

**PART III**  
**Heavy Rains**



# Observational Analysis of Heavy Rainfall during Southwest Monsoon over India

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## 1. Introduction

The climate of south Asia is largely dominated by monsoon circulation. Most of the rainfall received in India is during the four months of southwest monsoon season. In recent years, India has faced frequent and severe floods that caused havoc in terms of economic loss and loss of human lives. The devastating floods are occurring almost every year but the places are not same for every occurrence. Most of these floods are categorized as flash floods which are generally associated with heavy precipitation. Heavy precipitation with cloud burst also caused disasters, particularly in northern states of the country. It may be mentioned that the information on the changes in extreme weather events is more important than the changes in mean pattern for better disaster management and mitigation. There is also high temporal variability of monsoon rainfall. This causes the extreme years with high monsoon rainfall departure from the long period mean value, the positive departure causing flood and negative departure causing drought. The variability of monsoon rainfall has been studied by many climate scientists and they have also drawn several conclusions. However the study of variability of rainfall is different from the studies of other climate parameters.

Using the data for the period 1901-2003, Guhathakurta and Rajeevan (2008) have shown that the all-India rainfall has no long-term trend neither for the monsoon rainfall nor for any monsoon months individually. However conclusions have been drawn regarding weakening of monsoon circulation over India using the data for the period 1951-2003/2004 (Naidu et al., 2011; Bawiskar, 2009; Chung and Ramanathan, 2006; Ramesh and Goswami, 2007; Joseph and Simon, 2005). As mentioned, the variability (both temporal and

spatial) of rainfall is more than other climate parameters and the epochal variability of Indian monsoon rainfall has already been reported by several authors (Pant and Rupa Kumar, 1997; Guhathakurta and Rajeevan, 2008). Guhathakurta et al. (2011b) have considered annual frequency of rainfall events of different intensities and have identified zone of increasing trends in flood risk. The present study aims to analyze some of the extreme rainfall indices using reliable, consistent and sufficient number of raingauge station data. Since the country is divided in 36 meteorological sub-divisions, to know the distribution of properties of changes in frequency of heavy rainfall event spatially or more specifically for each of the 36 meteorological sub-divisions, we have calculated number of percentage of total stations having decreasing/increasing trends to the number of percentage of total stations for each sub-divisions. The trend analysis is done on the time series of frequencies considering three different periods viz. 1901-50, 1951- 2011 and 1901-2011. The consideration of frequency of station in percentage is due to unequal number of stations in three periods.

Thus it is required to present the latest status of trends in monsoon rainfall over India as a whole as well as in regional scales using the data for the period of 1901-2011.

## 2. Data Used and Methodology

For analysis of frequency of rain days (days with rainfall  $\geq 0.1$  mm), rainy days (days with rainfall amount 2.5 mm or more but less than 64.5 mm) and frequency of heavy rainfall (including very heavy and extremely heavy) days (days with rainfall amount 64.5 mm or more) we have considered daily rainfall data of more than seven thousand raingauge stations having good availability and also uniformly distributed over the country. For analysis of trend in mean rainfall we have considered new IMD districts, subdivision rainfall data series (Guhathakurta et al., 2011a). Our analysis contains three periods: (1) the complete period 1901-2011, (2) the first 50-year period 1901-50 and (3) the remaining period after 1950 i.e. 1951-2011.

Both monotonic and non-monotonic (i.e. climate jump or change point) changes are investigated. Monotonic trends are generally gradual changes that are either increasing or decreasing with no reversal of direction. The least square linear fit is generally used to examine the existence of monotonic trend in the rainfall time series data and the statistic used for testing the significance is the Student's *t*-distribution.

The well known Mann Kendal non-parametric trend test is used to find the trend (if any) in the frequency of different rainfall events.

Non-monotonic or abrupt change point (climate jump) is the sudden changes in climate pattern which is also known as climate jump. The test used here is for change point detection developed by Pettitt (1979) which is a non-parametric test, which is useful for evaluating the occurrence of abrupt

changes in climatic records (Smadi and Zghoul, 2006; Sneyers, 1990; Tarhule and Woo, 1998). One of the reasons for using this test is that it is more sensitive to breaks in the middle of the time series (Wijngaard et al., 2003). The statistic used for the Pettitt's test has been explained by Dhorde and Zarenistanak (2013), Kang and Yusof (2012) and many others. It is computed as follows:

The two samples  $(x_1, x_2, \dots, x_t)$  and  $(x_{t+1}, x_{t+2}, \dots, x_T)$  come from the same population. The test statistic  $U_{t,T}$  is given by

$$U_{t,T} = \sum_{i=1}^t \sum_{j=t+1}^T \text{Sgn}(x_i - x_j)$$

The most significant change-point is found where the value  $|U_{t,T}|$  is max:  $K_T = \max |U_{t,T}|$  and the significant level associated with  $KT^+$  or  $KT^-$  is determined approximately by

$$s = \exp\left(\frac{-6K_T^2}{T^3 + T^2}\right)$$

If  $p$  is smaller than the specific significance level, e.g., 0.05 in this study, the null hypothesis is rejected. In other words, if a significant change point exists, the time series is divided into two parts at the location of the change point.

In spatial scales, our analysis covers (1) the all-India area weighted rainfall and (2) regional scale covering 36 meteorological sub-divisions.

