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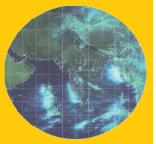

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NCC RESEARCH REPORT

Changes in extreme rainfall events and flood risk in India during the last century

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Executive Summary

1	Document title	Changes in extreme rainfall events and flood risk in India during the last century
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16	Abstract	The occurrences of some exceptionally very heavy rainfall during the recent years and causing flash floods in many areas forced to study the long term changes in extreme rainfall over India. The study includes the analysis of the frequency of rainy days, rain days and heavy rainfall days as well as one-day extreme rainfall and return period analysis in order to observe the impact of climate changes on Extreme weather events and flood risk in India. The report will give some interesting findings which are very useful for hydrological planning and disaster managements. It has been found that frequency of heavy rainfall events are decreasing in major parts of the central and north India while increasing in the peninsular India, east and north east India. Extreme rainfall and flood risk is increasing significantly particularly in many regions of the country except some parts of central India.
17	Key Words	Extreme rainfall, return period, climate change, flood risk

1. Introduction

In recent years, heavy precipitation events have resulted in several damaging floods in India. The consecutive flash floods over three major metro cities in the same year i.e. Mumbai in July 2005, Chennai in October 2005 and again in December 2005 and Bangalore in October 2005 caused heavy damages in economy, loss of life etc. Some of the recent studies (Goswami et al, 2006 ; Rajeevan et al, 2008) on extreme rainfall events over India were mostly concentrated in central India. The regions where the country experienced recent extreme rainfall events like 94.cm in Mumbai, 156.5 cm (country's highest ever recorded one day point rainfall or the regions of Chennai or Bangalore were not included in their study region. Therefore a detailed study on extreme weather events mostly rainfall is urgently needed to have a clear idea about the impact of climate change on the extreme weather events of the country. It may be mentioned that the information on the changes on extremes weather events is more important than the changes in mean pattern for the better disaster management and mitigation. According to the latest report of Intergovernmental Panel on Climate Change (IPCC, 2007) another aspect of these projected changes is that "*wet extremes are projected to become more severe in many areas where mean precipitation is expected to increase, and dry extremes are projected to become more severe in areas where mean precipitation is projected to decrease. In the Asian monsoon region and other tropical areas there will be more flooding".*

A large amount of the variability of rainfall is related to the occurrence of extreme rainfall events and their intensities. Therefore, there is a need to know the magnitudes of extreme rainfall events over different parts of the area under study. The study of spatial variability of extreme rainfall events helps to identify the zone of high and low value of ever extreme rainfall events. A detailed regionalized study is practically useful for the planners and other users. Earlier Rakhecha and Pisharoty (1996) have studied the heavy rainfall events during the southwest monsoon season for some selected stations over the country. Rakhecha and Soman, (1994) analyzed the annual extreme rainfall series in the time scale of 1 to 3 days duration at 316 stations, well distributed over the Indian region, covering 80-years of rainfall data from 1901 to 1980 for trend and persistence using standard statistical tests. They had reported that the annual extreme rainfall records of most stations are free from trend and persistence. However, the extreme rainfall series at stations over the west coast north of 12°N and at some stations to the east of the Western Ghats over the central parts of the Peninsula showed a significant increasing trend at 95% level of confidence. Stations over the southern Peninsula and over the lower Ganga valley have been found to exhibit a decreasing trend at the same level of significance. Stephenson et al (1999) using the data for the period June to September 1986–89 have investigated extreme daily rainfall events and their impact on ensemble forecasts of the Indian Monsoon. Most of the studies on extreme rainfall over India (Sen Roy & Balling, 2004; Rakhecha and Soman, 1994) used limited number of stations. However their results are very useful for studies and management of disaster. Recently Goswami et al (2006) have studied the extreme rainfall pattern of some selected area in central India using the daily gridded data of India Meteorological Department for the period 1951-2003. In their study they have reported in increase in significant rising trends in the frequency and the magnitude of extreme rain events and a significant decreasing trend in the frequency of moderate events over central India. It may be noted that for extreme rainfall analysis for studying the behavior of changes in the extreme events using of real or actual station data is more realistic than the gridded data as in the later case extreme events will be missed in most of the occasions due to interpolation or averaging scheme used in gridding. This even mislead regarding the signals of hydrological extremes for better disaster management.

The present study aims to analyze some of the extreme rainfall indices using reliable and consistent and sufficient number of raingauge station data, the changes in the frequency of rainy days, rain days as well as heavy rainfall days. One-day extreme rainfall analysis was also done to find out the changes in the intensity of extreme weather events. Increasing flood risk is now recognized as the most important sectoral threat from climate change in most parts of the world. Temporal variability in extremes is analyzed in fixed decades from 1951-60, 1961-1970, 1971-1980, 1981-1990 and 1991-2000, Return period analysis is used to analyze the changing probability of extreme rainfall events for observed data in order to find out the changes in flood risk.

2. Data and methodology

Daily rainfall data for the period 1901-2005 of more than 6000 raingauge stations over India are considered initially. The data is taken from the India Meteorological Department, Pune. From these network of stations 2599 stations are selected which are having 30 years or more data. Annual time series of the following indices are constructed for these stations.

1. Frequency of rainy days. A day is called rainy day according to India Meteorological Department if the rainfall of that is 2.5mm or more.
2. Frequency of rain days. A day is considered as rain day if the amount of rainfall of that day is 0.1mm or more.

3. Frequency of heavy rainfall days (including very heavy and extremely heavy). A day is called heavy rainfall day according to India Meteorological Department if the rainfall of that is 64.5mm or more. This includes very heavy (i.e. 124.5mm to 244.5mm) and extremely heavy (i.e. greater than 244.5mm) rainfall cases.
4. Annual one day Extreme rainfall series

While analyzing the data it has been found that there were some missing observations in some years of data. For all of these above three cases we have removed the effect of missing days observation by dividing the actual annual frequency with actual number of observation of that year and then multiplying by the number of days of that year.

Recent studies indicate that the most widely used method for detecting the trend is the non-parametric Mann-Kendall trend test. Mann (1945) originally derived the test and Kendall (1975) subsequently derived the test statistic commonly known as the Kendall's tau statistic. It was found to be an excellent tool for trend detection in different applications (Hirsch et al., 1982; Lettenmaier et al., 1994; Burn and Hag-Elnur, 2002).

Under the null hypothesis H0, that a series $\{x_1, \ldots, x_N\}$ come from a population where the random variables are independent and identically distributed (i.e. the null hypothesis is of no trend) the MK test statistic is

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \mathrm{sgn}(x_j - x_i),$$

where

$$\mathrm{sgn}(x) = \begin{cases} +1, x > 0 \\ 0, x = 0 \\ -1, x < 0 \end{cases}$$

And tau is estimated as

$$\tau = \frac{2S}{N(N-1)}$$

It may be mentioned that Mann-Kendall trend test is a Non-parametric test which allows missing data. It is not affected by gross data errors and outliers. However this test can be used only as a yes/no test for the existence of slope.

