Increase in spatial spread of extreme warm day temperature events: regional to national perspective for India (1951–2014)

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This study analysed gridded temperature dataset for last six decades over India and its different agro-climatic zones to determine the changes in land area affected by extreme warm day temperatures. The results indicated an unequivocal increase in the area influenced by different levels of extreme warm days over the country; the rate was significantly higher during the last three decades. The increase in land area affected by extreme-of-extreme temperature events occurred at a higher rate compared to the low-frequency extremes. Statistical tests indicated clear change in the probability distribution of the land area affected by extremes, signifying that comparatively high-frequency extremes are occurring over larger areas. The results showed regional dissimilarity, with five agro-climatic zones (ACZ-02, 09, 10, 11, 12) showing increase in land area under most levels of extremes, and three agro-climate zones (ACZ-08, 13, 14) showing increase in land area for a few extreme levels.

Keywords: Climate change, extreme temperature, warm days, land area, trend analysis.

OF late, climatic extremes have acquired the central point of climate change and variability discussions due to the unabated increase in different weather variables. It is the climatic extremes which make us feel the impact of climate change very strongly[1]. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change[2], the global average temperature, combined over both land and ocean, has increased by 0.85°C during 1880–2012, with the last 30 years being the warmest in the recent history of the earth (i.e. last 1400 years). But the associated changes in the extremes like frequency, intensity and duration of droughts, cyclones, high-intensity precipitation, cold days and cold nights, warm days and warm nights, etc. were much more intense during the past decade. Though these phenomena are common to almost all parts of the globe, but its nature, extent and intensity generally follow high spatio-temporal variations.

Since the last decade or so, researchers all over the globe have increasingly focused on extremes. As a result, now we have a broad-scale picture of the extremes of temperature and precipitation over the globe[3,4] as well as for several regions such as Asia[1], and even to the scale of specific countries like China[5]. There are only a few studies available in India, on the trends of extremes in rainfall and temperature. Rao et al.[6] used daily temperature (maximum and minimum) data from 103 well-distributed weather stations over India to determine the trend in extreme temperature during 1971–2000. They analysed the station data for two periods, March–May and November–January, and the results were presented for four broad zones of the country. Though this study could provide some early information about the extremes over different parts of India, the definition of extreme was mostly empirical. Kothawale et al.[7] defined the extreme values based on percentiles and studied changes in temperature extremes in India using 121 different meteorological stations for the period 1970–2005. But unlike the previous case of dividing the country empirically, they analysed the results based on seven temperature homogeneous regions of India, and restricted the study to only pre-monsoon season. Dash and Mamgain[8] adopted the most widely accepted methodology for the analysis of extremes given by Expert Team on Climate Change Detection and Indices (ETCCDI), while analysing the high-resolution daily temperature data (1° × 1°) of India Meteorological Department (IMD) for the period 1969–2005. They had accounted for the whole year and analysed the extremes based on specific definition of seasons using the threshold approach over the entire country and its seven temperature homogeneous regions. Panda et al.[9] determined the trends of extreme temperatures and their related indices in each grid to understand spatial variability in the extremes.

All these studies dealt with the trend of the extremes per se, but not their spatial spread over India. It is important to study the trends in extreme events but it is equally pressing, if not more, to understand the temporal change in the spatial extent covered by the extremes over the country as a whole and also at different sub-country
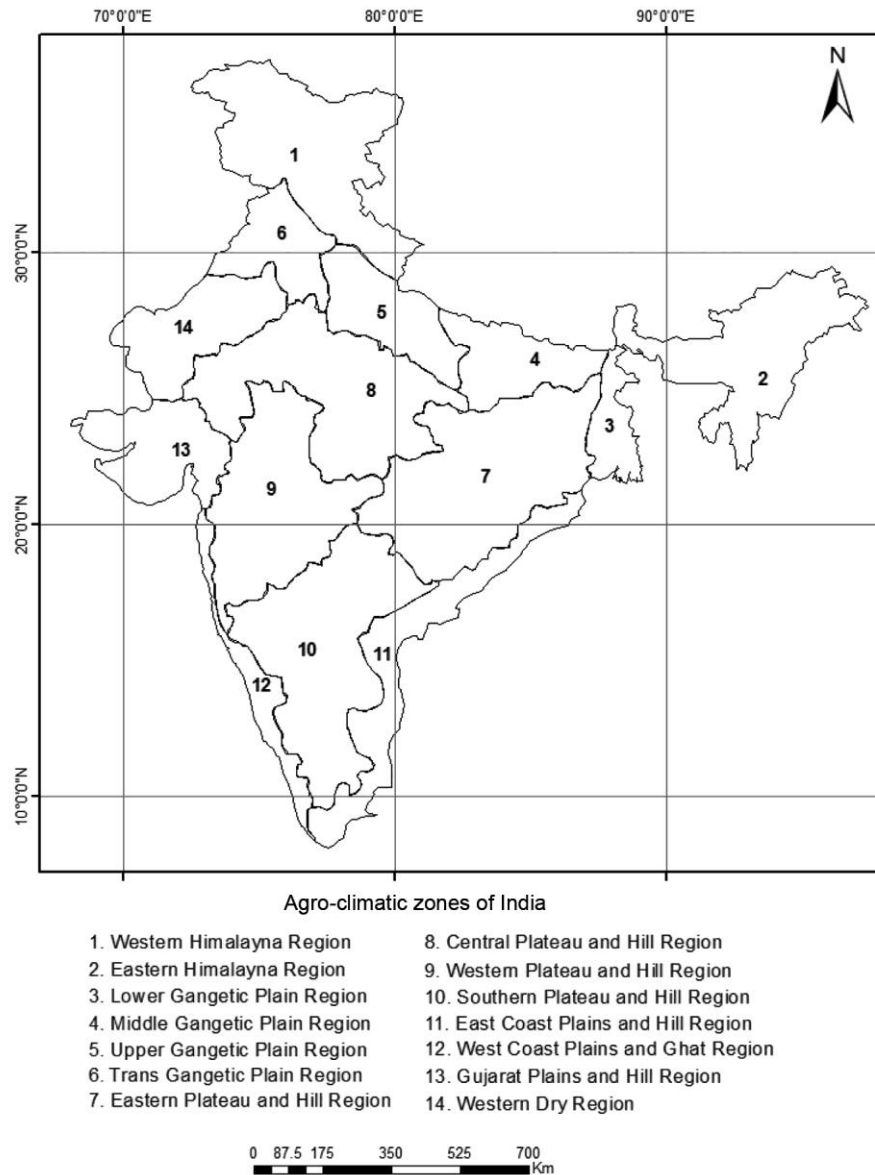
Figure 1. Agro-climatic zones of mainland India.

