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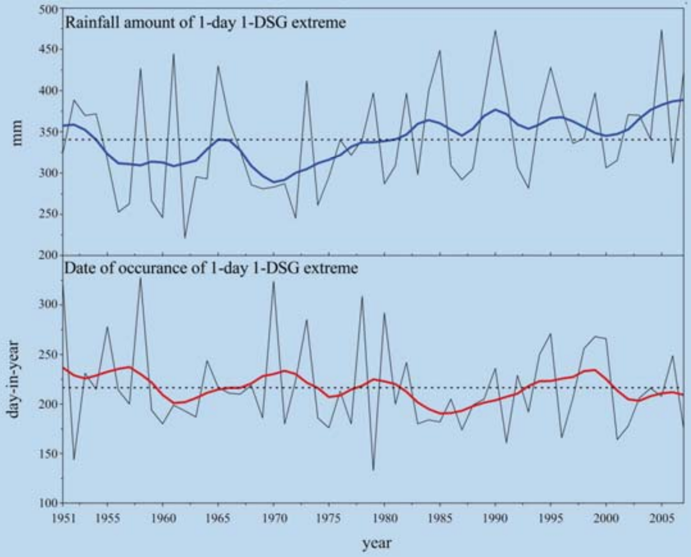

Trend in 1-day 1-DSG Spatio-temporal extreme rainfall over India: 1951-2007

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July 2010

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CONTENTS

List of Acronyms and Abbreviations

AE	Areal Extent
AOGCM	Atmosphere-Ocean General Circulation Model
CC	Correlation Coefficient
CME	Central Middle East
DMMR	Daily Mean Monsoon Rainfall
DSG	Degree Square grid
ERE	Extreme Rain Event
ERE-RI	Extreme Rain Event concerning Rainfall Intensity
ERE-AE	Extreme Rain Event concerning Areal Extent
ERE-RW	Extreme Rain Event concerning Rainwater
GARACII	General and Regional Atmospheric Circulation Intensity Index
IMD	India Meteorological Department
IMMC	Indonesia-Malaysia Maritime Continent
IPCC	Intergovernmental Panel for Climate Change
ITCZ	Inter-Tropical Convergence Zone
LLJ	Low Level Jet
LSWS	Llarge Scale Wet Spell
LSDS	Large Scale Dry Spell
MCICP	Myanmar-Central Indo-China peninsula
MCC	Multiple Correaltion Coeffcient
MLR	Multi-Linear Regression
MMWS	Main Monsoon Wet Spell
MSLP	Mean Sea Level Pressure
MTC	Mid-Tropospheric Cyclone
NWP	Numerical Weather Prediction
OLR	Outgoing Long-wave Radiation
PAI	Percentage Area of India
PPW	Precipitable water
RI	Rainfall Intensity
SA	South Asia
SC	Somali Coast
SD	Standard Deviation
ST-ERE-RI	Spatiotemporal Extreme Rain Event concerning rainfall Intensity
ST-ERE-AE	Spatiotemporal Extreme Rain Event concerning Areal Extent
ST-ERE-RW	Spatiotemporal Extreme Rain Event concerning Rainwater
TCC	Total Cloud Cover
THIKHIHILs	Tibet-Himalaya-Karakoram-Hindukush Highlands
WD	Wet day

Large-Scale Wet Spell and Spatio-Temporal Rainfall Extremes over India during 1951-2007

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ABSTRACT

Identification of large-scale wet and dry spells indicates occurrence of a main monsoon wet spell (MMWS) during 18 June and 16 September (91 days) during which rainfall occurs over 26.3PAI (Percent Area of India) with intensity 26.3 mm per day. The MMWS starts after the arrival of the warm moist monsoon wind system over the southern India peninsula. Two large-scale wet and two dry spells occur prior to the MMWS (during 3 June through 17 April) and three wet and three dry spells after (during 17 September through 15 November). During extreme rainfall events (EREs), the rainfall intensity could be 43.2 mm/day and areal extent of the wet condition 49.8PAI. For the extreme and the spatio-temporal EREs, the cumulative rainfall intensity of 1- to 25-day increases non-linearly with the duration. Investigation reveals that occurrence of unprecedented rainfall on 26-27 July 2005 over Mumbai Metropolitan City (Maharashtra State) is a realization of highly significant increasing trend in the spatio-temporal 1-DSG (degree square grid) extreme rainfall over the country. Among 13 selected general and regional circulation parameters, the U_{SURF} over central Arabian Sea has been found most important in affecting the daily rainfall over the country, and the others in decreasing order of influence are as: Korea-Japan-northwest North Pacific U_{TPAUS}, South Indian peninsula U_{TPAUS}, South Indian peninsula ($U_{SURF} - U_{TPAUS}$), Indo-Gangetic Plains Z200, central Bay of Bengal PW, Australia-South Pacific U_{TPAUS}, central Bay of Bengal V_{TPAUS}, Equatorial western Pacific U_{SURF}, THIKHIHILs (Tibet-Himalaya-Karakoram-Hindukush Highlands) upper troposphere thickness (Z200 – Z500), central Middle East lower troposphere thickness (Z500 – Z850), Indonesia-Malaysia maritime continent V_{SURF} and Myanmar-Indochina peninsula V_{SURF}. Simultaneous intensification of 3 to 4 circulation parameters produce essential atmospheric conditions for occurrence of large-scale, long period extreme rainfall event.

1. INTRODUCTION

Earlier the time series analyses of area-averaged extreme rainfall of 1- to 10-day durations over selected locations of India have been carried in order to understand if there was any change in the rainfall time distribution causing changes in the rainfall-runoff relationship though the annual total rainfall showed stationary fluctuation (Singh et al., 1988; Soman et al., 1988). In recent years, numerous studies have attempted to understand variability of extreme rainfall events (Durman et al., 2001; Kharin and Zwiers, 2000; Klein Tank et al., 2006; Zwiers and Kharin, 1998; and references therein) to investigate the hypothesis that '*hydrological cycle is supposed to be intensified under global climate change background*' (IPCC, 1996). The consensus among the current generation of coupled atmosphere-ocean general circulation models (AOGCMs) is that in warmer climate the intensity of the extreme high-rainfall would increase due to increased hydrological cycle resulting from warming at the surface and long wave cooling higher in the atmosphere (Senior et al., 2002). Hunt and Burgers (2002) have emphasized the important of studies on extreme precipitation variability in their philosophical commentaries. These initiated many regional studies on extreme precipitation/rainfall events in modern times.

Occurrence of rainfall gives rise to a pattern of wet and dry spells in the time domain. However, spatial and temporal variability of wet and dry spells is quite large. Keeping in view important of rainfall occurrences for practical purposes (agriculture, hydrology, ecology, water resources etc.), Singh and Ranade (2010) have carried out an elaborate fluctuation analysis of 40 parameters of the area-averaged actual and extreme wet and dry spells over the 19 subregions of India for the recent 57 years period (1951-2007). They found no spatially coherent significant long-term trend in any of the parameters. Nevertheless, the study provided some insight into rainfall variability in spatial domain, particularly of extreme events. The annual extreme rainfall event changes location from one year to another over the entire Indian region. The main motivation of this comprehensive study is to understand climatological and fluctuation features of the extreme rainfall events (EREs) considering detailed account of spatial variability of rainfall occurrences. Experiences suggest that the EREs are embedded in the large-scale, long period intense rainfall activities during the summer monsoon period. It may be noted that every year some parts of the country experience floods even during large-scale droughts (Tompkins, 2002). Thus the main objectives of the present study are:

1) To identify yearwise large-scale wet and dry spells (LSWSs and LSDSs) over India by applying objective criteria derived from space-time rainfall climatology;
2) To understand characteristics of extreme and spatio-temporal extreme rainfall events of sufficiently varying duration (1- to 25-day) over the country; and
3) To evaluate severity of the 26-27 July 2005 rainstorm over Mumbai Metropolitan City (Maharashtra State) in the backdrop of fluctuations of the spatio-temporal 1-DSG (degree square grid) extreme rainfall over the country.

2. DATA USED

The following two sets of data are utilized in the present study.

1. Daily rainfall of 1^o grid cells over India for the period 1951-2007 is provided by the India Metrological Department (IMD) (Rajeevan et. al., 2006); and
2. Daily meteorological data (MSLP, PW, TCC, OLR, and temperature, geopotential, U and V of standard isobaric levels within troposphere) for 2.5^o grid cells over the globe for the period 1951-2007 is obtained from the NCEP/NCAR website http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP NCAR/.CDAS 1/.DAILY (Kalnay et. al., 1996).

3. IDENTIFICATION OF LARGE-SCALE WET AND DRY SPELLS

A large-scale wet (dry) spell for the country has been defined as '*a continuous period with individual day more (less) than 10.4% area of the country under wet condition (actual daily rainfall over 1-DSG more than daily mean monsoon rainfall {DMMR} over the particular grid)'*. On an average, each day of the year, 10.4% area of the country is under wet condition. During non-monsoon period, much less percentage area country is under wet condition and during monsoon period much high. On daily basis, the 1-degree square grid (DSG) is identified under wet condition if actual rainfall exceeded the daily mean monsoon rainfall (DMMR) of the particular grid. The DMMR is the daily mean rainfall during normal monsoon period over the grid. The normal onset and withdrawal dates of the 19 subregions (Singh and Ranade, 2010) are assumed as normal onset and withdrawal dates respectively for the 1-DSG in the particular subregion. On the 1-DSG scale, the DMMR varies from less than 2mm/day in extreme northwest India to more than 24mm/day along central West Coast (Figure 1). On an average, 80 wet days (WDs) occur during the year over southern tip of peninsula due to tropical and oceanic influences, 75 WDs over extreme northeast India due to oceanic and orographic influences and 70 WDs over extreme northern India due to tropical-extratropical interactions and orographic effects. Over remaining parts, the WDs vary from 55 over southeast coastal areas to 15 over northwest dry province as the tropical and oceanic influences decrease and extra-tropical and continental influences increase (Figure 2). With the DMMR as the threshold, the smallest area of the country (2%) under wet condition occurs on 4 January and largest (32%) on 30 July, the average being 10.4%. The variation in the wet area with four chosen thresholds uniformly applied is as: 0.1mm/day, 4% on 5 January to 70% on 5 August (mean area 27.32%); 2.5mm/day, 1% on 5 January to 49% on 5 August (mean area 17.02%); 5.0mm/day, 1% on 5 January to 38% on 21 July (mean area 12.94%); and 10.0mm/day, 0.3% on 5 January to 27% on 30 July (mean area 8.44%). Therefore, 5 January is the driest day for India and the few wettest days occur during 21 July through 10 August. The daily histogram of the percentage area of the country under wet conditions according to the four chosen thresholds is shown in Figure 3. A brief description of actual daily wet area over the country is in order: a) during December through May the area under wet conditions is small and scattered across the country; b) during June through September the area under condition is large but well spread, weakly connected and distorted in shape; and c) during October through November the area under wet condition is medium, contiguous and mostly confined to peninsula as the ITCZ (Intertropical Convergence Zone) is located over the Arabian Sea-Indian peninsula-Bay of Bengal transect. The computational steps for identification of large-scale wet-dry spells are as follows:

1) For each day of the individual year, calculate percentage area of the country under wet condition;
2) Normalize the actual daily percentage area by dividing by the normal percentage area (10.4%);
3) Smooth out the normalized percentage area by applying the 5-point low-pass binomial filter;
4) Identify the large-scale wet spell (LSWS) if normalized, smoothed percentage area equal to or greater than 1.0, and large-scale dry (LSDS) otherwise; and
5) Yearwise sequence of the LSWS and LSDS over the country is shown in Figure 4 for the full period (1951-2007).

The most notable feature of Figure 4 is the occurrence of a long LSWS over the country each year. Examination reveals that this wet spell occurs during the summer monsoon period. This wet spell will be referred to as main monsoon wet spell (MMWS). Climatology of the important parameters of the MMWS (start, end, duration, rainfall intensity and areal extent) is given in Table 1. On an average, six wet spells (WSs) and five intervening (between two wet spells) dry spells (DSs) occur over the country each year. Two short WSs (each of duration ~6 days and rainfall intensity {RI} 23.7mm/day) and two long DSs (each of duration ~32 days and RI 0.3 mm/day) occur during 3 April through 17 June, a long WS (duration 91 days and RI 26.3 mm/day) during 18 June through 16 September and three short WSs (each of duration ~8 days and RI 24.6mm/day) and three medium size DSs (each of duration ~12 days and RI 0.3 mm/day) during 17 September through 15 November. Yearwise the third and the longest wet spell (the MMWS) occurs during the summer monsoon and stands out an important result, which has been chosen as a topic for detailed scientific investigation.

4. TIME SERIES ANALYSIS

Standard statistical methods (mean, standard deviation {SD} and highest and lowest values), techniques (least squares linear and polynomial fits) and tests (Mann-Kendall Rank test of randomness against trend {τ-test; Mitchell et al., 1966}, Wilcoxon–Mann–Whitney rank-sum test for two independent samples {U-test; Wilks, 2006} and Student's t-test for difference between means of two unequal sub periods) are used in the present study. On each time series, the U-test and t-test have been applied thrice, to test the difference of the latest 10 years (1998-2007) rank/mean from preceding 47 years (1951-1997) rank/mean, latest

20 years (1988-2007) rank/mean from preceding 37 years (1951-1987) rank/mean and latest 30 years (1978-2007) rank/mean from preceding 27 years (1951-2007) rank/mean in order to see robustness of the statistical inference about long-term trend.

5. RESULTS

5.1. Chief Features of the MMWS Parameters

To quantify the strength of the Indian summer monsoon circulation during different stages of its occurrence (onset, northward advance, establishment, southward retreat and withdrawal), Singh and Ranade (2010) have developed a general and regional atmospheric circulation intensity index (GARACII) by averaging normalized 30-day running means of the following seven parameters.

i. Lower troposphere thickness over central Middle East (CME; 25º-35ºN; 40º -75ºE)
ii. Upper troposphere thickness over the Tibet-Himalaya-Karakoram-Hindukush Highlands (THIKHIHILs: 25º-35ºN; 60º -95ºE)
iii. V850 along Somali Coast (SC: 5ºS-10ºN; 45º -55ºE)
iv. V850 over Indonesia-Malaysia maritime continent (IMMC: 5ºS-5ºN;100º -150ºE)
v. U850 over central Arabian Sea (AS: 5º-15ºN; 55º -70ºE)
vi. V850 over Myanmar and central Indochina peninsula (MCICP: 10º-30ºN; 90º -100ºE)
vii. Z200 over South Asia (SA: 25 º -35 º N; 50 º -100 º E)

The GARACII is 1.0 at the time of onset over the Kerala State, India (1 June). For the GARACII more than 1.4 a major portion of the Indian subcontinent experiences monsoon rains. Climatologically, the MMWS occurs during 18 June through 16 September (~91 days). The interannual variation (standard deviation; SD) of the starting date is 17 days and ending date 20 days. The MMWS can start as early as 22 May (1970) and as late as 10 August (1993), and end as early as 4 August (1965) and as late as 20 October (1999). The interannual variation in starting date and ending date is almost orthogonal (CC= -0.16; Table 2). Therefore, the SD of the duration is also very large (28.3 days) - the actual duration could be as short as 28 days (1972) and as long as 147 days (1956). Rainfall intensity (RI) is the least variable parameter- mean: 26.3mm/day; SD: 1.2mm/day; lowest observed: 24.2mm/day (1966), and highest 29.2mm/day (1997). The RI shows significant increasing trend according to different statistical tests. Quantitatively, however there is only a mild increase in the RI, from 25.8 mm/day during 1951-1977 to 26.7 mm/day during 1978-2007 i.e. 0.9 mm/day. Therefore, the total rainfall of the MMWS is highly dependent on the duration (CC= 0.99). During the MMWS, normally only 26.32PAI (percentage area of India) experiences wet condition- the actual area under wet condition ranges from 20.21PAI (1987) to 35.62 PAI (2005). The lowest, the mean and the highest contributions of the MMWS to the all-India annual rainwater are 19.54, 55.94 and 74.8 percent respectively. Seventy percent of the all-India summer monsoon rainwater occurs during the MMWS over 26.32PAI. The other 30% of the monsoon rainwater is spread over remaining 73.68PAI and during 122 days of the summer monsoon period June through September.

The parameters of the MMWS (Figure 5) do not possess any significant long-term trend as suggested by τ, U and t tests, except the mean rainfall intensity, which is significantly higher during 1978-2007 onwards compared to the preceding period 1951-1978. For the mean rainfall intensity series of the MMWS period, the Mann-Kendall τ-statistic is 2.27 (significant at 1% level), and the Wilcoxon–Mann–Whitney U-statistic for difference of the latest 30 years (1978-2007) rank from the preceding 27 years (1951-1977) rank is 2.96 (significant at 1%) and the Student's t-statistic for difference of the latest 30 years (1978-2007) mean from the preceding 27 years (1951-1977) mean is 4.37 (significant at 0.1. During the MMWS period the country gets rainfall over about 26 percent area at the rate of about 26 mm per day. To understand the extremes of rainfall intensity and areal extent on daily scale, the following extreme rainfall events has been analyzed.

i. the ERE concerning rainfall intensity (ERE-RI) of 1- to 25-day durations;
ii. the ERE concerning rainfall areal extent (ERE-AE) of 1- to 25-day durations;
iii. the ERE concerning rainwater (ERE-RW) of 1- to 25-day durations;
iv. the spatio-temporal ERE-RI (ST-ERE-RI) of 1- to 25-day durations;
v. the spatio-temporal ERE-AE (ST-ERE-AE) of 1- to 25-day durations;
vi. the spatio-temporal ERE-RW (ST-ERE-RW) of 1- to 25-day durations; and
vii. the spatio-temporal 1-DSG ERE of 1- to 150-day durations.

In the first three analyses, the grids on consecutive days under wet conditions are considered. On every individual day a particular grid may not be under wet condition, but if the rainfall of two consecutive days exceeded twice its DMMR the grid has been considered under wet condition for both days. Similarly, if three consecutive days total rainfall exceeded thrice its DMMR the grid is considered under wet condition for all the three days. These analyses are expected to provide useful information for hydrology, flood forecasting and water resources.

In the following three analyses, wet condition of any particular grid on any particular day is decided irrespective of its conditions on preceding day(s).The area under wet condition on each day is considered as an independent event. The information is useful for weather services and agricultural purposes.

Every year some parts of the country experience heavy floods even during large-scale droughts. Such extreme rainfall events exhibit large interannual spatial variability. To understand characteristics of the EREs over the country, an elaborate analysis of spatio-temporal variability of 1-DSG EREs of 1- to 150-day durations has been carried out. The main motivation of this special analysis is to evaluate severity of the 26-27 July 2005 Mumbai heavy rainfalls in the backdrop of spatio-temporal variability of the EREs over the country.

