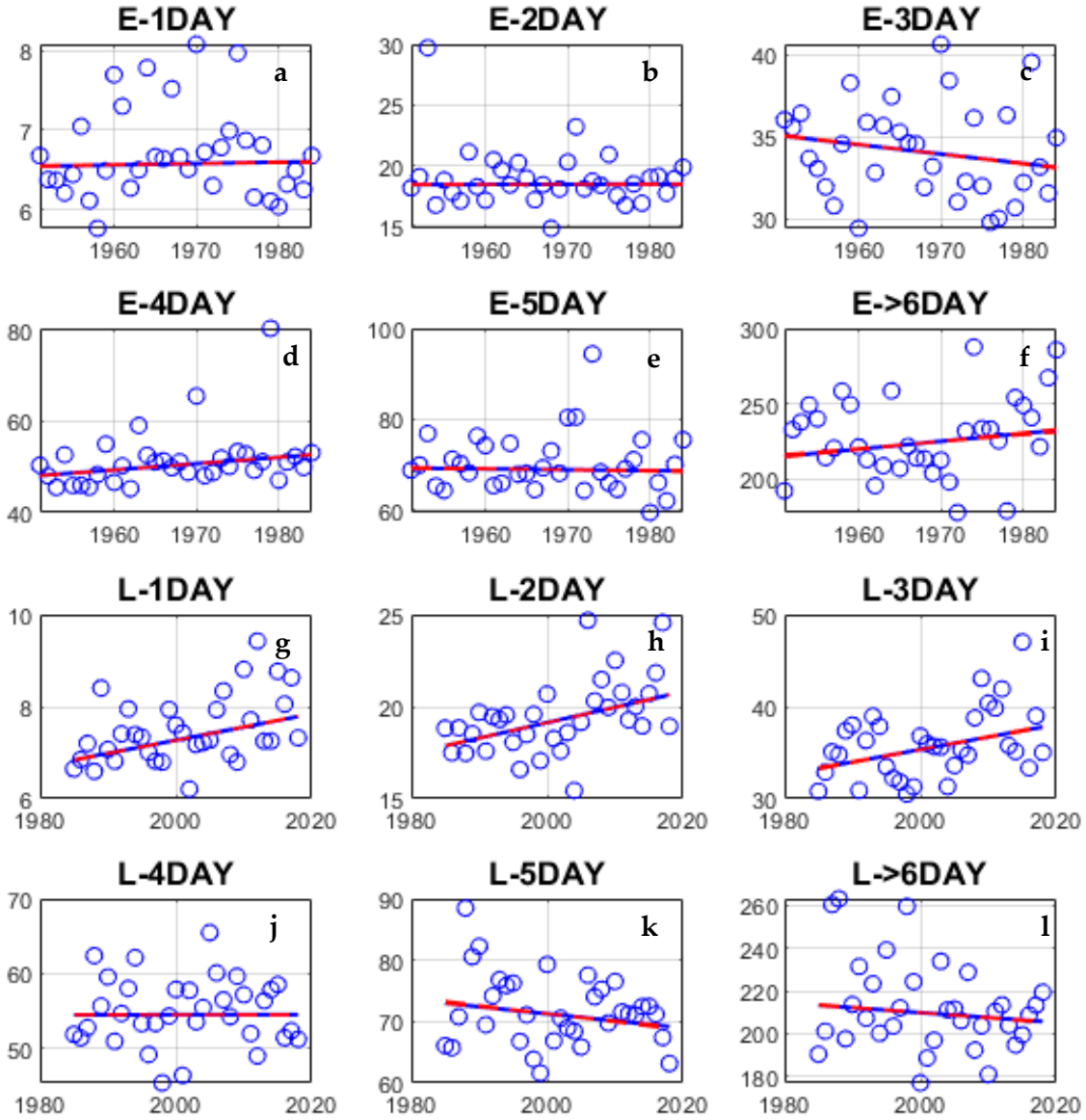


Figure 5. MK test for continuous rainfall magnitude over India for 1DAY to 5DAY and more than 6 DAY. On each panel prefix, "E" means, data considered from 1951 to 1984, while prefix "L" means, data consideration from 1985 to 2018. Continuous rainfall of 1 day, 2 days, 3 days, 4 days and N days are referred as 1DAY, 2DAY, 3DAY and NDAY respectively. The blue line shows the trend, while the red dotted lines show confidence at a 95% significance level here.