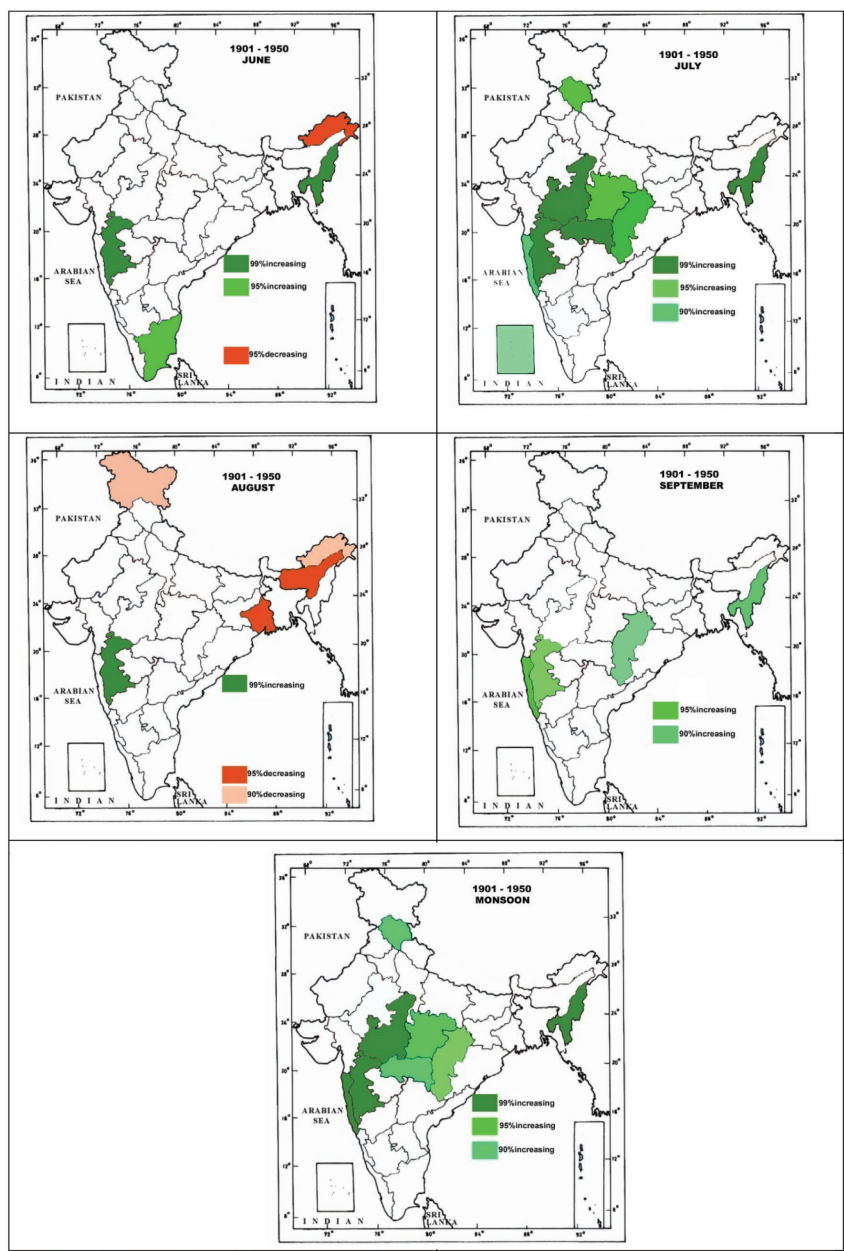
### 3. Variation of Rainfall in Regional Scale

#### 3.1 Period 1901-1950

Figure 1 shows the results of trend analysis of June, July, August and September rainfall and also for the southwest monsoon rainfall for the period 1901-50 for all the thirty six meteorological sub-divisions. Not a single meteorological sub-division showed significant decaying trend in monsoon rainfall in this period. Eight sub-divisions showed significant increasing trends in the monsoon rainfall. Mostly regions of central India showed increasing trend. The sub-divisions Konkan & Goa, Madhya Maharashtra, west and east Madhya Pradesh, Chattisgarh and Vidarbha from the central India, Nagaland, Manipur, Mizoram and Tripura from extreme northeastern parts and Himachal Pradesh from northern parts of India showed increasing trend. However there was large variation in monthly scale where three sub-divisions in June, eight in July, one in August and four sub-divisions in September showed increasing trend.

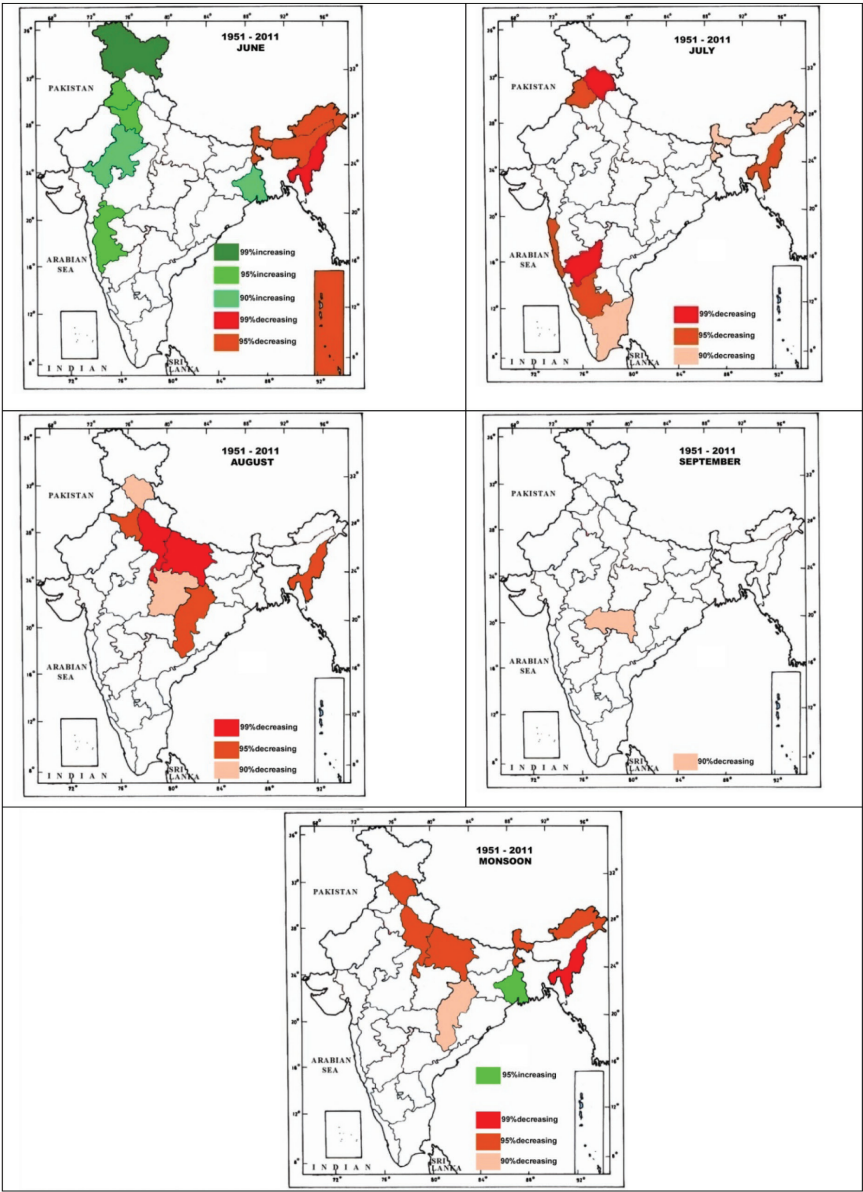
#### 3.2 Period 1951-2011

This period is dominated by decreasing trends in rainfall in many subdivisions (Fig. 2). Seven sub-divisions viz. Himachal Pradesh, west and east Uttar Pradesh, Chattisgarh, sub-Himalayan West Bengal, Arunachal Pradesh and



**Fig. 1:** Trends in the monthly and seasonal rainfall for the 36 meteorological sub-divisions of India for the period 1901-1950.