5.2. The extreme rainfall event concerning rainfall intensity (ERE-RI)

The annual maximum rainfall intensity series (1951-2007) for 1-day has been prepared by selecting yearwise rainfall event (ERE) of maximum mean rainfall intensity over the entire area of the country, which experienced wet conditions during the MMWS. Following similar procedure annual maximum rainfall intensity series for 2-, 3- … up to 25-day durations have been developed. The choice of longest duration of 25-day for rainfall intensity analysis is chosen keeping in view the shortest duration of the MMWS i.e. 28 days. Interannual variation in the 1-day extreme rainfall event concerning rainfall intensity (ERE-RI) can be in the range 32.7mm/day to 43.2mm/day that is always greater than the mean RI of the MMWS period. However, the areal extent of the 1-day ERE-RI is normally comparable to that of the MMWS period, but in extreme cases, it can be as small as 7.5PAI and as large as 47.6PAI. In addition, it can occur any time during the entire monsoon period (4 June through 5 October; Table 3). The distribution of cumulative rainfall intensity (highest observed, mean plus 2sd {standard deviation}, mean plus 1sd, mean minus 1sd, mean minus 2sd, mean minus 2sd. and lowest observed values; y-axis) for 1- to 25-day increases following a second-degree polynomial law with the duration (x-axis). The relationships are as follows (Equ. 1; Figure 6).

$$\begin{aligned}
y_{\max} &= 66.7 + 36.8x - 0.3x^2; \quad R^2 = 0.988 \\
y_{\bar{x}+2sd} &= 40.9 + 36.7x - 0.4x^2; \quad R^2 = 0.997 \\
y_{\bar{x}+sd} &= 35.8 + 32.4x - 0.3x^2; \quad R^2 = 0.998 \\
y_{\bar{x}} &= 30.7 + 28.1x - 0.3x^2; \quad R^2 = 0.998 \\
y_{\bar{x}-sd} &= 25.6 + 23.7x - 0.2x^2; \quad R^2 = 0.998 \\
y_{\bar{x}-2sd} &= 20.5 + 19.4x - 0.2x^2; \quad R^2 = 0.988 \\
y_{\min} &= 33.8 + 17.8x - 0.2x^2; \quad R^2 = 0.989
\end{aligned} \qquad \ldots (1)$$

From the set of expressions in Equ. 1, one can visualize that the rate of increase of rainfall intensity decreases in an exponential manner with the increase of the duration-increase on the 2nd day is 38.5 mm and on the 25th day 17.9 mm. The mean (P_{RI}) and standard deviation (SD_{RI}) relationship for the extreme rainfall intensity of 1- to 25-day duration is unambiguously linear (Equ. 2; Figure 7).

$$SD_{RI} = 2.54 + 0.14P_{RI}; R^2 = 0.995 \qquad \ldots (2)$$

The absolute measure of variability (SD) increases linearly with the increase in the mean maximum rainfall amount. The mean areal extent of the ERE concerning rainfall intensity is largest (25.8PAI) for 1-day and decreases in an exponential manner to 10.8 PAI for 25-day. For 1-day extreme, the largest areal extent could be as small as 7.5PAI (1971) and as large as 47.6% (1956); and for 25-day extreme as small as 3.1 PAI (1986) as large as 34.9PAI. The 1-day extreme event occurs around 1 August (SD= 34 days), the starting date for longer duration extreme events gradually shifts to earlier date and for 25-day event the date is 2 July (SD= 21 days). The correlation analysis suggests that extreme rain events of higher intensity occur at an earlier date and with smaller areal extent. A robust significant long-term trend is not seen in any of the parameters (RI, AE & date of occurrence) of the ERE-RI during the MMWS period (Figures 8 & 9).

5.3. The extreme rainfall event concerning areal extent (ERE-AE)

Kasper and Müller (2008) emphasized the incorporation of extremeness of the areal precipitation along with precipitation amount for the identification of heavy large-scale rainfall events in the Czech Republic. Normally, the mean RI of the ERE-AE over India is comparable to the MMWS but in some years, it can be as small as 20.4PAI while in others as large as 38.3mm/day (Table 4). The distribution of cumulative rainfall intensity (y-axis) for 1- to 25-day increases following a second-degree polynomial law with the duration (x-axis) (Equ. 3; Figure 10).

$$
\begin{aligned}
&y_{\max} = 28.7 + 24.5x - 0.2x^2; \quad R^2 = 0.994 \\
&y_{\bar{x}+2sd} = 29.4 + 21.7x - 0.2x^2; \quad R^2 = 0.998 \\
&y_{\bar{x}+sd} = 24.8 + 19.7x - 0.2x^2; \quad R^2 = 0.998 \\
&y_{\bar{x}} = 20.2 + 17.6x - 0.1x^2; \quad R^2 = 0.999 \qquad \ldots (3) \\
&y_{\bar{x}-sd} = 15.7 + 15.6x - 0.1x^2; \quad R^2 = 0.998 \\
&y_{\bar{x}-2sd} = 11.1 + 13.5x - 0.1x^2; \quad R^2 = 0.998 \\
&y_{\min} = 10.5 + 14.3x - 0.2x^2; \quad R^2 = 0.99
\end{aligned}
$$

The rate of increase of rainfall intensity of the ERE concerning areal extent (ERE-AE) decreases in an exponential manner with increase in the duration- 24.3 mm on the 2nd day and only 12.0 mm on the 25th day. Similar exponential decrease can be seen in the highest observed rainfall amount of the ERE-AE (34.5 mm on the 2nd day and only 5.0 mm on the 25th day) and the lowest observed rainfall amount (17.1 mm on the 2nd day and only 7.8 mm on the 25th day; Table 4). The occurrence of the 1-day ERE-AE is confined during 14 June through 6 September. The standard deviation (SD_{AE}) and mean rainfall (P_{AE}) relationship for the ERE-AE of 1- to 25-day durations is highly significant linear (Equ. 4; Figure 11).

$$SD_{AE} = 2.11 + 0.12P_{AE}; \quad R^2 = 0.994 \qquad \ldots (4)$$

The mean areal extent of the 1-day ERE-AE is 49.8PAI, and it decreases in an exponential manner to 35.1PAI for the 25-day duration. For the 1-day ERE-AE, the largest areal extent is 64.0PAI (1983) and the smallest 31.2PAI (1972), for the 25-day 52.7PAI (1956) and 16.8 PAI respectively. The ERE-AE of 1-day occurs around 23 July, and that of longer duration starts between 18 July and 23 July. The interannual variability (SD) of the areal extent is 6.2PAI and that of the stating date 15.0PAI for the 1- to 25-day ERE-AE. The mean RI (highest and lowest observed values) of the ERE-AE is lower by 54.36% (61.9% and 52.62%) than that of the ERE-RI but the areal extent is larger by 63.7% (32.7% and 84.44%). The parameters of the ERE-AE do not possess robust significant long-term trend (Figures 8 & 12).

5.4. The extreme rainfall event concerning rainwater (ERE-RW)

The annual maximum rainwater series (1951-2007) of 1- to 25-day has been analyzed to understand characteristics of the EREs concerning both the rainfall intensity and the areal extent (rainwater = rainfall multiplied by area). Normally the country gets 20.46 bcm (billion cubic metre or km^3) of rainwater each day during the MMWS (Table 5). The distribution of cumulative rainwater (y-axis) for 1- to 25-day increases following a second-degree polynomial law with the duration (x-axis) (Equ. 5; Figure 13).

$$\begin{aligned}
&y_{\max} = 91.1 + 31.3x - 0.4x^2; \quad R^2 = 0.992 \\
&y_{\bar{x}+2sd} = 56.9 + 25.9x - 0.2x^2; \quad R^2 = 0.998 \\
&y_{\bar{x}+sd} = 48.5 + 22.3x - 0.2x^2; \quad R^2 = 0.998 \\
&y_{\bar{x}} = 40.1 + 18.7x - 0.2x^2; \quad R^2 = 0.998 \qquad \ldots (5) \\
&y_{\bar{x}-sd} = 31.7 + 15.1x - 0.2x^2; \quad R^2 = 0.998 \\
&y_{\bar{x}-2sd} = 23.3 + 11.5x - 0.2x^2; \quad R^2 = 0.996 \\
&y_{\min} = 20.4 + 9.8x - 0.1x^2; \quad R^2 = 0.982
\end{aligned}$$

The standard deviation (SD_{RW}) and mean rainwater (P_{RW}) relationship for the ERE-RW for 1- to 25-day is explicit linear (Equ. 6; Figure 14).

$$SD_{RW} = -5.99 + 0.25P_{RW}; \quad R^2 = 0.995 \qquad \ldots (6)$$

The lowest rainwater occurred during drought years of 1972 (1- to 22-day) and 1987 (23- to 25-day), and the highest during wet monsoon year of 2005. The rainwater of extreme year 2005 was anomalously high, 70% to more than double of the mean rainwater of different durations (1- to 25-day). The extreme rainwater occurs/starts during 10 June through 4 October(Table 5), that is any time during the monsoon. The interannual variability (SD) of the stating date is about 16.5 days for 1- to 25-day ERE-RW. The parameters of the ERE-RW do not possess robust significant long-term trend (Figures 15 & 16). However, the outstanding rainwater of the year 2005 deserves investigation.

The mean RW of the ERE-RW is 92.65% higher than the RW associated with the ERE-AE and 5.79% higher than that associated with the ERE-AE. The mean RW of the ERE-AE is 82.66% higher than the RW associated with the ERE-RI. The ERE-RW accounts larger volume of rainfall, therefore, can be regarded as more important parameter for hydrological and water resource purposes than the other EREs concerning rainfall intensity and rainfall areal extent.

The correlation between the parameters of the ERE-RI, ERE-AE and ERE-RW is given in Table 6. For the ERE-RW, RW and AE and RW and RI are mostly highly correlated. This means, generally the ERE-RW is relatively more intense and well spread. The other noticeable feature is the start of the longer duration ERE-RI on earlier dates

5.5. The spatio-temporal extreme rainfall event concerning rainfall intensity (ST-ERE-RI)

For the ST-ERE-RI, the distribution of cumulative rainfall intensity (highest observed, mean plus 2sd {standard deviation}, mean plus 1sd, mean minus 1sd, mean minus 2sd, mean minus 2sd. and lowest observed values; y-axis) for 1- to 25-day increases following a second-degree polynomial law with the duration (x-axis) (Table 7). The relationships are as follows (Equ. 7; Figure 17).

$$\begin{aligned}
y_{\max} &= 45.6 + 37.8x - 0.2x^2; \quad R^2 = 0.999 \\
y_{\bar{x}+2sd} &= 33.9 + 35.4x - 0.2x^2; \quad R^2 = 0.999 \\
y_{\bar{x}+sd} &= 26.4 + 33.3x - 0.2x^2; \quad R^2 = 0.999 \\
y_{\bar{x}} &= 18.7 + 31.2x - 0.1x^2; \quad R^2 = 0.999 \\
y_{\bar{x}-sd} &= 11.1 + 29.8x - 0.1x^2; \quad R^2 = 0.999 \qquad (7) \\
y_{\bar{x}-2sd} &= 3.5 + 26.9x - 0.1x^2; \quad R^2 = 0.999 \\
y_{\min} &= 7.7 + 27.9x - 0.1x^2; \quad R^2 = 0.999
\end{aligned}$$

The rate of increase of cumulative rainfall intensity is at a faster rate compared to the ERE-RI. The variation in the areal extent of the ERE-RI for 1- to 25-day duration is very small- the mean area is 28PAI, the largest 44 PAI and the smallest 9PAI. The extremes of different durations occur during 1 June through 18 October. The regression of the standard deviation (SD) on the mean of the ST-ERE-RI for 1- to 25-day duration is unambiguously linear (Equ. 8; Figure 18).

$$SD_{RI} = 9.81 + 0.045P_{RI}; R^2 = 0.988 \tag{8}$$

This relationship is consistent with the SD-mean relationship for monthly, seasonal and annual rainfall across India (Singh and Mulye, 1991).

5.6. The spatio-temporal extreme rainfall event concerning areal extent (ST-ERE-AE)

Climatological features of the parameters of the ST-ERE-RI are given in Table 8. The distribution of cumulative rainfall intensity (y-axis) for 1- to 25-day increases following a second-degree polynomial law with the duration (x-axis). The expressions as follows (Equ. 9; Figure 19).

$$\begin{aligned}
y_{\max} &= 14.6.1 + 33.2x - 0.1x^2; \quad R^2 = 0.998 \\
y_{\bar{x}+2sd} &= 10.6 + 32.4x - 0.01x^2; \quad R^2 = 0.999 \\
y_{\bar{x}+sd} &= 7.0 + 30.0x - 0.05x^2; \quad R^2 = 0.999 \\
y_{\bar{x}} &= 3.5 + 27.6x - 0.02x^2; \quad R^2 = 0.999 \\
y_{\bar{x}-sd} &= -0.02 + 25.25x - 0.005x^2; \quad R^2 = 0.999 \\
y_{\bar{x}-2sd} &= -3.6 + 22.9x - 0.03x^2; \quad R^2 = 0.999 \\
y_{\min} &= -4.0 + 23.1x - 0.01x^2; \quad R^2 = 0.999
\end{aligned} \tag{9}$$

The rate of increase of cumulative rainfall intensity is at a faster rate compared to the ERE-RI. The mean areal extent of the ST-ERE-AE for 1-day is 50PAI and decreases in an exponential manner to 34PAI for 25-day. The largest areal extent decreases from 64PAI to 44PAI, and smallest from 31PAI to 25PAI. The ST-ERE-AE of different durations occurs during 1 June through 18 September. For some duration, the areal extent of the ERE-AE is larger than that of the ST-ERE-AE. It may be recalled that for calculation of area of the ERE-AE the procedure followed is as- if a particular grid is not under wet condition for two consecutive days but third day rainfall is high enough such that total rainfall of 3 consecutive days exceeds thrice of its DMMR, then all the three days are declared under wet condition. This time spreading of total rainfall does have considerable effect on the calculation of the areal extent for the ST-ERE-AE.

The regression of the standard deviation (SD) on the mean of the ST-ERE-AE for 1- to 25-day duration is unambiguously linear (Equ. 10; Figure 20):

$$SD_{AE} = 6.87 + 0.05P_{AE}; R^2 = 0.988 \tag{10}$$

5.7. The spatio-temporal extreme rainfall event concerning rainwater (ST-ERE-RW)

Climatological features of the parameters are given in Table 9. The expressions for distribution of cumulative rainwater (y-axis) for 1- to 25-day durations are as follows (Equ. 11; Figure 21).

$$
\begin{aligned}
y_{\max} &= 75.1 + 46.1x - 0.4x^2; \quad R^2 = 0.998 \\
y_{\bar{x}+2sd} &= 42.6 + 39.8x - 0.3x^2; \quad R^2 = 0.999 \\
y_{\bar{x}+sd} &= 34.1 + 35.9x - 0.3x^2; \quad R^2 = 0.999 \\
y_{\bar{x}} &= 25.6 + 31.9x - 0.2x^2; \quad R^2 = 0.999 \\
y_{\bar{x}-sd} &= 17.1 + 77.9x - 0.2x^2; \quad R^2 = 0.999 \\
y_{\bar{x}-2sd} &= 8.6 + 24.0x - 0.2x^2; \quad R^2 = 0.999 \\
y_{\min} &= 2.9 + 21.9x - 0.2x^2; \quad R^2 = 0.999
\end{aligned}
\tag{11}
$$

The rainwater of the ST-ERE-RW increases at a much faster rate with the duration compared to the ERE-RW. This is understandable. Each day the area of highest rainwater is considered irrespective of the wetness of the grids on previous day. It may be noted that the rainwater of 25-day (12 July to 5 August 2005; 971.9 bcm) was sufficient to fill all the 4,525 large reservoirs and the different aquifers of the country to the full of their capacity.

The regression of the standard deviation (SD) on the mean of the ST-ERE-RI for 1- to 25-day duration is unambiguously linear (Equ. 12; Figure 22).

$$SD_{RW} = 6.39 + 0.12P_{RW}; R^2 = 0.997 \tag{12}$$

5.8. The spatio-temporal 1-DSG extreme rainfall

This analysis is intended to investigate whether unprecedented rainfall on 25 July 2005 over Mumbai (India) was an isolated anomalous rainfall event or mere a realization of long-term trend in the spatio-temporal EREs over the country. The annual maximum 1-DSG rainfall series for 1-day has been prepared by selecting yearwise highest rainfall amount from among the 365/366 daily rainfall of the 292 1-DSGs. Similarly, the annual maximum 1-DSG rainfall series for 2-, 3-…150-day duration has been prepared. A large wandering over almost the entire country is seen in the occurrence of yearly 1-DSG spatio-temporal EREs for 1- to 5-day duration. The 1-DSG EREs for 6- to 30-day duration showed a tendency to occur relatively frequently along the West Coast. For more than 30-day duration the extreme rainfall occurred every year along the West Coast. Thus, the orographic effect of the Western

Ghats produces long duration extreme rainfall events along the west coast of India during the monsoon period. Role of topographic barriers in generating extreme rainfall events has been emphasized in recent studies (Rudari et al., 2004; Boni et al., 2008). Desai (1967) has discussed the synoptic meteorological aspects of the interactions between Arabian Sea monsoon and the Western Ghats. The distribution of 1-DSG extreme rainwater increases with the duration 1- to 150-day following a second-degree polynomial law (Equ. 13; Figure 23). It may be noted that the equation for mean minus 2sd does not exist, as minimum value is higher than the mean minus 2sd. Climatological features of the parameters are given in Table 10.

$$\begin{aligned}
y_{\max} &= 831.4 + 97.7x - 0.3x^2; \quad R^2 = 0.992 \\
y_{\bar{x}+2sd} &= 692.1 + 78.9x - 0.3x^2; \quad R^2 = 0.998 \\
y_{\bar{x}+sd} &= 603.4 + 67.2x - 0.2x^2; \quad R^2 = 0.999 \\
y_{\bar{x}} &= 514.7 + 55.5x - 0.2x^2; \quad R^2 = 0.999 \\
y_{\bar{x}-sd} &= 426.0 + 43.7x - 0.1x^2; \quad R^2 = 0.999 \\
y_{\min} &= 360.6 + 36.2x - 0.1x^2; \quad R^2 = 0.996
\end{aligned} \qquad \ldots (13)$$

The standard deviation (SD_{ST}) and mean rainfall (P_{ST}) relationship for the 1-DSG spatio-temporal EREs for 1- to 25-day duration is as follows (Equ. 14; Figure 24),

$$SD_{ST} = -4.16 + 0.20P_{ST}; \quad R^2 = 0.998 \qquad \ldots (14)$$

The 1-DSG 1-day lowest rainfall 221.4mm occurred during 1962 and the highest rainfall 473.4mm during 2005. The 1-DSG 1-day ERE occurs around 3 August but the date displays large interannual variation, SD is 44.5 days. The starting date of the longer duration EREs shifts to earlier period and its SD decreases. The mean starting date of the 1-DSG 150-day ERE is 20 May and the SD 11 days. For most of the selected durations, the 1-DSG extreme rainfall amount was smaller during earlier years (1957, 1959, 1962, 1966, 1972 and 1981) and larger during later years (1991, 2005, 2006 and 2007) indicating positive trend in the spatio-temporal EREs.

On an average the 1-day ERE-RW starts on 21 July and the 25-day on 17 July. Normally, the 1- to 25-day ERE-AE starts one day later than the respective ERE-RW. However, on interannual scale, the SD of the difference between starting dates of the ERE-RW and that of the ERE-AE for 1- to 25-day is 13 days. In one extreme year (1955), the EREs-AE started 24 days earlier than EREs-RW while in another extreme (1968) 34 days later. The mean date of occurrence of the 1-day ERE-RI is 1 August and that of 25-day 2 July. In general, the EREs-RI of different durations starts 13 days earlier than that of the EREs-RW. However, the SD of the difference between starting dates of the EREs-RW and that of the EREs-RI is 21 days. In one extreme year (1970) the EREs-RI started 42 days earlier than the EREs-RW while in another (1983) 42 days later. The 1-DSG extreme rainfall of 1- to 25-day duration starts normally 8 days earlier than the ERE-RW of the respective duration. However, the SD of difference between starting dates of the two extremes is 23 days. In extreme years, the 1-DSG extreme can start as early as 56 days (1987) and as late as 21 days (1978). In majority of cases, the ERE-RW and ERE-AE of particular year are the same, but there were considerable occasions when the starting dates of the two extremes were few days apart. On the other hand, the ERE-RI and 1-DSG extreme rainfall occurred/started earlier than the ERE-RW and the ERE-AE though there was some common period of few days, and extremes of smaller areal coverage (1-DSG and ERE-RI) were embedded in the larger extremes (ERE-RW and ERE-AE). In the era of changing global climatic conditions, analyses of different types of extreme rainfall events are expected to provide critical information to the researchers and users alike about the extremes of rainfall occurrences.

For visual examination, the time series (1951-2007) of 1-DSG 1-day spatio-temporal extreme rainfall amount and date of occurrence is shown in Figure 25. Considerable rising trend can be seen in extreme rainfall from 1970 onwards but a weak tendency for the event to occur at an earlier date. The results of detailed fluctuation analysis however are presented here for all the 150 extreme rainfall series of 1- to 150-day duration (Figure 26). From application of different statistical tests, a robust significant long-term rising trend is inferred in rainfall amount of the 1-DSG EREs of 1- to 5-day durations. Compared to the period 1951-1977, the 1- to 5-day extreme rainfall has increased by 9 to 15 percent during 1978-2007 and the longer duration extremes (6- to 150-day) by 1 to 6 percent (statistically not significant). In recent decades, the 1-DSG ERE has shown a tendency to occur at an earlier date by 12.5 days- the mean date during 1951-1977 was 9 August and during 1978-2007 27 July. However, this temporal shift is statistically not significant due to large standard deviation (44.5 days) of interannual occurrences of the 1-DSG ERE. From the results it appears that, the unprecedented rainfall over Mumbai on 26-27 July 2005 is a realization of significant rising trend in the spatio-temporal 1- to 5-day 1-DSG extreme rainfall over the country. However, this could be an impact of global warming on the Indian summer monsoon circulation and the associated rainfall activities. It appears that during global warming the 'heat-low' over northwest India and upper tropospheric anticyclone over Tibet-Himalaya highlands shift westward. Consequently, the area of convergence and associated rainfall activities show a tendency to shift westward from central to northwest India. However, this proposition requires investigation. Westward shift in the summer monsoon rainfall over northern India due to rising trend in the northern surface air temperature has been reported in Singh and Sontakke (2002) and Singh et al. (1992).