In the L-period, the magnitude of heavy rainfall frequency (HRF) increases throughout India, at the cost of light rainfall frequency (LRF) (Figure 6c,d). However, the same logic does not work for the E-period. The slopes of LRF in two periods (E and L) are almost the same, except for the opposite sign (Figure 6b,d). In particular, the magnitude of light rainfall dwindled in the L-period while the magnitude of heavy rainfall increased marginally. The light rainfall is beneficial to grow crops by recharging the upper soil layer (1 to 10 cm). The rainfall decreasing trend in the L-period for LRF may indicate an increased number of non-rainy days. An increase in the number of non-rainy days may shift the total rainfall distribution towards the heavy rainfall end.

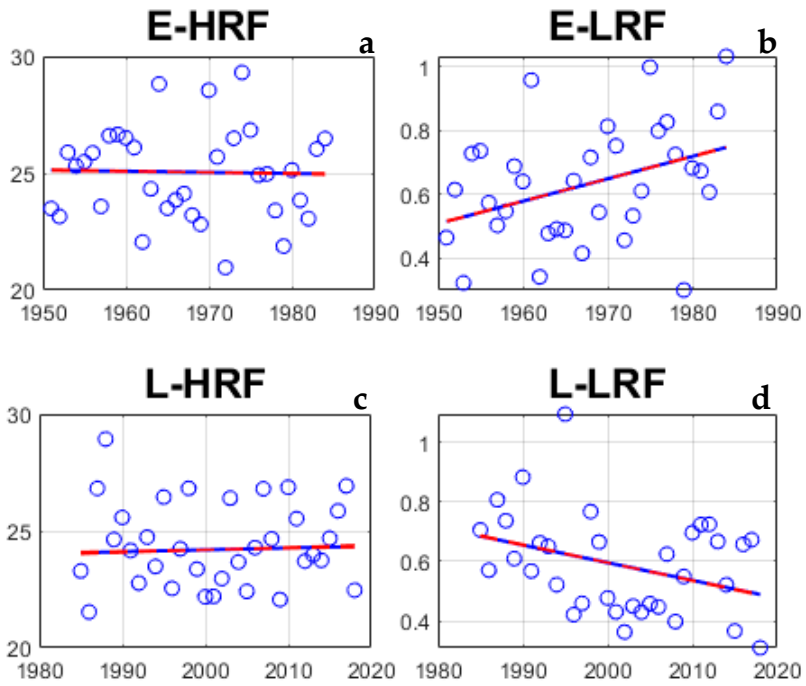


Figure 6. Rainfall magnitude (mm) as detected by (**a**,**c**) Extreme/Heavy events (top 90 percentile), and (**b**,**d**) Rainfall magnitude as identified by (lowest 10 percentile) over India.

3.4. Spatial Variability of Rainfall Frequency and Fraction for Continuous Rainfall Days

As it was discussed in Section 3.2, selected homogenous regions depicted contrast features in terms of continuous rainfall events and continuous rainfall magnitude in E-period and L-periods. This section further discusses the spatial variability of continuous rainfall frequency and fraction over the complete Indian region. Such attempt is informative to detect the nature of dominant events over various climatic regions. The rainfall frequency and fractions for the summer season for continuous rainfall for 1, 3, 6, and 11DAY are displayed in Figure 7a–h, respectively. The frequency of 1DAY rainfall is boosted over the desert (NW region e.g., Rajasthan) and rain shadow region (SE region e.g., Tamil Nadu). The rainfall for continuous 11DAY is most dominant over the regions of maximum rainfall, e.g., WC, NE, and a region of low-pressure-systems (area dotted by magenta in Figure 7d). The spatial pattern of rainfall frequency for 1DAY rainfall (Figure 7a) is almost opposite to the 11DAY (Figure 7d) over most parts of India.

The spatial pattern of 3 days continuous rainfall frequency shows a uniform pattern over most parts of India, except over WC, western Rajasthan, and NE regions. Among all panels, rainfall frequency for continuous 6 days seems to be uniform, except the drought-prone regions and Jammu Kashmir region. The spatial pattern of rainfall fraction does not follow a spatial pattern similar to rainfall frequency. Rainfall fraction is higher over NE and NW and eastern coastal regions for continuous 1DAY, 3DAY, 6DAY rainfall, except over WC and Jammu Kashmir region. There is an increase in rainfall intensity and frequency of extreme rainfall events randomly on different spatial scales [42–44]. Rainfall fraction for continuous 11DAY (Figure 7h) is similar to climatological rainfall (Figure 1b), where WC, CI, and NE regions receive more rainfall than other regions of India in the summer monsoon season. Monthly rainfall fraction differences between the two time periods (E and L) are shown in Figure S2. In August and September, rainfall fractions increase everywhere except over a few grid points here and there (Figure S2c,d), whereas it decreases over the desert region and rain shadow regions in June. Rainfall fractions in September are opposite to the June over most parts of India (Figure S1d). Notably, rainfall fractions are smoothened in June over most parts of India except the NE region (Figure S2a).

