

Spatial analysis of temporal trend of rainfall and rainy days during the Indian Summer Monsoon season using daily gridded ($0.5^\circ \times 0.5^\circ$) rainfall data for the period of 1971–2005

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ABSTRACT: Daily gridded ($0.5^\circ \times 0.5^\circ$) rainfall data between 1971 and 2005 were used to detect spatial patterns of trend in rainfall and rainy days during the Indian Summer Monsoon (June to September). A non-parametric (Mann–Kendall test) method was used to test for monotonic trend at each grid level. The magnitude of trend is estimated using Sen's method. Further, a field significance test was applied to assess significant trend at an aggregated level over each meteorological subdivision. A statistically significant ($\alpha = 0.1$) increasing trend of both rainfall and rainy days during the monsoon season was found over the east coast and Deccan Plateau region of India. Meteorological subdivisions over the west coast, western arid region and northeastern humid region showed significantly decreasing trends in both rainfall and rainy days. The northern hilly parts of the Himalaya were found to have a significantly increasing trend of rainfall but decreasing trend of rainy days. The north and central plains of India showed a decreasing trend of rainy days and the eastern plain was found to have a decreasing trend of rainfall during the summer monsoon period.

KEY WORDS Indian summer monsoon; rainfall; rainy days; median trend

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1. Introduction

Warming of the climate system is unequivocal, and also evident from observations on increasing global average air temperature (Jones *et al.*, 1999; Jones and Moberg, 2003). The growing concern about climate change has heightened the need for accurate information about the space-time distribution of precipitation (New *et al.*, 2001). The spatio-temporal distribution of precipitation is required for climate model evaluation (Hulme, 1994), for differentiating observed climate change from the natural variability (Hulme *et al.*, 1999a), for biogeochemical modelling (Cramer and Fischer, 1996) and for the construction of climatic scenarios for assessment of climate change impacts (Hulme *et al.*, 1999b). The changing pattern of rainfall influences the amount and distribution of runoff, soil moisture and groundwater reserves, and also affects the occurrence of droughts and floods. Further, it controls cropping patterns and crop productivity particularly for India where two-thirds of the agricultural lands are rainfed (Dore, 2005; Kumar *et al.*, 2010). The South Asian monsoon in general and Indian monsoon in particular is a unique phenomenon of Earth's climate system (Garnett and Khandekar, 1992). About 80% of the total rainfall over the Indian region is received during the summer monsoon season, i.e., June to September (Sahai *et al.*, 2003). Indian summer monsoon rainfall is critical for the availability of fresh water for drinking and irrigation, agricultural production, power generation, water resources management and the overall economy of the country. Therefore, a proper trend analysis of Indian Summer Monsoon (ISM) rainfall

is required for social and economic planning towards climate change.

Several studies have been conducted to investigate the trend of ISM rainfall at a country level, regional level or individual station level. A few studies have shown that there was no significant trend of average annual rainfall at country level (Mooley and Parthasarathy, 1984; Sarker and Thapliyal, 1988; Thapliyal and Kulshrestha, 1991; Lal, 2001; Sinha Ray and De, 2003), but significant trends were observed at regional level over the monsoon months and season. It is apt to mention here that the trends of rainfall found in previous studies were highly dependent on the period of the data analysis and the type of the data analysed (station data, zonal average, gridded data). The annual average rainfall of 1901–1960 were analysed by Parthasarathy and Dhar (1974) who found a positive trend over central India and parts of the Indian peninsula, and a decreasing trend over several parts of eastern India. Pal and Al-Tabbaa (2011) carried out an analysis of the rainfall data for the period 1954–2003 and concluded that there was a decreasing trend in the spring and monsoon rainfall and increasing trends in the autumn and winter rainfall over India. Pant and Hingane (1988) analysed the mean annual and southwest monsoon rainfall of India for the period 1901–1982 and found a positive trend over Punjab, Haryana, West Rajasthan, East Rajasthan and West Madhya Pradesh. Rupa Kumar *et al.* (1992) reported a significant increasing trend in monsoon rainfall along the west coast, central peninsula and northwest India, while a significant decreasing trend was observed over the northeast and northwest peninsula, and northeast India. Subbaramayya and Naidu (1992) analysed the trends of monsoon rainfall in different meteorological subdivisions of India for the period 1871–1988. Central and western Indian subdivisions were found to have a decreasing trend during the nineteenth century

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and over the 1960s. This trend reversed in the early 1970s. Krishnakumar *et al.* (2009) studied the temporal variation of monthly, seasonal and annual rainfall over Kerala for the period 1871–2005 and concluded that there was a significant decrease in southwest monsoon rainfall and an increase in post-monsoon rainfall.

Daily gridded rainfall data for the period 1951–2003 were analysed by Ramesh and Goswami (2007) who found negative trends in early and late monsoon rainfall and rainy days over India. They also reported a decreasing trend of summer monsoon rainfall over India and an increasing trend of pre-monsoon and post-monsoon rainfall. Guhathakurta and Rajeevan (2008) analysed the rainfall time series created using a network of 1476 rain gauge stations for the period 1901–2003 and found a significant negative trend of monsoon rainfall over Jharkhand, Chhattisgarh, Kerala. They also reported a significant increasing trend over Gangetic West Bengal, western Uttar Pradesh, Jammu and Kashmir, Konkan and Goa, Madhya Maharashtra, Rayalaseema, coastal Andhra Pradesh, and north Interior Karnataka. A few studies have also been conducted to investigate the trends of rainfall over the different Indian river basins. Mirza *et al.* (1998) reported no significant trend of rainfall over the Ganga river basin, whereas one subdivision of the Brahmaputra basin showed a decreasing trend and others showed an increasing trend. No significant trend of monsoon and annual rainfall was found over the Mahanadi basin during 1901–1980 (Rao *et al.* 1993). Singh *et al.* (2005) analysed rainfall data over 316 rain gauge stations and concluded that there was a negative trend of annual rainfall over the major basins in central India (Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi), whereas a positive trend was observed over the Indus, Ganga, Brahmaputra, Krishna and Cauvery basins. Kumar and Jain (2010) used gridded ($1^\circ \times 1^\circ$) rainfall data between 1951 and 2004 to determine trends of annual and seasonal rainfall and rainy days over different river basins across India. West-flowing rivers from Tapi to Tadri showed a significant negative trend, whereas east-flowing rivers from Krishna and Pennar were found to have a significant positive trend of annual rainfall. A significant decreasing trend of annual rainy days was observed over west-flowing rivers south of Tadri and Godavari, and in east-flowing rivers south of Cauvery.

Previous studies carried out on the time series of rainfall data over India, used either station-wise point data or gridded data to investigate the trends of rainfall over the stations or over the aggregated regions (meteorological subdivision, river basin, homogeneous monsoon zones). Estimation of trend using zonal average of rainfall may sometimes lead to an erroneous result, as the direction of trend within the sub zones may act in the opposite direction. Thus, it is important to analyse the continuous spatial pattern of the trend to investigate the regional variability and homogeneity. The present study was carried out to analyse the nature of spatially distributed monotonic trends of rainfall pattern (the amount of rainfall and rainy days) during the ISM months and season as a whole. The direction and magnitude of the trends of rainfall and rainy days at grid level were estimated using Mann–Kendall and Sen's methods, respectively. Further, a field significance test was adopted to ascertain the computed grid level trend across each meteorological subdivision. Thus, the present study could capture the spatial pattern of temporal trend of rainfall and rainy days and also provided a decision on persisting trend at aggregated level.

2. Methodology

2.1. Processing of gridded rainfall dataset

Daily rainfall data for 35 years (1971–2005) generated by the India Meteorological Department (IMD) at a grid size of 0.5° latitude \times 0.5° longitude were used in the present study. The dataset was developed using quality controlled rainfall data from more than 3000 rain gauge stations over India. The details of the gridded rainfall data generation are available in Rajeevan and Bhat (2009). The majority of the grids had continuous data with no data gaps. A few grids in the northern and northeastern part of India with a few data gaps were excluded from the present analysis. The daily rainfall data were converted to the monthly cumulative rainfall data over the Indian summer monsoon period (June to September). The monthly data were further cumulated over the monsoon season to obtain the total monsoon rainfall. Monthly and monsoon season rainfall anomalies for the last 35 years (1971–2005) were calculated as an absolute deviation of rainfall from its respective long term average. Further, the daily rainfall data were converted to rainy days to obtain the distribution of rainfall over a particular period. According to the Indian Meteorological Department (IMD), a day with rainfall more than 2.5 mm was considered as a rainy day (Shukla *et al.*, 2003; Mohapatra and Mohanty, 2006). The total number of rainy days in each monsoon month (June to September) and in the monsoon season as a whole, were calculated for the period 1971–2005. Monthly and monsoon season rainy day anomalies were calculated using absolute deviation of the number of rainy days from the long term average. Trend analyses at each grid level were performed on the time series anomalies of monthly rainfall and rainy days and monsoon rainfall and rainy days. The grid-wise computed trend was further assessed over 34 meteorological subdivisions of the Indian mainland (Figure 1).