On 26-27 July 2005 (0300 UTC 26 July 2005 to 0300 UTC 27 July 2005), the India Meteorological Department (IMD) observatory at Santacruz International Airport (19.11˚N, 72.85˚E) on the north side of the metropolis Mumbai (18˚56'N, 72˚51'E) located on the west coast of India between the Arabian Sea and the Western Ghats mountains recorded the highest 1-day rainfall of 944 mm. However, the non-IMD rainguage at Lake Virar (15 km northeast of Santacruz) recorded the same day rainfall of 1049 mm. Detailed spatial analysis of rainfall of 26-27 July 2005 shows that northern Mumbai received torrential rains but southern part was relatively dry (Jenamani et.al., 2006; Kumar et. al., 2008). Therefore, the rainfall of 27 July 2005 for 1-DSG (degree square grid) around Santacruz is drastically low (473.3mm). Nevertheless, for 1-DSG this is still the highest 1-day rainfall amount during the period of study (1951-2007). Using satellite and radar inputs combined with synoptic and thermodynamic analysis, Shyamala and Bhadram (2006) concluded that formation of mesoscale convective systems over Mumbai comprising super thunderstorm cells and their interaction with the synoptic scale low pressure area from the Bay of Bengal led to the concentrated very high intensity rainfall. It may be noted that active monsoon conditions over north Konkan are usually associated with a trough off the West Coast of India, formation of lows/depressions over north Bay of Bengal, presence of mid-tropospheric cyclonic circulation (MTC) off north Maharashtra-south Gujarat coast between 700 and 500 hPa and strong pressure gradient along the coast (Srinivasan, 1972). However, a detailed account of meteorological conditions over India and neighborhood associated with heavy rain event over Mumbai is provided in Jenamani et.al.(2007). The extreme event caused enormous loss of life and property. Attempts have been made with some success to simulate this extreme rainfall event using numerical weather prediction (NWP) models (Bohra et al., 2006; Kumar et al. 2008; Rama Rao et. al. 2007; Sikka and Rao, 2008; Vaidya and Kulkarni, 2007).

Perhaps similar meteorological condition can be attributed as possible cause of heavy rainstorms across the country.

6. RELATIONSHIP BETWEEN RAINWATER OVER INDIA AND CIRCULATION PARAMETERS

Two types of regression of the rainwater on the circulation parameters have been estimated: on inter-annual scale using mean value of the parameters and on yearly basis using daily data of the parameters of the MMWS period. Results are not found satisfactory for inter-annual scale.

6.1 Yearwise multiple linear regression of RW on the 13 circulation parameters

With the data of the MMWS period, the forward multiple linear regression (MLR) of RW on the 13 selected circulation parameters has been fitted for each year of the period 1951-2007. Three visibly different parameters entered the MLR every year and the multiple correlation coefficient (MCC) ranged between 0.49 and 0.91. However, a careful examination reveals that some parameters entered more frequently than others did. From largest to smallest number of years the circulation parameters entered in the MLR is in order.

- the U_{SURF} over central Arabian Sea (34 yrs.)
- the Korea-Japan-northwest North Pacific U_{TPAUS} (20 yrs.)
- the south Indian peninsula U_{TPAUS} (20 yrs.)

- the south Indian peninsula ($U_{SURF} – U_{TPAUS}$) (17 yrs.)
- the Indo-Gangetic Plains Z200 (13 yrs.)
- the central Bay of Bengal PWW(12 yrs.)
- the Australia-South Pacific U_{TPAUS} (11 yrs.)
- the central Bay of Bengal V_{TPAUS} (9 yrs.)
- the equatorial western Pacific U_{SURF} (9 yrs.)
- the THIKHIHILs upper troposphere thickness (Z200 – Z500) (7 yrs.)
- the central Middle East lower troposphere thickness (Z500 – Z850) (7 yrs.)
- the Indonesia-Malaysia maritime continent V_{SURF} (7 yrs.)
- the Myanmar-Indochina peninsula V_{SURF} (5 yrs.)

Parameters entering the MLR in a particular year depend on the space-time structure of the rainfall occurrences during the year. Simultaneous intensification of 3 to 4 circulation parameters produce essential conditions for occurrence of large-scale, long period extreme rainfall events: 1) high precipitation efficiency of the incoming airstream; 2) the presence of a moist, moderate to intense low-level jet (LLJ); 3) steep orography to help release the instability; 4) strong environmentally forced upward vertical motion; 5) the presence of a high moisture flow upstream; 6) a pre-existing large-scale convective system; 7) slow movement of the convective system; and 8) a conditionally or potentially unstable upstream airflow (Lin et al., 2001). Nevertheless, the U_{SURF} over central Arabian Sea is the most important parameters. This is consistent with findings of Shukla (1975) and Shukla and Misra (1977).

In another experiment, the daily rainwater of the MMWS period is arranged in the sequence of all the 57 years (1951-2007). Then the MLR of this intra-MMWS and interannual mixed long sequence of daily rainwater has been fitted on the corresponding daily value of the 13 circulation parameters. Here the length of the data sequence (number of observation; N) will become 5211. The results are quite unsatisfactory- the correlation coefficient and the multiple correlation coefficient does nor exceed 0.24.

7. SUMMERY AND CONCLUSION

- Every year the country experiences a main monsoon wet spell (MMWS) during 18 June through 16 September (91 days). Two very short large-scale wet spells (LSWSs; each of 6 days) and two dry spells (LSDSs; each of 35 days) occur before the MMWS and three LSWSs (each of 9 days) and three LSDSs (each of 13 days) after. During the MMWS, normally the country receives rainfall over 26.32% areas every day at the rate of 26.3mm/day. In terms of rainwater, this is equivalent to 20.46 bcm (billion cubic metre or km^3) per day.

- Seventy percent of the all-India summer monsoon rainwater occurs during the MMWS over 26.32% area of the country. The remaining 30% of the monsoon rainwater is spread over 73.68% area of the country and during 122 days of the summer monsoon period June through September.

- For 1-day extreme rainfall event concerning rainfall intensity (ERE-RI), the mean RI is 43.2 mm/day and the mean areal extent 25.8PAI. The distribution of cumulative rainfall intensity (highest observed, mean plus 2sd {standard deviation}, mean plus 1sd, mean minus 1sd, mean minus 2sd, mean minus 2sd. and lowest observed values) for 1- to 25-day increases following a second-degree polynomial law with the duration. For 1- to 25-day the cumulative mean RI increases from 43.2mm to 576.5mm and the mean areal extent decreases from 25.8PAI to 10.8PAI in an exponential manner.

- For 1-day ERE-AE, the mean RI is 29.1mm/ay and the mean areal extent 49.8PAI. For 1-to 25-day, the cumulative mean RI increases following a second-degree polynomial law from 29.1mm to 373.1mm and the mean areal extent decreases from 49.8PAI to 35.1PAI.

- For the ERE-RW, the cumulative mean RW for 1- to 25-day increases from 46.2 bcm to 394.1 bcm following a second-degree polynomial law.

- For the ST-ERE-RI, the cumulative mean RI increases from 43.2mm to 721.5mm but, the mean areal extent is about 28.6PAI for different durations (1- to 25-day).

- For the ST-ERE-AE, the cumulative mean RI increases from 29.1mm to 677.9mm, and the mean areal extent decreases from 49.8PAI to 33.9PAI for 1- to 25-day durations.

- For the ST-ERE-RW, the mean RW increases from 46.2 bcm to 679.5 bcm following a second-degree polynomial law for 1- to 25-day durations.

- For 1- to 150-day, the cumulative mean RI of the 1-DSG ST-ERE increases from 340.7mm to 4612.3mm. The interannual variation of the 1-day 1-DSG spatio-temporal extreme rainfall shows highly significant rising trend during 1951-2007. The unprecedented rainfall on 26-27 July 2005 over Mumbai Metropolitan city appears to be a realization of this long-term trend.

- The U_{SURF} over central Arabian Sea is the most important circulation parameter in affecting the daily rainfall activities over the country, and the others of the 13 selected parameters in order of decreasing influence are as: Korea-Japan-northwest North Pacific U_{TPAUS}, South Indian peninsula U_{TPAUS}, South Indian peninsula ($U_{SURF} - U_{TPAUS}$), Indo-Gangetic Plains Z200, central Bay of Bengal PWW, Australia-South Pacific U_{TPAUS}, central Bay of Bengal V_{TPAUS}, Equatorial western Pacific U_{SURF}, THIKHIHILs upper troposphere thickness (Z200 – Z500), central

Middle East lower troposphere thickness (Z500 – Z850), Indonesia-Malaysia maritime continent V_{SURF} and Myanmar-Indochina peninsula V_{SURF}. Simultaneous intensification of 3 to 4 circulation parameters produce essential conditions for occurrence of large-scale, long period extreme rainfall events.

The extreme and spatio-temporal extreme rainfall characteristics are expected to provide useful information for evaluating the extreme event performance of hydrological model and flood forecasting (Moore et al., 2006) and for disaster management and observation system design (Goswami and Ramesh, 2008).

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Table 1. Climatological features of the parameters of the MMWS over India

Parameters	Mean	SD	The low value (Year of occurrence)	The high value (Year of occurrence)
Starting date	18 Jun	16.9 days	22 May (1970)	10 Aug (1993)
Ending date	16 Sept	20.2 days	3 Aug (1965)	19 Oct (1999)
Duration (days)	90.7	28.3	28 (1972)	147 (1956)
Rainfall Amount (mm)	2372.7	714.8	701.8 (1972)	3730.9 (1956)
Rainfall intensity (mm/day/1-DSG)	26.3	1.2	24.2 (1966)	29.2 (1997)
Areal extent (%)	26.32	2.6	20.21 (1987)	35.62 (2005)
Contribution to annual rainfall (%)	55.94	13.8	19.54 (1972)	74.8 (1970)

Table 2. Correlation matrix for the parameters of the MMWS

parameter	Start	End	Duration	Rainfall amount	Rainfall intensity	Areal extent	% rain to annual total
Start	1						
End	-0.16	1					
Duration	-0.71	0.81	1				
Rainfall amount	-0.73	0.78	0.99	1			
Rainfall intensity	-0.01	-0.41	-0.29	-0.17	1		
Areal extent	-0.16	-0.12	0.01	0.03	0.17	1	
% rain to annual total	-0.71	0.73	0.95	0.96	-0.12	0.30	1

Table 3. Statistics (mean, sd highest, lowest observed) for extreme rain event concerning rainfall intensity for 1-25 day duration during the MMWS

Day (s)	Rainfall intensity (mm/day)					Areal extent (%age area of India)					Date of occurrence		
	Mean (SD)	high	Date of occurrence	low	Date of occurrence	Mean (SD)	High	Date of occurrence	low	Date of occurrence	Mean (SD in days)	late	early
1	43.2 (7.6)	73.3	25 Jul 05	32.7	30 Jun 52	25.8 (10.0)	47.6	2 Jul 56	7.5	14 Jun 71	2 Aug (34.0)	5 Oct 83	4 Jun 76
2	81.7 (12.9)	125.1	24 Jul 05	61.7	17 Aug 72	21.7 (9.2)	40.1	24 Jul 05	5.5	22 Jul 98	26 Jul (34.3)	13 Oct 61	4 Jun 76
3	114.5 (17.8)	180.2	4 Jun 76	88.8	15 Aug 93	18.3 (9.1)	39.4	24 Jul 05	4.4	22 Jul 98	16 Jul (30.0)	4 Oct 55	4 Jun 76
4	143.6 (22.4)	222.2	4 Jun 76	103.0	7 Aug 72	16.1 (8.1)	38.7	26 Jul 67	2.7	121 Oct 59	11 Jul (27.3)	12 Oct 59	4 Jun 76
5	170.4 (26.0)	250.4	18 Jun 05	121.7	3 Aug 72	15.4 (7.4)	40.8	25 Jul 67	3.1	3 Aug 72	6 Jul (22.5)	11 Sep 87	4 Jun 76
6	196.4 (30.1)	302.4	18 Jun 05	140.4	3 Aug 72	14.7 (6.8)	39.7	25 Jul 67	3.1	3 Aug 72	10 Jul (22.8)	5 Sep 69	4 Jun 76
7	219.8 (34.2)	352.1	18 Jun 05	159.1	7 Aug 72	15.0 (6.5)	30.8	23 Jul 52	3.1	23 Aug 86	9 Jul (20.8)	25 Aug 87	4 Jun 76
8	241.0 (34.8)	337.2	187 Jun 05	179.5	11 Aug 93	13.7 (6.5)	27.4	11 Jul 94	3.1	22 Aug 86	9 Jul (23.2)	8 Sep 87	4 Jun 76
9	262.9 (36.9)	351.4	21 Jun 83	198.0	13 Aug 93	14.8 (7.2)	34.9	14 Jul 88	3.4	16 Jun 95	8 Jul (22.7)	8 Sep 87	29 May 70
10	283.5 (42.4)	380.6	24 Jun 58	208.4	7 Aug 72	14.6 (7.1)	35.3	14 Jul 88	3.1	14 Jun 55	7 Jul (20.5)	18 Aug 87	31 May 70
11	307.0 (47.9)	422.1	14 Jul 51	212.4	11 Aug 93	13.4 (6.8)	30.1	5 Sep 06	3.8	29 May 70	5 Jul (22.5)	5 Sep 06	29 May 70
12	326.1 (50.9)	458.7	24 Jun 58	225.5	11 Aug 93	13.7 (7.6)	36.0	19 Jul 92	4.1	17 Jun 97	5 Jul (20.7)	5 Sep 06	29 May 70
13	346.5 (52.6)	480.3	23 Jun 58	238.5	24 Aug 93	13.1 (7.7)	32.9	17 Jul 92	2.1	26 Aug 01	6 Jul (21.5)	6 Sep 06	29 May 70
14	366.7 (55.0)	500.6	19 Jun 05	246.0	4 Aug 72	12.1 (6.8)	32.5	17 Jul 92	2.1	26 Aug 01	6 Jul (21.7)	6 Sep 06	4 Jun 76
15	386.4 (57.5)	555.2	22 Jun 58	261.4	4 Aug 72	11.9 (6.8)	33.6	17 Jul 88	1.7	26 Aug 01	7 Jul (20.4)	26 Aug 01	4 Jun 76
16	405.4 (59.8)	568.2	19 Jun 05	266.8	4 Aug 72	11.8 (6.5)	34.6	13 Jul 88	1.7	26 Aug 01	7 Jul (21.3)	5 Sep 06	8 Jun 89
17	425.9 (65.1)	624.8	19 Jun 05	278.1	4 Aug 72	11.5 (6.1)	34.3	13 Jul 88	1.7	26 Aug 01	7 Jul (21.7)	5 Sep 06	8 Jun 89
18	443.7 (65.9)	639.2	19 Jun 05	288.4	7 Aug 72	10.9 (5.7)	30.5	29 Aug 06	1.7	26 Aug 01	6 Jul (22.1)	29 Aug 06	8 Jun 89
19	460.3 (67.2)	635.1	19 Jun 05	298.8	4 Aug 72	10.6 (5.7)	30.8	29 Aug 06	1.7	26 Aug 01	5 Jul (21.8)	29 Aug 06	8 Jun 89
20	475.6 (68.8)	659.4	18 Jun 58	316.6	6 Aug 72	11.0 (5.6)	25.7	31 Aug 06	2.4	22 Aug 86	5 Jul (21.4)	31 Aug 06	8 Jun 89
21	488.8 (67.0)	652.3	18 Jun 58	338.1	12 Aug 93	10.8 (5.5)	28.8	2 Aug 92	2.4	12 Jun 56	3 Jul (20.7)	31 Aug 06	8 Jun 89
22	507.6 (68.7)	665.9	21 Jun 68	359.5	12 Aug 93	11.0 (5.5)	30.8	29 Aug 06	4.1	29 May 70	3 Jul (20.3)	29 Aug 06	29 May 70
23	528.4 (72.3)	723.5	21 Jun 68	376.7	12 Aug 93	11.3 (6.0)	31.2	29 Jun 94	4.5	12 Aug 93	2 Jul (19.9)	29 Aug 06	29 May 70
24	549.6 (79.3)	776.1	21 Jun 68	371.1	12 Aug 93	10.8 (5.7)	31.2	29 Jun 94	3.8	16 Jun 95	2 Jul (19.5)	24 Aug 06	29 May 70
25	567.5 (84.6)	810.0	12 Jun 68	383.8	22 Aug 93	10.8 (6.0)	36.0	19 Jul 92	3.1	22 Aug 86	3 Jul (21.3)	24 Aug 06	6 Jun 01

Table 4. Statistics (mean, sd , highest, lowest observed) for extreme rain event concerning areal extent for 1-25 day duration during the MMWS