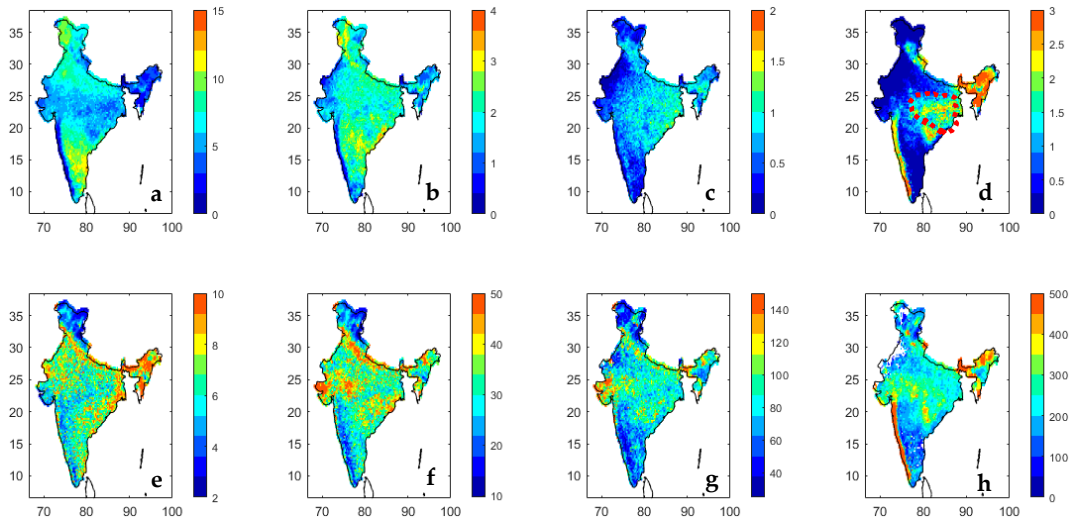


Figure 7. Spatial distribution of rainfall (mm) for continuous 1DAY, 3DAY, 6DAY, and 11DAY for L-period (**a**–**d**) rainfall frequency (**e**–**h**) rainfall fraction. Low pressure is dotted by magenta in Figure 7d.

3.5. Decadal Analysis of Continuous Rainfall Days

To analyze rainfall contribution from prolonged continuous rainfall, we compared the rainfall contribution (expressed in percentage) to the ISMR, up to continuous 10-days rainfall from 1951 to 2018 (Figure 8a) for 3 decades. In the recent 10 years (2009–2018), ~60% of rainfall was contributed from 2 to 6DAY of continuous rainfall, which is 20% more than the rainfall contributed during 1951–1960 from the same number of continuous rainfall days. Furthermore, it is obvious from the figure that rainfall contributed from a large number of continuous rainfall days (>8DAY) decreased in recent years. On the average of multi-years and 1–5 continuous rain days, rainfall percentage increased by 0.9% from 1951–1972 to 1995–2016, while the rainfall is decreased by 0.05% for 6–10 continuous rainfall days (Figure 8b). The difference in the rainfall percentage is quite small for 6–10 continuous rainfall days. Thus, for comparison, TRMM rainfall is compared for the recent decade, which turns out that the TRMM underestimates the rainfall as compared to IMD rainfall (Figure 8c). One known caveat of TRMM rainfall is underestimating orographic rainfall (e.g., rainfall over the Western Ghats) [25]. Averaged rainfall over Central India shows a strange trend (decreasing) when averaged for more than 20 years of span (Figure S3). These results also support that the rainfall is shifting towards a lesser number of continuous rainfall days with higher magnitudes. The change in rainfall duration and quantity also supports that the heavy rainfall events only last for shorter durations.