spatial scales. Apart from that, all these researchers analysed data up to the year 2005, while most extremes are more recent events[10]. Hence, the present study aimed to analyse the temporal variation in spatial spread of different levels of extremes over the country as a whole using data up to 2014. The study used observations only to define grid-specific extreme warm day temperature using percentile criterion, instead of using any specific empirical temperature thresholds to define extreme values. We further extended the analysis to sub-county level (i.e. agro-climatic zones) to understand the regional perspective. The study evaluated the temporal trend in day temperature extremes along with the temporal changes in spatial spread over the country, which can provide crucial information about the extent of extremes and help in devising adaptation and mitigation actions.

Materials and method

Study region

The entire Indian mainland region ($8°04′–37°06′$N and $68°07′–97°25′$E) was included in the study. The impact of climate change and variability spreads across almost all the sectors of the economy directly or indirectly, but agriculture is projected to be directly affected by it. Considering its impact on the sector, the analysis was carried out at the scale of agro-climatic zones of India (ACZs), as they represent major climate which are suitable for a certain range of crops[11]. Our analysis was restricted to 14 out of the 15 ACZs which fall in mainland India (Figure 1).

Data and its processing

The high-resolution daily gridded temperature data ($1° \times 1°$) developed by IMD were used for analysis[12]. This dataset was developed through modified Shepard's angular distance weighting algorithm interpolation of 395 quality-controlled stations' maximum (day) and minimum (night) temperatures. The dataset accuracy has been validated and it has been widely used since its release in 2009 (refs 12, 13). The dataset used in this study spans over six decades (1951–2014).

In the present study we have analysed the trend in the area affected by extreme warm day temperature. The time series of daily maximum (daytime) temperature for each gird covering the Indian mainland was analysed. As described by ETCCDI[14], extreme warm days (ExWDs) were those with values above the 90th percentile over a reference period (1961–92) for a particular day and location/grid[14–16]. The ExWDs were then aggregated from daily to the annual scale. To determine the spatial spread of ExWDs over the country as well as over the ACZs, we have estimated the land area/pixels affected by different levels of extreme warm days per year. Analysis of area affected by at least 10 extreme warm days per year – designated as exceedance (ExD) 10 or ExD10 – to as high as 100 ExWD per year was carried out[16]. Totally six different ExD levels corresponding to 10, 30, 50, 60, 80 and 100 days of extreme per year were estimated in this study. To compare the area affected by different levels of extremes, instead of the absolute value of area per se, land area ratio (LAR), i.e. the proportion of area covered under specific exceedance level compared to its mean area, was used for analysis[16]. LAR value of 2 and 4 for a particular exceedance level can be interpreted as the doubling and quadrupling of land area at that level compared to its mean.

Statistical analysis

The time-series of LAR affected by several ExDs were subjected to trend at ACZs and national scales. Several statistical tests are available for the identification and quantification of monotonic trends, which are mainly grouped into parametric and non-parametric tests. We have employed the Mann–Kendall (MK) test of non-parametric type and ordinary least square (OLS) linear regression slope as a parametric test for detection of the trend. Trend always indicates a continuous change, but in reality, many a times the change starts from a particular time-span, which these tests fail to determine. Hence, change point or break point tests which can provide better perspective in this regard, were also carried out.