Nagaland, Manipur, Mizoram and Tripura showed significant decreasing trend in monsoon rainfall while Gangetic West Bengal showed significant increasing trend. In the monthly scale, only June rainfall has shown significant

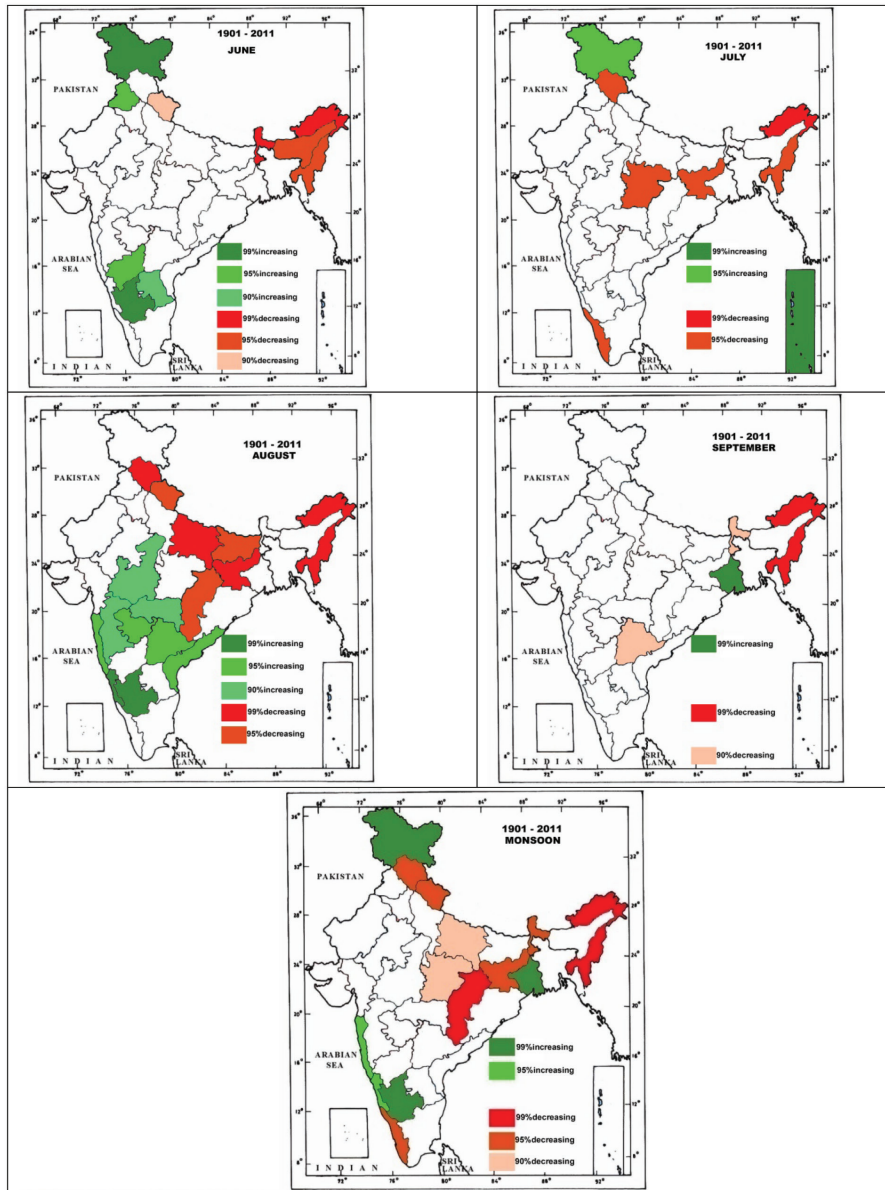


**Fig. 2:** Trends in the monthly and seasonal rainfall for the 36 meteorological sub-divisions of India for the period 1951-2011.

increasing trend in six sub-divisions with no increasing trend in subdivision rainfall for the other monsoon months.

**3.3 Period 1901-2011**

Figure 3 shows spatial variation of trend in rainfall for the monsoon months



**Fig. 3:** Trends in the monthly and seasonal rainfall for the 36 meteorological sub-divisions of India for the period 1901-2011.

and also for the monsoon season for the period 1901-2011. Major changes are noticed in August rainfall where nine sub-divisions viz. south interior Karnataka, coastal Karnataka, Konkan & Goa, Madhya Maharashtra, Marathwada, Vidarbha, Telengana, coastal Andhra Pradesh and west



Madhya Pradesh have reported significant increasing trends while eight subdivisions mostly from eastern, north eastern and northern parts of the country viz. Chattisgarh, Bihar, Jharkhand, Arunachal Pradesh, Nagaland, Manipur, Mizoram & Tripura, east Uttar Pradesh, Uttarakhand and Himachal Pradesh have reported significant decreasing trends. Rainfall has decreased significantly in all the four months and as a result in monsoon season for the two sub-divisions from north eastern region viz. Arunachal Pradesh and Nagaland, Manipur, Mizoram & Tripura. Monsoon rainfall has increased significantly in five sub-divisions viz. south interior Karnataka, coastal Karnataka, Konkan & Goa, Jammu & Kashmir, and Gangetic West Bengal. Chattisgarh, Jharkhand, Uttarakhand, Himachal Pradesh, Arunachal Pradesh, Nagaland, Manipur, Mizoram & Tripura, sub Himalayan West Bengal, Kerala, east Uttar Pradesh and east Madhya Pradesh have shown significant decreasing trends in monsoon rainfall during the period 1901-2011.

#### 4. Annual One-day Maximum Rainfall and Return Period Analysis

From the daily rainfall, annual one-day maximum rainfall series are prepared for each station. Table 1 gives the highest ever recorded one-day point rainfall of more than 90 cm over India. We have nineteen occurrences of more than 90 cm point rainfall. In this table we have shaded the cases which had occurred since the year 1970. Out of nineteen cases eleven cases happened after 1970 indicating increasing frequency of occurrence of extreme rainfall events in the recent years. Also there are only five occurrences of more than 90 cm one day point rainfall in India other than northeastern states.

We have done return period analysis of one-day extreme rainfall series of 25 years return period for the period 1901-50 and 1951-2005 to see the changes in flood risk. The extreme value (return value)  $x$  for a period of  $n$  years is determined by the following formula:

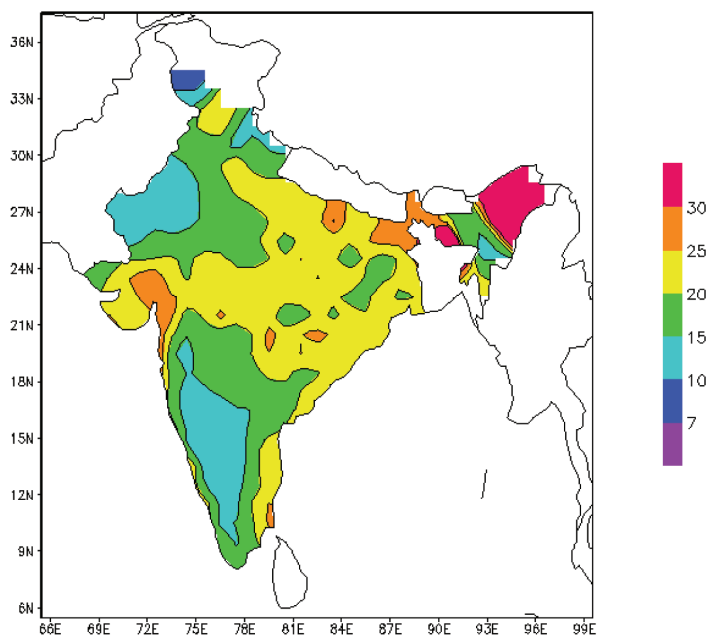
$$x = \psi - \beta \ln[-\ln(F)]$$

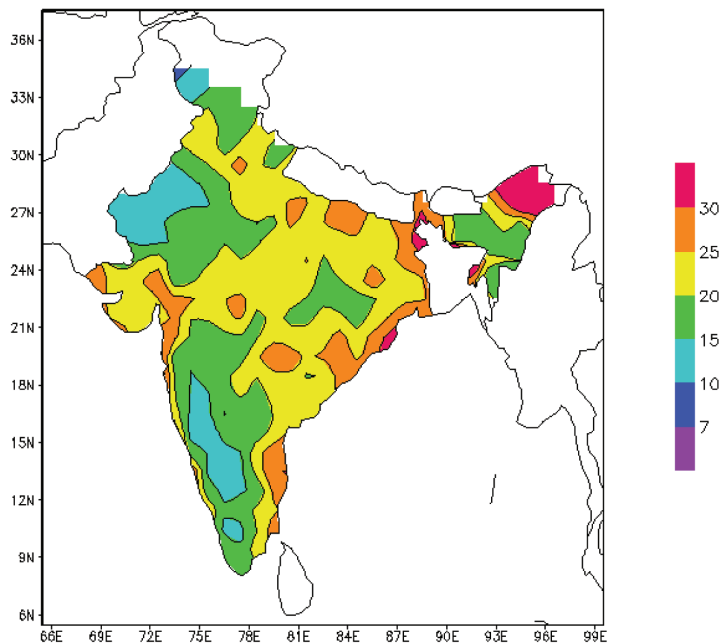
where  $\psi$  = average -  $\gamma\beta$  (where  $\gamma$  is Euler's constant, approximately 0.557),  $\beta$  =  $0.78\sigma$  (where  $\sigma$  is the standard deviation) and  $F = (n-1)/n$ .

Spatial variation of extreme values of 25 years return period are clearly seen in Figs 4 and 5 for the period of 1901-50 and 1951-2005 respectively. Figure 6 brings out the changes in the flood risk between 1951-2005 and 1901-50. The flood risk has increased in recent period (1951-2005) in most parts of the country except Chattisgarh, parts of Odisha, Bihar, extreme west Rajasthan and west Madhya Pradesh. The increase is more in West Bengal, Assam & Meghalaya, Jharkhand, coastal Odisha, coastal Andhra Pradesh, Uttarakhand and adjoining areas and Kutch.

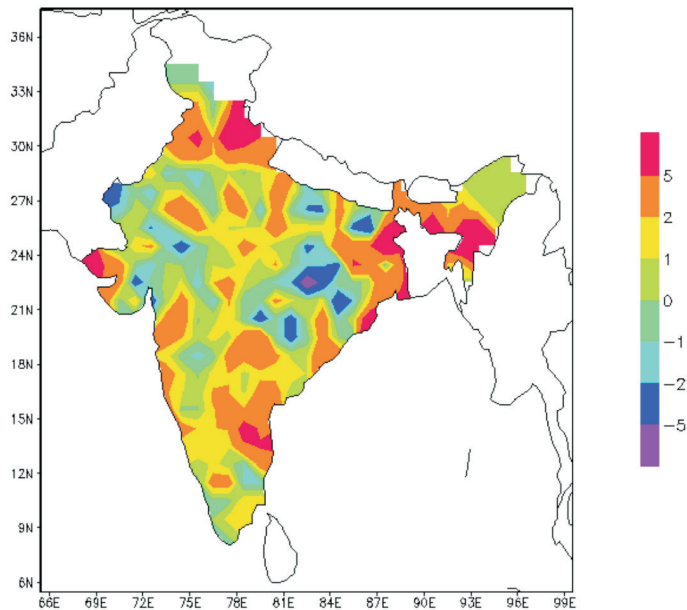
**Table 1:** List of stations having highest one-day point rainfall of more than 90 cm

	<i>Station</i>	<i>State</i>	<i>1-day rainfall in cm</i>	<i>Date of occurrence</i>
1	Cherrapunji Obsy	Meghalaya	156.3	16 Jun 1995
2	Amini Divi	Lakshadweep	116.8	6 May 2004
3	Cherrapunji	Meghalaya	103.6	14 Jun 1876
4	Ambarnath	Maharashtra	101.0	27 Jul 2005
5	Cherrapunji	Meghalaya	99.8	12 Jul 1910
6	Mawsynram	Meghalaya	99.0	10 Jul 1952
7	Dharampur	Gujarat	98.7	2 Jul 1941
8	Cherrapunji	Meghalaya	98.5	13 Sep 1974
9	Mawsynram	Meghalaya	98.0	4 Aug 1982
10	Tamenlong	Manipur	98.0	10 Aug 1970
11	Cherrapunji	Meghalaya	97.4	5 Jun 1956
12	Mawsynram	Meghalaya	94.5	7 Jun 1966
13	Mumbai	Maharashtra	94.4	27 Jul 2005
14	Tamenlong	Manipur	94.0	28 Jul 1970
15	Cherrapunji	Meghalaya	93.0	15 Jun 1995
16	Guna	Madhya Pradesh	92.8	23 Aug 1982
17	Cherrapunji obsy	Meghalaya	92.5	21 Jun 1934
18	Cherrapunji	Meghalaya	92.1	21 Jun 1934
19	Cherrapunji	Meghalaya	90.7	25 Jun 1970

**Fig. 4:** Extreme values in cm for 25 years return period during 1901-50.



**Fig. 5:** Extreme values in cm for 25 years return period during 1951-2005.



**Fig. 6:** Changes in flood risk (extreme values) in cm of 25 years return period during 1951-2005 from 1901-1950.

## 5. Changes in the Frequency of Rainfall of Different Categories

The daily rainfall has been classified in three categories (according to India Meteorological Department).

- |                       |  |
|-----------------------|--|
| 1. Rain day           | Rainfall of amount 0.1 mm or more                            |
| 2. Rainy day          | Rainfall of amount greater than 2.4 mm but less than 64.4 mm |
| 3. Heavy rainfall day | Rainfall of amount 64.5 mm or more                           |

Heavy rainfall day here includes heavy, very heavy and extremely heavy categories.

The frequencies of all the three categories of rainfall stated above are computed from the daily rainfall data of all the stations for the four monsoon months and monsoon season. The trend analysis are then done on the time series of frequencies considering three different periods viz. 1901-50, 1951-2011 and the complete period 1901-2011 latest available. Since there are many missing years and the availability of the data for all the stations are not same we have all the stations which have more than twenty five years for the first and second part of the period and all the stations which have more than 50 years of data for the complete period. To know the distribution of properties of trend spatially or more specifically for each of the 36 meteorological sub-divisions, we have calculated the number of percentage of total stations showing decreasing trend for each sub-divisions. The consideration of frequency of station in percentage is due to unequal number of stations in three periods (7598 stations in period 1951-2011, 2672 stations in the period 1901-50 and 7650 stations in the period 1901- 2011).