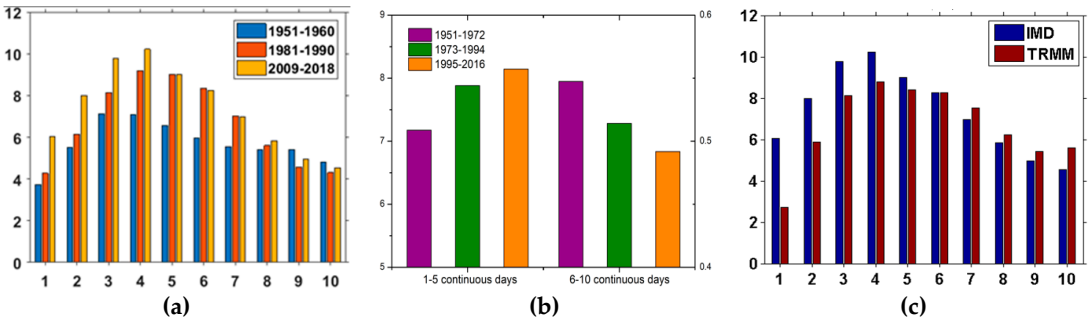


Figure 8. Rainfall contribution (in %) from the number of continuous rainfall days to the monsoon season over central India (**a**) IMD rainfall for 3 decades, (**b**) 1 to 5DAY and 6 to 10 DAY continuous combined days, (**c**) IMD rainfall vs. TRMM for the latest decade 2009–2018. Continuous rainfall of 1 day, 2 days, 3 days, 4 days and N days are referred as 1DAY, 2DAY, 3DAY and NDAY respectively.

4. Hydrological and Agricultural Aspects of Surface Rainfall

South to northward propagation of rainfall over the Indian landmass is quite fascinating but erratic. Sometimes, it progresses rapidly, while at other times, it is strangely slower [45]. Climatologically, monsoon takes one and a half months (45 days) to reach over the northwestern region of India. As the rainfall isochrones move northward, the farmers start planting rice crops hoping that the monsoonal rain will frequently visit rain-fed farming [3]. In the beginning, rice crop requires standing water for multiple days to grow. The ISMR holds a good correlation with the summer season crop's yield [46,47]. Figure 9 shows rainfall isochrones, rice production regions, and months of rice plantation, growth and harvesting.

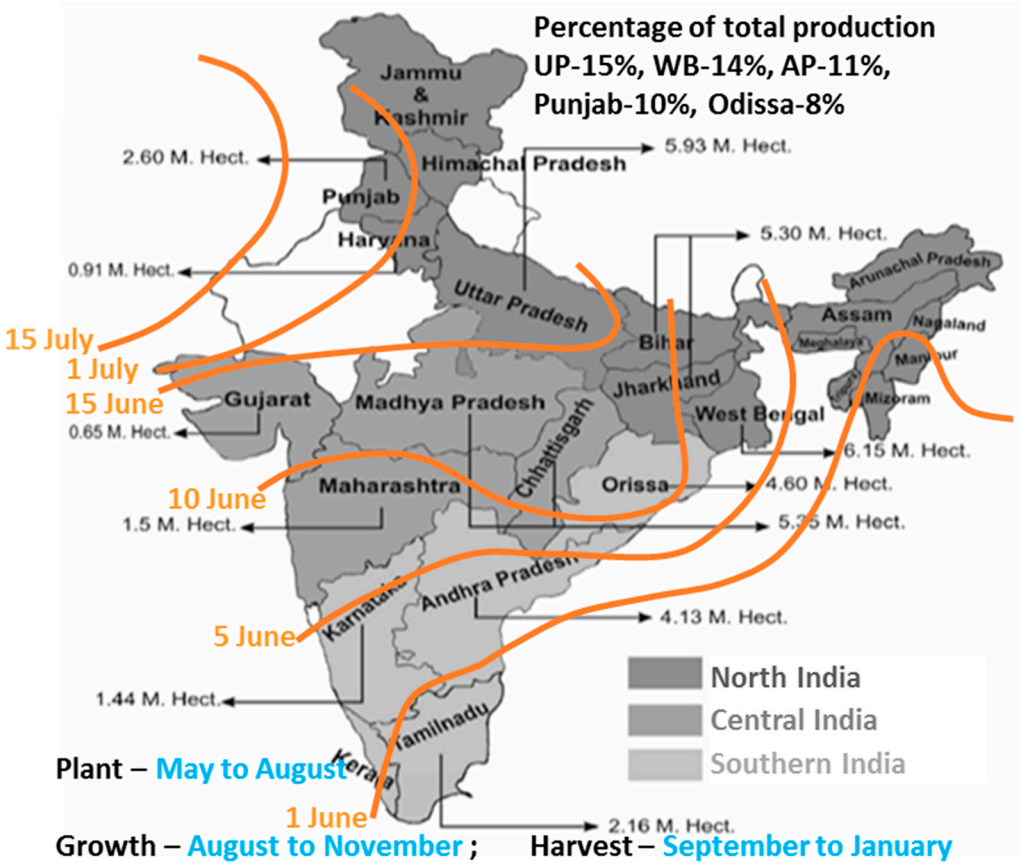


Figure 9. The date and line of the northern limit of the summer monsoon (climatological rainfall isochrones, orange lines) and area of land under rice crop production in each state (modified after [48]).