To find the amount of increase or decrease in 100 years we have adopted least square linear fit of the data. Advantage of linear regression is that it provides an estimate of slope, confidence interval, and quantifies goodness of fit. However it does not handle missing data and may be greatly affected by outliers and cyclic data. As mentioned earlier in our case we have removed the effect of missing days observation by dividing the actual annual frequency with actual number of observation of that year and then multiplying by the number of days of that year.

To determine the flood risk, extreme values for 25, 50 and 100 years return period are calculated. Probabilistic extreme value theory, which primarily deals with the stochastic behavior of the maximum and minimum random variables, extreme and intermediate order statistics and exceedance over (below) high (low) thresholds are determined by the underlying distribution.

Traditionally, the three extreme value distributions are applied to annual maximum daily rainfall. In this paper we have used the generalized extreme value (GEV) distribution, which has all the flexibility of all the other extreme value distributions The GEV distribution was developed by Jenkinson (1955), Hosking *et al* (1985) and Galambos (1987). The cumulative distribution function (cdf) of the GEV distribution is

$$F(x;\psi,\beta) = \exp(-(1+\zeta\frac{x-\psi}{\beta})^{-1/\zeta})$$

for $1+\xi(x-\psi)/\beta > 0$, where ψ, β and ξ are referred to as the location, scale and shape parameters respectively. The particular case of (1) for $\xi \rightarrow 0$ is the Gumbel distribution

$$F(x;\psi,\beta) = e^{-e^{(\psi-x)/\beta}}$$

The median is $\psi - \beta\ln(-\ln(\frac{1}{2}))$

The mean is $\psi + \gamma\beta$ where γ = Euler-Mascheroni constant ≈0.5772156649015328606.

The standard deviation is

$$\beta\pi/\sqrt{6}.$$

The mode is ψ.

Then from the Gumbel distribution with parameters ψ and β the extreme value (return value) *x* for a period of *n* years can be written by the following formula:

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

where ψ = average - $\gamma\beta$ (where γ is Euler's constant, approximately 0.557)

$\beta = 0.78\sigma$ (where σ is the standard deviation)

F is the random variate drawn from the uniform distribution in the interval [0, 1] = (n-1)/n

3. Result and Analysis

The country being within the tropical monsoon zone is having high spatial variation in rainfall and its frequencies. Fig 1a shows the location of 2599 raingauge stations over India which were considered for this study while Fig 1b gives the location of 36 meteorological sub-divisions of India. From the annual frequency of rainy days, rain days and heavy rainfall days, average or normal rainy days, rain days and heavy rainfall days were computed. High spatial variations of climatology of frequency of rainy days can be seen in Fig. 2. Annual normal rainy days varies from the low value of 10 over extreme western parts of Rajasthan to the high frequency of 130 days over north eastern parts of the country. The northeastern parts of the country as well as sub- Himalayan West Bengal and also extreme western coast line of the country received on an average more than 100 rainy days in a year.

Significant decreasing trends in the frequency of Rain days, rainy days and heavy rainfall days are being noticed over most parts of central, north and eastern parts of the country using both Mann-Kendall and t tests. Fig. 3 a and Fig. 3 b show the decreasing/increasing trend of stations having significant at 95% and 99% respectively in the frequency of rain days obtained by using Mann-Kendall test. Wet days have been increased in peninsular India particularly over Karnataka, Andhra Pradesh and parts of Rajasthan and some parts of eastern India while most of parts of central and northern India are having decreasing trends in frequency of rain days. Fig. 4 a and Fig. 4 b show the decreasing/increasing trend of stations having significant at 95% and 99% respectively in the frequency of rainy days obtained by using Mann-Kendall test. Fig. 5 a and Fig. 5 b show the decreasing/increasing trend of stations having significant at 95% and 99% respectively in the frequency of heavy rainfall days obtained by using Mann-Kendall test. Almost similar patterns of trends that have been observed in frequency of rain days in Fig 3 are also being observed in the frequency of rainy days in Fig 4. However the increasing trends in frequency of heavy rainfall days are being observed over very few numbers of stations mostly in Konkan & Goa and adjoining regions of western coast and some isolated stations of eastern India. Frequency of heavy rainfall events decreased significantly for most parts of the country. Fig. 6 is obtained by doing the contour analysis on the rate of decrease/increase i.e. slopes in 100 years for the significant values at 95% level obtained by using linear regression. The rate of increase in rain days has been observed to be around 40 to 50 days in 100 years in peninsular India particularly over Karnataka, Andhra Pradesh. Increased in rain days has also been observed over most parts of Rajasthan, parts of Gangetic West Bengal and adjoining parts of Jharkhand. These indicate that the great desert areas of India are becoming wet. It may be mentioned that Guhathakurta and Rajeevan(2008) in their study have reported the increasing trend in annual mean rainfall of these regions. However extreme southern parts of the country i.e. Kerala and Tamilnadu getting more dry days. Decreasing trends in annual mean rainfall over Kerala and Tamilnadu have also been reported by Guhathakurta and Rajeevan (2008). Fig. 6c clearly indicates that frequency of extreme rainfall events have been decreased most of the central and north India. It may be mentioned that Goswami et al (2006) reported the significant increasing trends in the frequency of extreme events over central India using gridded data. This type of false indication naturally happens while studying extreme rainfall with gridded data set. Maximum increase in the frequency of heavy rainfall events (20 to 50 days in 100 years) has been noticed in north east India.

Fig. 7 gives the spatial pattern of the India's highest 1-day ever recorded point rainfall. Occurrences of 40 cm or more rainfall are being noticed along the west and east cost of India, Gangetic West Bengal and north eastern parts of India. Table 1 gives the occurrence of 90 cm or more rainfall in one day (24 hrs) in India. There were 18 cases of occurrence of more than 90 cm rainfall in one day and out of these 11 cases were happened since 1970. Out of four occurrences of more than 100 cm rainfall in one day, two occurred during the recent decade 2001-2010. The occurrence of 156.3 cm in one day in Cherrapunji on 15th June 1995 is India's highest ever recorded one day point rainfall and also the consecutive two days rainfall of 249.3cm of rainfall on 14-15th June 1995 is now the world's highest 2-day point rainfall (Guhathakurta,2007).

Trend analysis was performed over annual one-day extreme rainfall series for each of the station. Fig. 8 a and Fig. 8 b show the increasing/ decreasing trend of stations having significant at 95% and 99% respectively in the one-day extreme rainfall obtained by using Mann-Kendall test. The nonparametric test shows significant increasing trend in one-day extreme rainfall over the south peninsular region, Maharashtra, Gujarat region, Bihar and some other isolated areas. The parametric test using linear regression helps to find out the rate of increase in 100 years and these are shown in Fig.9. Significant decrease both in intensity and frequency of extreme rainfall have been observed over Chattisgarh, Jharkhand and some parts of north India.