Tables 2, 3 and 4 show the results of the trend analysis for the 36 meteorological sub-divisions for the monsoon season during the three periods and for the frequency of rain day, rainy day and heavy rainfall day respectively. We can see that number of sub-divisions where +ve trend is more than the -ve trends are more in the period of 1901-50 than the later period for all the three categories of rainfall. In the recent period (1951-latest) positive (increasing) trends in heavy rainfall frequency was more for the sub-divisions Jharkhand, Odisha, Gangetic and sub Himalayan West Bengal, Arunachal Pradesh and west Rajasthan whereas frequency of decreasing trends in heavy rainfall are more in central India. In other words we can say the intensity of extreme rainfall events have decreased significantly in the central region during the period 1951-latest. Consideration of the complete period 1901-latest shows also that the intensity of extreme rainfall events have decreased significantly in the central region while it has been increased in peninsular India and coastal regions of eastern India and also eastern Rajasthan, Punjab, Haryana and Nagaland, Manipur, Mizoram and Tripura.

**Table 2:** Percentage frequency of number of stations in each subdivision having increasing (+ve) trend and decreasing (-ve) in rain days during southwest monsoon

Subd No.	No. of Stns	% of Stn 1901-1950		No. of Stns	% of Stns 1951-2011		No. of Stns	% of Stns 1901-2011	
		+ Trend	-Trend		+ Trend	-Trend		+ Trend	-Trend
1	1	0	0	7	0	85.7	7	0	14.3
2	3	0	0	50	0	0	51	0	0
3	105	7.6	34.3	217	0.9	6	219	0.5	30.1
4	28	7.1	14.3	96	0	6.3	96	0	10.4
5	27	11.1	29.6	60	3.3	8.3	61	1.6	24.6
6	116	6	19.8	154	2.6	3.9	166	0.6	20.5
7	119	5.9	35.3	377	<b>12.7</b>	3.2	378	0.5	17.2
8	97	<b>19.6</b>	9.3	209	2.4	16.7	210	0	24.8
9	147	7.5	21.8	428	3.7	11.9	428	0.2	19.2
10	126	<b>32.5</b>	4	195	1	47.2	195	0.5	60
11	127	<b>22</b>	3.1	172	1.2	48.8	172	0	71.5
12	39	<b>20.5</b>	2.6	98	0	42.9	99	0	35.4
13	52	7.7	15.4	103	<b>6.8</b>	3.9	104	3.8	9.6
14	40	<b>15</b>	5	94	0	22.3	94	0	19.1
15	19	0	10.5	106	2.8	30.2	106	0.9	17
16	41	7.3	24.4	72	4.2	4.2	83	1.2	9.6
17	66	1.5	16.7	149	<b>5.4</b>	4	159	<b>8.2</b>	4.4
18	136	<b>10.3</b>	2.2	375	<b>10.7</b>	4.8	378	7.1	9
19	110	<b>32.7</b>	1.8	212	1.4	27.4	213	5.2	22.1
20	88	<b>25</b>	0	159	0	35.8	159	0	44.7
21	83	<b>4.8</b>	2.4	238	0	25.6	238	0	26.1
22	30	3.3	13.3	165	1.8	13.9	165	0.6	9.1
23	51	<b>15.7</b>	2	76	0	18.4	77	2.6	24.7
24	110	9.1	9.1	166	1.8	27.1	167	1.8	39.5
25	8	<b>12.5</b>	0	70	1.4	12.9	70	1.4	4.3
26	88	<b>35.2</b>	0	160	1.3	18.1	160	0	35.6
27	74	<b>23</b>	2.7	117	0	46.2	117	0.9	46.2
28	103	2.9	33	490	3.5	7.3	490	1.4	7.6
29	64	3.1	3.1	460	0.2	15.7	462	0.2	9.3
30	71	0	23.9	291	4.8	7.2	291	1.4	11.7
31	235	5.1	22.1	612	1.6	23	612	1.5	29.4
32	22	<b>36.4</b>	0	139	1.4	7.2	139	0	7.2
33	49	<b>16.3</b>	18.4	440	<b>7.7</b>	3.9	440	<b>4.1</b>	3.4
34	115	1.7	27.8	725	<b>23.3</b>	1.9	725	<b>5.9</b>	3.2
35	80	<b>16.3</b>	5	111	0	31.5	114	0.9	59.6
36	2	<b>50</b>	0	5	0	0	5	<b>20</b>	0

## 6. Change Point or Climate Jump in Southwest Monsoon Rainfall over India

The Pettitt test is used to detect the change point in southwest monsoon rainfall over 36 meteorological subdivisions of India. Figure 7 shows the change

**Table 3:** Percentage frequency of number of stations in each subdivision having increasing (+ve) trend and decreasing (-ve) in rainy days during southwest monsoon

<i>Subd No.</i>	<i>Stns</i>	<i>% of Stn 1901-1950</i>		<i>Stns</i>	<i>% of Stns 1951-2011</i>		<i>Stns</i>	<i>% of Stns 1901-2011</i>	
		<i>+ Trend</i>	<i>-Trend</i>		<i>+ Trend</i>	<i>-Trend</i>		<i>+ Trend</i>	<i>-Trend</i>
1	1	0	0	7	0	85.7	7	0	14.3
2	3	0	0	50	0	0	51	0	0
3	105	1	21.9	217	1.4	5.1	219	0	25.6
4	28	7.1	7.1	96	1	3.1	96	1	7.3
5	27	0	11.1	60	3.3	6.7	61	0	18
6	116	4.3	15.5	154	0.6	3.2	166	0.6	19.3
7	119	0.8	24.4	377	<b>15.4</b>	2.4	378	0.3	9.3
8	97	<b>13.4</b>	8.2	209	3.3	9.6	210	0	19
9	147	5.4	17	428	2.8	8.9	428	0	16.6
10	126	<b>19</b>	3.2	195	0.5	35.9	195	0	57.4
11	127	<b>18.9</b>	0	172	0.6	39.5	172	0	54.1
12	39	<b>12.8</b>	0	98	0	42.9	99	0	34.3
13	52	1.9	9.6	103	1.9	5.8	104	1.9	4.8
14	40	<b>10</b>	2.5	94	0	22.3	94	0	14.9
15	19	<b>5.3</b>	0	106	0.9	30.2	106	0	17
16	41	0	19.5	72	1.4	1.4	83	1.2	9.6
17	66	0	6.1	148	2	4.1	158	2.5	3.2
18	136	<b>7.4</b>	0.7	375	3.7	4	378	1.9	3.2
19	110	<b>39.1</b>	0.9	212	0.9	19.3	213	3.3	10.8
20	88	<b>20.5</b>	0	159	0	27	159	0	31.4
21	83	0	0	238	0.4	3.4	238	0	3.4
22	30	0	0	165	0.6	3	165	0.6	0.6
23	51	<b>2</b>	0	76	5.3	5.3	77	0	3.9
24	110	<b>14.5</b>	0	166	2.4	7.2	167	<b>8.4</b>	4.2
25	8	0	0	70	0	11.4	70	0	2.9
26	88	<b>28.4</b>	0	160	0.6	11.9	160	0	12.5
27	74	<b>14.9</b>	1.4	117	0	48.7	117	0	47
28	103	3.9	8.7	490	1.4	6.1	490	1	2.4
29	64	<b>3.1</b>	0	460	0.2	10.2	462	0	5.2
30	71	0	2.8	291	<b>4.5</b>	2.4	291	1.7	2.4
31	235	0.9	10.2	611	1.5	25.2	611	1.3	24.2
32	22	<b>13.6</b>	0	139	0	1.4	139	0	0
33	49	<b>6.1</b>	4.1	440	2	2.5	440	<b>1.8</b>	0.5
34	115	3.5	6.1	725	<b>16.7</b>	0.4	725	<b>2.1</b>	1.7
35	80	3.8	3.8	111	0	25.2	114	0.9	49.1
36	2	<b>50</b>	0	5	0	0	5	<b>20</b>	0