2.2. Statistical techniques for trend analysis

The direction of trend of time series anomalies of rainfall and rainy days during the monsoon months/season was estimated using the nonparametric Mann–Kendall test. The magnitude of the trend was estimated using Sen's method. The advantage of this method over parametric statistics is that the missing values in time series data are included and the data do not require to conform any particular distribution (Yu *et al.*, 1993).

The Mann–Kendall test searches for a trend in a time series without specifying whether the trend is linear or nonlinear (Khaliq *et al.*, 2009). The Mann–Kendall method firstly calculates the S statistic, which indicates the sum of the difference between the data points indicated in Equation (1):

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

where, x_j is observed value at time j , x_k is observed value at time k , $j > k$ ($j = 2, \dots, n$; $k = 1, \dots, n-1$) and n is the length of the data set.

The sign of the value is defined as follows:

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases} \quad (2)$$

The value of S indicates the direction of trend. A negative (positive) value indicates falling (rising) trend. If $n \geq 8$, the

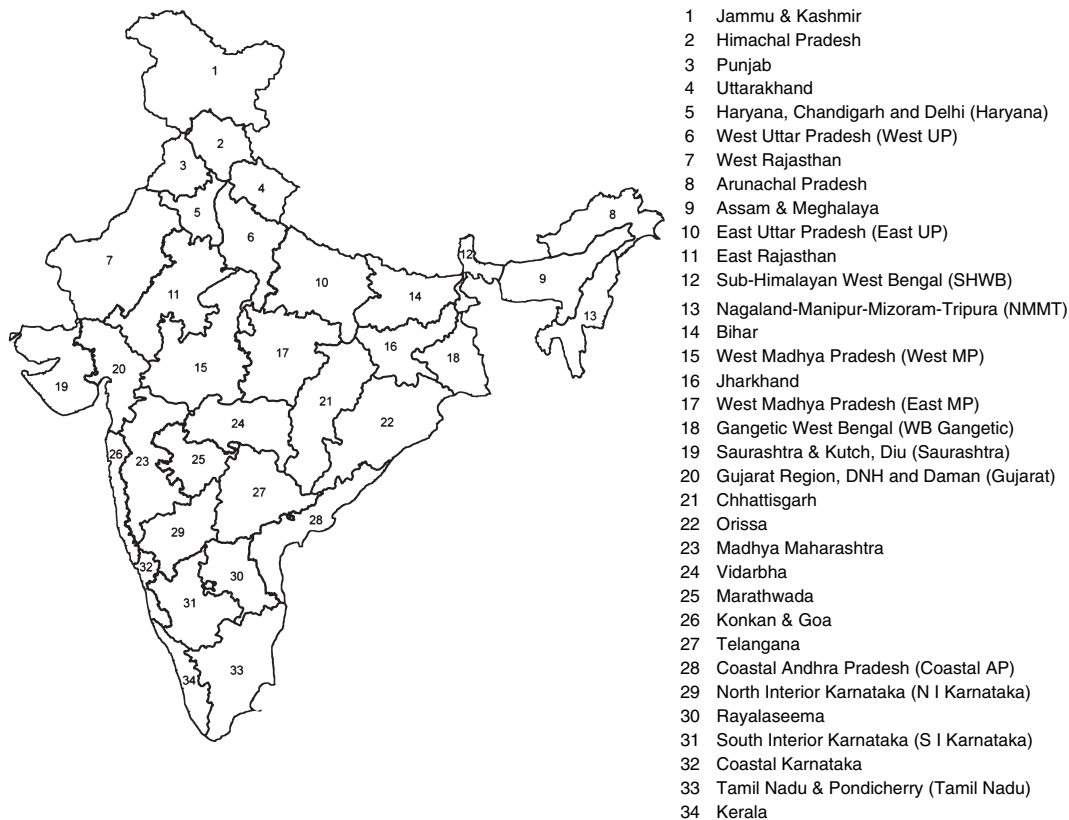


Figure 1. Study area with meteorological subdivision boundaries.

test statistic S is approximately normally distributed with mean and variance as follows:

$$E(S) = 0 \quad (3)$$

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^q t_p(t_p-1)(2t_p+5)}{18} \quad (4)$$

where n indicates the number of data points, q indicates the number of tied groups (a tied group is a set of sample data having the same value) and t indicates the number p of data points in the p^{th} group.

The statistical significance of S is checked using a test statistic (or Z score). The standardized Mann–Kendall statistics Z follows the standard normal distribution with zero mean and unit variance:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & ; S > 0 \\ 0 & ; S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & ; S < 0 \end{cases} \quad (5)$$

If the computed value of $|Z| > z_{\alpha/2}$, the null hypothesis (i.e. there is no distinct trend) is rejected at the α level of significance in a two sided test. In this analysis, the null hypothesis was tested at the 90% confidence level.

The linear regression method is generally used to estimate the slope of possible linear trend in time series, but for noisy short time series data, it may grossly miscalculate the magnitude of trend. Sen's slope estimator is a robust non-parametric trend operator and is highly immune to gross data error (Sen, 1968). An interesting feature of Sen's estimator is its breakdown bound. The breakdown bound for robust statistics

is the number of wild values that can occur within a series before it will be affected. For Sen's estimator, the breakdown bound is approximately 29%. Thus, the estimated trend is said to have persisted for more than 29% of the length of the time series (Hoaglin *et al.*, 2000). In the present study, the magnitude of the trend over time was estimated according to Sen (1968). It was calculated by determining the possible slope between all possible data pairs and then finding the median value as:

$$Q_i = \frac{x_j - x_k}{j - k} \quad (6)$$

where, Q_i is the slope between data points, $i = 1 \dots N$. For n values of the time series of x results, $N = n(n-1)/2$ values of Q_i . The Sen's estimator is median value of Q_i is:

$$Q = Q\left(\frac{N+1}{2}\right) \quad \text{if } N \text{ is odd,} \quad (7)$$

$$Q = \frac{1}{2} \left(Q\left[\frac{N}{2}\right] + Q\left[\frac{N+2}{2}\right] \right) \quad \text{if } N \text{ is even.} \quad (8)$$

2.3. Field significance test

While analysing time series anomalies of rainfall and rainy days at grid level over a large region such as India to identify trends, it is also important to ascertain the computed trend across the region using the field significance test (Livezey and Chen, 1983). In the present study, the field significance test was performed at $\alpha = 0.1$ over each meteorological subdivision (field or global). First, the trend was computed at each individual grid level as discussed earlier, and the number of grids having increasing/decreasing trend were used as an

input to the field significance test for checking the hypothesis that the respective meteorological subdivision had a trend (increasing/decreasing) or no trend.

In terms of probability theory, a collection of N independent significance tests (trend analysis of N grid points) is perfectly analogous to N tosses of a loaded coin. Instead of heads or tails, with odds based on the coin load, the outcome for a 0.1 significance level test is passed (probability equal to 0.1) or test failed (probability equal to 0.9). This can be modelled with a binomial distribution as:

$$Pr(M) = \binom{N}{M} (0.1)^M (1 - 0.1)^{N-M} \quad (9)$$

where $M = 0, 1, 2, \dots$

The field significance test is considered to be passed if the number (M) of individual tests (grid) passing (out of N tests), with $\alpha = 0.1$, exceeds a threshold number (M_0). As an example, a meteorological subdivision having 40 grids is tested for trends using the Mann–Kendal test at $\alpha = 0.1$. As *per* the binomial distribution (Equation (9)), the probabilities are exactly

0.01478, 0.06569, 0.014233, 0.20032, 0.20588, 0.16471 and 0.10676 for 0, 1, 2, 3, 4, 5 and 6 passed tests out of 40 grids. Thus, the cumulative probabilities are 0.20627 for five or more passed test and 0.099517 for six or more. Therefore, if the field significance test of a meteorological subdivision (having 40 grids) is performed, a minimum of 6 grids (threshold number, M_0) must pass to guarantee at least 90% (in this case 0.90048%) significance. Following this procedure, the threshold number (M_0) of grids having significant trend were computed for each meteorological subdivision at the 90% level of significance. The meteorological subdivisions were declared to have significant trend (increasing/decreasing) if total grids with significant trend (increasing/decreasing) were equal to or more than the threshold number (M_0).