The extreme values for 25 return periods showed large variation (Fig. 10). The 25 year return period values varied from 10 cm over Rajasthan, parts of north Interior Karnataka and Marathwada to 30 cm over West Bengal, Orissa and parts of north east India. To find the change in flood risk we have studied the decadal variability of 25 year return period. Temporal variability in extremes has also been analyzed in fixed decades from 1961-1970, 1971-1980, 1981-1990 and 1991-2000 earlier by Fowler and Kilsby(2003) for investigating the flood risk over United Kingdom though large uncertainty prevails along with the change of time. Fig. 11 shows the decadal variability of extreme values (cm) for 25 years return period for the decades 1951-60, 1961-70, 1971-80, 1981-90 and 1991-2000. In the decades 1991-2000 the probability of occurrence of extreme values of more than 25 cm or more were located along northern parts of west coast, throughout the eastern coast, West Bengal and Gujarat regions. Fig 12 brings out the percentage frequencies of extreme values (cm) for 25 years return period in different range for each of the decade. Percentage frequencies for different ranges are calculated from the decadal return values of all the 2249 rain gauge stations. It is clear that frequency of extreme values greater than 30 cm were more in the recent two decades viz. 1981-90 and 1991-2000. The evidence of increase in flood risk during the recent decades is clearly noticed.

4. Conclusions

The study brings noticeable changes in the extreme rainfall events that happened in the past century over India. The country experienced large spatial variations in annual normal rainy days. Annual normal rainy days varied from 10 over extreme western parts of Rajasthan to the high frequency of 130 days over north eastern parts of the country. Both non parametric test and linear trend analysis identified decreasing trends in the frequency of wet days in most parts of the country. Trend analysis of frequency of rain days, rainy days and heavy rainfall days shows significant decreasing trends over central and many parts of north India while increasing trends over peninsular India. Also the great desert areas of the country have experienced increase number of wet days. Analysis of one-day extreme rainfall series has shown that the intensity of extreme rainfall has been increased over Coastal Andhra Pradesh and adjoining areas, Saurashtra and Kutch, Orissa, West Bengal, parts of northeast India, east Rajasthan. Significant decrease both in intensity and frequency of extreme rainfall have been observed over Chattisgarh, Jharkhand and some parts of north India. The flood risk also increased significantly over India. The flood risk was more in the decades 1981-90, 1971-80 and 1991-2000.

To observe the compatibility of this changes with the climate model simulation we may see the climate change scenarios projected by using the second generation Hadley Centre Regional Model (HadRM2) and the IS92a future scenarios of increased GHG concentrations (IPCC,2007). The projections indicate that above 25°N latitude, the maximum temperature may rise by 2-4°C during the 2050s and in the northern region the increase in maximum temperature may exceed 4°C. The minimum temperature in the 2050s is expected to rise by 4°C all over India, with a further rise in temperature in the southern peninsula. At an all-India level, little change in monsoon rainfall is projected up to the 2050s. There is an overall decrease in the number of rainy days over a major part of the country. This decrease is greater in the western and central parts by more than 15 days. The decreases in the number of rainy days over major parts of the country are also being observed in this study. However in the present case for the first time the analysis of frequency of wet days and the intensity of extreme rainfall was done by using maximum network of observing stations. This helps to bring out the smaller scales observed changes in frequency and intensity of rainfall.

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Table 1. Occurrences of 90 cm or more rainfall in one day in India

SN	Station	State	1-day rainfall in cm	Date of occurrence
1	Cherrapunji Obsy	Meghalaya	156.3	16-Jun-1995
2	Amini Divi	Lakshadeep	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	Mausynram	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	Meghalaya	92.5	27-Jun-1934
18	Cherrapunji	Meghalaya	90.7	25-Jun-1970