Uttar Pradesh, West Bengal, Andhra Pradesh, Punjab, and Odisha are the top five states, and those grow staple rice crop. It is observed that in some of the states, plantation of rice starts before the arrival of monsoon, which is counted in the category of an early plantation of rice crops. Notably, all states in India grow rice, except western Rajasthan, which is a desert region. In some years, the very first monsoonal rain reach over the northern states quite late from the onset date of monsoon, which may delay rice plantation by up to early August [48].

Moderate but continuous rainfall is beneficial for rice crop and groundwater recharge because the soil gets enough time for infiltration/percolation to facilitate soil moisture conservation for rain-fed agriculture. Generally, water from intense and heavy rainfall over a short duration results in higher runoff into rivers and streams. Thus, we compared the number of rainy days during the first 45 days of monsoonal rainfall (1 June to 15 July) during the E-period and the L-period and found that the rainfall days declined in the L-period (Figure 10) than the E-period (1951 to 1984). Overall, the rainfall trend from 1951

to 2018 decreased for the first 45 days (Figure S4). The magnitude of the Sen's slope in E-period and L-period are 0.006 and −0.023, respectively. The results from Tables 1 and 2 and Figure 10 for the recent 30-years indicate the number of rainfall days and rainfall quantity increase in June while decreased in July over northern regions.

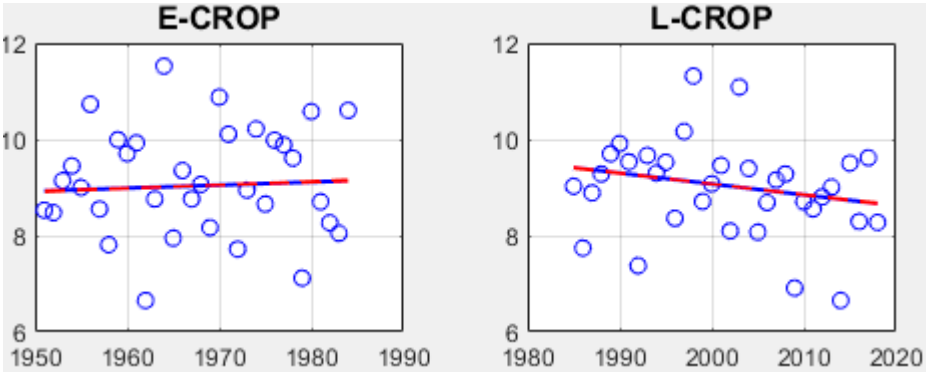


Figure 10. MK test for the number of rainy days over India from 1 June to 15 July.

Timely information on hydrological variables (e.g., rainfall, soil moisture) in June is crucial for the plantation of rice crops. Soil moisture, evaporation, and runoff are the important hydrological aspects of monsoonal rainfall. The hydrological processes of the surface and sub-surface depend on the land cover and land use (LCLU, Figure S5), which vary erratically over the desert, forest, crops, shrubs, and bare land regions [49]. Hydrological variables are being averaged over a uniform LCLU (Figure S5 and Figure 11) e.g., Agricultural land over Punjab (lon = 75.15°E, lon = 76°E, lat = 30.1°N, lat = 30.4°N), shrub land over Rajasthan (lon = 70°E, lon = 70.75°E, lat = 26.75°N, lat = 27.25°N), forest over western Ghats (lon = 74°E, lon = 75°E, lat = 14°N, lat = 15°N), deciduous over Assam (lon = 92.9°E, lon = 93.4°E, lat = 26°N, lat = 27°N), crop land in Utter Pradesh (lon = 78°E, lon = 79°E, lat = 27°N, lat = 29.5°N), and Lucknow in Utter Pradesh (lon = 80.8°E, lon = 81.25°E, lat = 26.65°N, lat = 27°N). LCLU does not change much over a period of 10 years. The selected regions of uniform LCLU, well represent the 5-homogenous region (Figure 1a). Figure 11a–f displays the daily variations of surface precipitation, volumetric soil moisture for layer-1 (0–7cm), and evaporation over 6-selected regions dominated by cropland, deciduous, forest respectively for summer 2015 and 10 years (summer 2009–2018, Figure 11g) over cropland of northern India. The volumetric soil moisture is associated with the soil classification and soil layers/depths. On a daily scale, the rainfall and soil moisture correlation varies from 0.50 to 0.87, while rainfall and evaporation correlate −0.46 to 0.87 (Table 3). There are quite variations in monsoonal rainfall (called an active-break cycle), but the soil moisture keeps low variations. Soil moisture (slowly varying variable) varies smoothly compared to rainfall and picks up suddenly on a daily time scale. For a longer time scale (10 years, Figure 11e), we did not find any new insight than the individual years. During extreme rainfall cases, the soil moisture does not increase in the same proportion as low/moderate rainfall because runoff, evaporation, and impervious of soil/LULU limits the infiltration of water into the soil (Figure 11). The 10-year time series of the hydrological variables do not add much except yearly seasonal fluctuations (Figure 11g). Soil moisture possess have a good correlation with rainfall over cropland, deciduous forest and scrublands. Continuous rainfall for a short duration (e.g., 2 days, 3 days) enhances the soil moisture dramatically. In contrast, small fluctuations in rainfall do not influence the slowly varying soil moisture significantly. Heavy and extreme rainfall enhances flooding and runoff as compared to soil moisture [50]. The percolation of water into the soil depends on the rainfall duration, intensity, and continuity. A moderate to low rainfall will enhance the soil moisture up to a great depth. However, it hard to relate soil moisture to continuous rainfall for more than 2 days, because soil moisture values never reach zero, while a region can receive zero rainfall, which is very common news.