Trend analysis

Mann–Kendall test: According to this test, assumption of the null hypothesis H_0 is of having no trend, i.e. all data points are independent and random, which is tested against the alternative hypothesis H_1, assuming presence of trend. Here, each value in the series is compared to others in a sequential manner. The following is the expression of the MK test statistic[17]

$$S = \sum_{i=1}^{n} \sum_{j=1}^{i-1} \text{sgn}(x_i - x_j), \quad (1)$$

where n denotes the total number of elements of the data, x_i and x_j are two sequential values of the data and function $\text{sgn}(x_i - x_j)$ is as expressed as

$$\text{sgn}(x_i - x_j) = \begin{bmatrix} 1, & (x_i - x_j) > 0 \\ 0, & (x_i - x_j) = 0 \\ -1, & (x_i - x_j) < 0 \end{bmatrix}. \quad (2)$$

The MK-test statistic (S) follows an asymptotically normal distribution with mean E as zero and variance Var computed as[18]

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

$$\text{Var}(S) = \frac{1}{n}\left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right], \quad (4)$$

where t denotes the extent of any given tie and $\sum t$ denotes the summation over all tie number of values[19]. The standardized statistics Z of the MK-test is computed as

$$Z = \begin{bmatrix} \dfrac{S+1}{\sqrt{\text{Var}(S)}}, & \text{if} \quad S > 0 \\ 0, & \text{if} \quad S = 0 \\ -1, & \text{if} \quad S < 0 \end{bmatrix}. \quad (5)$$

Positive value of standardized statistic Z indicates an increasing or upward trend, while negative value indicates a decreasing or downward trend in series. To ascertain the test significance, comparison of computed absolute value of Z with the standard normal cumulative value of $Z(1 - p/2)$ at $p\%$ significance level obtained from standard table was done for accepting or rejecting the null hypothesis.

Change point test: Pettitt test is another non-parametric rank test[20]. The ranks $r_1, ..., r_n$ of the series $Y_1, ..., Y_n$ are used for calculation of the statistics[21]

$$X_k = 2\sum_{i=1}^{k} r_i - k(n+1) \quad k = 1,...,n. \quad (6)$$

Table 1. Trend (Mann–Kendall) in proportion of area above the corresponding exceedance days in a year over the zones for the two periods

Country/ ACZ	ExD10		ExD30		ExD50		ExD60		ExD80		ExD100	
	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II
India	**1.88***	**2.18**	1.43	**3.05***	0.18	**4.11***	0.72	**4.15***	–0.46	**3.5***	1.36	**3.35***
ACZ-01	0.45	1.87*	–1.18	1.67*	–2.22**	0.94	–2.35**	0.59	–2.26**	0	0	–1.19
ACZ-02	1.26	**1.9***	0.03	**3.86***	–0.26	**4.05***	0.47	**3.71***	0	**3.73***	0	**2.97***
ACZ-03	1.76*	–0.04	1.42	0.82	0.24	1.54	1.3	1.36	1.3	0	0	–1.19
ACZ-04	0.1	0.85	0.02	**2.02**	0.05	0.46	1.08	1.08	0.9	0	0	–1.19
ACZ-05	–0.7	0.86	–0.02	0.96	–0.16	0.88	–0.1	–0.31	0	–1.19	0	–1.19
ACZ-06	0.15	1.23	–0.67	**2.01**	0	0.7	–1.62*	0	–1.62*	–1.19	0	–1.19
ACZ-07	**3.16***	**1.96**	**2.26**	**2.49***	**2.17**	**2.31**	1.25	1.38	0.9	1.52	0	1.08
ACZ-08	0.03	0.5	0.52	1.09	–0.03	0.94	0.87	1.03	1.3	–0.54	0	–1.19
ACZ-09	1.15	0.85	0.59	**2.47***	–0.56	**3.04***	0.7	**2.99***	0.54	**1.73***	0.54	**1.68***
ACZ-10	**3.08***	0.77	**2.15**	**3.37***	**2.39**	**2.68***	0.68	**2.63***	0	1.4	0	0.52
ACZ-11	**3.2***	1.37	**2.62***	**3.19***	**3.13***	**2.48***	1.32	**1.98**	0	**2.75***	0	1.37
ACZ-12	**2.92***	0	**2.44***	**2.55***	0.62	**3.03***	0	**3.28***	0	**2.77***	0	**1.69***
ACZ-13	–1.38	1.45	–0.12	1.45	0.34	0.83	0.68	0.88	0	–0.26	0	–1.19
ACZ-14	0.51	1.34	0.91	0.56	–0.16	0.6	–0.93	0.16	0	–1.19	0	–1.19

***, ** and * denote trends at 1%, 5% and 10% significance level respectively. Values indicate Mann–Kendall's Z statistics.