3. Results and discussion

Although the climatological mean summer monsoon rainfall data of India showed that it remained stable over the past

Table 1. Gridwise account of temporal trend of time series anomalies of rainfall and rainy days during June.

Meteorological subdivisions	Positive trend				Negative trend				No trend	
	Rainfall		Rainy days		Rainfall		Rainy days		Rainfall	Rainy days
	N (a)	Slope	N (a)	Slope	N (a)	Slope	N (a)	Slope	N	N
Jammu and Kashmir	37 (11)	0.81	16 (7)	0.08	32	−0.22	10 (1)	−0.05	18	61
Himachal Pradesh	7	0.86	2	0.12	6	−0.52	3 (1)	−0.09	1	9
Punjab	7	0.27	4 (1)	0.07	8	−0.73	2	−0.04	0	9
Uttarakhand	7 (1)	1.16	5 (1)	0.09	8 (6)	−1.93	7 (6)	−0.21	4	6
Haryana	6 (1)	0.39	2 (1)	0.06	5 (2)	−1.03	2 (2)	−0.08	0	7
West UP	7	0.72	0	0.00	17 (3)	−1.03	11 (3)	−0.08	0	13
West Rajasthan	17 (6)	0.42	8 (4)	0.04	38 (9)	−0.34	14 (8)	−0.05	7	40
Arunachal Pradesh	7 (3)	4.43	3	0.10	10 (9)	−8.83	7	−0.07	15	22
Assam and Meghalaya	14 (4)	4.65	8 (2)	0.08	13 (3)	−3.10	11 (4)	−0.09	6	14
East UP	19 (2)	1.26	14 (2)	0.07	19	−0.73	3	−0.07	2	23
East Rajasthan	10	0.34	4 (3)	0.06	28 (3)	−0.60	9 (2)	−0.07	0	25
Sub-Himalayan West Bengal	3 (1)	2.84	2	0.11	7 (3)	−5.56	6	−0.07	7	9
Nagaland-Manipur-Mizoram-Tripura	6 (1)	0.85	3 (1)	0.06	19 (7)	−3.26	20 (8)	−0.12	16	18
Bihar	17 (3)	1.42	10 (1)	0.08	14 (1)	−1.45	8	−0.07	1	14
West MP	8	0.80	3 (1)	0.07	41 (3)	−0.92	15 (2)	−0.07	0	31
Jharkhand	11	0.97	5	0.09	10 (2)	−1.52	6	−0.09	0	10
East MP	8	0.61	6	0.06	37 (2)	−1.25	21 (2)	−0.07	0	18
Gangetic WB	19 (2)	2.08	17 (1)	0.08	2	−1.06	0	0.00	7	11
Saurashtra	8	0.71	1	0.05	14	−0.40	6	−0.04	17	32
Gujarat	24	0.81	6	0.04	9	−0.31	3	−0.05	1	26
Chhattisgarh	21	1.31	11 (1)	0.07	15	−0.81	8	−0.07	0	17
Orissa	40 (5)	2.15	20 (6)	0.09	15 (3)	−2.08	20 (7)	−0.09	4	19
Madhya Maharashtra	19 (7)	2.10	11 (5)	0.12	2	−1.02	2	−0.07	0	8
Vidarbha	24	0.95	9 (4)	0.07	8 (1)	−0.97	6 (2)	−0.08	0	17
Marathwada	24 (5)	1.43	15 (2)	0.07	0	0.00	2	−0.05	1	8
Konkan and Goa	5	2.87	1	0.08	13	−2.88	14 (1)	−0.10	4	7
Telangana	23 (2)	1.14	7 (1)	0.07	11 (4)	−0.80	9 (2)	−0.07	0	18
Coastal AP	24 (1)	0.70	4 (1)	0.04	14 (2)	−1.00	14 (4)	−0.07	6	26
N I Karnataka	16 (1)	0.66	6 (1)	0.09	11 (1)	−1.31	7 (1)	−0.08	0	14
Rayalaseema	11	0.43	2 (1)	0.05	7	−0.51	1	−0.05	0	15
S I Karnataka	20 (6)	0.69	12 (3)	0.08	6	−0.15	4 (1)	−0.06	2	12
Coastal Karnataka	5	1.14	2	0.07	7 (1)	−5.67	8 (5)	−0.19	1	3
Tamil Nadu	31 (9)	0.51	12 (8)	0.06	19 (1)	−0.51	9 (2)	−0.10	1	30
Kerala	4 (1)	0.81	1	0.04	20 (6)	−6.71	20 (15)	−0.16	4	7

N , Number of grids having positive or negative or no trend. Number of grids showing significant trend ($\alpha = 0.1$) are presented in brackets. Average magnitude of trend (positive or negative) estimated by Sen's method are presented as slope (mm year^{−1} for rainfall and days year^{−1} for rainy days). Meteorological subdivisions passed 'field significant test' at $\alpha = 0.1$ are marked as bold.

Table 2. Gridwise account of temporal trend of time series anomalies of rainfall and rainy days during July.

Meteorological subdivisions	Positive trend				Negative trend				No trend	
	Rainfall		Rainy days		Rainfall		Rainy days		Rainfall	Rainy days
	<i>N</i> ^(a)	Slope	<i>N</i> ^(a)	Slope	<i>N</i> ^(a)	Slope	<i>N</i> ^(a)	Slope	<i>N</i>	<i>N</i>
Jammu and Kashmir	50 (14)	1.40	22 (7)	0.12	23	−0.30	23 (2)	−0.07	14	42
Himachal Pradesh	6	2.30	2	0.14	7 (1)	−1.71	6 (3)	−0.15	1	6
Punjab	6 (1)	2.22	7 (1)	0.10	9 (2)	−2.08	2 (1)	−0.11	0	6
Uttarakhand	7 (1)	3.50	4	0.12	8 (3)	−2.73	8 (6)	−0.19	3	6
Haryana	2	1.55	1	0.13	9 (2)	−1.73	7 (2)	−0.12	0	3
West UP	8 (1)	1.99	3	0.09	16 (3)	−2.46	17 (5)	−0.11	0	4
West Rajasthan	19	0.36	1	0.06	40 (10)	−0.97	29 (10)	−0.09	3	32
Arunachal Pradesh	7 (1)	3.17	4	0.08	9 (5)	−7.80	6 (3)	−0.15	16	22
Assam and Meghalaya	9 (2)	4.44	4 (2)	0.08	18 (6)	−2.69	12 (3)	−0.08	6	17
East UP	3	0.93	2	0.08	35 (11)	−3.04	32 (10)	−0.10	2	6
East Rajasthan	12 (1)	1.84	6 (2)	0.09	26 (9)	−2.18	18 (3)	−0.09	0	14
Sub-Himalayan West Bengal	5	3.68	1	0.04	5 (4)	−9.09	4 (1)	−0.05	7	12
Nagaland-Manipur-Mizoram-Tripura	13 (3)	3.05	7 (2)	0.07	12 (4)	−2.54	11 (3)	−0.10	16	23
Bihar	11	1.78	2	0.07	20 (2)	−2.15	24 (4)	−0.10	1	6
West MP	23	1.74	3	0.08	26 (1)	−1.66	24 (4)	−0.10	0	22
Jharkhand	2	0.72	0	0.00	19 (4)	−2.72	17 (6)	−0.12	0	4
East MP	21 (3)	2.40	8 (2)	0.10	24 (4)	−1.86	23 (4)	−0.09	0	14
Gangetic WB	6	0.62	2	0.06	15 (3)	−2.09	7 (2)	−0.09	7	19
Saurashtra	12	1.03	11	0.06	14	−0.94	1	−0.03	13	27
Gujarat	26	2.09	7 (1)	0.07	8	−0.47	7	−0.05	1	21
Chhattisgarh	17 (3)	2.19	4 (3)	0.13	23 (1)	−1.46	21 (1)	−0.07	0	11
Orissa	32 (1)	1.60	11 (1)	0.09	23 (1)	−1.46	21 (5)	−0.08	4	27
Madhya Maharashtra	13 (4)	2.09	6 (5)	0.22	8	−1.52	7 (1)	−0.10	0	8
Vidarbha	23 (1)	1.95	9 (3)	0.09	9	−1.02	9 (2)	−0.07	0	14
Marathwada	22 (1)	1.15	13 (3)	0.08	3	−0.61	1 (1)	−0.14	0	11
Konkan and Goa	12 (1)	5.18	1	0.10	6 (3)	−6.46	8 (4)	−0.08	4	13
Telangana	30 (2)	1.86	19 (7)	0.13	4	−0.70	3	−0.10	0	12
Coastal AP	33 (10)	1.61	25 (12)	0.12	5 (1)	−1.14	3 (1)	−0.10	6	16
N I Karnataka	19 (1)	1.06	6 (3)	0.11	8	−1.59	3	−0.06	0	18
Rayalaseema	17 (2)	1.06	14 (5)	0.10	1	−0.10	0	0.00	0	4
S I Karnataka	23 (4)	1.06	13 (6)	0.13	5	−0.39	2	−0.06	0	13
Coastal Karnataka	5 (1)	5.18	2	0.07	7 (2)	−9.31	3 (2)	−0.42	1	8
Tamil Nadu	17 (2)	0.44	6 (1)	0.08	33 (6)	−0.99	22 (8)	−0.10	1	23
Kerala	11 (1)	2.39	7 (1)	0.10	14 (3)	−4.78	9 (2)	−0.09	3	12