Day (s)	Rainfall intensity (mm/day)					Areal extent (%age area of India)					Date of occurrence		
	Mean (SD)	high	Date of occurrence	low	Date of occurrence	Mean (SD)	High	Date of occurrence	low	Date of occurrence	Mean (SD in days)	late	early
1	29.1 (4.1)	38.3	2 Jul 80	20.4	14 Aug 87	49.8 (5.6)	64.0	25 Jul 83	31.2	24 Aug 72	23 Jul (16.9)	6 Sep 07	14 Jun 01
2	53.4 (8.2)	72.8	13 Jul 94	37.5	24 Aug 72	43.8 (5.6)	56.9	25 Jul 83	26.4	24 Aug 72	24 Jul (16.7)	6 Sep 07	28 Jun 55
3	74.3 (11.6)	110.3	23 Jul 89	50.6	1 Sep 93	41.3 (5.6)	56.2	25 Jul 83	23.6	23 Aug 72	24 Jul (17.9)	6 Sep 07	10 Jun 91
4	90.9 (13.6)	131.6	22 Jul 89	62.1	1 Sep 93	39.0 (5.5)	53.1	25 Jul 83	23.3	23 Aug 72	23 Jul (15.8)	1 Sep 93	28 Jun 55
5	107.9 (15.1)	140.3	23 Jul 89	77.0	1 Sep 93	38.7 (5.3)	50.3	25 Jul 83	24.0	23 Aug 72	23 Jul (15.8)	1 Sep 93	27 Jun 80
6	122.9 (17.1)	163.1	24 Aug 87	92.7	1 Sep 93	38.5 (5.5)	50.3	25 Jul 83	22.6	23 Aug 72	23 Jul (15.7)	1 Sep 93	27 Jun 80
7	138.1 (18.2)	186.6	25 Jul 67	103.9	18 Jul 84	38.2 (5.7)	49.7	25 Jul 83	21.6	23 Aug 72	23 Jul (15.5)	1 Sep 93	27 Jun 80
8	153.3 (20.2)	215.7	30 Jun 07	115.6	17 Jul 85	37.7 (5.8)	49.7	25 Jul 83	19.5	17 Aug 72	23 Jul (16.1)	1 Sep 93	27 Jun 80
9	167.2 (23.0)	239.8	30 Jun 07	116.4	16 Aug 55	37.4 (6.0)	49.0	25 Jul 83	19.5	8 Aug 72	23 Jul (14.7)	1 Sep 93	30 Jun 07
10	183.2 (24.1)	265.6	30 Jun 07	140.4	1 Sep 93	37.2 (6.1)	48.3	25 Jul 83	20.2	8 Aug 72	22 Jul (14.2)	1 Sep 93	30 Jun 07
11	199.5 (25.1)	282.9	30 Jun 07	151.0	1 Sep 93	36.8 (6.1)	48.0	3 Jul 56	19.9	6 Aug 72	22 Jul (14.3)	1 Sep 93	27 Jun 80
12	213.6 (25.9)	293.9	30 Jun 07	161.9	1 Sep 93	36.6 (6.1)	46.9	3 Jul 56	19.9	6 Aug 72	22 Jul (14.5)	1 Sep 93	27 Jun 80
13	225.0 (29.1)	304.7	30 Jun 07	159.7	13 Jul 84	36.3 (6.0)	46.2	19 Jul 95	18.8	6 Aug 72	22 Jul (15.1)	1 Sep 93	27 Jun 80
14	238.0 (30.1)	314.7	30 Jun 07	169.8	13 Jul 84	36.2 (6.1)	46.9	25 Jul 83	19.2	6 Aug 72	22 Jul (14.1)	1 Sep 93	30 Jun 07
15	248.6 (30.3)	321.7	30 Jun 07	179.4	22 Aug 96	36.1 (6.2)	48.3	25 Jul 83	18.2	6 Aug 72	22 Jul (14.6)	1 Sep 93	29 Jun 98
16	262.6 (32.6)	372.1	12 Jul 05	190.9	22 Aug 96	35.9 (6.4)	48.3	25 Jul 83	17.5	6 Aug 72	21 Jul (14.4)	1 Sep 93	29 Jun 98
17	273.2 (34.1)	388.4	12 Jul 05	191.9	13 Aug 57	35.8 (6.6)	49.3	25 Jul 83	17.1	6 Aug 72	21 Jul (14.2)	1 Sep 93	29 Jun 98
18	287.7 (33.8)	376.6	28 Aug 06	211.3	22 Aug 96	35.7 (6.7)	50.0	3 Jul 56	18.2	6 Aug 72	20 Jul (14.2)	1 Sep 93	28 Jun 05
19	300.2 (34.8)	400.3	28 Aug 06	217.0	22 Aug 96	35.5 (6.8)	49.7	3 Jul 56	17.5	6 Aug 72	19 Jul (14.6)	1 Sep 93	28 Jun 05
20	307.8 (39.2)	426.2	12 Jul 05	203.4	7 Aug 87	35.4 (6.8)	50.0	3 Jul 56	17.8	8 Aug 72	20 Jul (13.8)	1 Sep 93	30 Jun 07
21	323.7 (43.7)	445.1	12 Jul 05	214.7	7 Aug 87	35.3 (6.9)	50.7	3 Jul 56	17.8	8 Aug 72	20 Jul (14.0)	1 Sep 93	29 Jun 98
22	337.6 (43.9)	459.8	27 Aug 06	220.6	7 Aug 87	35.3 (6.9)	50.7	3 Jul 56	18.2	6 Aug 72	19 Jul (14.0)	1 Sep 93	30 Jun 07
23	348.5 (43.1)	478.8	5 Jul 05	233.9	7 Aug 87	35.2 (6.9)	50.3	3 Jul 56	17.8	8 Aug 72	19 Jul (14.1)	1 Sep 93	27 Jun 71
24	361.6 (43.2)	493.4	5 Jul 05	250.2	7 Aug 87	35.1 (7.0)	51.7	3 Jul 56	17.5	8 Aug 72	19 Jul (14.2)	1 Sep 93	27 Jun 71
25	373.1 (45.5)	498.6	5 Jul 05	258.0	7 Aug 87	35.1 (7.3)	52.7	3 Jul 56	16.8	8 Aug 72	18 Jul (14.9)	1 Sep 93	14 Jun 01

Table 5. Statistics (mean, s d , highest, lowest observed) for extreme rainwater for 1-25 day duration during the MMWS

Day (s)	Rainwater (bcm)					Date of occurrence		
	Mean (SD)	high	Date of occurrence	low	Date of occurrence	Mean (SD in days)	late	early
1	46.2 (9.4)	98.2	25 Jul 05	25.1	17 Aug 72	22 Jul (21.1)	4 Oct 55	10 Jun 91
2	76.3 (15.2)	148.5	25 Jul 05	42.0	17 Aug 72	23 Jul (21.0)	3 Oct 55	9 Jun 91
3	97.7 (20.1)	191.7	25 Jul 05	51.3	12 Aug 72	23 Jul (20.6)	3 Oct 55	8 Jun 91
4	114.9 (23.9)	219.1	25 Jul 05	58.8	17 Aug 72	22 Jul (18.3)	5 Sep 06	8 Jun 91
5	132.1 (26.7)	246.8	23 Jul 05	63.2	17 Aug 72	21 Jul (17.6)	5 Sep 06	7 Jun 91
6	148.5 (29.5)	265.8	23 Jul 05	67.5	17 Aug 72	21 Jul (17.7)	5 Sep 06	7 Jun 91
7	164.3 (32.2)	283.9	25 Jul 05	76.9	6 Aug 72	22 Jul (17.7)	5 Sep 06	7 Jun 91
8	180.1 (36.1)	317.0	25 Jul 05	87.2	6 Aug 72	22 Jul (17.9)	5 Sep 06	7 Jun 91
9	195.1 (40.4)	338.7	25 Jul 05	103.5	6 Aug 72	23 Jul (15.0)	1 Sep 93	30 Jun 07
10	210.8 (45.3)	362.6	25 Jul 05	112.9	6 Aug 72	23 Jul (15.0)	1 Sep 93	29 Jun 80
11	224.8 (49.6)	389.6	25 Jul 05	120.1	6 Aug 72	23 Jul (15.2)	1 Sep 93	22 Jun 80
12	237.5 (53.4)	423.5	25 Jul 05	126.4	6 Aug 72	22 Jul (15.1)	1 Sep 93	22 Jun 80
13	250.8 (55.3)	446.4	25 Jul 05	126.7	6 Aug 72	21 Jul (15.0)	1 Sep 93	22 Jun 80
14	264.4 (57.1)	459.7	25 Jul 05	130.0	6 Aug 72	23 Jul (15.2)	1 Sep 93	22 Jun 80
15	276.0 (58.6)	471.5	25 Jul 05	129.3	6 Aug 72	23 Jul (15.4)	2 Sep 93	22 Jun 80
16	288.3 (62.2)	501.7	25 Jul 05	128.9	6 Aug 72	22 Jul (15.5)	2 Sep 93	22 Jun 80
17	299.6 (65.3)	503.1	25 Jul 05	134.1	6 Aug 72	22 Jul (15.5)	2 Sep 93	22 Jun 80
18	311.1 (68.7)	501.7	12 Jul 05	148.6	6 Aug 72	20 Jul (15.3)	2 Sep 93	22 Jun 80
19	321.4 (73.2)	515.5	12 Jul 05	152.2	6 Aug 72	20 Jul (15.1)	2 Sep 93	22 Jun 80
20	333.6 (77.3)	537.1	12 Jul 05	155.1	6 Aug 72	19 Jul (15.2)	2 Sep 93	22 Jun 80
21	345.0 (80.8)	556.4	12 Jul 05	160.9	6 Aug 72	20 Jul (15.3)	2 Sep 93	22 Jun 80
22	358.1 (84.1)	575.3	5 Jul 05	175.5	14 Aug 87	19 Jul (14.7)	2 Sep 93	22 Jun 80
23	370.4 (88.5)	608.1	5 Jul 05	174.7	24 Aug 87	19 Jul (15.0)	2 Sep 93	22 Jun 80
24	382.3 (91.1)	626.6	5 Jul 05	174.3	24 Aug 87	18 Jul (15.9)	2 Sep 93	21 Jun 75
25	394.1 (95.4)	644.4	4 Jul 05	173.7	24 Aug 87	18 Jul (16.2)	2 Sep 93	14 Jun 01

Table 6. Correlation coefficient between the parameters indicated for extreme rain event concerning rainfall intensity and areal extent as well as extreme rainwater for 1- to 25-day duration during the MMWS over India

Duration	Concerning RI			Concerning area			Extreme rainwater					
	RI vs date	RI vs area	Date vs area	RI vs date	RI vs area	Date vs area	RW vs date	RW vs area	Date vs area	RW vs RI	RI vs area	RI vs date
1	-.09	.00	-.15	-.37	-.03	-.21	-.11	.22	-.07	.73	-.48	-.07
2	-.11	-.03	-.20	-.37	-.06	-.23	-.13	.42	-.08	.61	-.44	-.11
3	-.25	.00	.01	-.35	-.02	-.21	-.12	.52	-.07	.60	-.34	-.12
4	-.24	-.30	-.02	-.35	.06	.24	-.18	.54	-.08	.59	-.34	-.16
5	-.35	-.19	.14	-.19	-.03	-.26	-.18	.55	-.15	.53	-.40	-.08
6	-.43	-.25	.20	-.14	.03	-.37	-.16	.54	-.18	.63	-.30	-.03
7	-.46	-.48	.34	-.10	.09	-.37	-.17	.64	-.16	.52	-.31	-.03
8	-.48	-.37	.35	-.20	.09	-.29	-.15	.69	-.14	.43	-.34	-.03
9	-.52	-.43	.50	-.27	.14	-.29	-.25	.72	-.29	.42	-.32	.01
10	-.51	-.42	.53	-.32	.22	-.23	-.23	.70	-.28	.51	-.24	.00
11	-.43	-.38	.51	-.29	.09	-.24	-.26	.73	-.25	.51	-.20	-.10
12	-.42	-.40	.53	-.25	.11	-.28	-.24	.73	-.28	.52	-.19	-.04
13	-.44	-.36	.40	-.26	.11	-.24	-.16	.77	-.09	.52	-.12	-.18
14	-.48	-.31	.41	-.17	.10	-.20	-.25	.78	-.15	.43	-.21	-.23
15	-.49	-.32	.24	-.23	.05	-.18	-.23	.79	-.19	.41	-.22	-.14
16	-.50	-.33	.29	-.29	.05	-.21	-.21	.77	-.18	.47	-.18	-.14
17	-.54	-.32	.29	-.26	.07	-.20	-.25	.80	-.21	.40	-.21	-.14
18	-.51	-.31	.36	-.15	.06	-.20	-.24	.83	-.15	.33	-.23	-.21
19	-.50	-.21	.27	-.15	.08	-.19	-.21	.84	-.13	.37	-.18	-.22
20	-.56	-.30	.38	-.19	.26	-.16	-.19	.85	-.11	.36	-.17	-.21
21	-.52	-.23	.36	-.23	.30	-.23	-.20	.84	-.13	.39	-.15	-.21
22	-.54	-.25	.49	-.23	.27	-.22	-.21	.84	-.13	.39	-.15	-.22
23	-.51	-.18	.41	-.37	.35	-.17	-.24	.84	-.17	.35	-.19	-.19
24	-.52	-.25	.33	-.34	.34	-.18	-.18	.84	-.11	.32	-.24	-.19
25	-.49	-.25	.24	-.22	.35	-.13	-.18	.85	-.14	.34	-.18	-.11
Mean	**-0.44**	**-0.27**	**0.29**	**-0.25**	**0.12**	**-0.21**	**-0.20**	**0.71**	**-0.16**	**0.47**	**-0.25**	**-0.13**

Table 7. Statistics (mean, s d, highest, lowest observed) for spatio-temporal extreme rain event concerning rainfall intensity for 1- to 25-day duration during the MMWS

Day (s)	Rainfall intensity (mm/day)					Areal extent (%age area of India)					Date of occurrence		
	Mean (±SD)	high	Date of occurrence	low	Date of occurrence	Mean (±SD)	High	Date of occurrence	low	Date of occurrence	Mean (±SD in days)	Late	Early
1	43.2 (7.7)	73.3	25 Jul 05	32.7	31 Jun 52	25.8 (10.0)	47.6	2 Jul 56	7.5	14 Jun 73	2 Aug (34.0)	5 Oct 83	4 Jun 76
2	79.3 (11.1)	120.4	24 Jul 05	60.9	14 Aug 72	28.3 (10.1)	47.6	1 Jul 56	10.5	23 Aug 86	28 Jul (34.7)	18 Oct 99	4 Jun 76
3	112.2 (14.2)	158.4	11 Aug 79	90.1	14 Aug 72	29.1 (9.1)	46.1	24 Jul 05	11.8	23 Sep 69	26 Jul (33.1)	18 Oct 99	4 Jun 76
4	143.6 (16.6)	198.4	10 Aug 79	117.0	14 Aug 93	29.2 (8.8)	48.1	24 Jul 05	12.6	11 Jun 60	25 Jul (32.5)	18 Oct 99	4 Jun 76
5	173.8 (17.8)	229.6	10 Aug 79	146.9	11 Aug 93	29.1 (8.6)	47.3	23 Jul 05	9.7	6 Oct 60	25 Jul (31.9)	9 Oct 73	6 Jun 91
6	203.6 (19.4)	265.7	10 Aug 79	173.0	13 Aug 72	29.1 (8.8)	46.5	30 Jun 56	9.4	9 Oct 73	26 Jul (32.5)	9 Oct 73	5 Jun 91
7	233.3 (21.1)	295.3	10 Aug 79	198.7	12 Aug 72	28.6 (8.5)	45.9	22 Jul 05	8.8	98 Oct 73	23 Jul (32.5)	9 Oct 73	5 Jun 91
8	262.2 (23.3)	331.9	10 Aug 79	221.6	11 Aug 72	28.7 (8.1)	45.0	21 Jul 05	10.5	5 Oct 60	22 Jul (31.4)	6 Oct 03	3 Jun 91
9	290.5 (24.7)	365.7	30 Jun 07	249.5	10 Aug 72	28.3 (7.8)	44.8	22 Jul 05	9.7	5 Oct 60	23 Jul (31.0)	6 Oct 03	2 Jun 91
10	319.0 (26.0)	401.0	30 Jun 07	275.4	11 Aug 93	28.7 (7.9)	46.5	23 Jul 05	9.0	6 Oct 03	22 Jul (29.9)	6 Oct 03	2 Jun 91
11	347.0 (27.0)	436.3	29 Jun 07	299.4	11 Aug 93	28.6 (7.4)	45.7	22 Jul 05	8.4	6 Oct 03	20 Jul (28.7)	6 Oct 03	3 Jun 91
12	374.4 (28.4)	470.9	29 Jun 07	322.8	11 Aug 93	29.6 (7.2)	45.3	22 Jul 05	8.0	6 Oct 03	18 Jul (27.1)	6 Oct 03	2 Jun 91
13	402.0 (30.3)	502.6	29 Jun 07	345.6	11 Aug 93	29.0 (7.9)	45.0	22 Jul 05	7.5	5 Oct 60	19 Jul (29.0)	6 Oct 03	2 Jun 91
14	429.2 (31.1)	530.3	29 Jun 07	374.9	5 Aug 72	28.8 (7.8)	44.6	21 Jul 05	7.0	5 Oct 60	18 Jul (29.0)	6 Oct 03	2 Jun 91
15	456.4 (31.6)	554.0	10 Aug 79	396.0	4 Aug 72	29.4 (7.2)	45.7	22 Jul 05	7.8	6 Oct 03	18 Jul (26.3)	6 Oct 03	3 Jun 91
16	483.2 (32.2)	581.0	10 Aug 79	418.4	3 Aug 72	29.1 (7.0)	40.5	29 Jun 56	8.1	6 Oct 03	16 Jul (26.7)	6 Oct 03	2 Jun 91
17	510.2 (33.7)	607.6	23 Jun 07	441.5	30 Aug 72	28.7 (7.1)	40.0	28 Jun 56	8.6	6 Oct 03	17 Jul (27.0)	6 Oct 03	9 Jun 70
18	537.1 (34.7)	640.3	23 Jun 07	469.7	29 Aug 72	28.7 (6.9)	39.6	27 Jun 56	9.3	6 Oct 03	17 Jul (26.6)	6 Oct 03	11 Jun 01
19	563.7 (35.0)	671.7	22 Jun 07	489.6	11 Aug 93	28.8 (6.7)	43.3	22 Jul 05	10.0	6 Oct 03	18Jul (25.7)	6 Oct 03	12 Jun 01
20	589.8 (36.0)	701.3	22 Jun 07	508.6	11 Aug 93	28.5 (6.6)	40.5	23 Jul 05	10.3	6 Oct 03	17 Jul (26.3)	6 Oct 03	12 Jun 01
21	616.0 (37.0)	727.8	22 Jun 07	530.4	8 Sep 93	28.4 (6.3)	40.3	22 Jul 05	10.3	6 Oct 03	18 Jul (27.3)	6 Oct 03	12 Jun 01
22	642.6 (37.8)	753.4	29 Jun 07	555.7	6 Sep 93	28.2 (6.1)	39.1	22 Jul 05	10.0	6 Oct 03	17 Jul (27.4)	6 Oct 03	11 Jun 70
23	669.2 (39.3)	786.8	29 Jun 07	581.1	6 Sep 93	28.2 (5.8)	39.1	21 Jul 05	9.7	6 Oct 03	16 Jul (27.4)	6 Oct 03	1 Jun 70
24	695.5 (40.6)	813.6	29 Jun 07	604.1	5 Sep 93	28.2 (5.8)	40.7	4 Jul 05	9.5	6 Oct 03	15 Jul (27.5)	6 Oct 03	10 Jun 70
25	721.5 (41.7)	844.4	16 Jun 07	624.1	4 Sep 93	28.3 (5.9)	41.0	4 Jul 05	9.2	6 Oct 03	15 Jul (26.6)	6 Oct 03	10 Jun 80

Table 8. Important climatological features of the spatio-temporal extreme rain events concerning areal extent of 1- to 25-day duration during the MMWS

Day (s)	Rainfall intensity (mm/day)					Areal extent (%age area of India)					Date of occurrence		
	Mean (±SD)	high	Date of occurrence	low	Date of occurrence	Mean (±SD)	High	Date of occurrence	low	Date of occurrence	Mean ((±SD in days)	late	early
1	29.1 (4.1)	38.3	2 Jul 80	20.4	14 Aug 87	49.8 (5.6)	64.0	25 Jul 83	31.2	24 Aug 72	24 Jul (16.9)	6 Sep 07	14 Jun 01
2	58.3 (7.7)	72.9	26 Jul 05	44.1	1 Sep 93	46.9 (5.1)	57.5	25 Jul 83	31.0	23 Aug 72	24 Jul (15.8)	1 Sep 93	28 Jun 55
3	86.3 (10.3)	112.3	12 Jul 94	67.0	31 Aug 93	44.9 (4.7)	54.5	25 Jul 83	30.5	23 Aug 72	25 Jul (16.8)	6 Sep 69	28 Jun 55
4	115.5 (15.0)	174.6	25 Jul 05	87.1	22 Aug 72	43.1 (4.6)	52.4	25 Jul 83	29.9	22 Aug 72	25 Jul (16.6)	6 Sep 69	27 Jun 55
5	142.1 (15.2)	172.6	21 Jul 89	107.7	21 Aug 72	42.1 (4.4)	49.9	20 Jul 95	28.7	21 Aug 72	23 Jul (15.6)	1 Sep 93	27 Jun 55
6	168.7 (16.0)	207.9	13 Jul 88	139.9	22 Aug 72	41.2 (4.2)	50.8	19 Jul 95	28.3	22 Aug 72	24 Jul (15.7)	1 Sep 93	30 Jun 98
7	196.8 (19.0)	240.0	13 Jul 88	149.8	19 Aug 72	40.3 (4.0)	49.8	18 Jul 95	28.0	19 Aug 72	23 Jul (15.7)	1 Sep 93	27 Jun 80
8	223.8 (20.8)	275.0	28 Jun 05	185.9	1 Aug 74	39.5 (3.9)	48.6	18 Jul 95	28.2	17 Aug 72	22 Jul (15.9)	1 Sep 93	26 Jun 80
9	250.3 (23.8)	303.8	21 Jul 89	205.1	6 Aug 51	38.8 (3.8)	47.1	27 Jun 05	28.4	17 Aug 72	23 Jul (15.5)	31 Aug 93	27 Jun 05
10	277.0 (24.7)	341.3	21 Jul 89	227.5	7 Aug 51	38.3 (3.8)	46.8	26 Jul 05	27.8	16 Aug 72	22 Jul (14.7)	30 Aug 93	28 Jun 98
11	301.7 (25.0)	353.5	12 Jul 94	252.4	7 Aug 51	37.9 (3.8)	46.8	26 Jul 05	27.7	17 Aug 72	23 Jul (15.1)	29 Aug 93	29 Jun 98
12	331.4 (27.2)	395.3	25 Jul 05	276.4	6 Aug 51	37.5 (3.8)	46.7	25 Jul 05	27.4	16 Aug 72	22 Jul (15.0)	29 Aug 93	29 Jun 98
13	357.6 (28.7)	421.4	25 Jul 05	299.7	4 Aug 51	37.1 (3.8)	46.6	25 Jul 05	26.9	16 Aug 72	21 Jul (14.5)	29 Aug 93	28 Jun 98
14	385.8 (31.0)	467.1	24 Jul 05	324.6	4 Aug 51	36.8 (3.7)	46.4	24 Jul 05	26.9	12 Aug 72	20 Jul (14.4)	28 Aug 93	28 Jun 60
15	411.8 (33.0)	498.5	23 Jul 05	344.4	7 Aug 55	36.4 (3.6)	46.2	23 Jul 05	26.9	11 Aug 72	21 Jul (14.8)	29 Aug 93	27 Jun 60
16	437.3 (32.9)	521.6	23 Jul 05	369.1	3 Aug 51	36.1 (3.6)	45.9	23 Jul 05	26.7	10 Aug 72	20 Jul (14.8)	29 Aug 93	27 Jun 56
17	463.6 (35.1)	550.7	22 Jul 05	390.6	8 Aug 55	35.7 (3.6)	45.4	22 Jul 05	26.7	11 Aug 72	20 Jul (14.7)	29 Aug 93	27 Jun 80
18	493.7 (35.6)	575.6	21 Jul 05	415.2	7 Aug 55	35.4 (3.6)	45.0	21 Jul 05	26.5	10 Aug 72	19 Jul (14.4)	29 Aug 93	27 Jun 80
19	519.1 (37.5)	598.8	25 Aug 06	440.2	6 Aug 55	35.1 (3.6)	44.5	20 Jul 05	26.2	10 Aug 72	19 Jul (14.8)	29 Aug 93	26 Jun 80
20	546.3 (36.7)	625.1	12 Jul 89	465.6	6 Aug 55	34.8 (3.6)	44.0	19 Jul 05	26.3	8 Aug 72	18 Jul (14.9)	29 Aug 93	21 Jun 80
21	575.3 (38.9)	658.9	25 Aug 06	488.7	5 Aug 55	34.6 (3.6)	43.9	18 Jul 05	26.0	8 Aug 72	17 Jul (14.8)	29 Aug 93	21 Jun 80
22	597.5 (39.2)	672.4	15 Jul 05	511.4	4 Aug 55	34.4 (3.6)	43.8	15 Jul 05	26.0	6 Aug 72	17 Jul (15.0)	28 Aug 93	21 Jun 80
23	625.0 (42.8)	726.8	25 Aug 06	534.3	3 Aug 55	34.2 (3.6)	43.9	14 Jul 05	25.8	6 Aug 72	17 Jul (14.9)	26 Aug 93	21 Jun 80
24	650.7 (43.3)	752.4	25 Aug 06	557.6	17 Aug 96	34.0 (3.7)	43.9	14 Jul 05	25.4	25 Aug 93	16 Jul (14.8)	25 Aug 06	21 Jun 80
25	677.9 (44.0)	786.8	25 Aug 06	578.9	16 Aug 96	33.9 (3.7)	43.9	12Jul 05	25.2	1 Sep 93	16 Jul (15.0)	1 Sep 93	21 Jun 80

