

Variability and trends in extreme rainfall over India

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सार – इस शोध पत्र में भारत के विभिन्न क्षेत्रों और समूचे भारत में अत्यधिक वर्षा की मौसमी और वार्षिक प्रवृत्तियों और भिन्नताओं की जाँच करने का प्रयास किया गया है। प्रवृत्तियों और भिन्नताओं की जाँच निम्नलिखित प्राचलों के आधार पर की गई (i) अत्यधिक वर्षा की तीव्रता (ERI) की आवृत्ति व परिमाण और कुल वर्षा में इनका योगदान (ii) सबसे अधिक वर्षा की घटनाएँ (iii) अत्यधिक वर्षा की घटनाओं और दिनों की आवृत्ति (iv) भारत के विभिन्न क्षेत्रों और समूचे भारत में ग्रिड बाक्स ($1^\circ \times 1^\circ$) में 100 मि. मी. और 200 मि. मी. से ऊपर दैनिक वर्षा सहित वर्षा की घटनाओं और दिनों की आवृत्ति/अत्यधिक वर्षा की घटनाओं से संबंध प्रवृत्तियों और भिन्नताओं की जाँच करने के लिए ($1^\circ \times 1^\circ$) विभेदन पर उपलब्ध भारत मौसम विज्ञान विभाग (IMD) के दैनिक ग्रिड-युक्त वर्षा के आंकड़ों का उपयोग किया गया। श्रेणी 1 और श्रेणी 2 की अत्यधिक वर्षा की तीव्रता/घटनाओं के थ्रेशहोल्ड के रूप में दैनिक कुल/अधिकतम वर्षा के दीर्घावधि 95 और 99 प्रतिशत मानों के आधार पर 1951-2007, 1951-1980 और 1981-2007 की अवधि के लिए उपर्युक्त उल्लिखित प्राचलों की प्रवृत्तियों और भिन्नताओं का विश्लेषण किया गया है।

समूचे देश और प्रायद्वीपीय भारत में अत्यधिक तीव्रता की वर्षा के परिमाण में वृद्धि हुई : 1951-1980 की अवधि की तुलना में 1981-2007 के दौरान 1% की वृद्धि देखी गई। श्रेणी 1 की अत्यधिक वर्षा की तीव्रता (ERI) की तीव्रता में उत्तरी मध्य क्षेत्र में उल्लेखनीय रूप से वृद्धि (0.4 दिन/दशक) देखी गई और मॉनसून पूर्व ऋतु में उत्तर पूर्वी क्षेत्र में उल्लेखनीय रूप से कमी (0.5 दिन/दशक) की प्रवृत्ति देखी गई। उत्तर पूर्वी और दक्षिण प्रायद्वीपीय क्षेत्रों को छोड़ कर समूचे क्षेत्र में ग्रिड बाँक्स में 24 घंटों की अत्यधिक वर्षा के परिमाण में उल्लेखनीय रूप से वृद्धि देखी गई। समूचे देश में और भारत के विभिन्न क्षेत्रों में वार्षिक अत्यधिक वर्षा की घटना के साथ मेल खाते सामान्यकृत चरम मान (GEV) वितरण से देश के उत्तरी मध्य क्षेत्र में अध्ययन अवधि के उत्तरार्ध के दौरान ग्रिड बाँक्स में अधिक संभाव्य 24 घन्टे की अधिकतम वर्षा के परिमाण में वृद्धि का पता चलता है। इस विश्लेषण से 1950-1980 की तुलना में 1981-2007 की अवधि के दौरान उत्तर पश्चिमी, उत्तरी मध्य और पश्चिमी प्रायद्वीप में अत्यधिक वर्षा की आवृत्ति और तीव्रता में वृद्धि का भी पता चलता है।

वर्तमान अध्ययन (1951-2007) की अवधि के दौरान देश में दोनों श्रेणियों की चरम वर्षा सहित दिनों और घटनाओं की वार्षिक आवृत्ति में बहुत अधिक उल्लेखनीय रूप से वृद्धि हुई है। केवल मॉनसून ऋतु में ही दोनों श्रेणियों की चरम वर्षा सहित दिनों की आवृत्ति में उल्लेखनीय रूप से बढ़ी हुई प्रवृत्तियाँ देखी गई हैं जबकि चरम वर्षा की घटनाओं से समूचे देश में मॉनसून और शीत ऋतु में बढ़ी हुई प्रवृत्तियाँ देखी गई हैं। 100 मि. मी. और 200 मि. मी. से ऊपर किसी भी ग्रिड बाँक्स में दैनिक वर्षा सहित दिनों की संख्या और घटनाओं की देश में उल्लेखनीय रूप से वृद्धि देखी गई है। छह क्षेत्रों में से उत्तरी मध्य और उत्तरी पूर्वी क्षेत्रों में ग्रिड बाक्स में 100 मि. मी. से ऊपर वर्षा के वार्षिक दिनों की संख्या में उल्लेखनीय रूप से वृद्धि की प्रवृत्तियाँ देखी गई और उत्तर पश्चिमी और उत्तर मध्य क्षेत्रों में 200 मि. मी. से ऊपर वर्षा में उल्लेखनीय रूप से वृद्धि देखी गई।

ABSTRACT. This study has been attempted to investigate the seasonal and annual trends and variations in the occurrence of extreme rainfall over different Indian region and India as a whole. Trends and variations are examined on the basis of following parameters (i) frequency and magnitude of extreme rainfall intensity (ERI) and its contribution in

total rainfall (ii) highest rainfall events (iii) frequency of extreme rainfall events and days (iv) frequency of rainfall events and days with daily rainfall above 100 mm and 200 mm in a grid box ($1^\circ \times 1^\circ$) over different Indian regions and India as a whole. Daily gridded rainfall data from India Meteorological Department (IMD) available at $1^\circ \times 1^\circ$ resolution has been used to examine trends and variations associated with extreme rainfall events. Based on the long term 95 and 99 percentile values of daily total /maximum rainfall as a threshold for extreme rainfall intensity/events of category 1 and category 2 respectively, the trends and variations in above mentioned parameters are analyzed for the periods 1951-2007, 1951-1980 and 1981-2007.