century with some inter-decadal variability (Goswami *et al.*, 2006), it is not always true at a finer spatial scale (Kumar *et al.*, 2010). To obtain the details of the finer spatial variability of the trend of rainfall pattern, the temporal trends of rainfall and rainy days for June, July, August, September and the monsoon season were computed using $0.5^\circ \times 0.5^\circ$ gridded rainfall dataset and presented in Tables 1–5, respectively. The number of grids having positive/negative or no trend, under each meteorological subdivision, are also presented in Tables 1–5. In each meteorological subdivision, the number of grids having statistically significant ($\alpha = 0.1$) positive/negative trends are presented in brackets. The magnitude of trend (slope) in the positive or negative categories was estimated at grid level by Sen's method and averaged over each meteorological subdivision (mm year^{-1} in the case of rainfall, numbers of days year^{-1} in case of rainy days). If a meteorological subdivision passed the field significance test it is marked as bold in Tables 1–5. For visualization of the spatial variability of the trend, spatial pattern of median trend (Sen's slope) of rainfall and rainy days along with the grids of significant trend over the monsoon months (June to September) see Figures 2 and 3, respectively. Similarly, the spatial pattern of median trend of rainfall and rainy days over the monsoon season is presented in Figures 4 and 5, respectively.

3.1. Trends of rainfall and rainy days over the monsoon months

3.1.1. June

The Indian summer monsoon hits the west coast of the Indian sub-continent (Kerala, Coastal Karnataka) in the first week of June and spreads all over the subcontinent (except to the western arid region of Rajasthan) within June. Rainfall during June plays a vital role in triggering the preparatory agricultural operations for sowing. The present study showed highly negative trend of June rainfall ($< -2 \text{ mm year}^{-1}$) over the west coast covering Kerala, coastal Karnataka, Konkan and Goa (Table 1, Figures 2 and 3). A similar magnitude of trend was also observed in isolated areas of east and northeastern parts of India. A moderate negative trend of rainfall (0 to -2 mm year^{-1}) was seen in large contiguous areas of north and western India. A moderate positive trend (0 – 2 mm year^{-1}) of rainfall was observed in south and eastern parts of India. A highly positive trend ($> 2 \text{ mm year}^{-1}$) of rainfall was observed in isolated parts of Madhya Maharashtra, Orissa, Gangetic West Bengal, Arunachal Pradesh, Assam and Meghalaya. A highly negative trend of rainy days during June ($< -0.1 \text{ days year}^{-1}$) was observed on the west coast of India (Kerala, coastal Karnataka, Konkan and Goa) and Uttarakhand.

Table 3. Gridwise account of temporal trend of time series anomalies of rainfall and rainy days during August.

Meteorological subdivisions	Positive trend				Negative trend				No trend	
	Rainfall		Rainy days		Rainfall		Rainy days		Rainfall	Rainy days
	<i>N</i> (^a)	Slope	<i>N</i> (^a)	Slope	<i>N</i> (^a)	Slope	<i>N</i> (^a)	Slope	<i>N</i>	<i>N</i>
Jammu and Kashmir	51 (13)	1.46	27 (1)	0.09	22 (9)	−1.14	25 (13)	−0.10	14	35
Himachal Pradesh	10 (5)	4.15	7 (2)	0.11	3	−1.42	4 (2)	−0.14	1	3
Punjab	5	1.19	3	0.09	10	−1.14	6	−0.06	0	6
Uttarakhand	10 (5)	4.07	6 (3)	0.17	5	−1.01	7 (2)	−0.16	3	5
Haryana	8	0.81	3	0.09	3	−1.15	6 (1)	−0.10	0	2
West UP	16 (2)	2.87	2	0.07	8	−1.47	14 (4)	−0.09	0	8
West Rajasthan	11	0.18	0	0.00	42 (12)	−0.96	47 (30)	−0.10	9	15
Arunachal Pradesh	8 (3)	4.74	5 (2)	0.12	8 (1)	−5.12	4	−0.12	16	23
Assam and Meghalaya	16 (4)	2.94	14 (2)	0.08	11 (1)	−1.82	4 (1)	−0.09	6	15
East UP	27 (3)	2.32	10 (1)	0.10	11 (1)	−1.73	15 (1)	−0.08	2	15
East Rajasthan	5	0.23	1	0.04	32	−1.16	27 (7)	−0.10	1	10
Sub-Himalayan West Bengal	7 (1)	3.39	4 (1)	0.10	3 (1)	−5.78	2	−0.05	7	11
Nagaland-Manipur-Mizoram-Tripura	20 (1)	1.80	8 (5)	0.13	6	−1.31	7 (1)	−0.09	15	26
Bihar	29 (5)	2.59	8 (3)	0.08	2	−3.53	6	−0.06	1	18
West MP	5	0.56	1	0.06	44 (8)	−3.03	44 (22)	−0.13	0	4
Jharkhand	9	1.11	5 (1)	0.07	12	−1.31	8 (1)	−0.08	0	8
East MP	13 (5)	2.31	6	0.10	32 (6)	−2.95	32 (14)	−0.11	0	7
Gangetic WB	10 (1)	2.20	9 (1)	0.07	11	−1.72	3	−0.06	7	16
Saurashtra	16	0.74	1	0.05	9	−0.54	11 (1)	−0.05	14	27
Gujarat	8	0.38	0	0.00	23	−1.46	27 (7)	−0.11	4	8
Chhattisgarh	16 (2)	1.15	6 (1)	0.08	20	−1.67	13 (1)	−0.08	0	17
Orissa	18	1.54	12 (2)	0.08	37	−1.78	24 (2)	−0.08	4	23
Madhya Maharashtra	9 (3)	2.15	5	0.16	11	−1.38	13 (6)	−0.12	1	3
Vidarbha	12	1.60	5	0.05	20 (3)	−2.41	17 (4)	−0.09	0	10
Marathwada	17 (1)	0.88	4	0.07	6	−0.45	3	−0.06	2	18
Konkan and Goa	9	3.44	1	0.06	9	−4.37	9 (3)	−0.07	4	12
Telangana	32 (5)	2.37	9 (4)	0.13	2	−1.24	7	−0.06	0	18
Coastal AP	35 (8)	1.84	23 (7)	0.10	3	−0.61	4	−0.06	6	17
N I Karnataka	24 (1)	1.07	10 (1)	0.08	0	0.00	4	−0.06	3	13
Rayalaseema	17 (1)	1.37	15 (2)	0.09	1	−0.04	1	−0.07	0	2
S I Karnataka	28 (6)	1.17	19 (8)	0.12	0	0.00	1	−0.09	0	8
Coastal Karnataka	5	3.57	1	0.08	7 (2)	−7.48	6 (2)	−0.25	1	6
Tamil Nadu	29 (3)	0.73	13	0.07	20 (2)	−0.82	7 (1)	−0.09	2	31
Kerala	10 (1)	1.74	4 (1)	0.06	15	−1.80	18 (4)	−0.10	3	6

A moderately negative trend (0 to -0.1 days year^{−1}) was found in central (West and East Madhya Pradesh), north-west (East and West Rajasthan) and northeast parts of India (Assam and Meghalaya, Nagaland-Manipur-Mizoram-Tripura (NMMT), Arunachal Pradesh). In the rest of India, a moderately increasing trend (0.04–0.12 days year^{−1}) of rainy days was observed in June.

Statistically significant positive trends both in the case of rainfall and rainy days during June were found in Tamil Nadu and Madhya Maharashtra, whereas Kerala, NMMT, Uttarakhand and Haryana showed significant negative trends both in rainfall and rainy days. A significant positive trend in rainfall only was found in south interior Karnataka and Marathwada. On the other hand, Western Rajasthan, Arunachal Pradesh and Sub-Himalayan West Bengal (SHWB) showed a significant negative trend in June rainfall, without any significant trend of rainy days. A statistically significant decrease in the number of rainy days without any significant trend in rainfall amount during June was found in coastal Karnataka.