According to the test, if the time series breaks in year *E*, then the value of the statistic is maximal or minimal near the year *k* = *E*. Critical values of X_E are calculated after Pettitt[20].

$$X_E = \max |X_k|, \quad \text{for } 1 \le k \le n. \qquad (7)$$

Comparison of time series of ExD between two periods

In order to compare the changes occurring in extremes over the time-period, we divided the total period into two parts: PI (1951–1982) and PII (1983–2014). Accordingly, the trends of 'area affected by extreme warm days' were also analysed for the two periods for comparison. Along with the trends and change point, it is also important to determine the change in mean of the area affected by the specific exceedance levels for the two periods. It can provide a better understanding of the region which has faced a significant change in the mean area affected by the extremes over the last 30 years compared to that more than half a century ago. We used the Kruskal–Wallis rank test, a widely used non-parametric test for detecting change in the central tendency, for this analysis[22–24]. Further, the time series of PI and PII were compared through Kolmogorov–Smirnov test (KS test) to understand the change in the distribution properties of the two series[25].

All the analyses were carried out and figures were prepared using open-source R software and its IDE R-Studio[26,27].

Results and discussion

Trend in land area affected by extreme warm days

The time series of land area affected by different levels of exceedance of extreme warm days per year (ExD10, ExD30, ExD50, ExD60, ExD80 and ExD100), were subjected to two different trend tests. The results from both the tests, viz. MK test and linear regression (LM) test clearly indicate a sharp increasing trend of land area affected by ExWD over the country as a whole (Tables 1 and 2 respectively). For all the six levels of exceedance, starting from occurrences of 10 ExWD/year (ExD10) to even as high as 100 ExWD/year (ExD100), Figure 2 clearly show the increase over India. When comparing the trend for the two periods (PI and PII), the figure clearly indicates that the land area influenced by ExWD unequivocally increased during PII as compared to PI. Using gridded weather data, Seneviratne *et al.*[16] also found that the land area affected by different levels of temperature extremes had increased over the whole globe during 1997–2012. Trend analysis at the level of ACZs clearly shows the spatial differences in the trends of LAR at different levels of ExD (Tables 1 and 2). Among the 14 mainland ACZs, in six of them, namely ACZ-02, ACZ-07, ACZ-09 to ACZ-12, significant change in land area influenced by several frequencies of extreme warm days (ExD30, ExD50 and ExD60) was observed. All these zones have also witnessed a sharp increase in mean surface air temperature compared to the other parts of the country, as reported by Hingane *et al.*[28] using 1901–1982 data. Kothawale *et al.*[7] also reported higher rate of increase in the warm days over coastal and peninsular India during 1970–2005, while negative trend was found for the North East region. It is important to note that Kothawale *et al.*[7] analysed data only for pre-monsoon months, while our observations are based on analysis of data for whole years leading to different results. For other ACZs, the trend was either not significant or the responses were scattered, i.e. significant for some specific exceedance level and non-significant for most others.

If we analyse the results from a temporal perspective, it can be seen from Figure 2 that the increase in land area

Table 2. Trend (linear regression) in proportion of area above the corresponding exceedance days in a year over the zones for the two periods (slope per decade)

Country/ ACZ	ExD10		ExD30		ExD50		ExD60		ExD80		ExD100	
	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II
India	0.1*	0.1*	0.2	0.3***	0.1	0.8***	0.1	0.9***	0	1.3***	0	1.6***
ACZ-01	0	0.1	–0.2	0.3*	–0.6**	0.3	–1.2**	–0.2	–3.5**	0	0	–2.7
ACZ-02	0	0.1	0.1	0.5***	0.1	1.5***	0.2	1.8***	0	2.3***	0	2.6***
ACZ-03	0.1	0	0.3	0.3	0.7	0.3	1.5*	0.3	2.9	0	0	–2.7
ACZ-04	0	0	0	0.5**	0.2	1*	0.7	1	1.4	0	0	–2.7
ACZ-05	0	0	0	0.3	0.1	0.1	0.5	–0.2	0	–2.7	0	–2.7
ACZ-06	0	0.2*	–0.2	0.3	–0.6	0.2	–1.3*	–1	–1.2*	–1.8	0	–2.7
ACZ-07	0.2***	0	0.5***	0.4**	0.7**	1**	0.6*	1.2*	0.1	2.2*	0	2.5
ACZ-08	0	0.1	0.2	0.2	0.1	0.5	0.3	0.2	0.9	–0.1	0	–2.7
ACZ-09	0	0.1	0.2	0.4***	0.1	0.8**	0.2	0.8**	0.2	0.9	0.2	1.5
ACZ-10	0.2***	0	0.3**	0.3***	0.2	0.8***	0.1	0.8**	0	0.7	0	0
ACZ-11	0.2***	0	0.4***	0.3***	0.3***	0.8***	0.1	0.9**	0	1.3**	0	1.1
ACZ-12	0.2***	0	0.2**	0.3***	0	0.8***	0	1.2***	0	1.4***	0	1.2*
ACZ-13	–0.1	0.1	0	0.3	0.1	0.2	0	0.1	0	–1.8	0	–2.7
ACZ-14	0	0.1	0	0.1	0	0.3	0	0	0	–2.7	0	–2.7