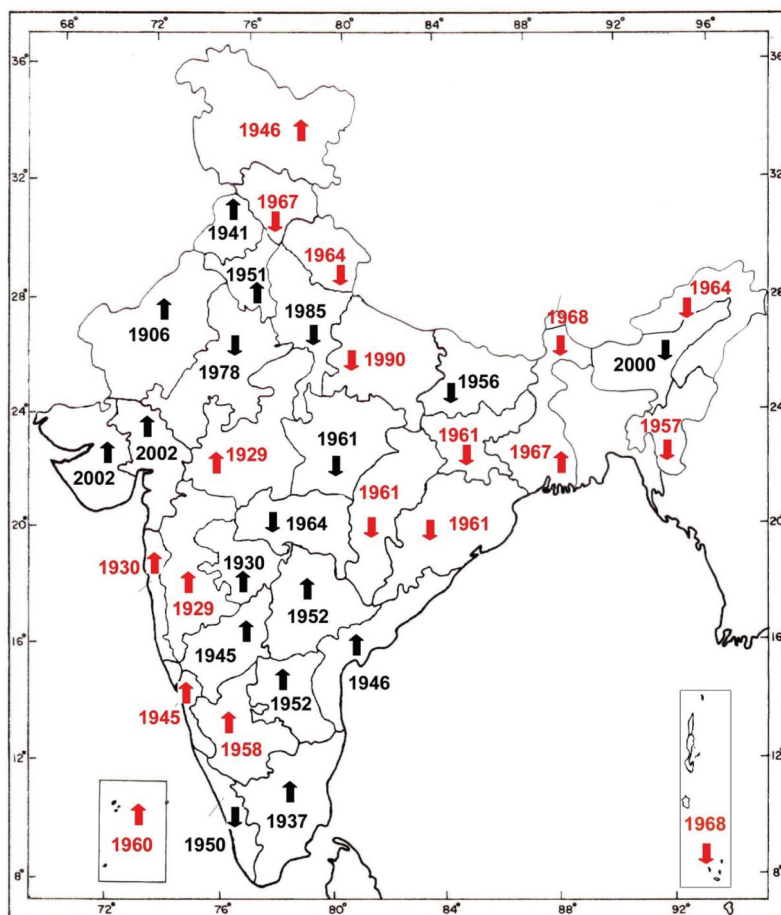
point (year) for each of the 36 met-subdivisions. The significant change point (95% confidence level) is highlighted with red colour whereas text with black indicates change but not significant. Also upward and downward arrows are

**Table 4:** Percentage frequency of number of stations in each subdivision having increasing (+ve) trend and decreasing (-ve) in heavy rainfall days during southwest monsoon

Subd No.	Stns	% of Stn 1901-1950		Stns	% of Stns 1951-2011		Stns	% of Stns 1901-2011	
		+ Trend	-Trend		+ Trend	-Trend		+ Trend	-Trend
1	1	0	0	7	0	0	7	0	0
2	3	0	0	50	<b>2</b>	0	51	0	0
3	105	6.7	7.6	214	1.9	1.9	216	2.8	6.5
4	28	<b>14.3</b>	0	93	1.1	2.2	93	<b>2.2</b>	1.1
5	27	3.7	3.7	60	<b>6.7</b>	1.7	61	1.6	6.6
6	116	3.4	6	154	<b>1.9</b>	0.6	166	<b>2.4</b>	1.8
7	118	<b>7.6</b>	0.8	375	<b>11.5</b>	0.8	377	<b>4</b>	1.1
8	97	<b>6.2</b>	2.1	208	<b>8.2</b>	6.7	209	1.9	9.1
9	147	5.4	8.8	427	3.7	3.7	427	2.1	4.2
10	126	<b>5.6</b>	1.6	191	2.1	18.8	191	1	22
11	127	<b>7.1</b>	3.9	169	2.4	27.8	169	2.4	16.6
12	39	2.6	7.7	93	1.1	24.7	94	0	24.5
13	52	0	3.8	100	3	5	101	<b>8.9</b>	1
14	40	<b>5</b>	0	93	0	14	93	<b>3.2</b>	0
15	19	0	0	98	2	18.4	98	0	7.1
16	34	0	2.9	61	0	0	70	0	0
17	64	<b>3.1</b>	0	136	<b>2.2</b>	0	147	1.4	1.4
18	136	<b>2.2</b>	0.7	369	1.9	1.9	372	<b>2.7</b>	0.8
19	110	<b>22.7</b>	1.8	209	1.4	8.1	210	1	3.3
20	88	<b>8</b>	0	159	1.9	4.4	159	1.3	8.2
21	83	<b>6</b>	0	236	<b>2.1</b>	0.8	236	<b>5.1</b>	0
22	30	<b>10</b>	0	162	<b>1.2</b>	0.6	162	<b>1.2</b>	0
23	51	<b>11.8</b>	0	76	0	26.3	77	<b>16.9</b>	5.2
24	110	<b>11.8</b>	0	165	1.2	4.2	166	<b>4.8</b>	1.2
25	8	0	0	70	<b>2.9</b>	0	70	<b>4.3</b>	0
26	88	<b>2.3</b>	0	160	0	3.1	160	1.3	6.3
27	73	<b>6.8</b>	0	116	1.7	20.7	117	0	12.8
28	103	1	1.9	478	1.5	1.7	478	<b>1</b>	0.6
29	64	0	0	450	<b>1.3</b>	0.9	452	<b>1.8</b>	0
30	71	<b>1.4</b>	0	277	<b>0.4</b>	0	277	<b>0.4</b>	0
31	232	1.3	1.3	550	1.3	2.9	553	2.2	2.4
32	22	0	0	139	1.4	2.9	139	<b>0.7</b>	0
33	44	0	0	424	0.9	1.2	424	<b>0.5</b>	0
34	114	0	0.9	700	2.3	3.7	700	<b>1.3</b>	0.6
35	80	1.3	5	111	0	17.1	114	0.9	25.4
36	2	<b>50</b>	0	5	0	0	5	0	0

used to indicate the upward shift or downward shift in southwest monsoon rainfall pattern.