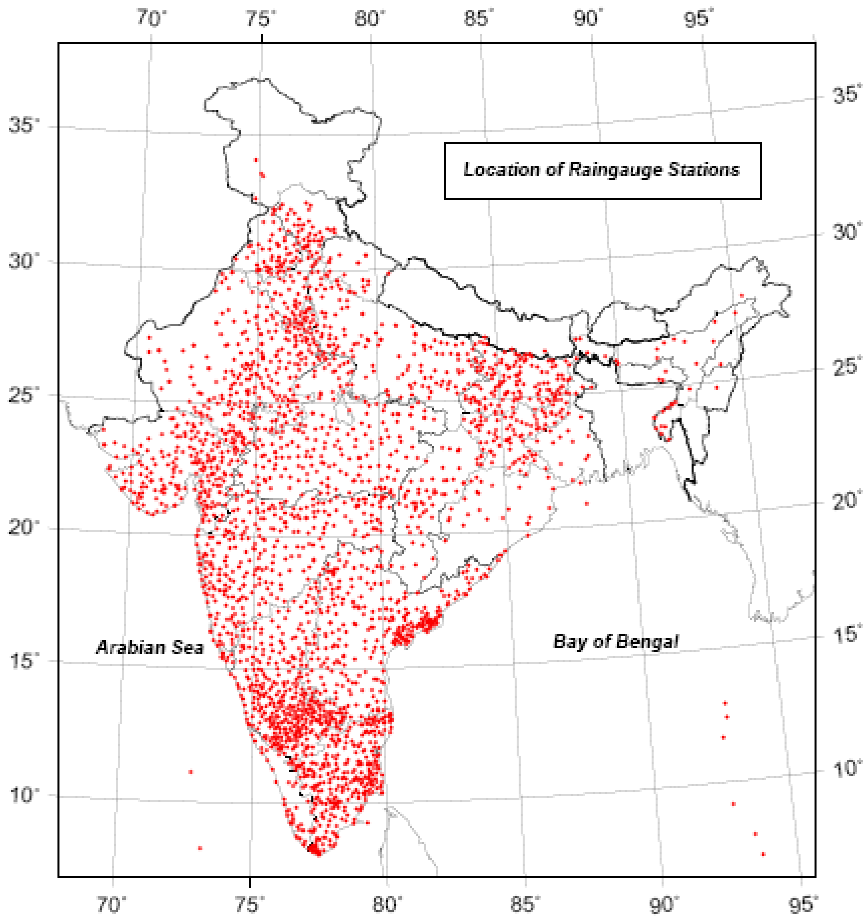


Fig. 1a. Location of 2599 raingauge stations over India

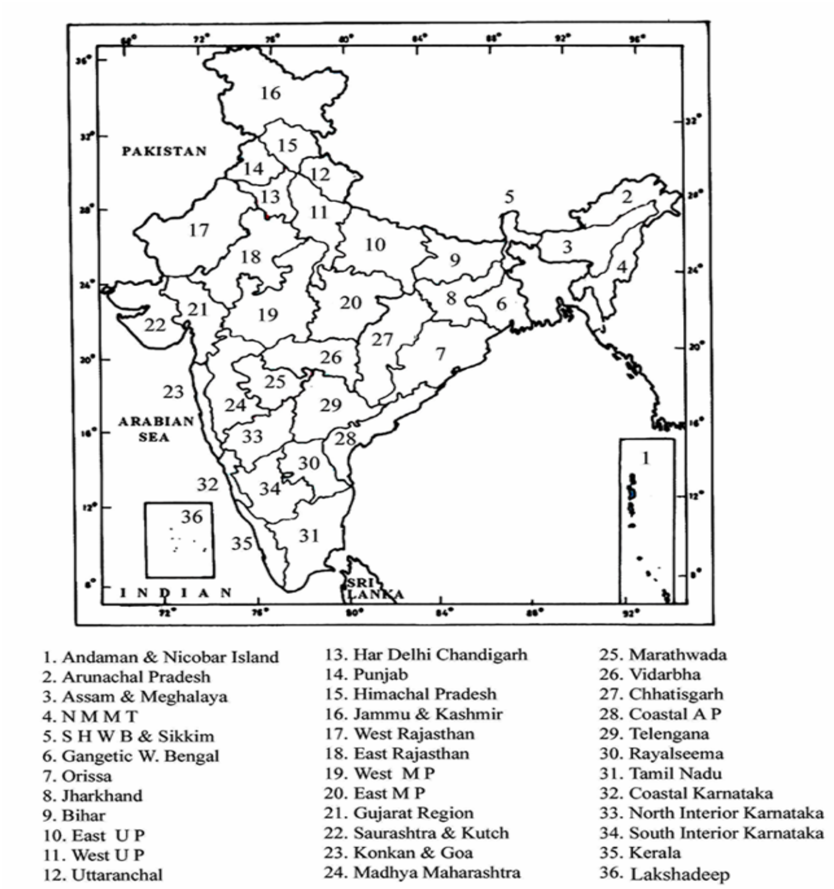


Fig. 1 b. Geographical location of India's 36 meteorological sub-divisions

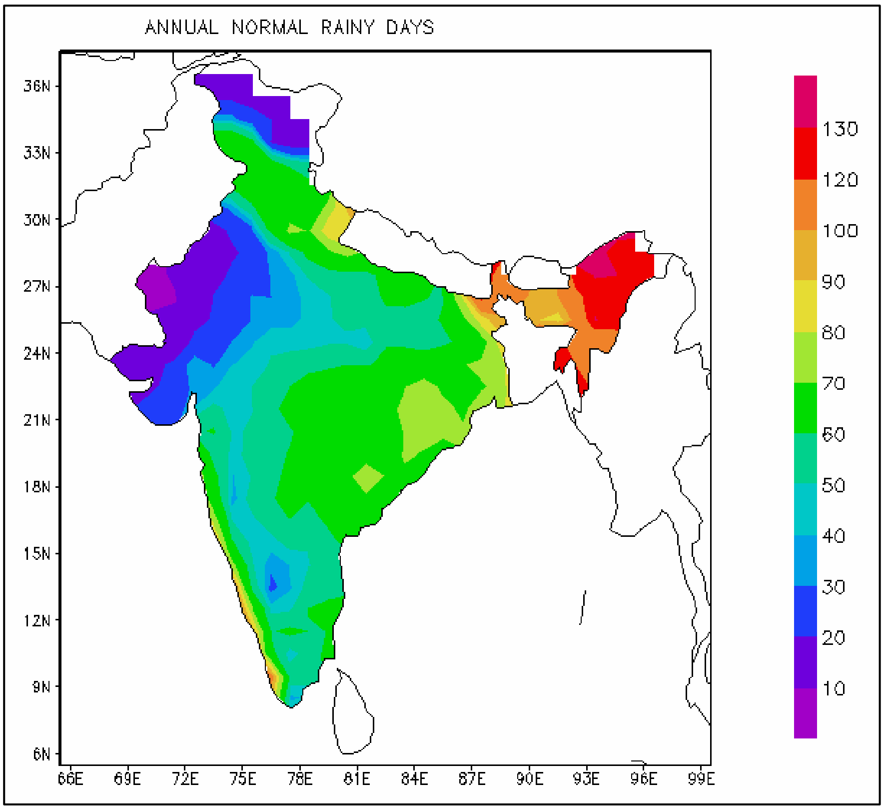


Fig. 2. Annual frequency of normal rainy days

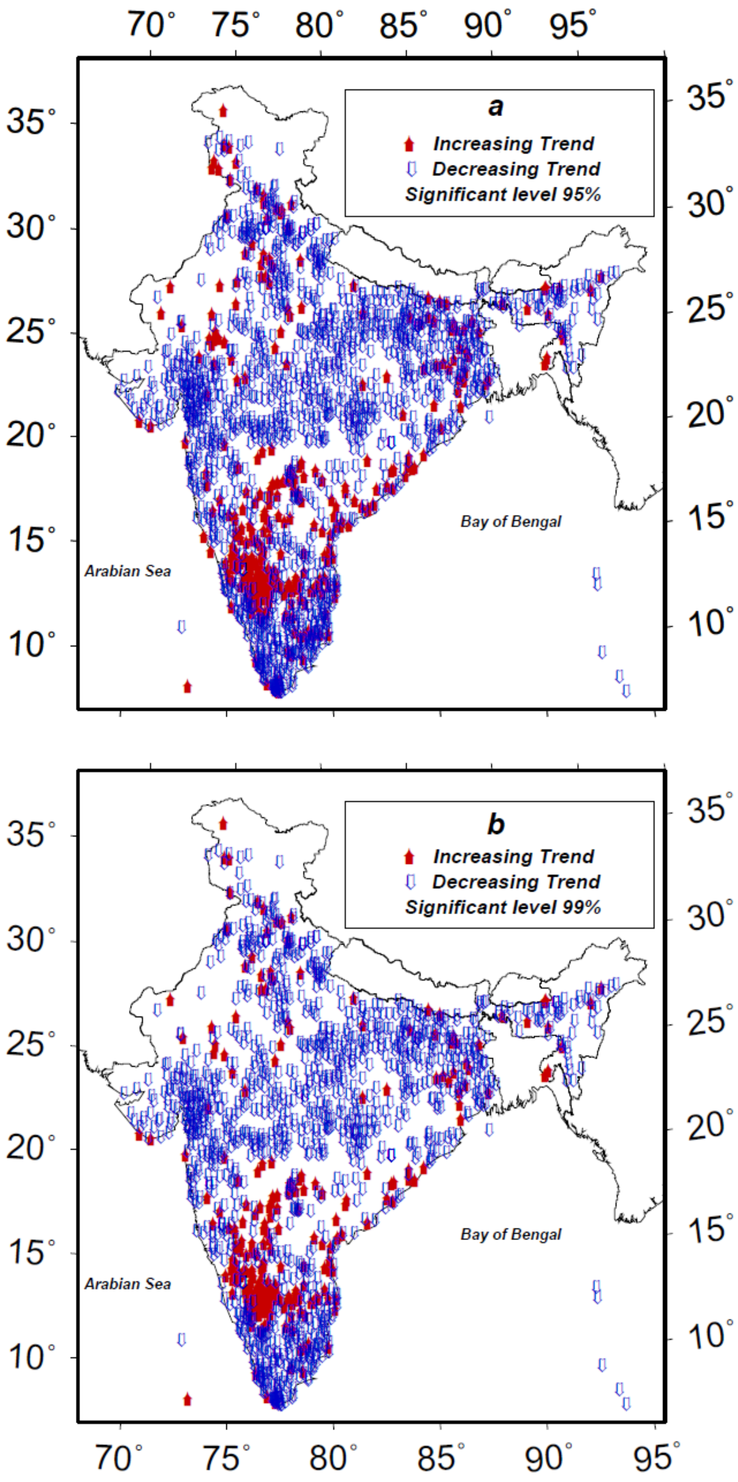


Fig. 3. Stations with significant increasing/decreasing trend in frequency of rain day at (a) 95% significant level and (b) 99% significant level using Mann-Kendall non parametric trend test .