Table 9. Important climatological features of the spatio-temporal extreme rainwater of 1- to 25-day duration during the MMWS

Day (s)	Rainwater (bcm)					Date of occurrence		
	Mean (±SD)	high	Date of occurrence	low	Date of occurrence	Mean (±SD in days)	Late	early
1	46.2 (9.4)	98.2	25 Jul 05	25.1	17 Aug 72	22 Jul (21.1)	4 Oct 55	10 Jun 91
2	86.3 (15.2)	157.7	24 Jul 05	49.8	17 Aug 72	23 Jul (21.0)	3 Oct 55	9 Jun 91
3	121.1 (20.6)	212.1	24 Jul 05	69.6	16 Aug 72	22 Jul (20.8)	3 Oct 55	8 Jun 91
4	153.0 (25.8)	267.0	24 Jul 05	85.3	15 Aug 72	22 Jul (21.7)	2 Oct 55	7 Jun 91
5	184.4 (28.9)	309.6	24 Jul 05	109.2	14 Aug 72	21 Jul (21.2)	31 Sep 55	6 Jun 91
6	213.3 (32.0)	349.6	23 Jul 05	128.0	13 Aug 72	22 Jul (20.4)	30 Sep 55	6 Jun 91
7	241.5 (34.3)	380.5	22 Jul 05	149.3	12 Aug 72	22 Jul (20.3)	29 Sep 55	6 Jun 91
8	268.5 (36.8)	409.9	22 Jul 05	167.3	11 Aug 72	21 Jul (20.2)	28 Sep 55	6 Jun 91
9	295.6 (40.6)	452.7	24 Jul 05	186.6	10 Aug 72	19 Jul (17.6)	31 Aug 93	5 Jun 91
10	321.7 (45.2)	492.8	23 Jul 05	202.7	9 Aug 72	19 Jul (17.4)	31 Aug 93	4 Jun 91
11	347.6 (48.6)	526.7	23 Jul 05	223.4	8 Aug 72	18 Jul (17.1)	30 Aug 93	3 Jun 91
12	373.3 (52.4)	560.2	23 Jul 05	239.9	7 Aug 72	18 Jul (16.8)	31 Aug 93	7 Jun 01
13	399.3 (55.2)	598.4	24 Jul 05	257.6	6 Aug 72	19 Jul (15.5)	31 Aug 93	21 Jun 80
14	424.3 (58.0)	638.5	23 Jul 05	273.1	6 Aug 72	18 Jul (15.5)	31 Aug 93	21 Jun 80
15	449.5 (60.3)	672.3	23 Jul 05	292.3	10 Aug 72	18 Jul (15.6)	30 Aug 93	20 Jun 80
16	473.6 (62.4)	703.2	22 Jul 05	311.3	12 Aug 72	18 Jul (15.8)	31 Aug 93	19 Jun 80
17	496.4 (64.6)	729.6	21 Jul 05	329.3	11 Aug 72	18 Jul (15.5)	30 Aug 93	23 Jun 07
18	520.4 (66.4)	755.9	21 Jul 05	348.5	10 Aug 72	17 Jul (16.0)	29 Aug 93	22 Jun 07
19	544.3 (68.0)	778.6	18 Jul 05	365.8	10 Aug 72	16 Jul (15.3)	29 Aug 93	21 Jun 07
20	566.5 (70.8)	812.4	18 Jul 05	385.3	8 Aug 72	15 Jul (15.8)	29 Aug 93	20 Jun 07
21	589.1 (73.6)	838.8	18 Jul 05	398.6	29 Aug 93	15 Jul (15.5)	29 Aug 93	19 Jun 07
22	611.1 (77.0)	865.0	16 Jul 05	405.9	29 Aug 93	15 Jul (16.0)	29 Aug 93	18 Jun 07
23	634.3 (80.7)	893.7	12 Jul 05	415.7	29 Aug 93	14 Jul (15.8)	29 Aug 93	17 Jun 07
24	657.3 (84.2)	931.7	12 Jul 05	426.6	25 Aug 93	14 Jul (15.4)	26 Aug 06	16 Jun 07
25	679.5 (88.2)	971.9	12 Jul 05	444.0	1 Sep 93	14 Jul (15.7)	1 Sep 93	15 Jun 07

Table 10. Climatology of rainfall amount and date of occurrence of 1-DSG extreme for 1 to 150 day duration

Day (s)	Rainfall Amount (mm)					Date of occurrence		
	Mean (SD)	high	Date of occurrence	low	Date of occurrence	Mean (SD in days)	late	early
1	340.7 (61.5)	473.4	27 Jul 05	221.4	12 Jul 62	5 Aug (44.5)	24 Nov 58	14 May 79
2	491.7 (79.7)	750.5	9 Jun 91	328.1	27 Jun 57	5 Aug (43.4)	22 Dec 83	11 May 90
3	600.8 (98.0)	911.1	8 Jun 91	437.0	27 Jun 57	1 Aug (39.9)	20 Nov 70	11 May 90
4	677.3 (110.4)	936.8	7 Jun 07	509.4	30 Jun 72	24 Jul (36.2)	20 Nov 70	11 May 90
5	755.9 (127.8)	1088.9	29 Jun 05	561.4	3 Jul 59	21 Jul (29.2)	19 Nov 70	8 Jun 91
6	830.6 (147.6)	1224.3	19 Jun 05	641.3	29 Jun 81	15 Jul (24.2)	19 Sep 00	5 Jun 61
7	899.8 (164.5)	1415.9	18 Jun 05	689.4	3 Jul 01	13 Jul (20.8)	2 Sep 66	6 Jun 61
8	963.7 (184.1)	1488.6	18 Jun 05	702.9	2 Sep 66	14 Jul (19.1)	2 Sep 66	7 Jun 91
9	1020.4 (193.7)	1551.4	25 Jul 07	707.5	2 Sep 66	13 Jul (19.4)	2 Sep 66	4 Jun 61
10	1078.1 (204.8)	1724.2	24 Jun 06	765.7	28 Jun 87	13 Jul (17.6)	23 Aug 78	11 Jun 96
20	1573.7 (307.6)	2716.5	27 Aug 06	990.1	26 Jun 87	8 Jul (17.0)	27 Aug 06	6 Jun 71
30	2008.6 (419.6)	3544.0	19 Aug 06	1271.8	26 Jul 02	2 Jul (15.9)	19 Aug 06	1 Jun 71
40	2428.9 (505.4)	4070.2	2 Aug 06	1614.3	10 Jul 02	27 Jun (13.4)	2 Aug 06	3 Jun 00
50	2830.7 (577.4)	5208.2	29 Jul 06	1845.3	24 Jun 02	24 Jun (12.3)	29 Jul 06	27 May 00
60	3180.5 (631.5)	5681.1	26 Jul 06	2141.9	19 Jun 02	22 Jun (12.1)	26 Jul 06	19 May 00
70	3498.8 (732.9)	6033.0	18 Jun 05	2268.6	12 Jun 66	16 Jun (11.7)	25 Jul 06	16 May 00
80	3745.7 (761.3)	6263.0	20 Jul 06	2362.1	13 Jun 66	12 Jun (9.5)	20 Jul 06	22 May 99
90	3945.3 (787.4)	6619.7	26 Jun 06	2581.5	14 Jun 66	10 Jun (10.1)	2 Jul 54	15 May 99
100	4118.5 (842.5)	6956.8	25 Jun 06	2660.6	4 Jun 66	6 Jun (11.5)	3 Jul 62	9 May 99
110	4253.8 (859.1)	7190.6	20 Jun 06	2717.4	13 Jun 66	5 Jun (12.1)	2 Jul 62	12 May 05
120	4380.0 (869.7)	7348.1	28 May 06	2815.6	7 Jun 66	4 Jun (10.8)	2 Jul 62	1 May 05
130	4486.4 (895.0)	7694.9	31 May 06	2834.6	4 Jun 66	5 Jun (10.7)	24 Jun 97	7 May 90
140	4560.3 (911.8)	7788.6	23 May 06	2879.5	4 Jun 66	29 May (11.4)	18 Jun 97	30 Apr 58
150	4612.3 (916.7)	7797.5	11 May 06	2914.0	3 May 66	22 May (11.0)	19 Jun 97	1 May 58

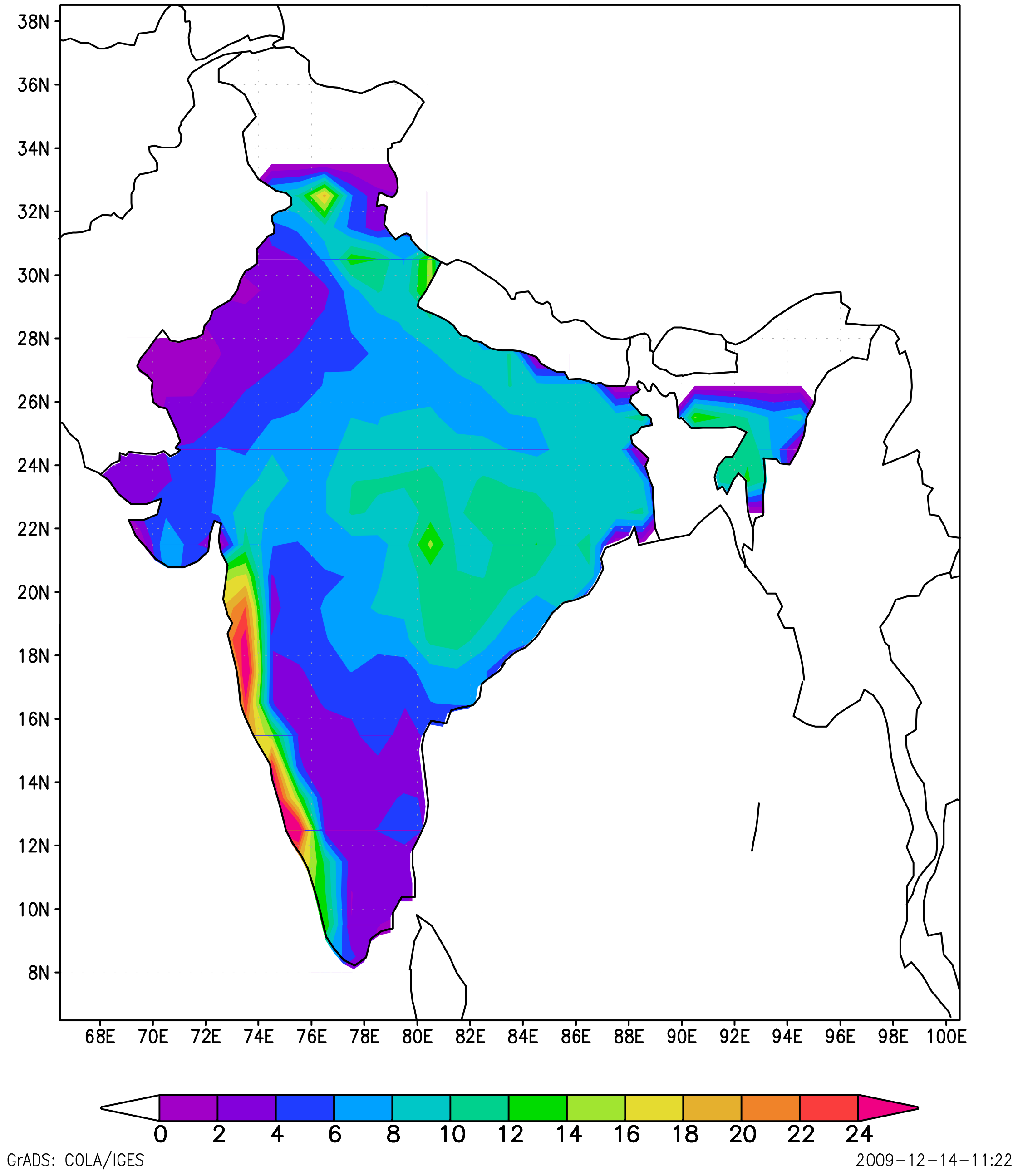

Figure 1. The daily mean monsoon rainfall (DMMR) across the country in mm per day.

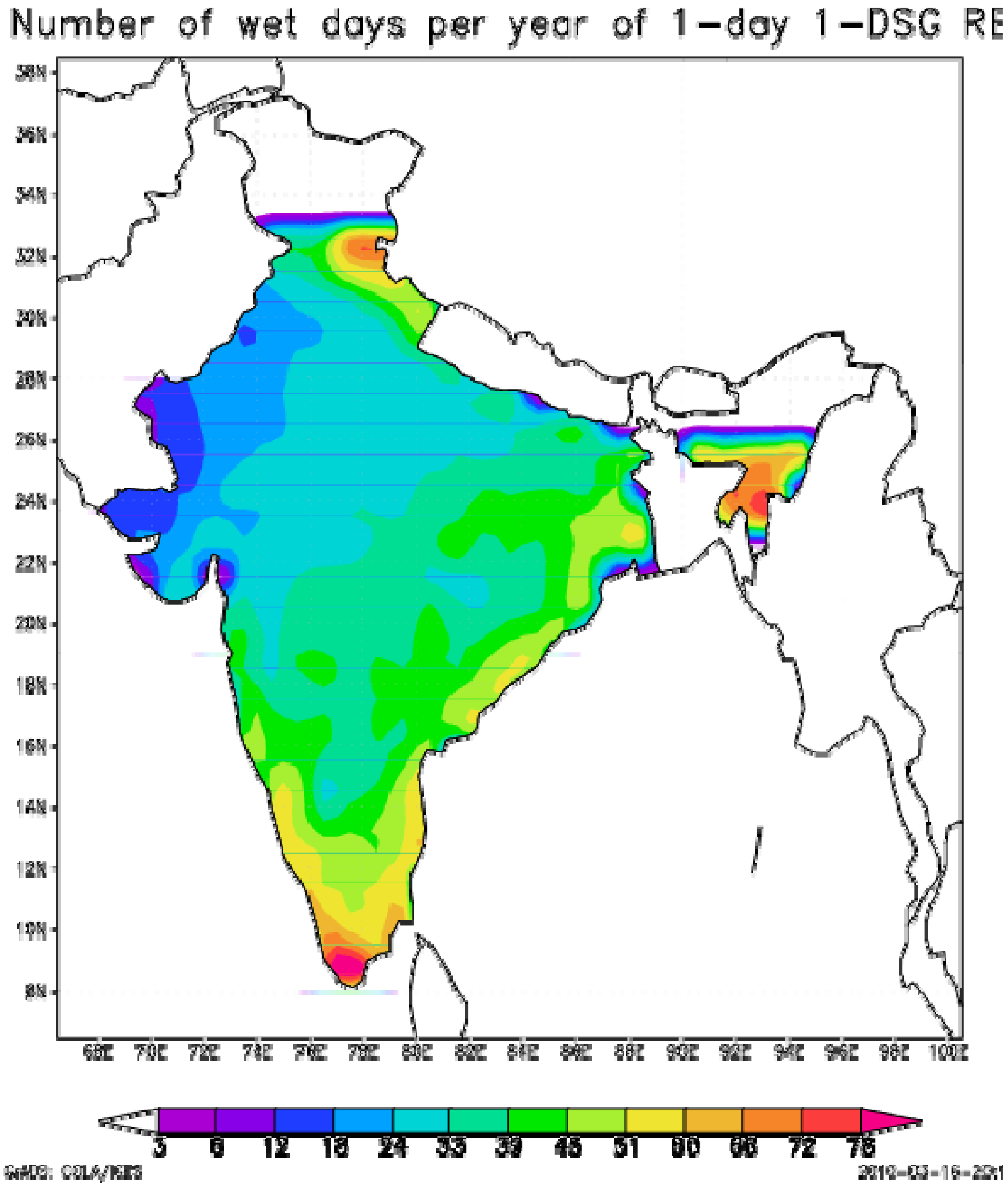

Figure 2. The annual mean number of wet days across the country according to the DMMR threshold.