3.1.2. July

July is an active monsoon month, and rainfall during this month is crucial for progression of sowing operations all over India. Any negative impact on July rainfall has a deep impact on

Indian agriculture in terms of reduction of sown area or delayed sowing. Trends of rainfall and rainy days during the month of July are presented in Table 2 and Figures 2 and 3. Negative trends of July rainfall were observed over the Indo-Gangetic plain, western coastal area, western arid region and the southern tip of India. A highly negative trend (< -2 mm year^{−1}) was observed in large contiguous area of Haryana, Uttarakhand, West and East Uttar Pradesh, Arunachal Pradesh, East Rajasthan, Bihar, NMMT, Jharkhand, Kerala, Coastal Karnataka, Konkan and Goa. A moderate negative trend (0 to -2 mm year^{−1}) was found in West Rajasthan, Gangetic West Bengal and Tamil Nadu. The rest of the part of India covering the central and southern regions showed a positive trend of rainfall during July up to a magnitude of 2 mm year^{−1}. The spatial pattern of trend of rainy days during July followed a pattern similar to that of the rainfall trend. There was a decreasing trend of rainy days (0.03–0.15 days year^{−1}) over the Indo-Gangetic plain, the western arid zone, the northeast region, the west coastal region, central India and Tamil Nadu. The southern peninsula and Deccan Plateau (Madhya Maharashtra, Marathwada, Vidarbha, south and north interior Karnataka, Telangana, Rayalaseema, coastal Andhra Pradesh) and Saurashtra and Kutch showed a positive trend (0.04–0.22 days year^{−1}) of rainy days during July.

Table 4. Gridwise account of temporal trend of time series anomalies of rainfall and rainy days during September.

Meteorological subdivisions	Positive trend				Negative trend				No trend	
	Rainfall		Rainy days		Rainfall		Rainy days		Rainfall	Rainy days
	<i>N</i> (^a)	Slope	<i>N</i> (^a)	Slope	<i>N</i> (^a)	Slope	<i>N</i> (^a)	Slope	<i>N</i> (^a)	<i>N</i>
Jammu and Kashmir	60 (21)	0.93	27 (16)	0.10	11	−0.10	3 (1)	−0.06	16	57
Himachal Pradesh	10 (8)	2.41	10 (5)	0.12	3	−0.24	1	−0.04	1	3
Punjab	13 (2)	1.09	6 (3)	0.09	2	−0.10	0	0.00	0	9
Uttarakhand	10 (2)	2.33	8 (6)	0.17	5	−0.52	1	−0.07	3	9
Haryana	10	0.60	3 (1)	0.08	1	−0.05	0	0.00	0	8
West UP	22 (8)	2.48	20 (6)	0.11	2	−0.20	0	0.00	0	4
West Rajasthan	13	0.16	0	0.00	38 (3)	−0.16	5 (3)	−0.05	11	57
Arunachal Pradesh	4 (1)	2.88	0	0.00	12 (5)	−4.26	12 (8)	−0.16	16	20
Assam and Meghalaya	9 (3)	3.10	7 (1)	0.09	18 (1)	−2.02	14 (6)	−0.10	6	12
East UP	27 (3)	1.69	23 (4)	0.10	11	−1.10	0	0.00	2	17
East Rajasthan	27	0.51	12 (1)	0.06	11 (1)	−0.34	0	0.00	0	26
Sub-Himalayan West Bengal	1	2.66	2 (2)	0.21	9 (4)	−5.41	5	−0.08	7	10
Nagaland-Manipur-Mizoram-Tripura	20 (10)	2.47	15 (3)	0.10	4	−0.39	5 (10)	−0.08	15	21
Bihar	9	1.18	5 (1)	0.08	22 (7)	−2.43	14 (2)	−0.08	1	13
West MP	31	0.73	19 (2)	0.07	18	−0.53	2	−0.07	0	28
Jharkhand	12	1.18	10 (2)	0.08	9	−0.58	2	−0.04	0	9
East MP	33 (2)	1.46	21 (2)	0.08	12	−0.73	2	−0.06	0	22
Gangetic WB	15	1.56	8 (4)	0.09	6 (1)	−1.21	2	−0.05	7	18
Saurashtra	10	0.13	1	0.06	14	−0.62	9 (1)	−0.06	15	29
Gujarat	23	0.34	3	0.05	10	−0.24	3	−0.04	2	29
Chhattisgarh	25	0.95	16 (2)	0.08	11	−0.51	1	−0.12	0	19
Orissa	30 (1)	0.83	14 (2)	0.07	25 (1)	−0.95	17	−0.06	4	28
Madhya Maharashtra	12	1.06	6 (1)	0.07	9	−0.83	5 (1)	−0.06	0	10
Vidarbha	22 (1)	1.17	8	0.08	10	−0.41	3	−0.06	0	21
Marathwada	22	0.75	7 (1)	0.07	3	−0.96	1	−0.04	0	17
Konkan and Goa	5	1.03	4	0.07	13	−1.99	3	−0.07	4	15
Telangana	12	0.44	6 (1)	0.10	22	−0.54	6	−0.07	0	22
Coastal AP	19	0.76	10	0.06	19	−0.76	14 (3)	−0.07	6	20
N I Karnataka	2	0.40	3	0.05	25	−0.94	10 (1)	−0.08	0	14
Rayalaseema	13	0.83	6	0.06	5	−0.44	1	−0.07	0	11
S I Karnataka	3	0.40	0	0.00	25 (3)	−1.53	20 (2)	−0.08	0	8
Coastal Karnataka	4	0.68	0	0.00	8 (3)	−2.55	6 (2)	−0.16	1	7
Tamil Nadu	10	0.79	5 (1)	0.08	40 (7)	−1.34	26 (6)	−0.10	1	20
Kerala	6	0.32	1	0.04	19 (3)	−1.67	19 (3)	−0.09	3	8

A statistically significant positive trend both in rainfall and rainy days during July was found over coastal Andhra Pradesh and Madhya Maharashtra, whereas, Uttarakhand, Haryana, West Rajasthan, East Uttar Pradesh and Jharkhand showed a significant negative trend both in rainfall and rainy days. Jammu and Kashmir showed significant positive and SHWB, East Rajasthan, Assam and Meghalaya, and Arunachal Pradesh had significant negative trends of rainfall, with no significant trend in rainy days. Rainy days were found to increase significantly over Telangana, Rayalaseema and south interior Karnataka, whereas they decreased significantly over Punjab, West Uttar Pradesh, Konkan and Goa, and Tamil Nadu without any significant trend of rainfall.

3.1.3. August

Rainfall activity used to be at its peak during August, and thus it governs Indian agriculture in terms of rice crop transplantation and establishment of the already sown crop. A negative anomaly of rainfall during this period leads to maximum reduction of agricultural output. Trends of rainfall and rainy days during August are presented in Table 3, and Figures 2 and 3. A highly negative trend (< -2 mm year^{−1}) of rainfall during August was found in contiguous areas of East

and West Madhya Pradesh and isolated areas of coastal Karnataka, Konkan and Goa, Vidarbha and Orissa. A moderately negative trend (0 to -2 mm day^{−1}) of rainfall was observed in West and East Rajasthan, Gujarat, Punjab and Haryana. A positive trend (0.7–4 mm year^{−1}) of rainfall during August was found over the southern part (Tamil Nadu, south and north interior Karnataka, Telangana, Rayalaseema, Coastal Andhra), central part (Madhya Maharashtra, Marathwada), eastern part (Chhattisgarh, Bihar, Assam and Meghalaya, NMMT, Arunachal Pradesh) and northern part (East and West Uttar Pradesh, Himachal Pradesh, Uttarakhand, Jammu and Kashmir) of India. A highly negative trend of rainy days during August (< -0.1 days year^{−1}) was seen over West and East Rajasthan, West and East Madhya Pradesh, and Gujarat. On the other hand, a moderate negative trend of rainy days (0 to -0.1 days year^{−1}) was found over Saurashtra and Kutch, Punjab, Haryana, Konkan and Goa, Coastal Karnataka, Kerala and isolated places over east Uttar Pradesh, Bihar, Vidarbha, Chhattisgarh and Orissa. The rest of southern, eastern and north-eastern India showed a positive trend (0.05–0.17 days year^{−1}) of rainy days during August.

Statistically significant decreasing trends of both rainfall and rainy days during August were found in West Rajasthan and West Madhya Pradesh, whereas an increasing trend of

Table 5. Gridwise account of temporal trend of time series anomalies of rainfall and rainy days during monsoon season.