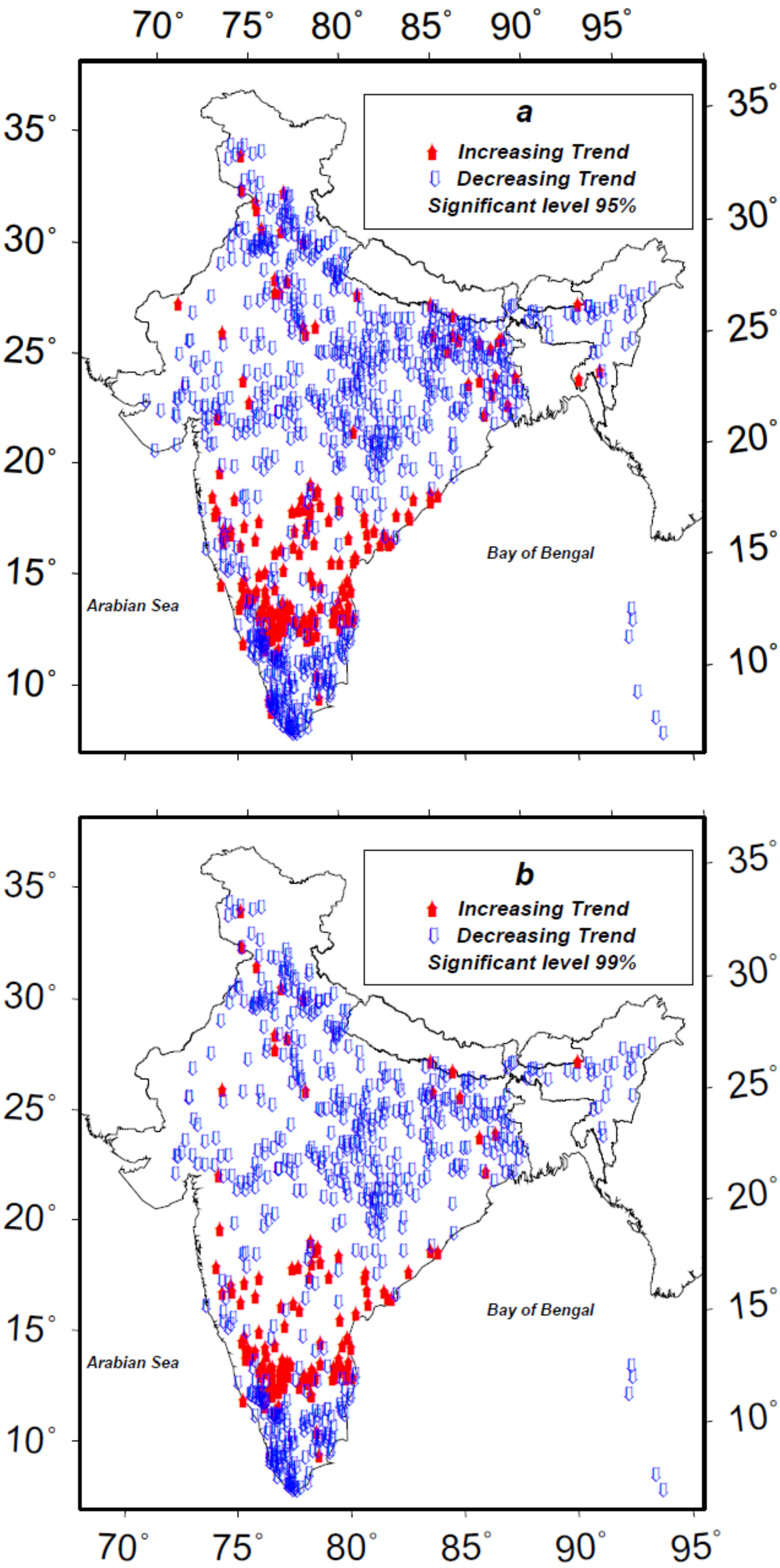
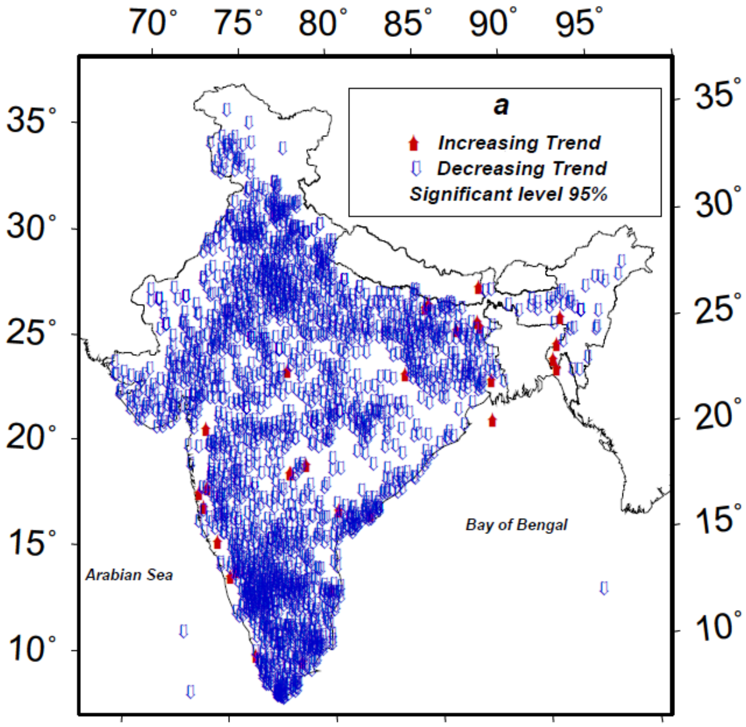


Fig. 4. Stations with significant increasing/decreasing trend in frequency of rainy day at (a) 95% significant level and (b) 99% significant level using Mann-Kendall non parametric trend test .