Figure 7 indicates that there was a upward climate shift over Peninsular India around 1945-55. Around 1960 there was downward shift over



**Fig. 7:** The climate jump or change point (year) in southwest monsoon rainfall over 36 meteorological sub-divisions in India. Red colour indicates the change is significant (95% confidence level). Upward and downward arrows represent upward and downward shift respectively.

Chattisgarh, east M.P., Vidarbha, Odisha, Jharkhand, Bihar, Sub Himalayan, West Bengal and most part of the north eastern region. It is necessary to study other climate features and their shift in light of the shift of rainfall pattern.

## 7. Rainfall Analysis for Neighbouring Countries: Bangladesh and Nepal

Using the same catagories of rainfall i.e. dry day if rainfall is zero, rain day, rainy day and heavy rainfall day as stated earlier we have done trend analysis (Mann Kendal non-parametric test) of rainfall stations (Table 5) for the period 1947-83 of Nepal and of Bangladesh (Table 6) for the period 1891-1946 and 1949-2011.



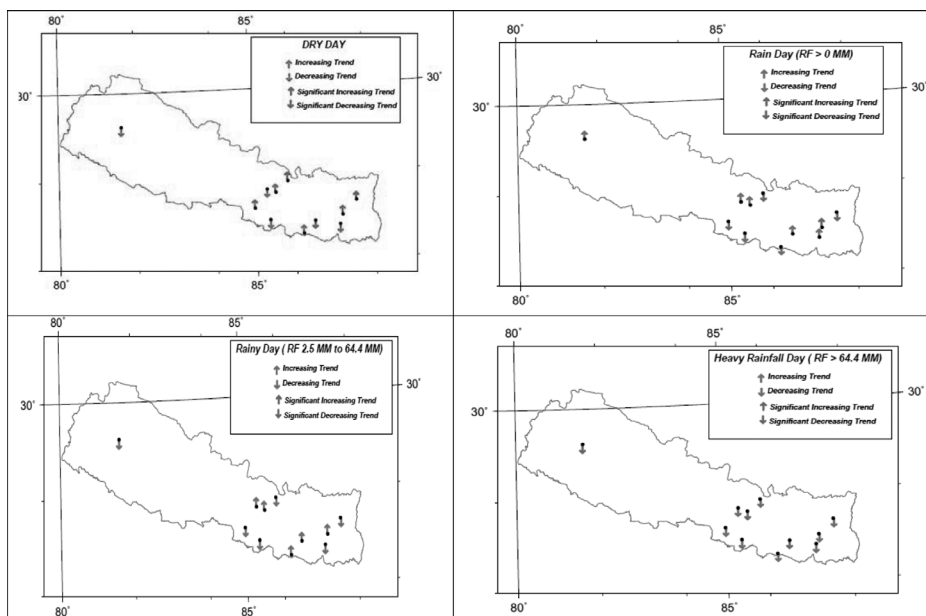
**Table 5:** List of stations of Nepal considered for analysis

<i>Station name</i>	<i>Latitude</i>	<i>Longitude</i>
Amlekganj	27.28	85.00
Bairia	27.00	85.38
Bijapur	29.23	81.63
Chatra	26.82	87.15
Dhulikhel	27.62	85.55
Dumuhan	27.35	87.60
Ghumthang	27.87	85.87
Kathmandu	27.70	85.33
Munga	27.03	87.23
Sirha	26.65	86.22
Udaipur	26.93	86.52

**Table 6:** List of stations of Bangladesh considered for analysis

<i>Station name</i>	<i>Latitude</i>	<i>Longitude</i>
Barisal	22.75	90.37
Bogra	24.85	89.37
Chittagong	22.27	91.82
Comilla	23.43	91.18
Coxs Bazar	21.45	91.97
Dhaka	23.77	90.38
Dinajpur	25.65	88.68
Faridpur	23.60	89.85
Hatiya	22.43	91.10
Jessore	23.18	89.17
Khulna	22.78	89.53
M.Court	22.87	91.10
Mymensingh	24.72	90.43
Rajshahi	24.37	88.70
Rangamati	22.53	92.20
Rangpur	25.73	89.23
Sandwip	22.48	91.43
Satkhira	22.72	89.08
Sitakunda	22.58	91.70
Srimangal	24.30	91.73
Sylhet	24.90	91.88
Teknaf	20.87	92.30

Figure 8 shows the results of trend analysis for Nepal. Significant increase in the frequency of dry day during SW monsoon over two stations in eastern parts of Nepal has been noticed. Even other four stations in this region have also reported increasing trend but not significant. Frequency of rain day has shown significant decreasing trends over three stations of east Nepal. There is



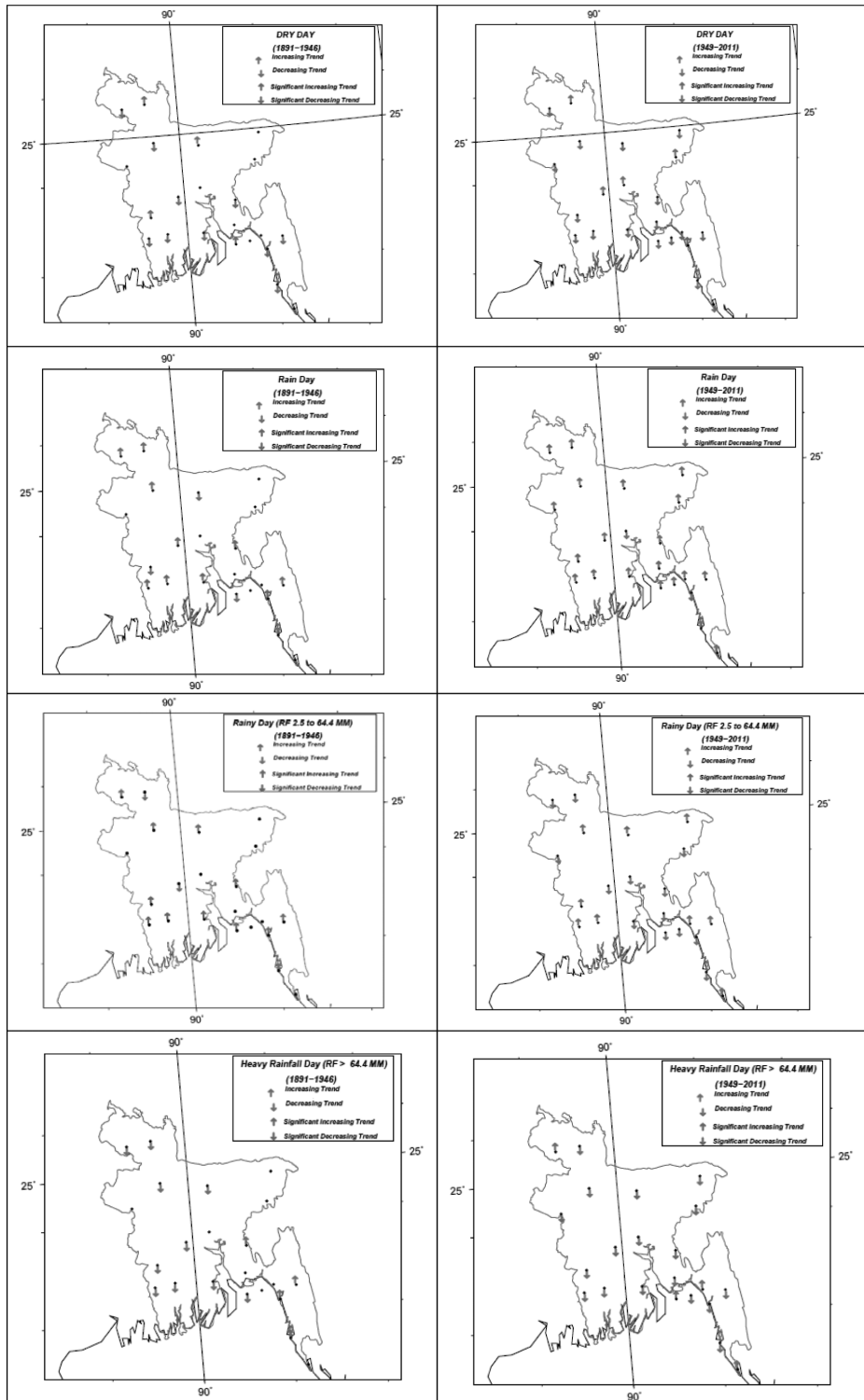
**Fig. 8:** Results of trend analysis of frequency of rainfall events of different intensities of Nepal.