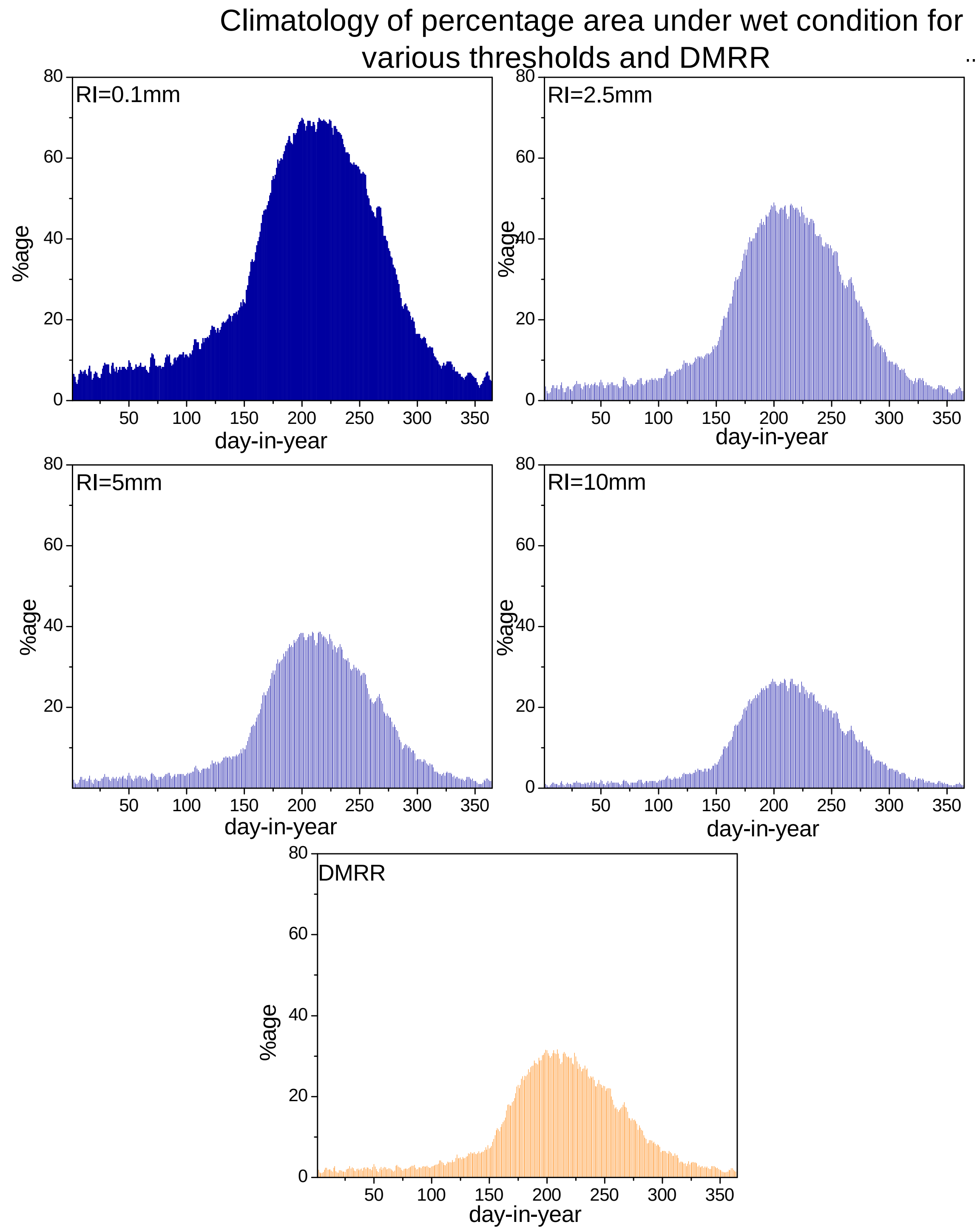

Figure 3. The daily histogram of the area of the country under wet conditions according to the four chosen thresholds (0.1, 2.5, 5.0 and 10.0mm/day and the DMMR).

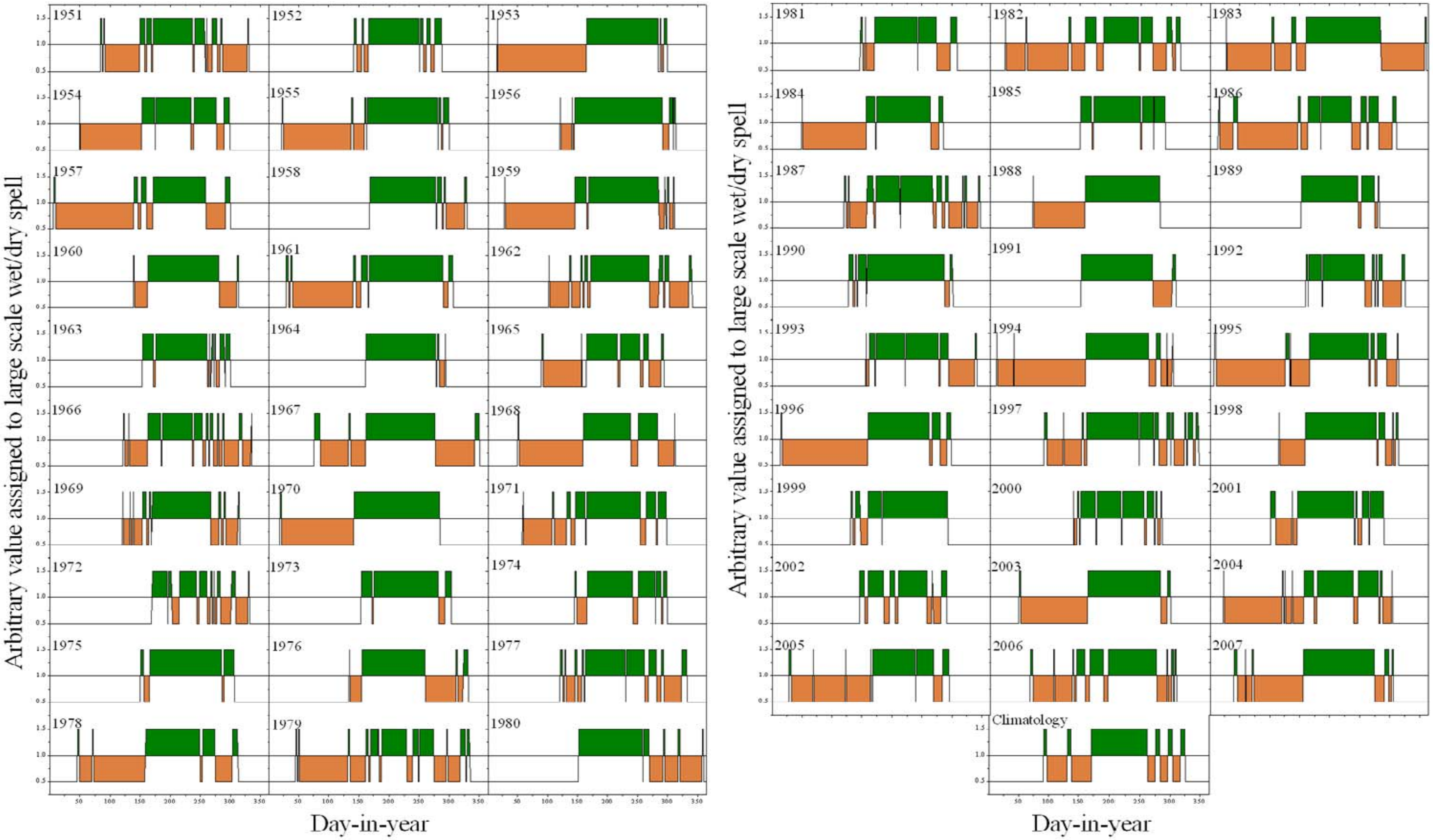

Figure 4. Year-wise sequence of large-scale wet and dry spells over India during 1951-2007. Green bars indicate large-scale wet spell and orange bars large-scale dry spell.

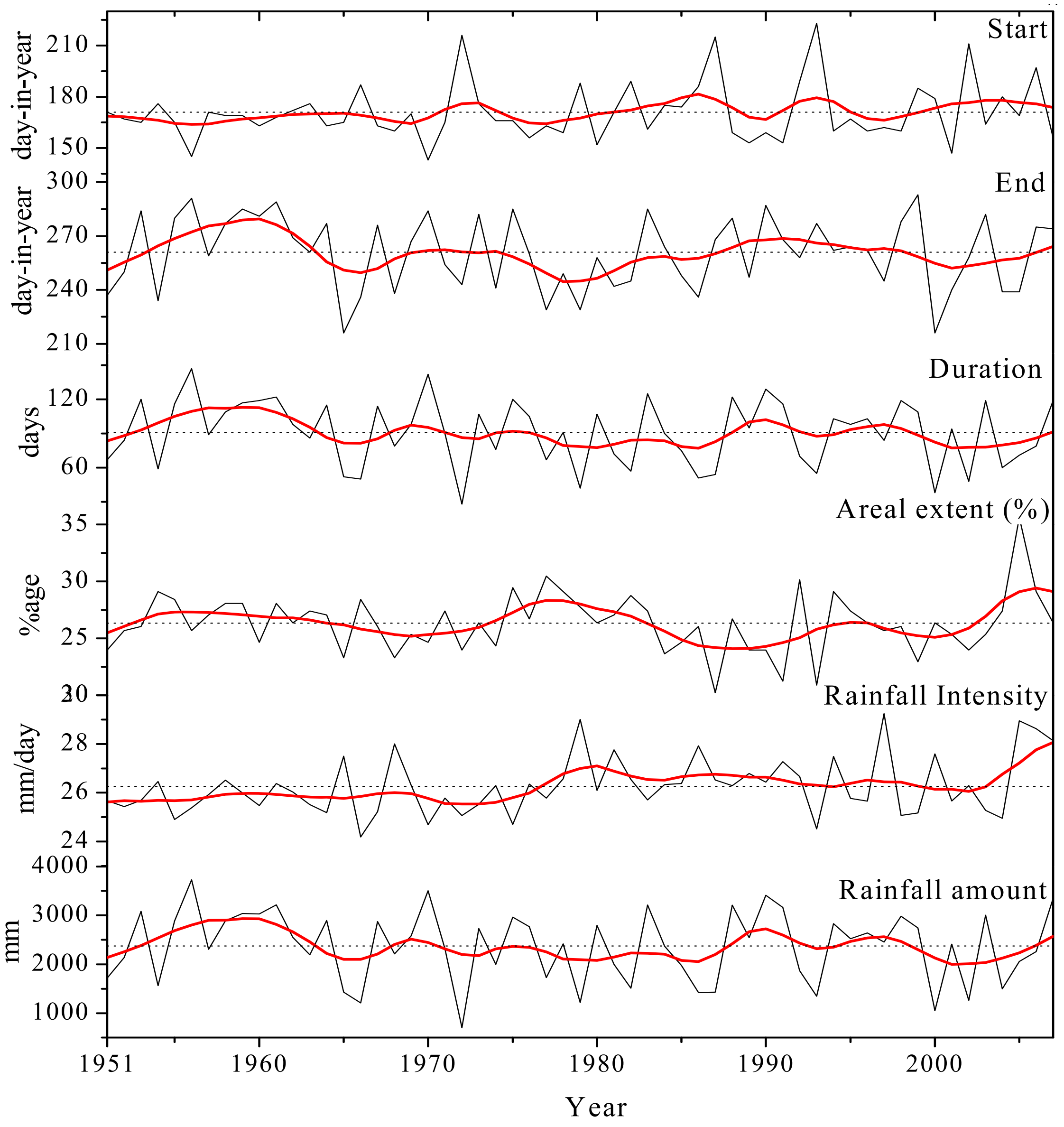

Figure 5. Fluctuations in the parameters of the main monsoon wet spell (MMWS): 1951-2007. Thin curve is the actual values and thick curve 9-point Gaussian low-pass filtered values.

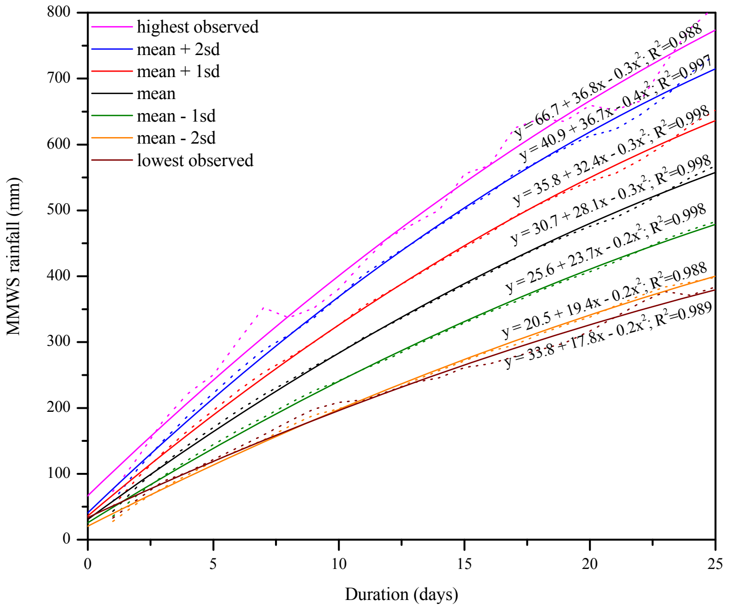

Figure 6. Increase in highest/lowest observed, mean ± 2sd (standard deviation), mean ± 1sd and mean rainfall with increase in duration from 1- to 25-day extreme rain event concerning rainfall intensity during the MMWS over India. Dashed curve is the actual values and continuous curve second-degree polynomial fit.

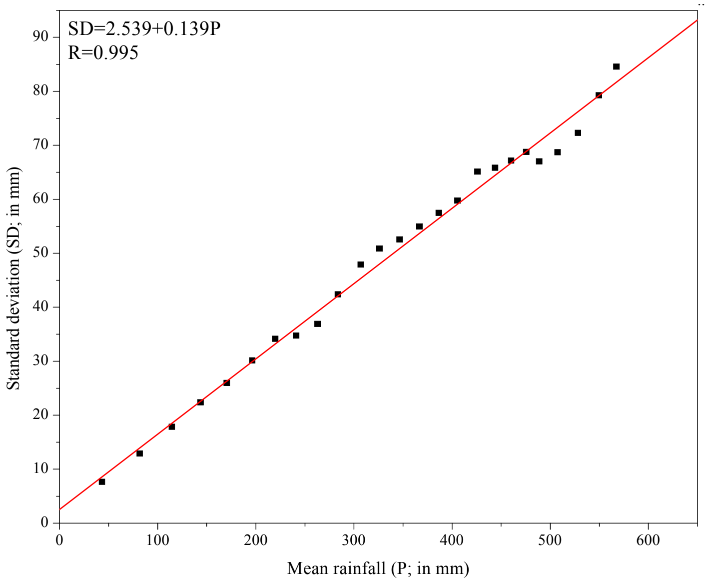

Figure 7. Relationship between standard deviation and mean of 1- to 25-day extreme rainfall concerning rainfall intensity during the MMWS over India. Filled squares indicates actual values and continuous the fitted line.

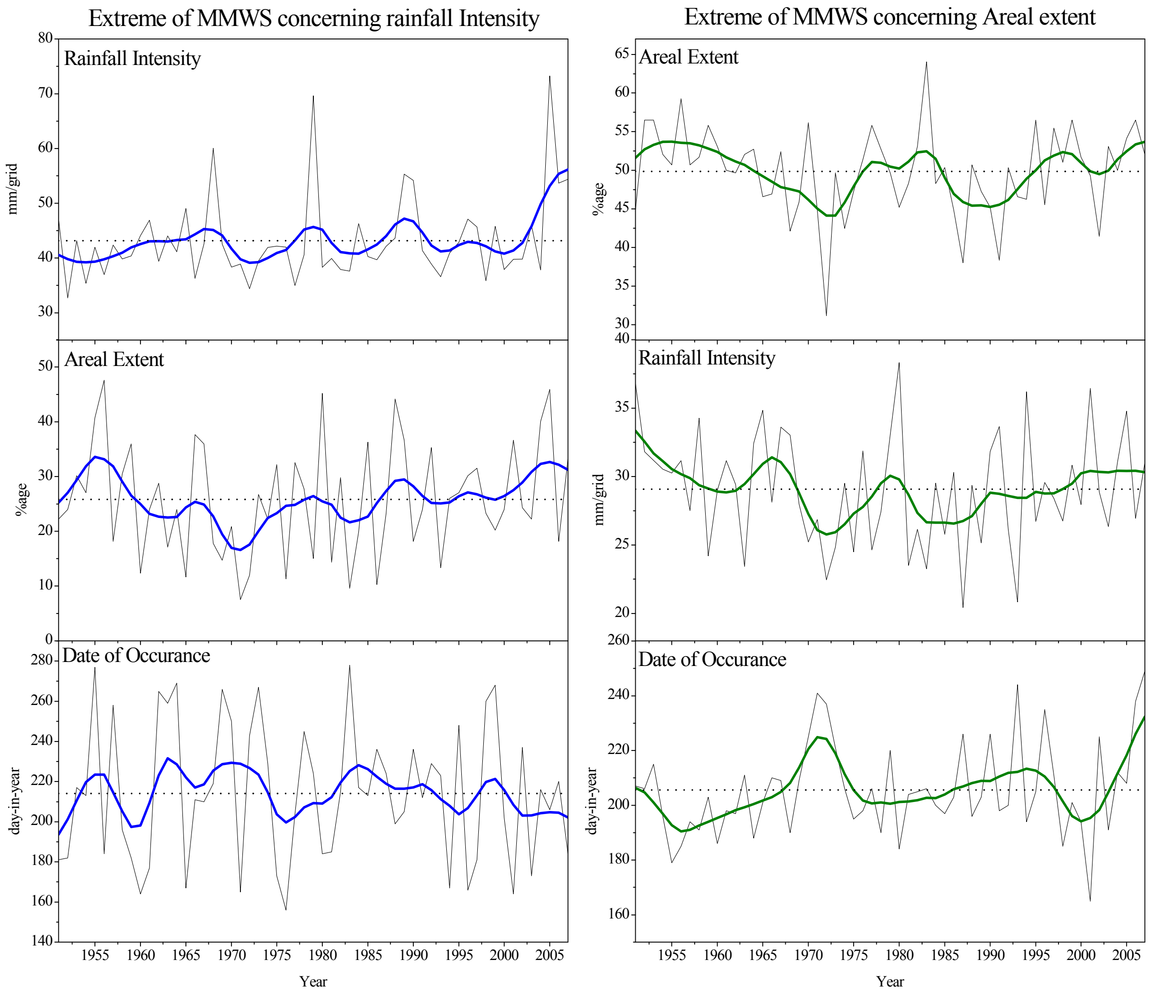

Figure 8. Interannual variation of the parameters of the 1-day extreme rain event concerning rainfall intensity and areal extent during the MMWS. Thin curve is the actual values and thick curve 9-point Gaussian low-pass filtered values.

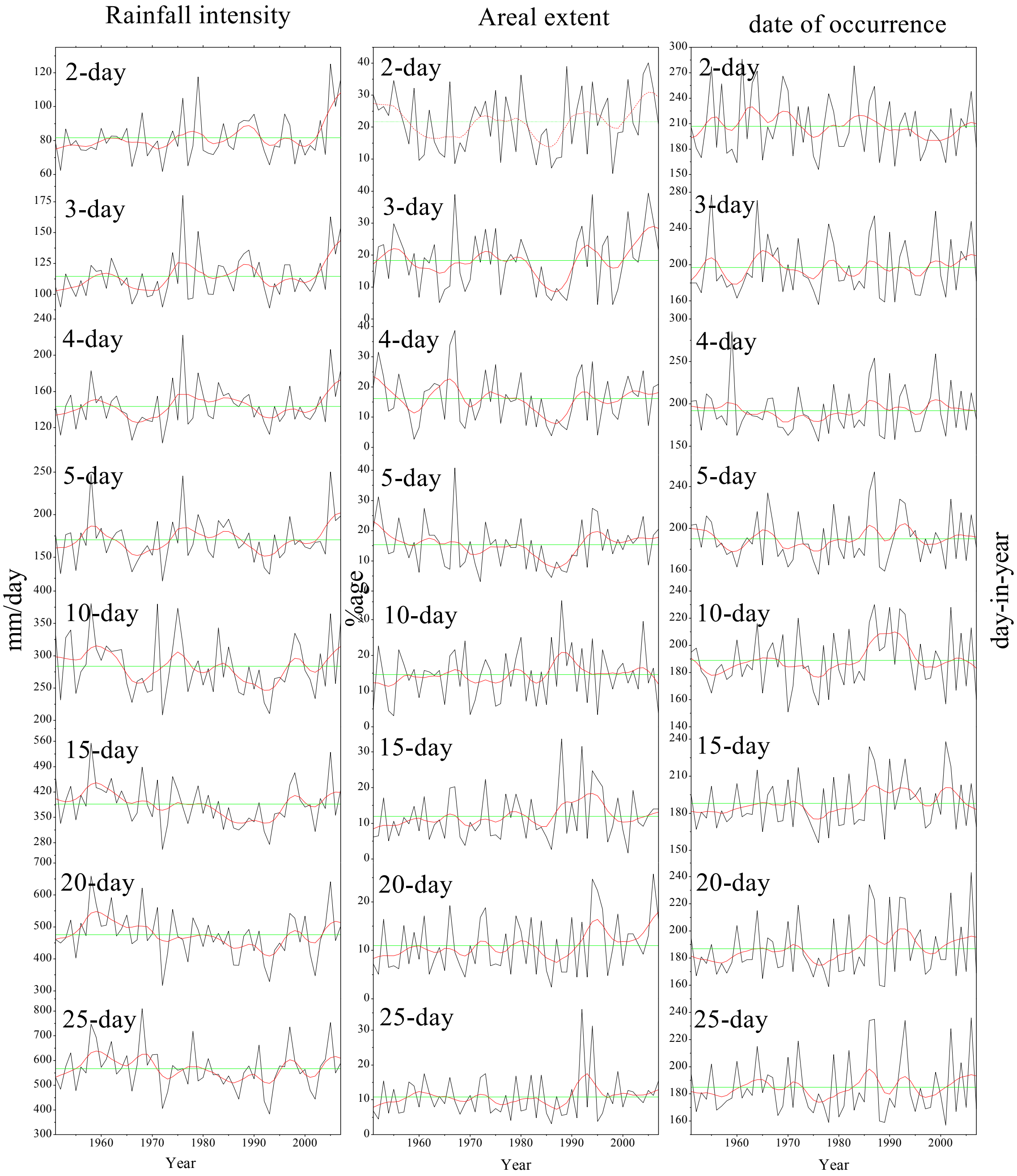

Figure 9. Interannual variation of the parameters of the extreme rain event concerning rainfall intensity for 2- to 25-day duration during the MMWS. Thin curve is the actual values and thick curve 9-point Gaussian low-pass filtered values.