***, ** and * denote trends at 1%, 5% and 10% significance level respectively. Values indicate slope per decade.

affected by ExD10, ExD30 and to some extent ExD50 started from PI, though it was only found to be statistically significant in ExD10 by both the tests (Tables 1 and 2). However, both the tests show statistically significant increasing trend in PII, which can be clearly seen in Figure 2 for all the exceedance levels. Similar results of increase in ExD10 during PI were found for the four ACZs, viz. ACZ-07, ACZ-10 to ACZ-12 (Tables 1 and 2). In these zones the increasing trend of ExD30 and ExD50 was also significant during PI, but their rates increased significantly during PII (Table 2). It is interesting to note that none of the zones showed a significant trend in ExD60 during PI, but five zones (ACZ-02, ACZ-09 to ACZ-12) showed highly significant trend in ExD60 during PII. Our results indicate that the area under extreme warm days has significantly increased in the North East region, western and southern plateau and both the coastal zones. These results are in conformity with those reported by Panda et al.[9], who showed that the number of warm days has been increasing in these regions, though they did not analyse the increase in area as was done in this study.

An important observation made in this study is that the rate of increase in land area affected by the 'extremes-of-extremes' such as ExD80 and ExD100 was even higher compared to the others, as confirmed by both the statistical tests (Tables 1 and 2 and Figure 2). Before the 1980s, only a small proportion of the land area experienced occurrences of over 80 days of extremes or more in a year, but after 2000, there has been hardly any year which has not faced such extremes in some part of the country. The land area affected by ExD80 has more than doubled its normal occurrence after 2000, steadily increasing since then and after 2010, it has nearly qua-

drupled. In the case of ExD100, even after 2000, there were years when no land area was influenced by it, but since 2010, there has been hardly any year which has not experienced such extreme temperatures in some part of the country. The rate of increase is quite alarming and is to the tune of more than four times its normal occurrences over the country. Seneviratne et al.[16] also found that the rate of change of area under the most extreme days was larger over the whole globe during 1997–2012. These findings are similar to those of ours over India, though Seneviratne et al.[16] had analysed data only for ExD10, ExD30 and ExD50. Dash and Mamgain[8] also reported an increase in the percentage of occurrences of most extreme warm days (99th percentile), with the highest rate of increase occurring during the decade of 1996–2005 compared to other levels of extreme. The sub-country level analysis showed such extreme occurrences were confined to some of the zones only. It was statistically significant for four ACZs (ACZ-02, ACZ-09, ACZ-11 and ACZ-12). It is interesting to note that among these four zones, the trend was not significant in any category of exceedance level for ACZ-02 and ACZ-09 during PI. But during PII, in almost all categories, it was statistically significant. These observations indicate that the North Eastern region, western plateau and hills and both the coastal plains are witnessing sharp increasing trend in the area of the extremes, followed by the eastern plateau and hills. Our results are in line with the findings of Dash and Mamgain[8] for both the coastal regions, but differ for the North East region and the western plateau. While other zones might also be experiencing extreme temperatures, the trend remains statistically non-significant. In some zones a negative trend was also found, but it was mostly non-significant.
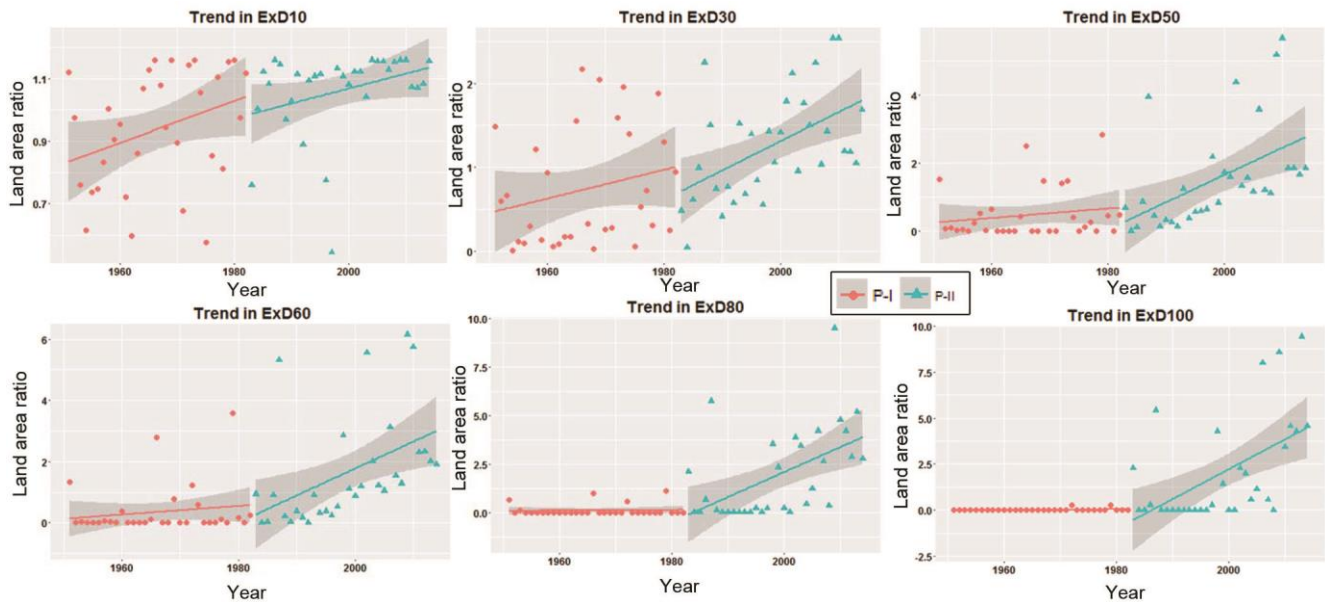
Figure 2. Trend in the land area ratio affected by different levels of occurrence in the exceedance of extreme warm days over India during the two periods (PI: 1951–1892; PII: 1983–2014).
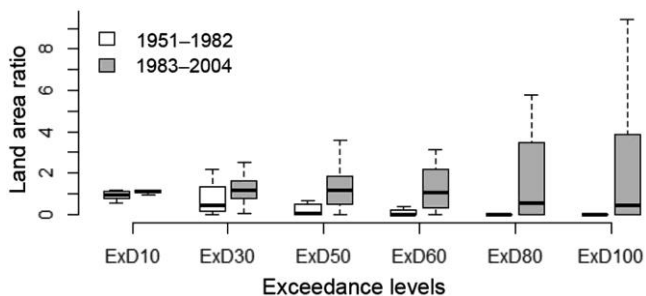
Figure 3. Comparison of exceedance levels in ExWD over India between the two periods (PI: 1951–1982; PII: 1983–2014).