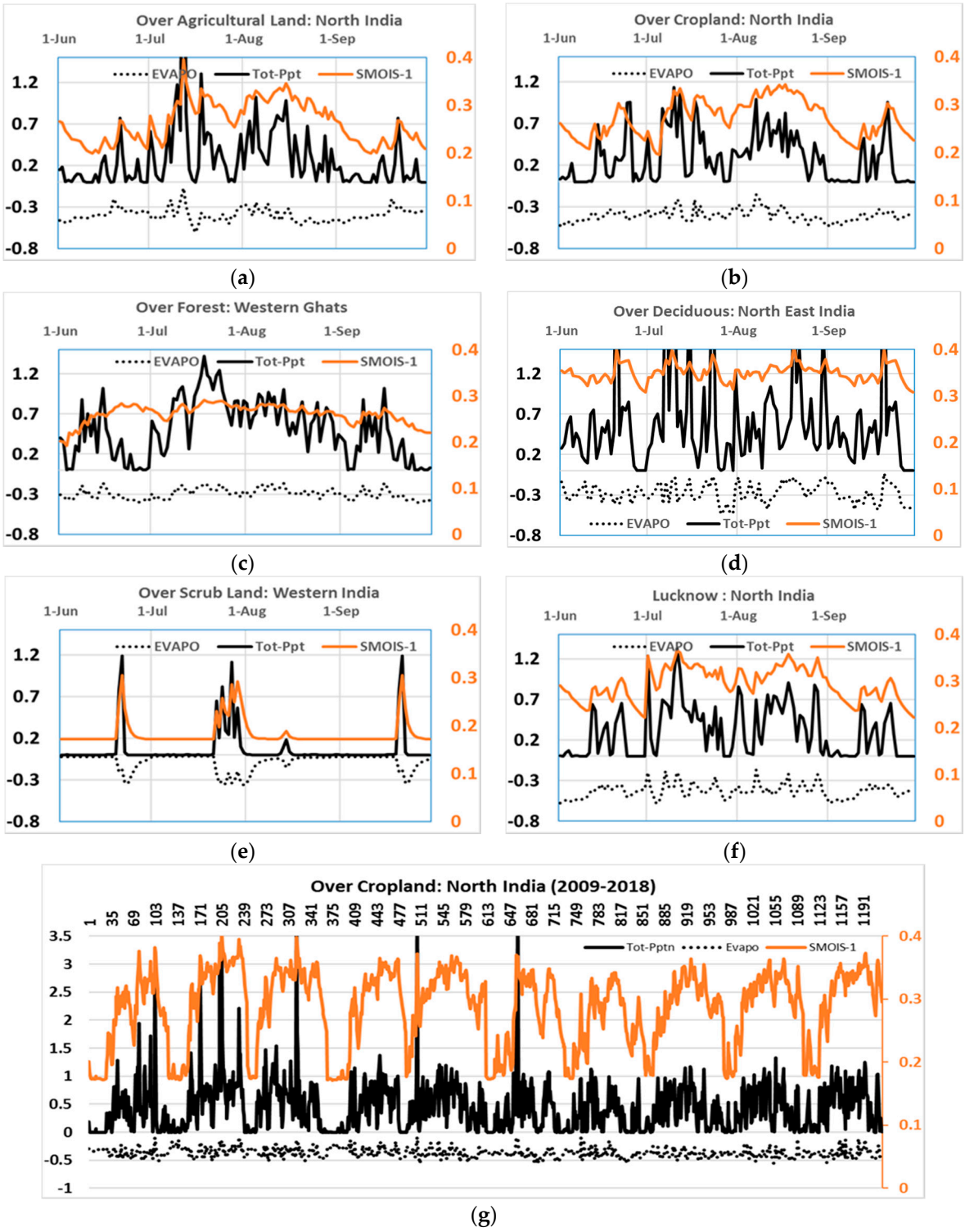


Figure 11. Variations of hydrological parameters such as evaporation (Evapo), total precipitation (Tot-Pptn), and soil moisture layer 1 (upper 7cm, SMOIS-1) for summer 2015 over selected regions of uniform land cover and land use (**a**) agricultural land, (**b**) crop land (**c**) forest, (**d**) deciduous, (**e**) urban area, (**f**) scrub land, and (**g**) crop land for ten years (2008–2019).

Table 3. Correlation between total precipitations with hydrological parameters.

LCLU types and Regions	Soil Moisture	Evaporation	Runoff
Agricultural land–Punjab (75.15°E–76°E, 30.1°N–30.4°N)	0.60	0.44	−0.36
Crop land–Utter Pradesh (78°E–79°E, 27°N–29.5°N)	0.67	0.51	−0.07
Forest–Goa–Karnataka (74°E–75°E, 14°N–15°N)	0.61	0.87	0.56
Deciduous forest–Assam (92.9°E–93.4°E, 26°N–27°N)	0.72	0.40	0.08
Urban area–Lucknow (80.8°E–81.25°E, 26.65°N–27°N)	0.50	0.66	−0.48
Scrub land–Rajasthan (70°E–70.75°E, 26.75°N–27.25°N)	0.87	−0.46	−0.08

5. Conclusions and Discussions

Indian summer monsoon rainfall does not show a significant trend over the long-term periods of 70 years, 100 years, 120 years, and 140 years on monthly to seasonal scales [7,10]. On different time and spatial scales (over regions or megacities), monthly to seasonal rainfall show mixed trends of decreasing and increasing trends in rainfall [51]. After a rigorous analysis of rainfall data, this research work brought some of the interesting points about spatial and temporal variability of the Indian summer monsoon rainfall in light of the number of rainfall days and frequency of continuous rainfall events and magnitudes. We applied a non-parametric Mann–Kendall test to daily gridded rain gauge data for trend analysis. A detailed investigation was carried out on the climatological trend of the number of rainy days and continuous rainfall events. Rainfall quantity and number of rainfall days trends were calculated at 95% confidence level for two periods of 34 years (1951–1984 and 1985–2018) utilizing the IMD gridded rainfall datasets. Though two different periods indicate a marked change in the event magnitudes and types, the change in event magnitude is less pronounced than the change in the number of events from the early period to the late period. Continuous rainfall of 1 day, 2 days, 3 days, 4 days and N days are referred as 1DAY, 2DAY, 3DAY and NDAY respectively. We analyzed the spatial distribution of frequency and fraction of different rain events over different climatic zones.