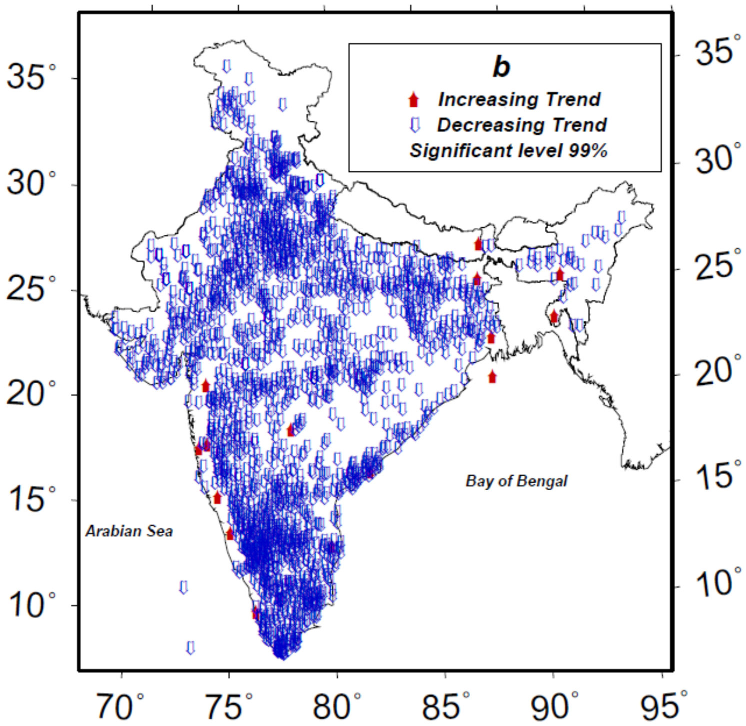


Fig. 5 Stations with significant increasing/decreasing trend in frequency of heavy rainfall day at (a) 95% significant level and (b) 99% significant level using Mann-Kendall non parametric trend test .

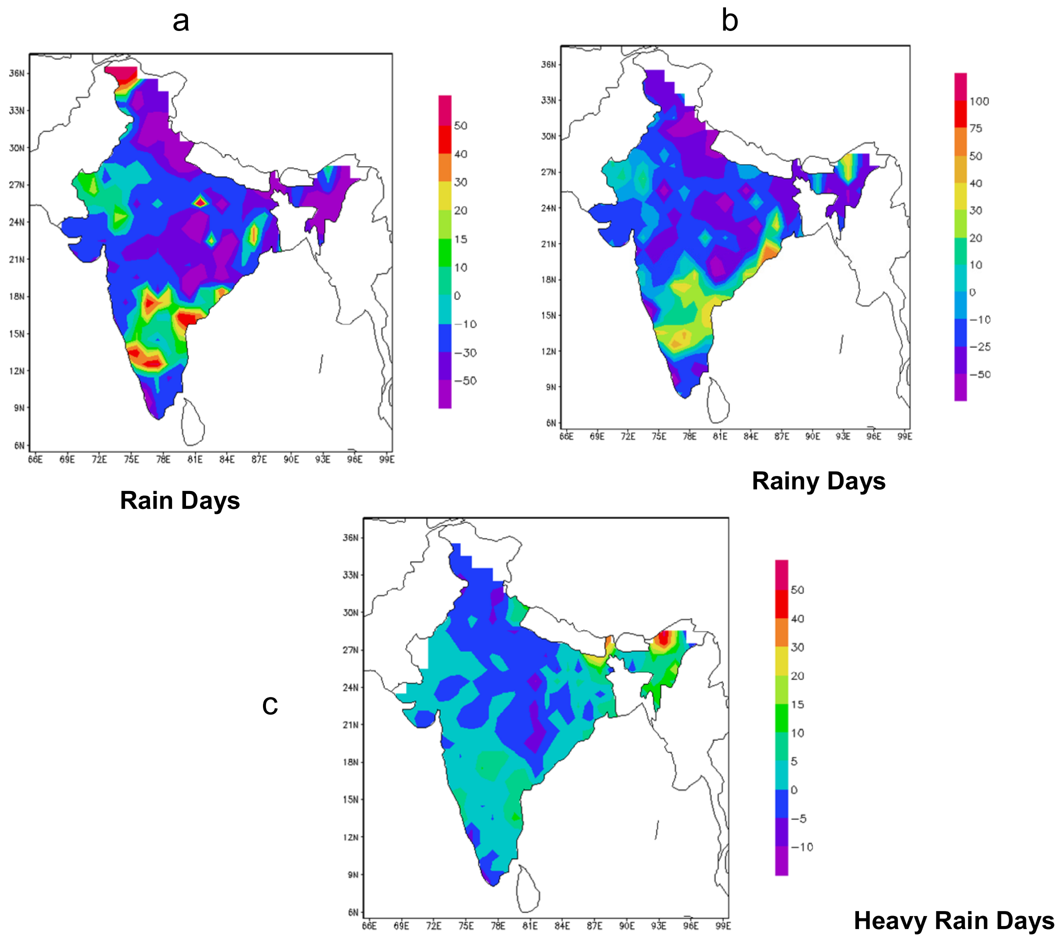


Fig. 6. Increase/decrease in frequency of (a) Rain Days (b) Rainy Days and Heavy Rainfall Days in 100 years