Meteorological subdivisions	Positive trend				Negative trend				No trend	
	Rainfall		Rainy days		Rainfall		Rainy days		Rainfall	Rainy days
	<i>N</i> (^a)	Slope	<i>N</i> (^a)	Slope	<i>N</i> (^a)	Slope	<i>N</i> (^a)	Slope	<i>N</i>	<i>N</i>
Jammu and Kashmir	56 (22)	5.83	38 (14)	0.28	17	−1.67	27 (11)	−0.18	14	22
Himachal Pradesh	10 (3)	7.83	6 (2)	0.33	3 (2)	−7.13	6 (3)	−0.32	1	2
Punjab	8 (1)	3.79	8 (1)	0.19	7 (1)	−5.70	5 (1)	−0.12	0	2
Uttarakhand	8 (6)	11.60	7 (2)	0.43	7 (2)	−7.55	8 (7)	−0.57	3	3
Haryana	5	2.90	4	0.18	6 (1)	−1.92	6 (4)	−0.24	0	1
West UP	15 (3)	6.07	7 (2)	0.21	9 (3)	−4.56	16 (4)	−0.20	0	1
West Rajasthan	12	0.64	2	0.04	49 (13)	−2.31	50 (21)	−0.19	1	10
Arunachal Pradesh	6 (2)	15.93	4 (1)	0.21	10 (7)	−21.86	11 (5)	−0.30	16	17
Assam and Meghalaya	15 (4)	10.48	11 (3)	0.19	12 (3)	−8.24	13 (5)	−0.25	6	9
East UP	16 (2)	3.77	14 (2)	0.16	22 (2)	−3.47	16 (1)	−0.16	2	10
East Rajasthan	8	1.91	7 (1)	0.17	30 (6)	−3.51	26 (6)	−0.18	0	5
Sub-Himalayan West Bengal	4	6.10	4 (2)	0.31	6 (3)	−18.37	6 (1)	−0.21	7	7
Nagaland-Manipur-Mizoram-Tripura	13 (6)	8.63	10 (5)	0.23	12 (3)	−.92	13 (6)	−0.27	16	18
Bihar	18 (2)	4.87	5 (3)	0.18	13 (3)	−5.47	23 (3)	−0.17	1	4
West MP	5	1.61	7 (1)	0.10	44 (3)	−3.65	39 (12)	−0.23	0	3
Jharkhand	4 (1)	4.70	5 (1)	0.18	17 (4)	−4.98	12 (4)	−0.21	0	4
East MP	13 (4)	6.22	6 (4)	0.41	32 (1)	−3.31	32 (9)	−0.20	0	7
Gangetic WB	11 (2)	4.32	15 (2)	0.14	10 (1)	−4.21	5	−0.09	7	8
Saurashtra	13	2.59	4	0.12	13	−1.83	17	−0.11	13	18
Gujarat	29 (1)	2.83	4	0.13	5	−1.98	23 (1)	−0.15	1	8
Chhattisgarh	18 (1)	3.02	9 (2)	0.25	18 (1)	−2.30	23 (2)	−0.15	0	4
Orissa	31 (2)	3.66	23 (7)	0.19	24 (2)	−3.85	29 (12)	−0.24	4	7
Madhya Maharashtra	16 (2)	5.07	8 (5)	0.39	5 (1)	−3.81	10 (1)	−0.26	0	3
Vidarbha	23 (3)	4.46	10 (2)	0.15	9 (1)	−3.98	17 (1)	−0.16	0	5
Marathwada	23 (4)	3.86	12 (2)	0.20	2	−0.50	6	−0.11	0	7
Konkan and Goa	10 (1)	11.06	2 (1)	0.27	8 (3)	−14.79	14 (4)	−0.27	4	6
Telangana	30 (3)	4.39	18 (5)	0.23	4	−1.43	13	−0.12	0	3
Coastal AP	30 (11)	3.94	24 (8)	0.19	5	−2.50	8 (4)	−0.21	6	12
N I Karnataka	13 (1)	1.85	8 (1)	0.17	14 (2)	−2.99	10 (1)	−0.21	0	9
Rayalaseema	16 (4)	3.46	15 (5)	0.20	2	−0.74	1	−0.11	0	2
S I Karnataka	12 (1)	3.30	15 (2)	0.22	16	−1.20	9 (1)	−0.12	0	4
Coastal Karnataka	5 (1)	11.61	2	0.13	7 (4)	−32.47	9 (7)	−0.67	1	2
Tamil Nadu	21 (2)	2.16	18 (2)	0.14	29 (5)	−2.89	22 (8)	−0.24	1	11
Kerala	7	5.08	3 (1)	0.23	18 (7)	−12.89	21 (13)	−0.34	3	4

both rainfall and rainy days was found in Uttarakhand, Coastal Andhra Pradesh, and south interior Karnataka. Further, Himachal Pradesh and Bihar exhibited a significant increasing trend of August rainfall without any significant trend in the cases of rainy days. A significant negative trend in rainy days only was observed in west Uttar Pradesh, east Rajasthan, east Madhya Pradesh, Gujarat, and Madhya Maharashtra. Although Jammu and Kashmir showed a significant increasing trend of rainfall the trend of rainy days was significantly negative.

3.1.4. September

The Indian summer monsoon (southwest monsoon) starts withdrawing during September. The rainfall during this period is critical for crop establishment and development. Trends of rainfall and rainy days during September are shown in Table 4, and Figures 2 and 3. The present study revealed a highly negative trend ($< -2 \text{ mm year}^{-1}$) of rainfall during September over Coastal Karnataka, Konkan and Goa, SHWB, Assam and Meghalaya, and Arunachal Pradesh. A moderate decreasing trend (0 to -2 mm year^{-1}) of rainfall was found over the southern part (Tamil Nadu, Kerala, south and north interior Karnataka, Telangana, Rayalaseema) and west Rajasthan. The rest of the parts of the country showed a positive trend of rainfall during September. The decreasing trend of rainy days

(0.05–0.16 days year^{-1}) was found over southern parts (Tamil Nadu, Kerala, south and north interior Karnataka, coastal Karnataka, Telangana), parts of Saurashtra and Kutch, Gujarat, Assam and Meghalaya, Arunachal Pradesh, west Rajasthan, coastal Andhra Pradesh, and Orissa. The rest of the areas of India showed a positive trend (0.04–0.2 days year^{-1}) of rainy days during September.

A statistically significant increase in both rainfall and rainy days during September was found over Jammu and Kashmir, Himachal Pradesh and west Uttar Pradesh. On the other hand, significant decreasing trends of rainfall and rainy days were observed over Arunachal Pradesh. There has been a significant increasing trend in rainfall and a decreasing trend in rainy days during September over NMMT. A significant decreasing trend only in the case of rainfall was observed over SHWB, Bihar, and Coastal Andhra Pradesh. A significant positive trend in rainy days only was found in Punjab and Uttarakhand. Assam showed a significant negative trend in rainy days only during September.

3.2. Trends of rainfall and rainy days over the Indian summer monsoon season

Trends of rainfall and rainy days during the monsoon season are presented in Table 5, and Figures 4 and 5. Highly