Following are the major conclusion drawn from the study:

1. The 1-day rainfall frequency and variability dominate over drought-prone regions such as North West (NW) and South East (SE) parts of India.
2. There is a decrease in the number of rainfall days (Table 1) over central India (CI) and the Western Coast (WC) during recent years (1985–2018, L-period). However, the southern region of WC (Southern Karnataka, the boundary of Kerala and Tamil Nadu) shows a decrease in rainy days in recent years, which is an abnormality in the rainfall over the Western Ghats range.
3. In July and September, the number of rainfall days and monthly mean rainfall show a decreasing and increasing trend respectively during the L-period over all climatic regions of India. There are few exceptions in monthly rainfall such as an increase in trend over NW in July and a decrease in trend over CI in September.
4. The number of rainfall days and monthly mean rainfall decreased over NE in L-period for the summer season. Further, the number of rainfall days decreased in all the months over NE. The monthly mean rainfall shows a decreasing trend in June and July while increasing in August (at 95% significant) and September. On a regional scale, the number of rainfall days are decreased by ~0.1 days/yr and ~0.3 days/yr over CI and NE, respectively, in L-period as compared to E-period.
5. The continuous rain events escalated from 1 to 4DAY, while de-escalated for higher number of days ($\geq$6DAY) during L-period as compared to E-period. The de-escalation of rainfall events for higher continuous days show that continuous rainfall shower for a fewer number of rainfall days in L-period than E-period. The magnitude of $\geq$6DAY continuous rainfall decreased by 10 mm in L-period.
6. The trends of light rainfall frequency (LRF) in two periods (E and L) are almost the same, except for the opposite sign, while light rainfall frequency shows a drastic

decrease in recent decades, which may have implications associated with ground discharge and agriculture.