Comparison of time series of land area affected by extreme warm days

Figure 3 gives a broad view of the variation in extreme warm days over India between the two periods PI and PII. To compare the land area influenced by different levels of exceedance of ExWDs, they were first subjected to normality tests, as extreme values hardly follow normal distribution. The Anderson–Darling and Shapiro–Francia test results confirmed that the data were non-normal (Supplementary Tables 1 and 2). Hence non-parametric Kruskal–Wallis rank test, that is widely used for detecting change in the central tendency, was employed for analysis. The results showed that, over India, for all the exceedance levels, the average area during PII was significantly ($P < 0.01$) higher compared to P-I (Table 3). The case was almost similar for the five ACZs (ACZ-02, ACZ-09 to ACZ-12). The analysis also revealed that three other zones (ACZ-08, ACZ-13 and ACZ-14) also

faced significant changes in average land area influenced by different levels of ExDs. None of the three zones had a statistically significant trend for ExD80 and ExD100. The results indicate that though there was no trend in these zones, the average area affected by extremes had increased significantly during PII compared to PI. The result of this test reaffirms that the North East region, western and southern plateau and both the coastal plains have experienced significant increase in area of all levels of extremes, while the central plateau, Gujarat plains and dry western region have witnessed moderate increase in some levels of extremes. In the rest of the country, the trends were not statistically significant.

While comparing the land area affected by extremes over the two periods along with the changes in mean, it also becomes important to test the probability distribution of the time-series as a whole in order to determine its change over time, if any. In this case, the two-sample KS test, one of the most useful and general non-parametric methods for comparing two samples, was employed as it is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples. The results of the test confirmed that the probability distribution of land area affected by all levels of extremes has significantly changed over India (Supplementary Table 3). This shows that not only the location which indicates the central tendency has changed, but the shape of the distribution has changed as well. Shape can be linked with the type of frequency distribution of the parameter, which in this case is land area over the region. Figure 4 clearly shows that the frequency distribution of land area affected by extremes has changed

Table 3. Kruskal–Wallis rank sum test statistic for comparison of proportion of area above the corresponding exceedance days in a year between the two periods (PI: 1951–82; PII: 1983–2014)