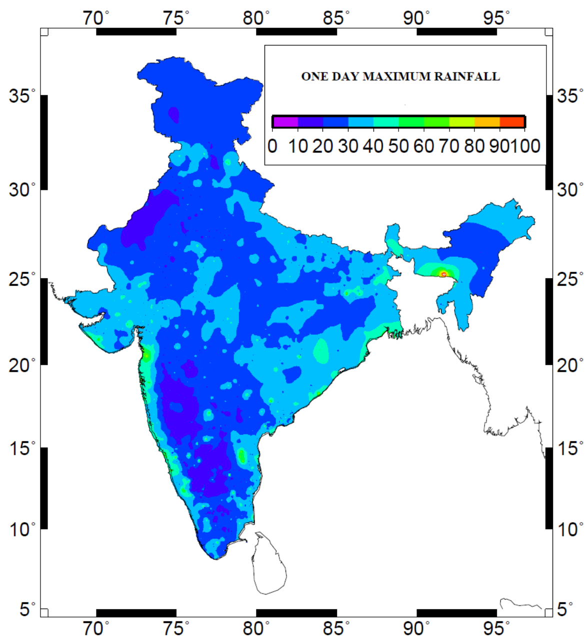


Fig. 7. Highest One-day Extreme Rainfall in India

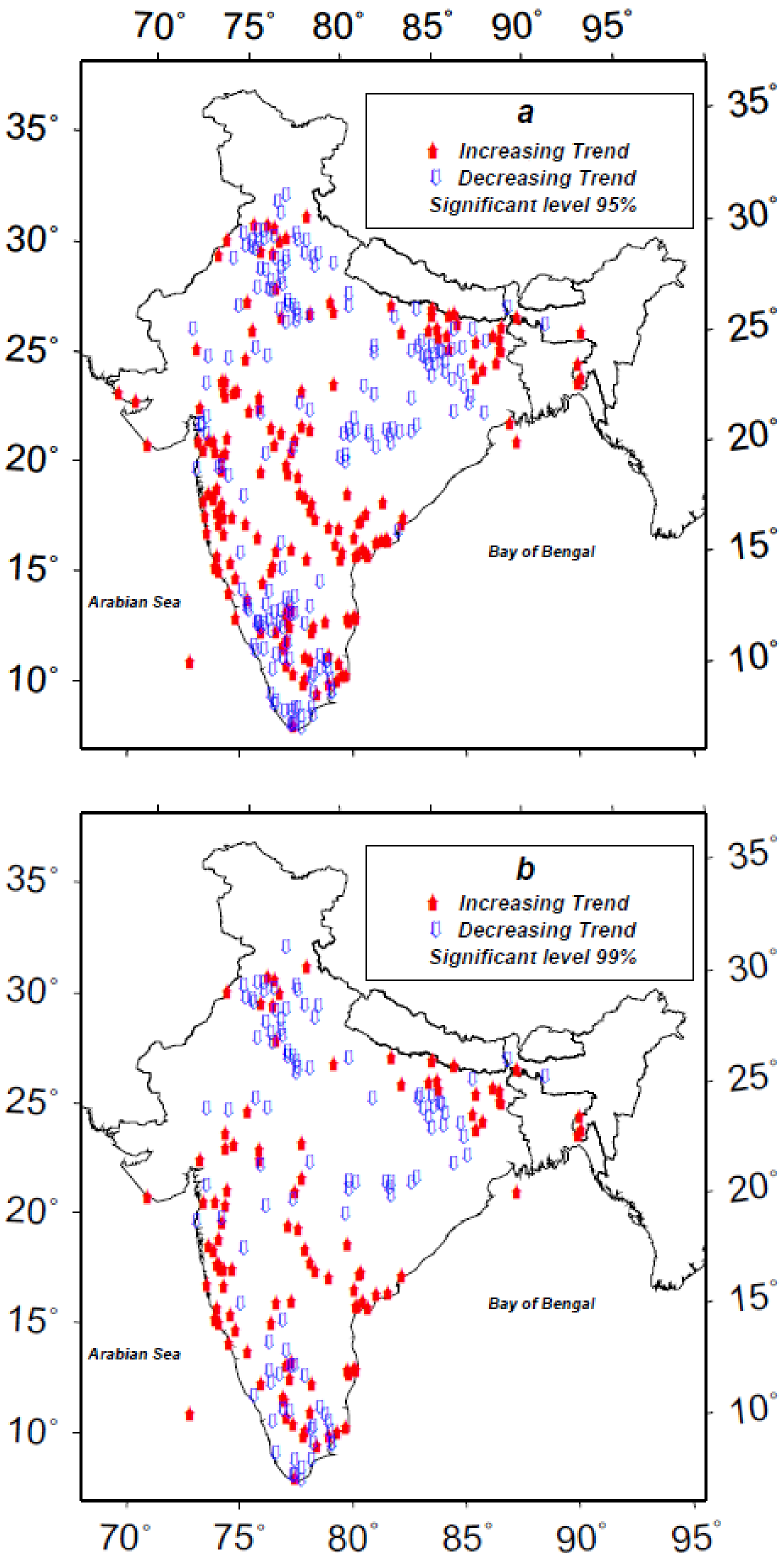


Fig. 8. Stations with significant increasing/decreasing trend in one-day extreme rainfall at (a) 95% significant level and (b) 99% significant level using Mann-Kendall non parametric trend test .