no significant trend in the frequency of rainy days. But the frequency of heavy rainfall events has decreased in all the stations with significant trend in three stations during the period 1947-83.

Comparative results of trend analysis of two periods viz. 1891-1946 and 1949-2011 of the frequency of rainfall events of different intensities in Bangladesh are shown in Fig. 9. Frequency of dry day has shown significant decreasing trends in eight out of 22 stations while only one station has significant increasing trend during the recent period. Almost similar pattern was present during 1891-1946. In general frequency of rain day and rainy day have shown increasing trends during both the periods. However frequency of heavy rainfall events has significantly decreased during the recent period which was not seen in the previous period. Thus for Bangladesh it can be concluded that southwest monsoon has become more favourable for agriculture and water sectors as dry days are becoming lesser and days with rainfall of moderate intensities are increasing.

## 8. Conclusions

The rainfall data of longer series (1901-2011) were analyzed to study the temporal and spatial variability of rainfall pattern in India. The earlier study by Guhathakurta and Rajeevan (2008) analyzed the rainfall data for the period 1901-2003 and have shown the significant changes in the rainfall pattern in many meteorological sub-divisions of India. However during 2004 to 2011



**Fig. 9:** Results of trend analysis of frequency of rainfall events of different intensities of Bangladesh for the periods 1891-1946 and 1949-2011.

country experienced two droughts and it necessitated to detect the changes in the rainfall pattern in the regional scale using the upto date data.

The trend analysis in the regional scales for the recent period 1951-2011 shows significant increasing trend in June rainfall only in six sub-divisions viz. Madhya Maharashtra; east Rajasthan; Punjab; Haryana, Delhi & Chandigarh; Jammu & Kashmir and Gangetic West Bengal while no sub-divisions reported increasing trend in other monsoon months. Seven sub-divisions viz. Himachal Pradesh, west and east Uttar Pradesh, Chattisgarh, sub-Himalayan West Bengal, Arunachal Pradesh and Nagaland, Manipur, Mizoram & Tripura showed significant decreasing trend in monsoon rainfall while Gangetic West Bengal showed significant increasing trend in monsoon rainfall.

Analysis of the rainfall data for the complete period reveals that monsoon rainfall has increased significantly in five sub-divisions viz. south interior Karnataka, coastal Karnataka, Konkan & Goa, Jammu & Kashmir, and Gangetic West Bengal. Chattisgarh, Jharkhand, Uttarakhand, Himachal Pradesh, Arunachal Pradesh, Nagaland, Manipur, Mizoram & Tripura, sub Himalayan West Bengal, Kerala, east Uttar Pradesh and east Madhya Pradesh have shown significant decreasing trends in monsoon rainfall. In August rainfall in nine sub-divisions viz. south interior Karnataka, coastal Karnataka, Konkan & Goa, Madhya Maharashtra, Marathwada, Vidarbha, Telengana, coastal Andhra Pradesh and west Madhya Pradesh have reported significant increasing trends while eight subdivisions mostly from eastern, north eastern and northern parts of the country viz. Chattisgarh, Bihar, Jharkhand, Arunachal Pradesh, Nagaland, Manipur, Mizoram & Tripura, east Uttar Pradesh, Uttarakhand and Himachal Pradesh have reported significant decreasing trends. In July six subdivisions viz. Kerala, Jharkhand, east Madhya Pradesh, Himachal Pradesh, Arunachal Pradesh and Nagaland, Manipur, Mizoram & Tripura have reported decreasing trends while Jammu & Kashmir and Andaman & Nicobar Island have reported increasing trends.

Analysis of frequency of rainfall occurrence of different categories shows that frequencies of rain day have decreased in most parts of the country except west Rajasthan north and south interior Karnataka and Lakshadweep. Frequencies of rainy day (rainfall of moderate intensity in a day) have decreased in most parts of the country except Madhya Maharashtra, north and south interior Karnataka and Lakshadweep. In the large regions of the country i.e. seventeen sub-divisions viz. Nagaland, Manipur, Mizoram & Tripura, Gangetic West Bengal, Odisha, Haryana, Delhi & Chandigarh, Punjab, east Rajasthan, Gujarat, Saurashtra & Kutch, Konkan & Goa, Madhya Maharashtra, Marathwada, coastal Andhra Pradesh, Rayalaseema, Telengana, coastal Karnataka, north and south interior Karnataka, increasing trends in the frequency of heavy rainfall events dominated during the period 1901-2011. In the recent period (1951-2011) only in the eleven subdivisions increasing trends in the frequency of heavy rainfall were dominant. However, in the

central region there was no significant increase in the frequency of heavy rainfall events.

Changes in flood risk over India has been tested by comparing extreme values of 25 years return period between 1901-50 and 1951-2005. The flood risk has increased in recent period (1951-2005) in most parts of the country except Chattisgarh, parts of Odisha, Bihar, extreme west Rajasthan and west Madhya Pradesh. The increase is more in West Bengal, Assam & Meghalaya, Jharkhand, coastal Odisha, coastal Andhra Pradesh, Uttarakhand and adjoining areas and Kutch.

In Bangladesh dry days are becoming less and days with rainfall of moderate intensities are increasing. Frequency of heavy rainfall events (more than 64.5 mm in a day) has decreased in all the stations during 1949-2011. In Nepal also frequency of heavy rainfall events has decreased in all the stations during 1947-1983.

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