Country/ACZ	ExD10	ExD30	ExD50	ExD60	ExD80	ExD100
India	6.7***	9.33***	17.65***	21.76***	20.11***	19.77***
ACZ-01	2.78*	0.81	0	0.45	2.03	1
ACZ-02	3.18*	4.84**	9.35***	12.55***	11.56***	6.5***
ACZ-03	0.26	0.3	0	0.14	1	1
ACZ-04	0	0.35	0.3	0	2.03	1
ACZ-05	1.69	0.3	0.09	0.24	1	1
ACZ-06	0.73	0.05	0.69	3.69**	0	1
ACZ-07	3.33*	3.33*	0.4	0.83	0.3	1
ACZ-08	3.18*	3.98**	2.96*	3.33*	0.34	1
ACZ-09	2.91*	9.24***	7.51***	9.47***	8.25***	2
ACZ-10	30.97***	33.18***	31.37***	29.3***	17.29***	11.57***
ACZ-11	28.43***	23***	21.11***	21.91***	17.29***	8.95***
ACZ-12	31.19***	38.95***	34.82***	33.16***	20.45***	11.56***
ACZ-13	1.28	4.14**	1.68	3.74**	1.02	1
ACZ-14	3.08*	4.91**	7.31***	3.4*	1	1

***, ** and * denote trends at 1%, 5% and 10% significance level respectively.
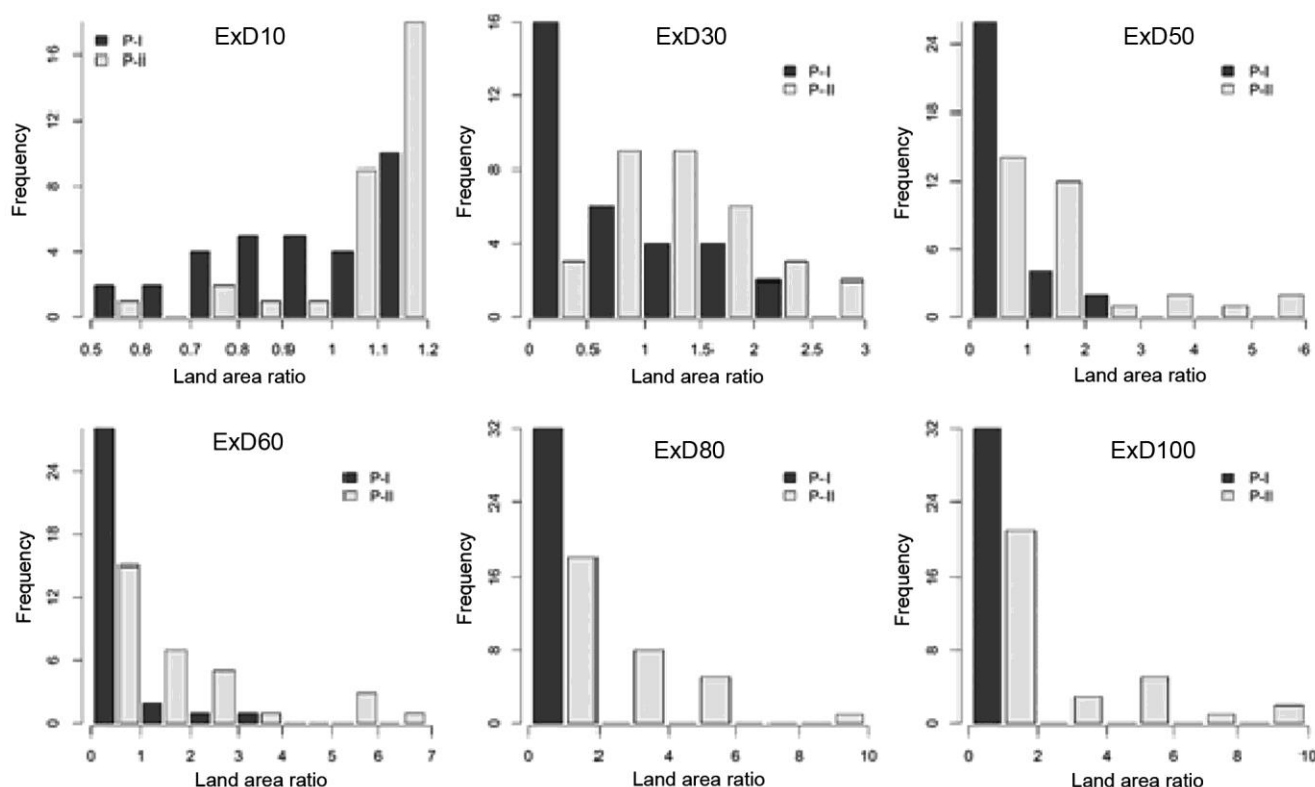
Figure 4. Frequency distribution of different exceedance levels in ExWD over India between the two periods (PI: 1951–1982; PII: 1983–2014).

significantly from PI to PII. It implies that during PII, the frequency of extremes has increased drastically.