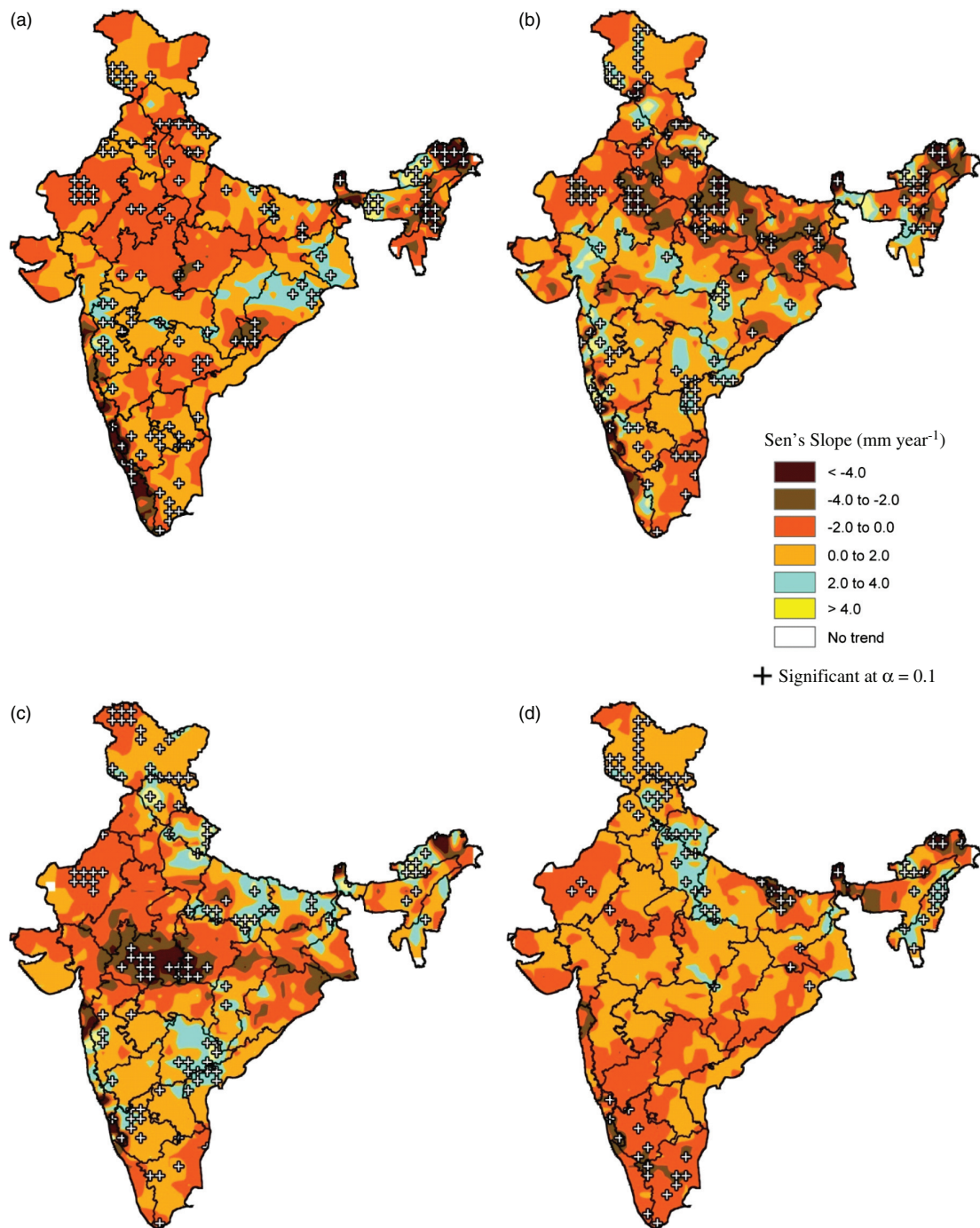


Figure 2. Spatial pattern of median trend estimated by Sen's slope over the time series anomalies (1971–2005) of rainfall during (a) June, (b) July, (c) August, and (d) September; significant grid at $\alpha = 0.1$ are shown as '+'. This figure is available in colour online at wileyonlinelibrary.com/journal/met

negative trends ($< -4 \text{ mm year}^{-1}$) of the monsoon rainfall were found over Kerala, Coastal Karnataka, Konkan and Goa, Jharkhand, SHWB and Arunachal Pradesh. Moderate negative trends ($0 \text{ to } -4 \text{ mm day}^{-1}$) were observed over east and west Rajasthan, east and west Madhya Pradesh, Tamil Nadu, Jharkhand and Bihar. Highly positive trends ($> 4 \text{ mm year}^{-1}$) of monsoon rainfall were found over Jammu and Kashmir, Himachal Pradesh, Uttarakhand, West Uttar Pradesh, Assam and Meghalaya, NMMT, Vidarbha, Telangana and Coastal Andhra Pradesh. Moderate positive trends ($0\text{--}4 \text{ mm year}^{-1}$) were visible in Madhya Maharashtra, Marathwada, south interior Karnataka, Rayalaseema, Gujarat, Saurashtra and

Kutch, Chhattisgarh and Orissa. Decreasing trends of monsoon rainy days ($0.09\text{--}0.67 \text{ days year}^{-1}$) were found over the west coast (Kerala, coastal Karnataka, Konkan and Goa), western India (west and east Rajasthan, Gujarat, Saurashtra and Kutch), central India (west and east Madhya Pradesh, Chhattisgarh), northern India (Haryana, west and east Uttar Pradesh, Bihar, Jharkhand) and eastern India (Assam, SHWB, Arunachal Pradesh). Positive trends of monsoon rainy days ($0.04\text{--}0.39 \text{ days year}^{-1}$) were observed in the south part of India covering south and north interior Karnataka, Rayalaseema, Telangana, Coastal Andhra Pradesh, Madhya Maharashtra, and Marathwada.

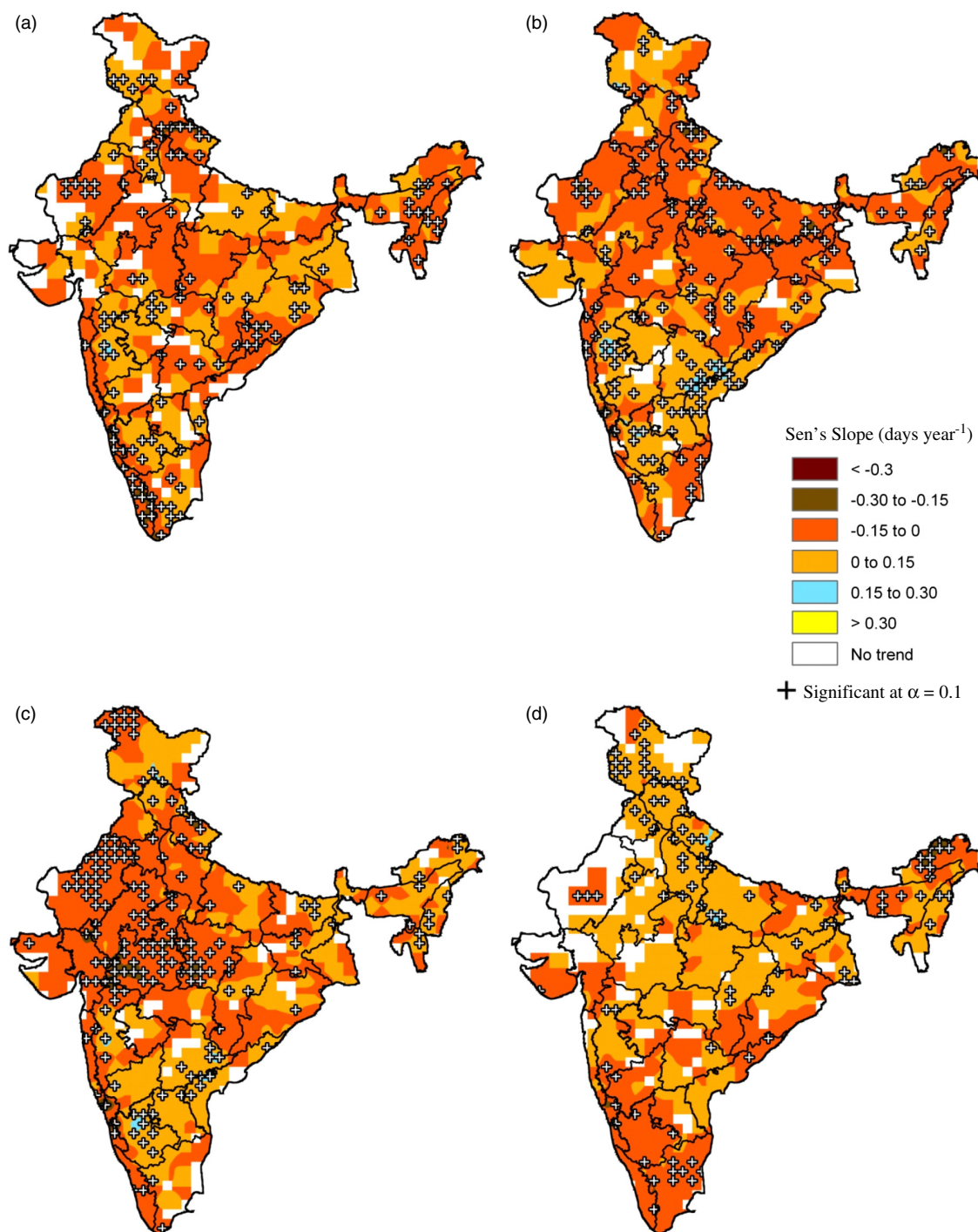


Figure 3. Spatial pattern of median trend estimated by Sen's slope over the time series anomalies (1971–2005) of rainy days during (a) June, (b) July, (c) August, and (d) September; significant grid at $\alpha = 0.1$ are shown as '+'. This figure is available in colour online at wileyonlinelibrary.com/journal/met

Significant positive trends both in cases of monsoon rainfall and rainy days were found over Jammu and Kashmir, Coastal Andhra Pradesh and Rayalaseema. Significant negative trends both in cases of monsoon rainfall and rainy days were observed over Kerala, Coastal Karnataka, Jharkhand, east and west Rajasthan and Arunachal Pradesh. Though Himachal Pradesh and Uttarakhand showed a significantly positive trend in monsoon rainfall, monsoon rainy days had a significant decreasing trend. Monsoon rainfall was found to have a significantly decreasing trend over SHWB and an increasing trend over

Marathwada, without any significant trend of rainy days. On the other hand, with no significant trend of the monsoon rainfall, monsoon rainy days was found to have an increasing trend over Madhya Maharashtra and decreasing trend over Haryana, West Uttar Pradesh, west and east Madhya Pradesh, Orissa, Konkan and Goa, and Tamil Nadu.