7. The rainfall for continuous day 11 is most dominant over the regions of maximum rainfall, e.g., WC, NE, and a region of low-pressure-systems. The spatial pattern of rainfall frequency for 1DAY rainfall is almost opposite to the 11DAY over most parts of India. Rainfall fraction for continuous 11DAY is similar to climatological rainfall, where WC, CI, and NE regions receive more rainfall than other regions of India in the summer monsoon season.
8. In the 10 years from 2009–2018, ~60% of rainfall is contributed from 2DAY to 6DAY of continuous rainfall, which is 20% more than the rainfall contributed during 1951–1960 from the same number of continuous rainfall days. The rainfall contributed from a large number of continuous rainfall days (>8DAY) decreased in recent years. For 1–5 continuous rainy days, the rainfall amount is increased by 0.9% from 1951–1972 to 1995–2016, while the rainfall is decreased by 0.05% for 6–10 continuous rainfall days.
9. The rainfall is shifted towards a lesser number of continuous rainfall days with higher magnitudes. A continuous rainfall of >5DAY decreased in the recent years.
10. The rainfall trend from 1951 to 2018 displays a declining trend for the first 45 days (1 June to 15 July) from the onset of monsoon. The total number of rainy days in rice crops season (i.e., first 45 days, crop season, from the onset of monsoon) is decreased by half days during L-period than E-period over India.
11. On a daily scale, the rainfall and soil moisture correlation varies from 0.50 to 0.87, while rainfall and evaporation correlate at the range of −0.46 to 0.87 over selected parts of Indian regions. Continuous light/moderate rainfall seems to be a controlling factor for replenishing the soil moisture in upper layer.

The yield of the crops further depends on the inclusion of new technology, field & irrigation management, soil moisture, fertilizer applications, crop hybrid management, and many more parameters. Production of rice is well affected by rainfall, temperature, and their interaction; or better to say climate change [52,53]. They further added that temperature variability is an important factor for rice yield over highly irrigated and heavy rainfall regions of India [52]. On a state level, extreme rainfall and drought affected the rice yield in the rain-fed area, while drought had more impact than extreme rainfall [53]. Moreover, the rice harvest dates do not match with monsoon season, which makes it further complex to reach a robust relationship between rice crop yield and trends in rainy days.

Additionally, the results support the fact that the increasing trend of extreme rainfall over various climatic regions. Local, regional, or remote processes may influence long-term trends of rainfall fraction and rainfall days. The possible impact of long-term changes in rainfall days on LCLU, soil moisture, evaporation is presented. This study helps understand how continuous rainfall days and magnitude are changing in different regions of India. There is still a need to perform rigorous studies on developing a real-time forecasting system that can be used for adaptive decision making. Further research should be advanced on estimating ENSO's effects on the number of rainfall days and applying regional scale modeling aspects to investigate rainfall intensity, duration, and fraction. The constant decline in the number of rainfall days may be linked to regional assistance and remote teleconnection's combined factors. Some of the factors that impact rainfall duration may be the frequency of El Niño, weakening monsoonal circulation, increased air pollution, and warming of the Indian Ocean.

Supplementary Materials: The following are available online at https://www.mdpi.com/2072-4292/13/3/398/s1, Figure S1: MK test for the number of rainy days (rainfall $\geq$ 2.5mm) over 5 homogeneous regions of India. The Blue line shows the trend, while red dotted lines show confidence at 95% significance level here and in the rest of the figures, Figure S2: Difference in the rainfall fraction between two periods 1951–1984 and 1985–2018 (a) June, (b) July, (c) August, (d) September, Figure S3: MK test for continuous rain days over India from 1 June to 15 July during 1951–2018, Figure S4: Rainfall contribution to monsoon season (JJAS) in percentage from the number of continuous rainfall days from IMD rainfall for almost average of two-decades over Central India, Figure S5: Land Cover and Land Use (2015–16) for (a) Punjab, (b) Karnataka, (c) Assam, (d) Utter Pradesh, (d) Rajasthan states of India. Figures were plotted online from https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php#.

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