Change point analysis of land area affected by extreme warm days

Change point analysis tests can help in determining the point of change or break in the time series and Pettit test

is one of the widely used methods among them. The test can estimate change points in the time series of land area affected by all levels of exceedance (Table 4). Over India, it can be clearly seen that the change points for different levels of ExDs followed a specific temporal trend; the less extremes like ExD10 occurred much earlier than the others. ExD10 occurred during 1978, followed by ExD30 in 1985, ExD50 and ExD60 during 1992 and

Table 4. Change point analysis of proportion of area above the corresponding exceedance days in a year over the zones for the period 1951–2014

Country/ ACZ	ExD10		ExD30		ExD50		ExD60		ExD80		ExD100	
	Stat	Year	Stat	Year	Stat	Year	Stat	Year	Stat	Year	Stat	Year
India	480**	1978	558***	1985	697***	1992	727***	1992	688***	1996	635***	1996
ACZ-01	240	NO	288	NO	206	NO	146	NO	122	NO	36	NO
ACZ-02	315	NO	580***	1993	622***	1993	546***	1993	470**	1997	288	NO
ACZ-03	165	NO	244	NO	173	NO	147	NO	35	NO	36	NO
ACZ-04	191	NO	309	NO	107	NO	125	NO	70	NO	36	NO
ACZ-05	223	NO	142	NO	119	NO	73	NO	36	NO	36	NO
ACZ-06	133	NO	248	NO	158	NO	183	NO	61	NO	36	NO
ACZ-07	564***	1964	466**	1971	355	NO	252	NO	123	NO	58	NO
ACZ-08	349	NO	398*	1985	259	NO	240	NO	84	NO	36	NO
ACZ-09	347	NO	557***	1985	600***	1995	635***	1996	381*	1997	193	NO
ACZ-10	814***	1979	868***	1981	804***	1981	737***	1982	448**	1982	320	NO
ACZ-11	784***	1978	752***	1978	674***	1978	606***	1982	521***	1997	256	NO
ACZ-12	748***	1978	935***	1984	834***	1984	756***	1985	575***	1997	342	NO
ACZ-13	231	NO	449**	1992	229	NO	244	NO	79	NO	36	NO
ACZ-14	312	NO	389*	1984	359	NO	202	NO	36	NO	36	NO

***, ** and * denote trends at 1%, 5% and 10% significance level respectively. Values indicate Pettit's test statistics (Stat) and the year of change (Year) in the time series if the test was significant.

the ExD80 and ExD100 during 1996. These results clearly show that the land area with different levels of extremes has increased temporally and most extremes are recent. Similar to the results of the previous tests, in this case also five ACZs (ACZ-02, ACZ-09 to ACZ-12) showed most number of significant changes, though there were temporal differences among these zones. Except ACZ-02 (north east region), where the shifts had taken place in the 1990s, in all other cases the changes started from late 1970s for different levels of exceedance. But in all the cases, the shift in time series of land area affected by less extremes occurred earlier than that of the higher extremes. A few other zones showed some scattered responses. But none of these five zones showed statistically significant change over period for the most extreme ExD100.

Conclusion

Several studies in India have reported a trend in the extreme temperature per se, but the present study is unique in that it analyses the trend in 'the land area affected by extremes' over the country as a whole and at the scale of sub-country ACZs. It used information stored in the high-resolution, quality-checked and widely used temperature dataset of IMD spanning over six decades to understand the spatio-temporal variation in the extreme temperature using robust statistical tests. The study clearly shows a sharp increase in land area affected by different levels of extreme warm days during 1983–2014 compared to 1951–1982, at the country level. Further, it concludes that the rate of increase in land area affected by the 'extremes of extremes' such as ExD80 and ExD100 is even higher compared to the other lower frequency

extremes. This increase in land area under extremes is unevenly distributed across the climatic zones as shown by the sub-country level analysis. Among the 14 ACZs, five zones covering North East India, western and southern plateau and hills along with both the coastal plains (eastern and western) have witnessed sharp increasing trend in land area experiencing the extremes. Besides these five zones, the central plateau, Gujarat plains and western dry region have also witnessed a significant change in mean area affected by extremes, though the trend was non-significant in these zones. It is a concern to note that the probability distribution of land area affected by all levels of extremes has significantly changed over the country, in terms of increase in both mean and variance. The shift in the change of land area witnessing extreme warm days also showed a distinct temporal trend, the low-frequency extremes (ExD10, ExD30, ExD60) occurring earlier and high-frequency extremes (ExD80, ExD100) occurring in recent times.

All these observations indicate that the spread of extreme warm day temperature has unequivocally risen over the country with regional variations. Extreme warm days have many direct impacts on the ecosystem as a whole and over human lives in particular. Agricultural crops, which are always exposed to the vagaries of weather and climate, are likely to be one of the worst hit by the change in extremes. Extreme day temperatures will not only influence the water demand, transpiration rate, respiration and photosynthesis of plants, but may cause serious harm if they coincide with the critical reproductive stage of the crops. It may either influence the viability of pollen of the crops, or the crucial grain-filling or translocation of the photosynthates to the storage organs, which remains the prime focus for economic productivity. This study

needs to be extended to determine the relationship between the changes in the extremes with those in growth and yield of different crops over various zones of India. What is worrisome is that most climate change adaptation policies are focused towards managing impacts of increasing trends in temperature in the future, but not strategizing for managing the extremes which are spreading at a higher rate across the landmass of the country, and are a reality now.

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