The results obtained in the present study, have corroboration with the observations found by Ghosh *et al.* (2009), where a significant decreasing trend in the mean annual summer monsoon rainfall was observed on the western coast and in the

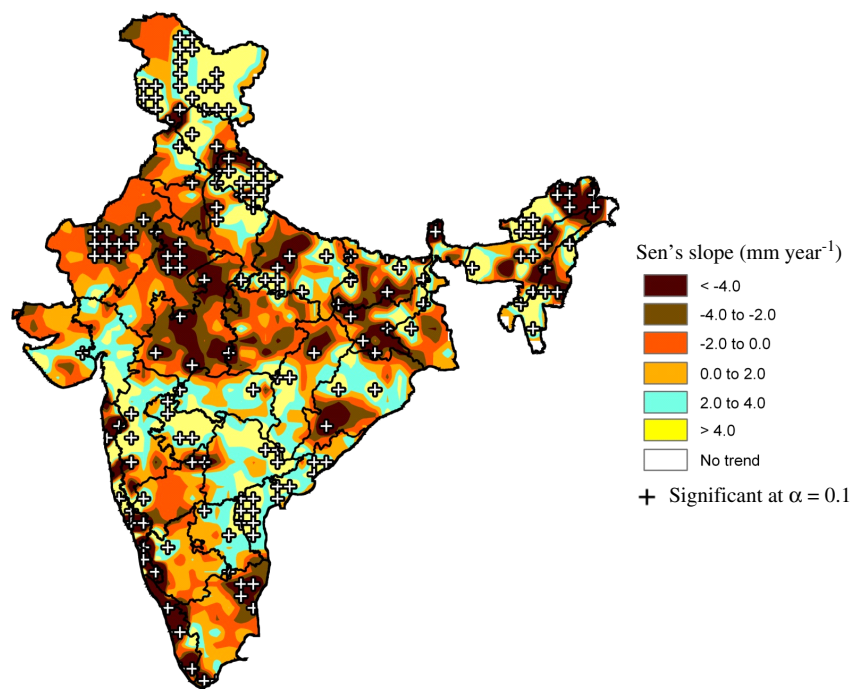


Figure 4. Spatial pattern of median trend estimated by Sen's slope over the time series anomalies (1971–2005) of monsoon rainfall; significant grid at $\alpha = 0.1$ are shown as '+'. This figure is available in colour online at wileyonlinelibrary.com/journal/met

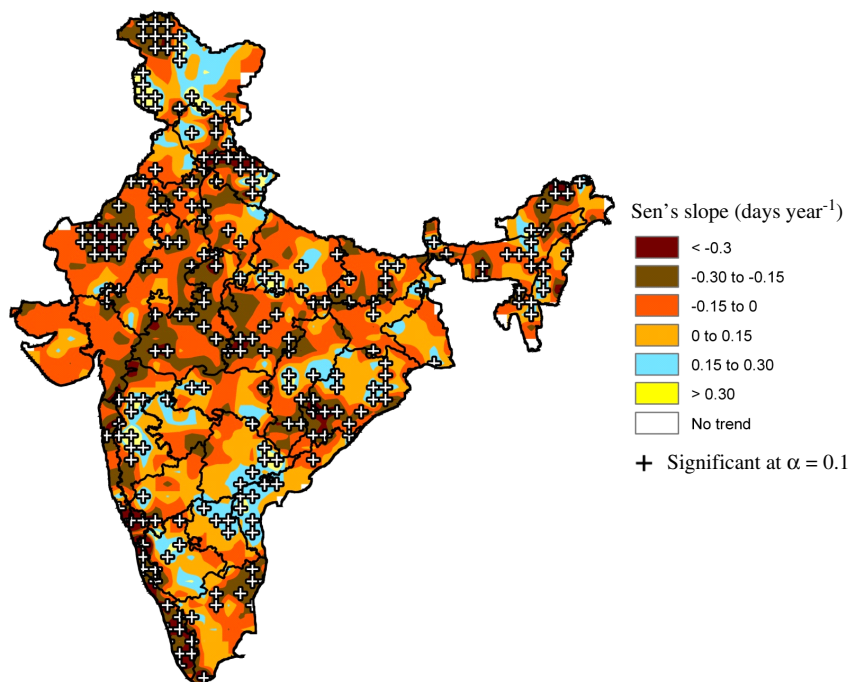


Figure 5. Spatial pattern of median trend estimated by Sen's slope over the time series anomalies (1971–2005) of monsoon rainy days; significant grid at $\alpha = 0.1$ are shown as '+'. This figure is available in colour online at wileyonlinelibrary.com/journal/met

central Indian region. Further, a similar kind of response was also recorded by Rajendran and Kitoh (2008) using a super high-resolution global circulation model for Indian summer monsoon rainfall, with significant decrease in rainfall over the west coast of India (Kerala, Karnataka) and northeastern part of India. The influence of the regional and local factors over the observed trends of rainfall and rainy days is outside the scope of the present study. Although recent studies demonstrated that increase of greenhouse gases (GHGs) leading to global warming affects the ISM rainfall pattern. Global warming causes a

higher moisture content over the warmer troposphere region or intensification of moisture transport into the region leading to increased rainfall over the Indian subcontinent at a larger scale (Kitoh *et al.*, 1997; May, 2002; Meehl *et al.*, 2003). Conversely, Goswami and Patra (2004) reported significant differences between warming trends over the ocean basins and the Indian land mass. This may result in a reduced land-ocean temperature contrast and weakening of the strength of organized convergence over India. Thus, even if the average trend in surface temperature over the Indian ocean is positive,

the spatial distribution of trends does not encourage spatially coherent warm sea surface temperature (SST) or the organized dynamics necessary for the monsoon. The ISM rainfall over the west coast and northeastern hilly region is dominantly affected by orography. Drastic reduction of the westerly wind, local moisture convergence at 850 hPa and increased northerly and easterly components in moisture transport along the steep mountains dominate over the increased moisture effect in reducing local rainfall (Rajendran and Kitoh, 2008). Despite the effect of global warming, ISM rainfall is substantially affected by local changes, such as rapid urbanization, industrialization and deforestation (Ghosh *et al.*, 2009).

4. Summary and conclusions

In the present study, the trends of time series anomalies of rainfall and rainy days over the monsoon months and season were estimated using daily gridded rainfall data for the last 35 years (1971–2005). The statistically significant trends at a spatially distributed level were calculated using non-parametric Mann–Kendall statistics and Sen's method and were further assessed over the meteorological subdivision level using a field significance test. The spatial patterns of trend of rainfall and rainy days were analysed and conclusions derived from the present study are summarized as follows.

1. The southern region of the Indian peninsula, covering the Deccan Plateau and east coast, showed positive trends of rainfall and rainy days. Statistically significant increasing trends of both rainy days and rainfall during the monsoon season were found in coastal Andhra Pradesh and Rayalaseema. Maximum contributions of this increasing trend were found during the July and August. Marathwada, south interior Karnataka, Telangana, Madhya Maharashtra covering almost the whole Deccan Plateau showed a significant increasing trend either in rainfall or rainy days in the initial part of the monsoon season (June and July).
2. Three distinct regions of the Indian subcontinent showed significant negative trends both in case of rainfall and rainy days during the monsoon season. These were the west coast (Kerala, coastal Karnataka), the eastern part (Jharkhand, Arunachal Pradesh) and western desert region (east and west Rajasthan). A decreasing trend of rainfall amount and its poor distribution may lead to higher probability of drought and lower prospect of ground water, particularly in the western arid region.
3. A significant decrease in rainfall either in monsoon months or season was observed in the northeastern region of India covering Sub-Himalayan West Bengal, Assam, and Nagaland–Manipur–Mizoram–Tripura.
4. A significant negative trend of rainy days either over the monsoon months or season was observed in the north and central region of India covering Punjab, Haryana, west and east Uttar Pradesh, west and east Madhya Pradesh, Gujarat, and Orissa. These north and central plains cover a significant portion of the potential agricultural land over the Indian region. A decreasing trend of rainy days over these regions might have negative impacts on agricultural production and soil water management.
5. There has been a statistically significant increasing trend of rainfall with decreasing trend of rainy days over the monsoon season in Uttarakhand and Himachal Pradesh. A similar situation was also found in Jammu and Kashmir for

August. Thus, there would be a higher probability of high intensity rainfall and flash floods over these regions.

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