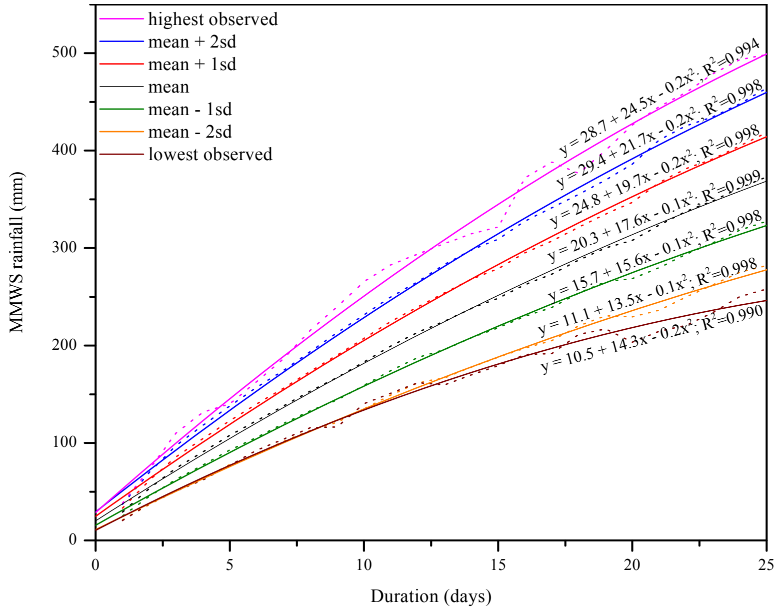

Figure 10. Increase in highest/lowest observed, mean ± 2sd (standard deviation), mean ± 1sd and mean rainfall with increase in duration from 1- to 25-day extreme rain event concerning areal extent during the MMWS over India. Dashed curve is the actual values and continuous curve second-degree polynomial fit.

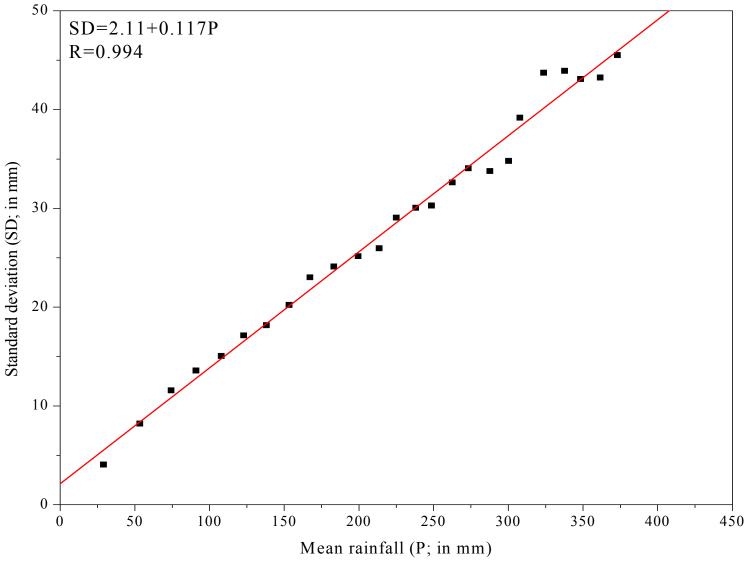

Figure 11. Relationship between standard deviation and mean of 1- to 25-day extreme rainfall concerning areal extent during the MMWS over India. Filled squares indicates actual values and continuous the fitted line.

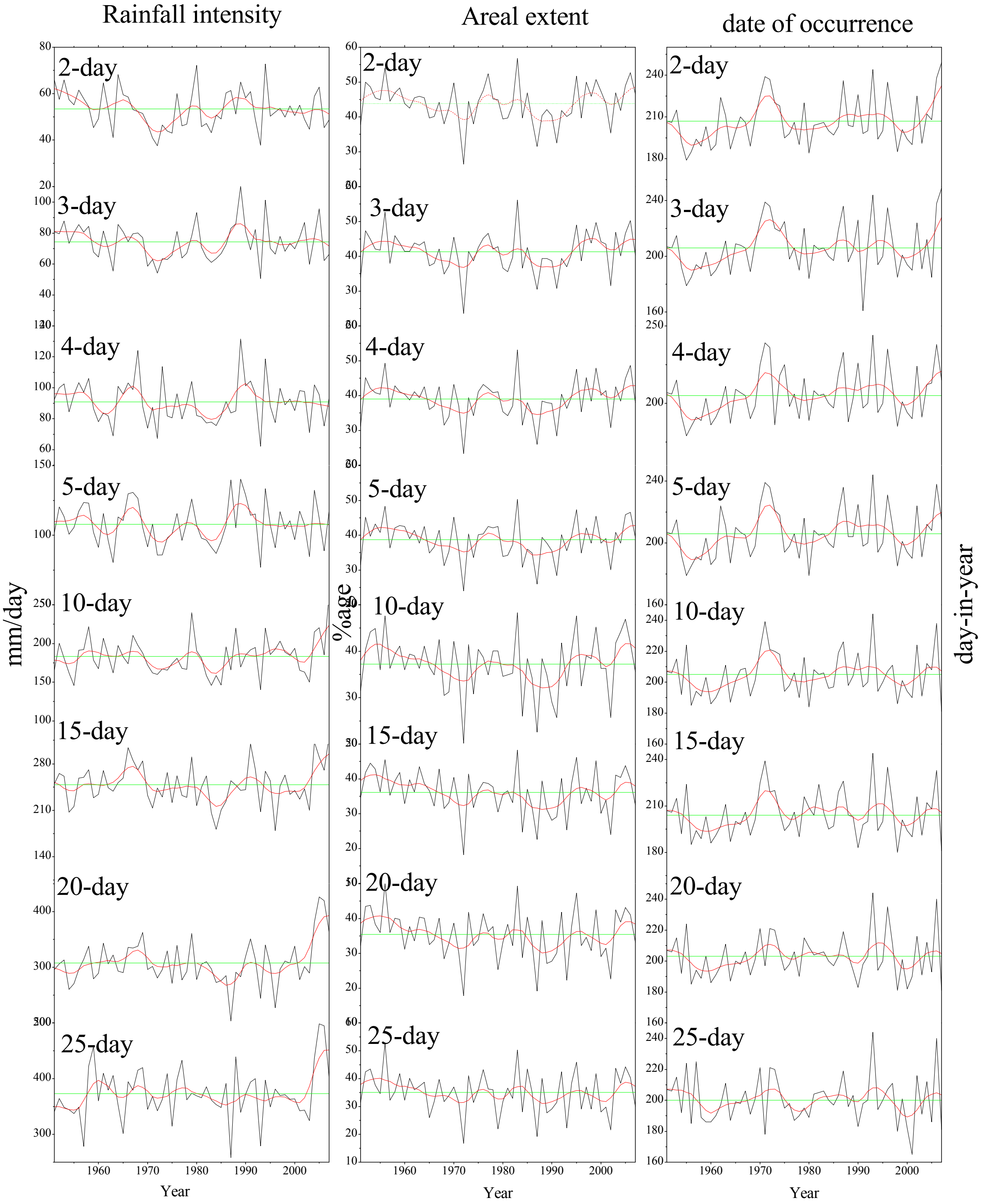

Figure 12. Interannual variation of the parameters of the extreme rain event concerning areal extent for 2- to 25-day duration during the MMWS. Thin curve is the actual values and thick curve 9-point Gaussian low-pass filtered values.

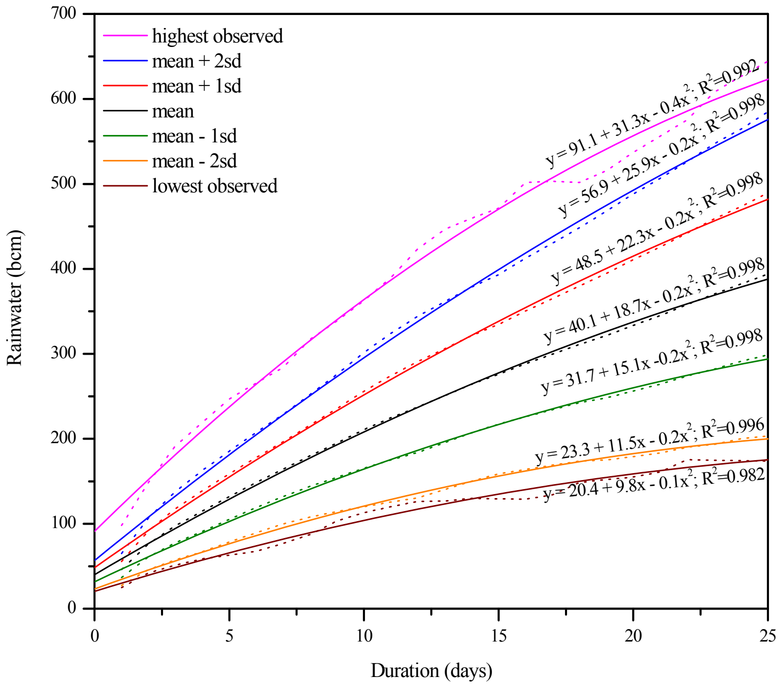

Figure 13. Increase in extreme highest/lowest observed, mean ± 2sd (standard deviation), mean ± 1sd and mean rainwater with the increase in duration from 1- to 25-day during the MMWS over India. Dashed curve is the actual values and continuous curve second-degree polynomial fit.

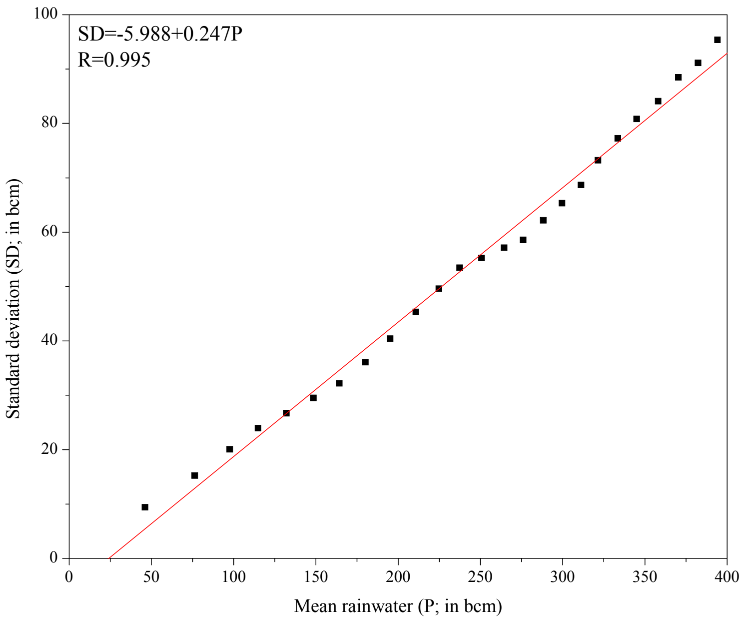

Figure 14. Relationship between standard deviation and mean of 1- to 25-day extreme rainwater during the MMWS over India. Filled squares indicates actual values and continuous the fitted line.

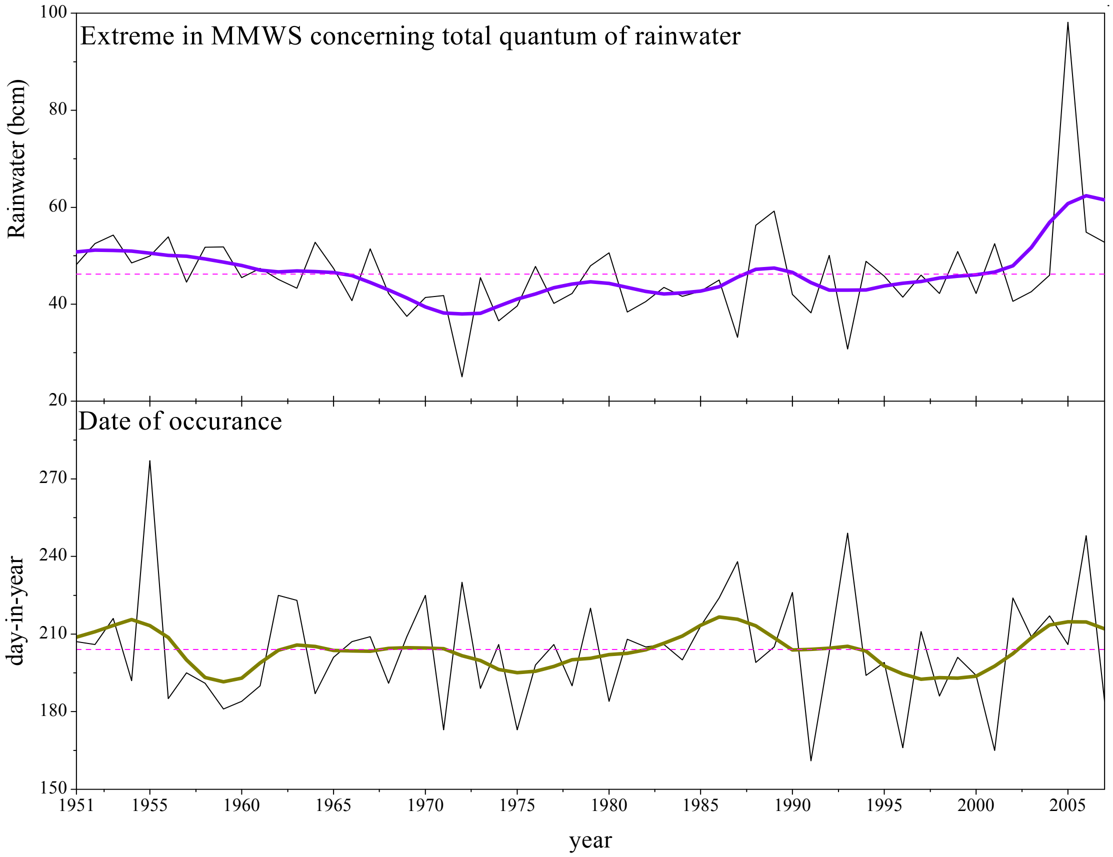

Figure 15. Interannual variation of the 1-day extreme rainwater and the date of occurrence extent during the MMWS. Thin curve is the actual values and thick curve 9-point Gaussian low-pass filtered values.

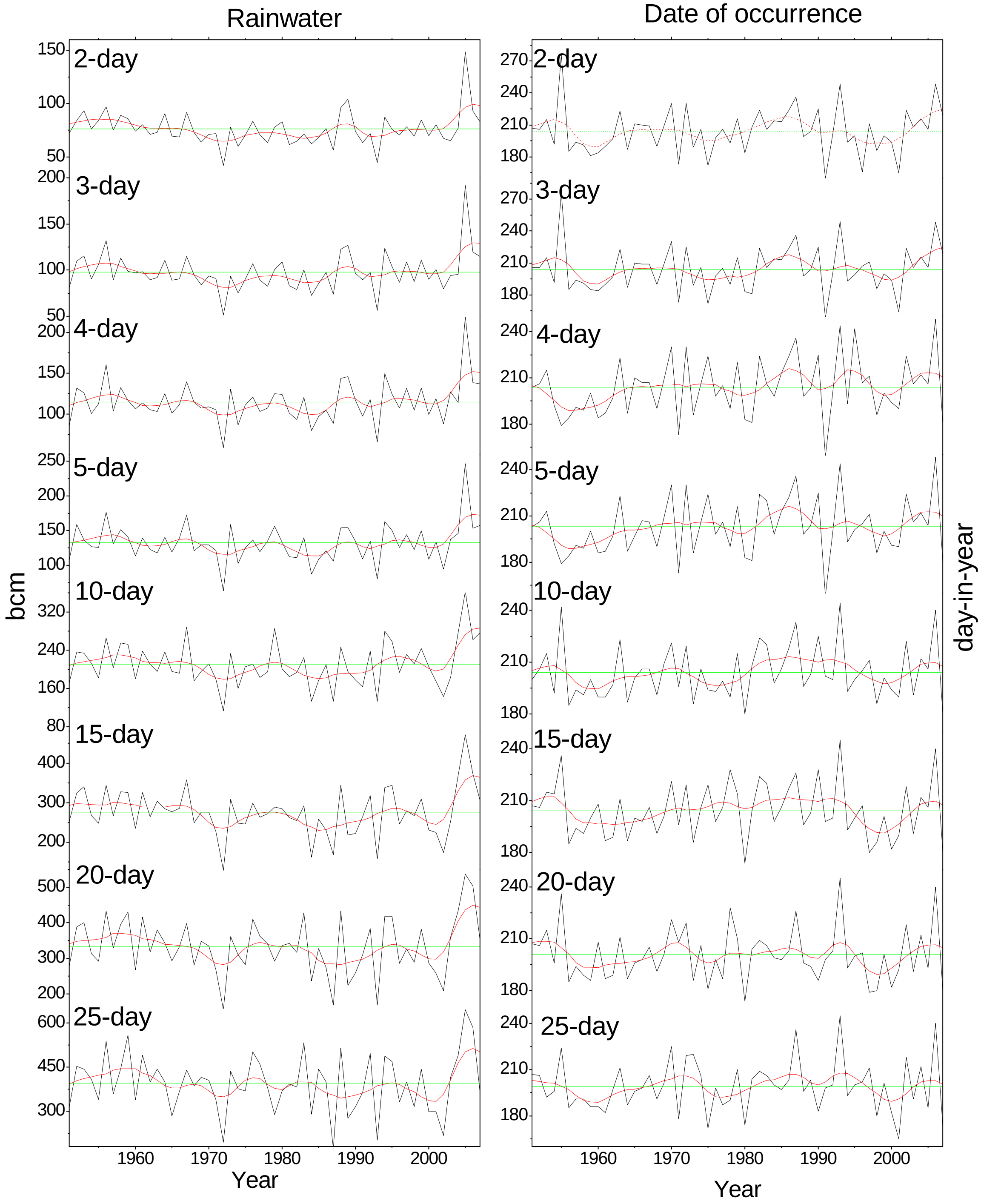

Figure 16. Interannual variation of the extreme rainwater and the date of occurrence extent for 1- to 25-day duration during the MMWS. Thin curve is the actual values and thick curve 9-point Gaussian low-pass filtered values.