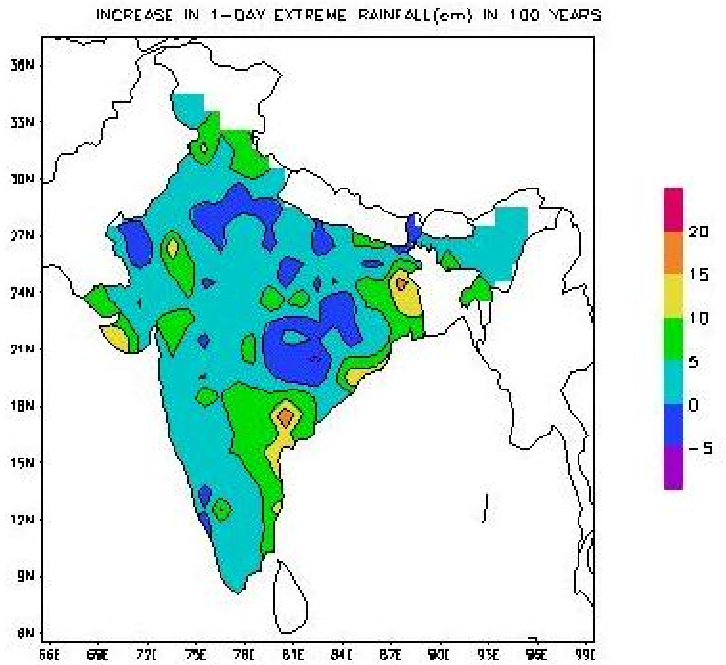


Fig. 9. Increase/decrease in one day extreme rainfall (cm) in 100 years

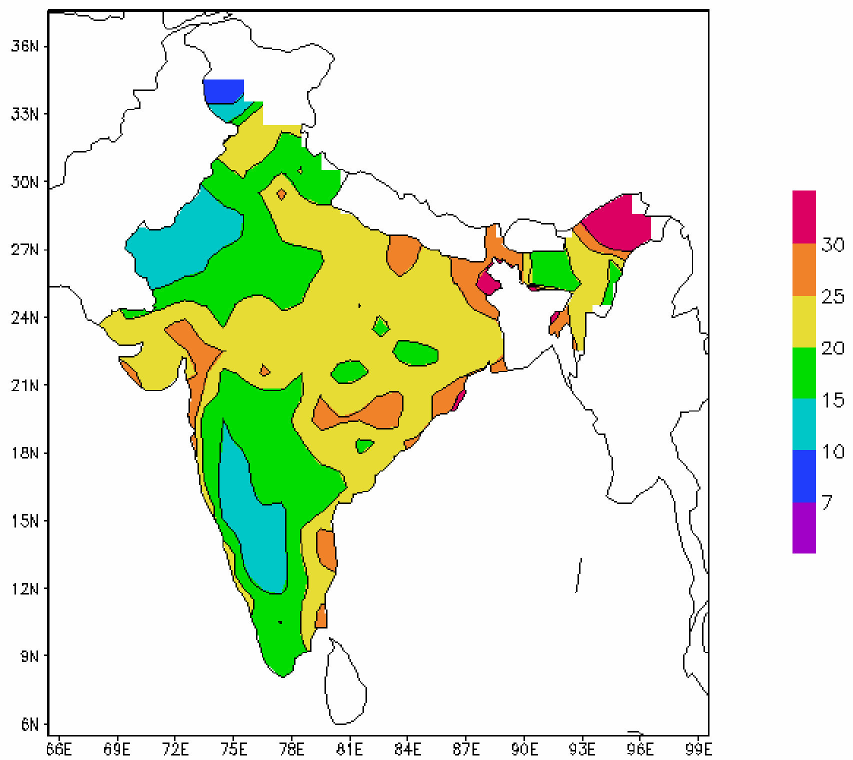


Fig. 10. Extreme values for 25 years return period

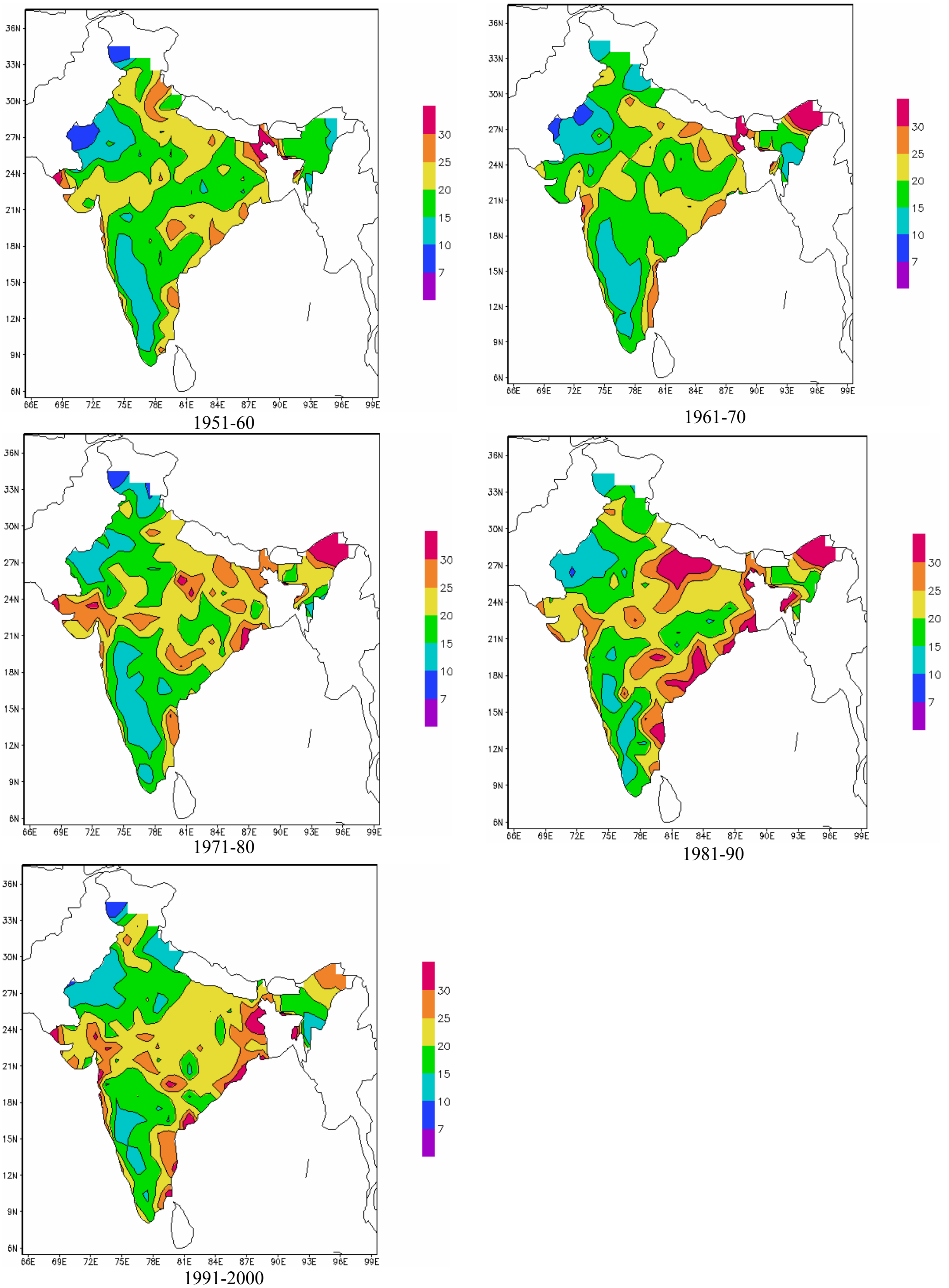


Fig. 11. Decadal variability of extreme values (cm) for 25 years return period

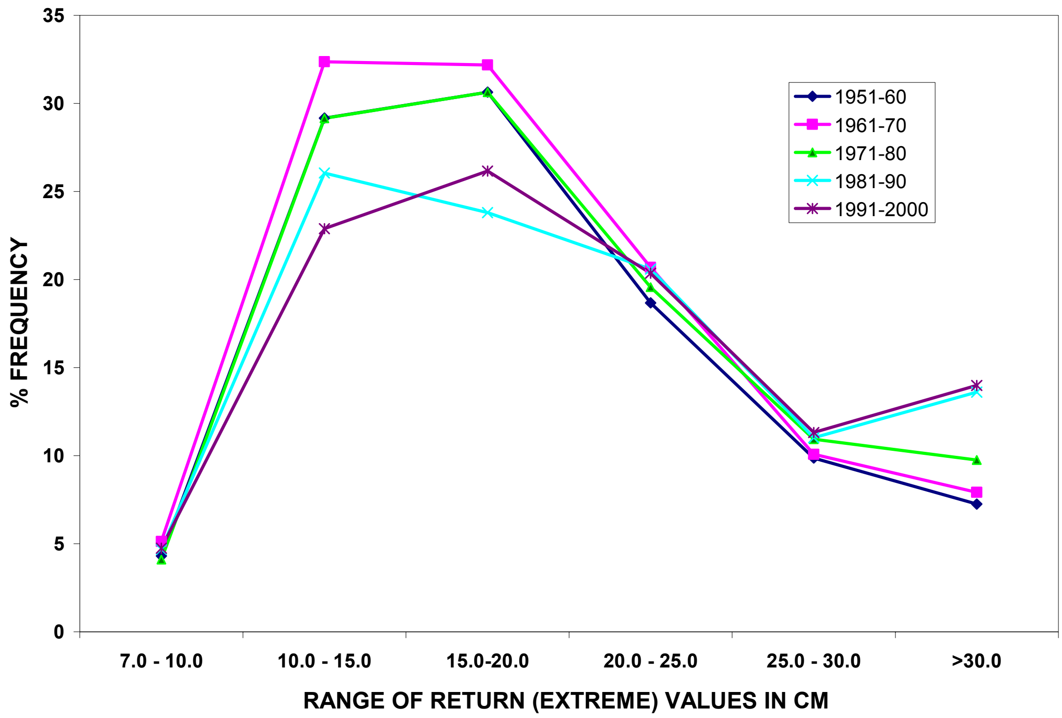


Fig. 12. Percentage frequencies of extreme values (cm) for 25 years return period in different range for each of the decade.

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