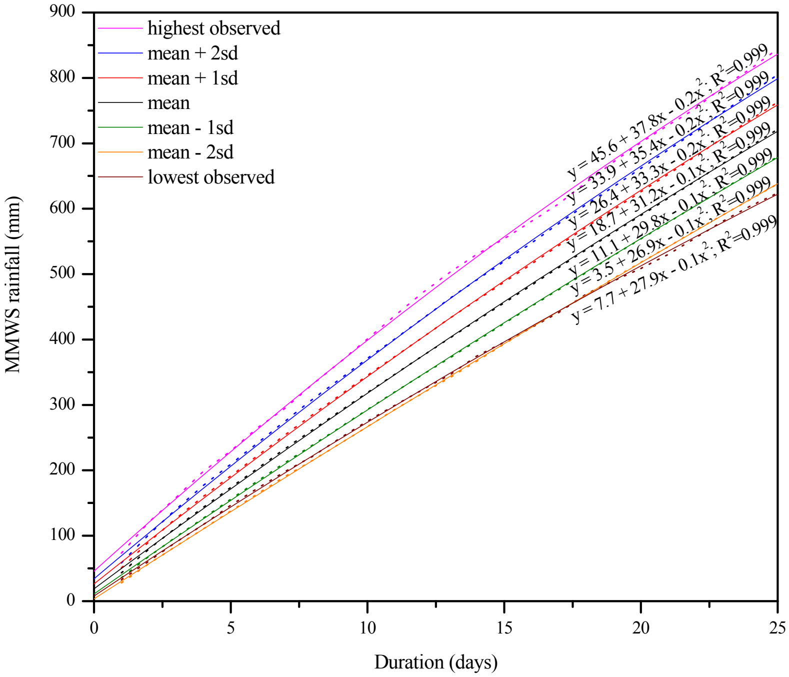

Figure 17. Increase in highest/lowest observed, mean ± 2sd (standard deviation), mean ± 1sd and mean rainfall with increase in duration from 1- to 25-day spatio-temporal extreme rain event concerning rainfall intensity during the MMWS over India. Dashed curve is the actual values and continuous curve second-degree polynomial fit.

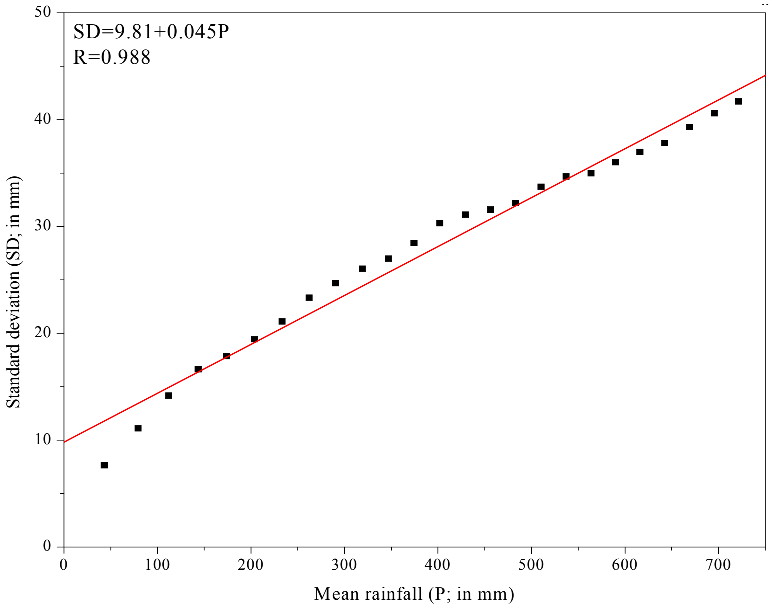

Figure 18. Relationship between standard deviation and mean of 1- to 25-day spatio-temporal extreme rainfall concerning rainfall intensity during the MMWS over India. Filled squares indicates actual values and continuous the fitted line.

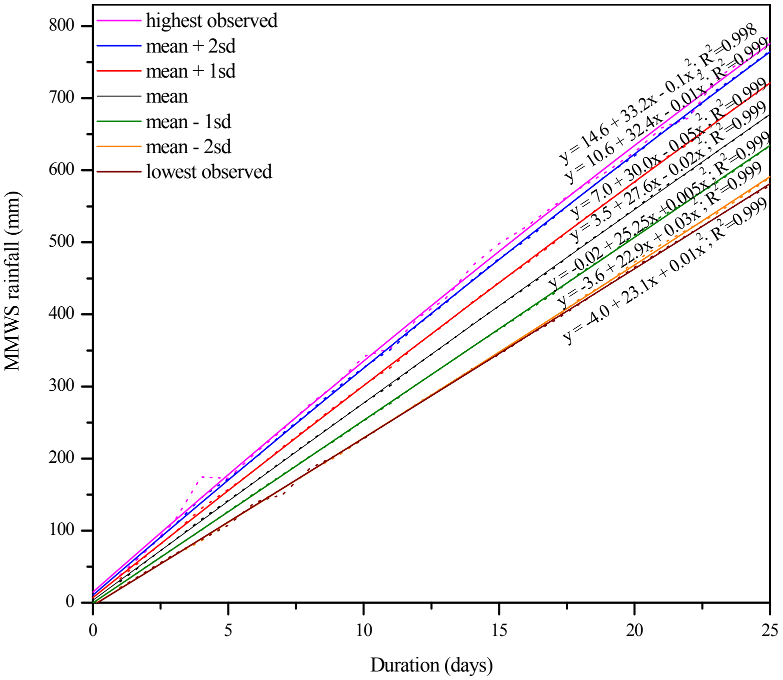

Figure 19. Increase in highest/lowest observed, mean ± 2sd (standard deviation), mean ± 1sd and mean rainfall with increase in duration from 1- to 25-day spatio-temporal extreme rain event concerning areal extent during the MMWS over India. Dashed curve is the actual values and continuous curve second-degree polynomial fit.

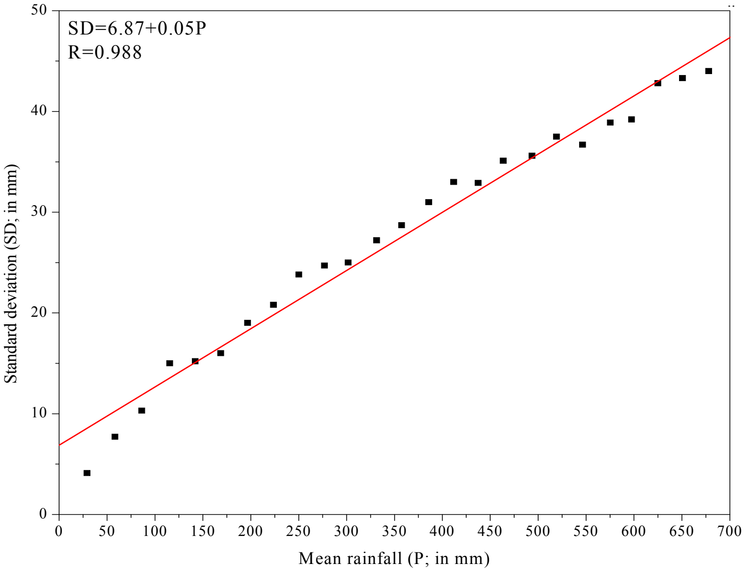

Figure 20. Relationship between standard deviation and mean of 1- to 25-day spatio-temporal extreme rainfall concerning areal extent during the MMWS over India. Filled squares indicates actual values and continuous the fitted line.

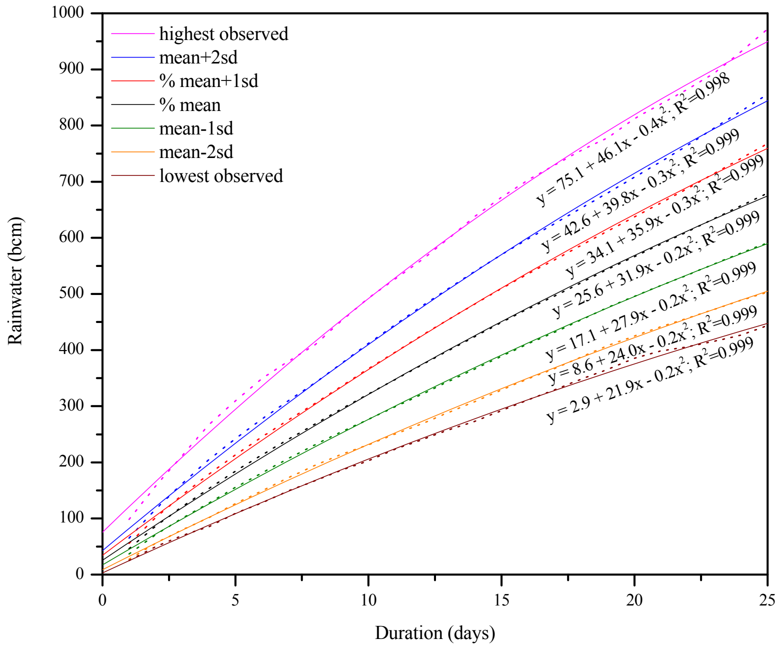

Figure 21. Increase in spatio-temporal extreme highest/lowest observed, mean ± 2sd (standard deviation), mean ± 1sd and mean rainwater with the increase in duration from 1- to 25-day during the MMWS over India. Dashed curve is the actual values and continuous curve second-degree polynomial fit.

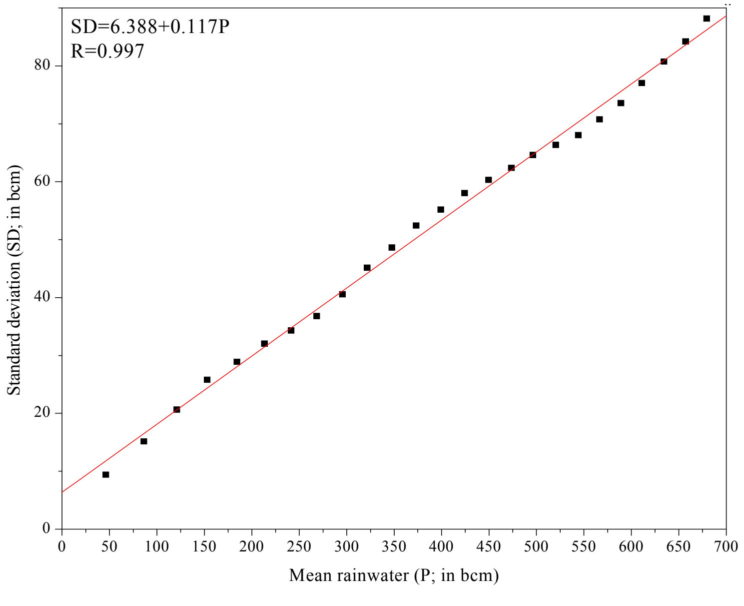

Figure 22. Relationship between standard deviation and mean of 1- to 25-day spatio-temporal extreme rainwater during the MMWS over India. Filled squares indicates actual values and continuous the fitted line.

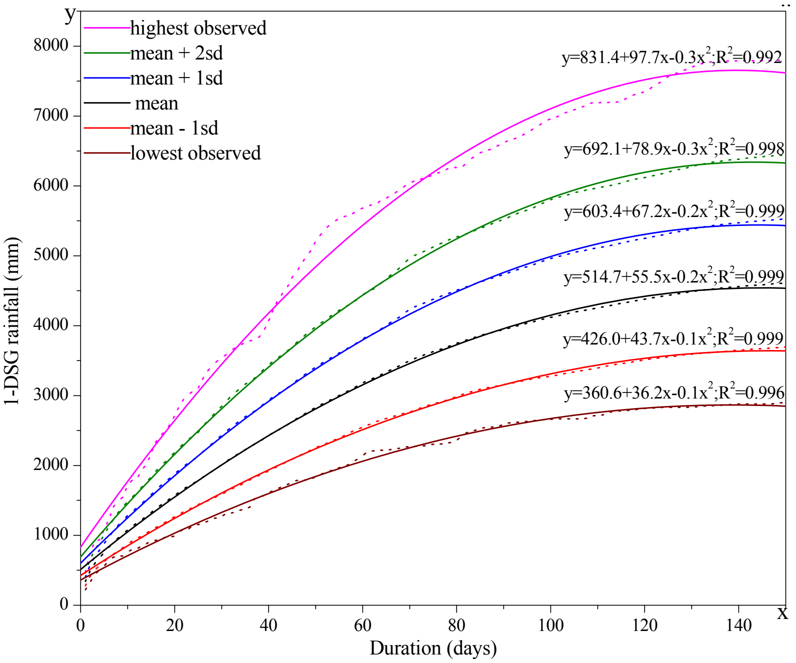

Figure 23. Increase in highest/lowest observed, mean plus 2sd (standard deviation), mean ± 1sd and mean rainfall of extreme 1-DSG rainfall over India with increase in duration from 1 to 150 days. Dashed curve is the actual values and continuous curve second-degree polynomial fit.

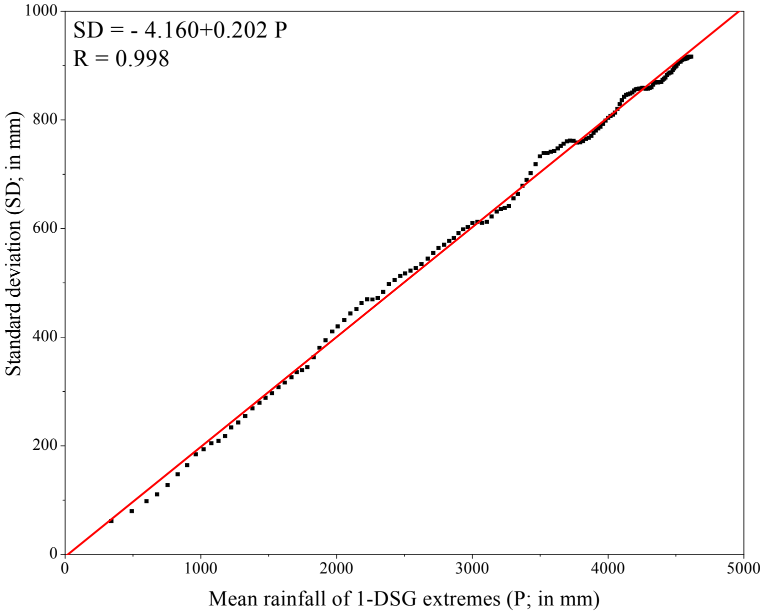

Figure 24. Relationship between standard deviation and mean of 1- to 150-day 1-DSG extreme rainfall over India. Filled squares indicates actual values and continuous the fitted line.

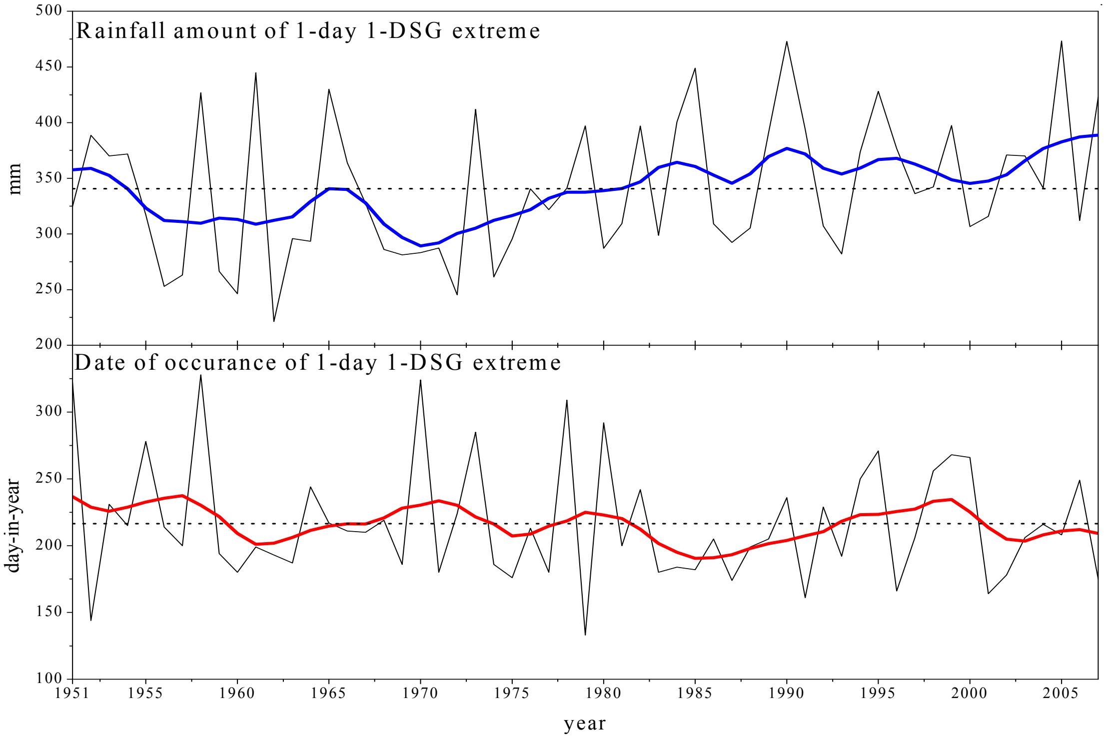

Figure 25. Interannual variation in rainfall amount of 1-day 1-DSG extreme event and its date of occurrence. Thin curve is the actual values and thick curve 9-point Gaussian low-pass filtered values.

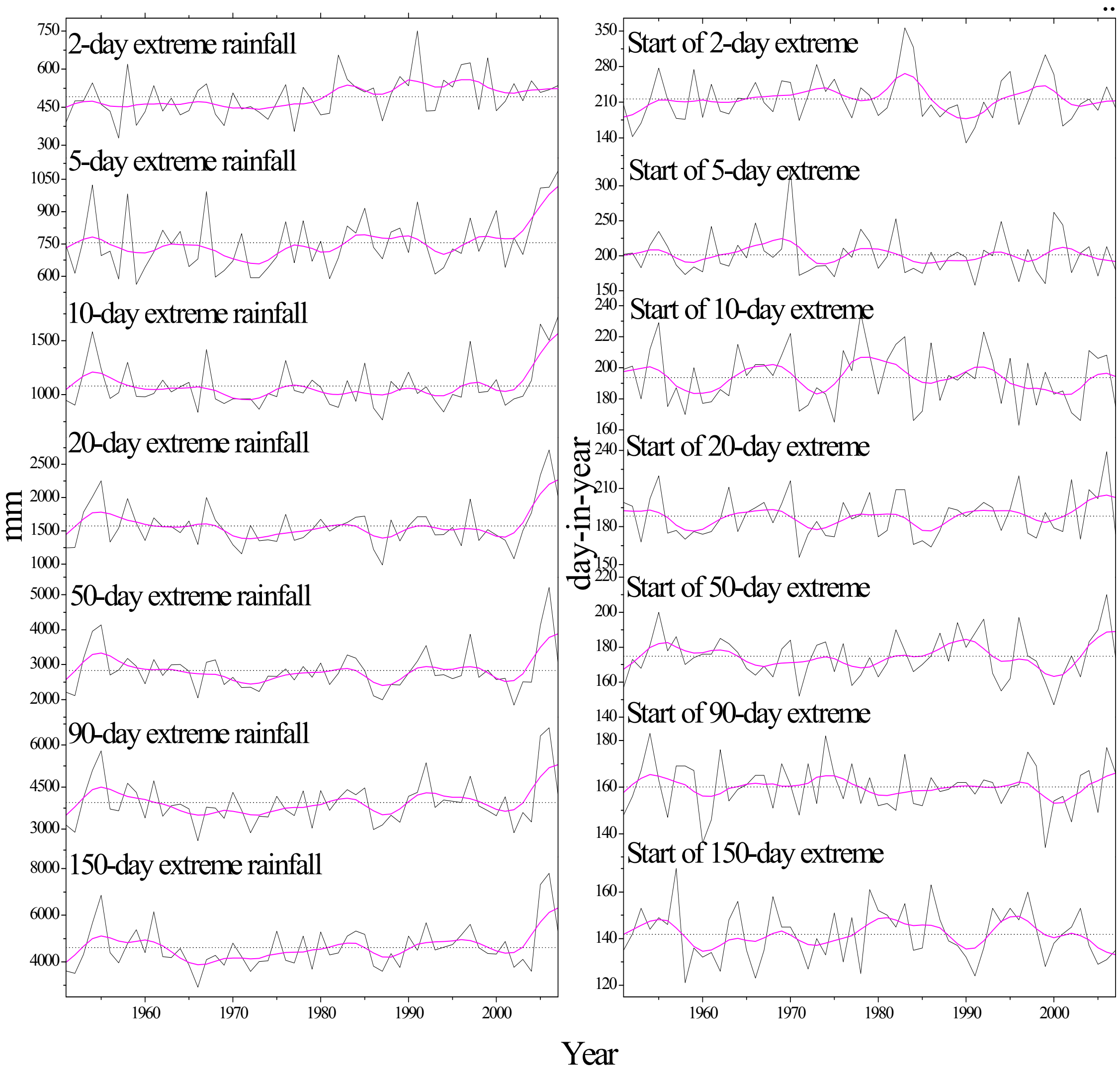

Figure 26. Interannual variation in rainfall amount of 1-DSG extremes (2- to 150 days) and their starting dates. Thin curve is the actual values and thick curve 9-point Gaussian low-pass filtered values.