The magnitude of highest intensity rainfall is increased over country as a whole and over peninsular India; it is found to be increased by 1% during 1981-2007 as compared to period 1951-1980. The frequency of extreme rainfall intensity (ERI) days of category 1 is found to be significant increasing (0.4 days/decade) over north central region and significant decreasing trend is found over north east region (0.5 days/decade) during the pre-monsoon season. The magnitude of 24 hours highest rainfall in a grid box is found to be significant increasing over all regions under consideration except over north east and south peninsular regions. Over the last ten years period of the present study, most of the 24 hours highest rainfall events in a grid box are seen over west peninsular region. Generalized extreme value (GEV) distribution fitted with annual highest rainfall event over the country as a whole and over different Indian region indicates an increase in magnitude of most probable 24 hours highest rainfall in a grid box during second half of the study period over north central region of the country. Analysis also reveals an increase in frequency and severity of extreme rainfall over north west, north central and west peninsular regions during the period of 1981-2007 as compared to 1950-1980.

Annual frequency of days and events with extreme rainfall of both categories is increased most significantly over country during the period of present study (1951-2007). Significant increasing trends in frequency of days with extreme rainfall of both categories is noticed only during the monsoon season while extreme rainfall events showed increasing trends during monsoon and winter season over country as a whole. Number of days and events with daily rainfall in any grid box above 100 mm and 200 mm is observed to be significantly increased over the country. Out of six regions, significant increasing trends in annual number of days with rainfall above 100 mm in a grid box is observed over north central and north east regions and for rainfall above 200 mm significant increase is observed over north west and north central regions.

Key words – Extreme rainfall events, Extreme rainfall intensity, Significant trend, Increasing trend.

1. Introduction

One of the most significant consequences of global warming due to increase in greenhouse gases would be an increase in magnitude and frequency of extreme precipitation events. Physical considerations and model studies [Trenberth, 2005; Easterling *et al.*, 2000; Karl *et al.*, 2003; Hennessy *et al.*, 1998] indicate that the tropospheric warming might increase the moisture content of the atmosphere and is associated with an increase in heavy rainfall events. Even if the total number of extreme events over a homogeneous large-scale environment have an increasing trend, but no significant trend may appear in data from a single station because of the large spatial variability of rainfall. By using a daily rainfall data set, Goswami *et al.* (2006) showed significant rising trends in the frequency and the magnitude of extreme rain events and significant decreasing trends in the frequency of moderate events over central India during the monsoon seasons from 1951 to 2000. Similarly, Rajeevan *et al.* (2008) examined the variability and long-term trends of extreme rainfall events over central India by using 104 years (1901 - 2004) of high resolution daily gridded rainfall data and observed significant inter-annual and inter-decadal variations in addition to a statistically significant long term trend of 6% per decade in the frequency of extreme rainfall events. A detailed study on extreme rainfall events over the entire regions of the country is needed to get the impact of climate change on

the extreme weather events over the country. A large amount of variability in 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 regions of country. The study of spatial variability in extreme rainfall events will help to identify the zones of high and low values of extreme rainfall events. Sinha Ray and Srivastava (2000) have done trend analysis of heavy rainfall events over some selected stations in India and reported a decreasing trend over most parts of the country. However, over the north west coast and a few stations in the northern parts (Haryana and Punjab), a significant increasing trend was noticed. Rakhecha and Pisharoty (1996) have studied heavy rainfall events during southwest monsoon seasons for some selected stations in the country. Floods mostly occur due to the extreme spatial and temporal variations in the rainfall pattern over the short monsoon period of 4 months, resulting in a very heavy discharge from rivers Ganga, Brahmaputra, Indian Peninsula rivers and their tributaries during this period. Rakhecha and Soman (1994) analyzed the annual extreme rainfall series in the timescale of 1 to 3 days at 316 stations, well distributed over the country, covering 80 years of rainfall data from 1901 to 1980 for studying trends and persistence using standard statistical tests. They have reported that the annual extreme rainfall records of most stations are free from trends 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 exhibit a decreasing trend at the same level of significance. Stephenson *et al.* (1999) using the data for the period June to September 1986-1989 have investigated extreme daily rainfall events and their impact on ensemble forecasts of the Indian monsoon rainfall. Most of the studies on extreme rainfall over India [Rakhecha and Soman (1994); Sen Roy and Balling (2004)] used limited number of stations. Sen Roy and Balling (2004) have considered parameters such as total annual precipitation, 5-day total precipitation and 30-day total precipitations in their extreme rainfall analysis. Guhathakurta *et al.* (2011) analyzed one-day extreme rainfall series and showed that the intensity of extreme rainfall has increased over coastal Andhra Pradesh and its adjoining areas, Saurashtra and Kutch, Orissa, West Bengal, parts of northeast India and east Rajasthan. Significant decrease in intensity as well as frequency of extreme rainfall has been observed over Chattisgarh, Jharkhand and some parts of north India. Dash *et al.* (2009) used daily gridded ($1^\circ \times 1^\circ$) rainfall data of India Meteorological Department for the period 1951-2004 and examined the possible changes in the frequency of rain events in India in terms of their duration and intensity per day. It was observed that the frequencies of moderate and low rain days considered over the entire country have significantly decreased in the last half century. On the basis of the duration of rain events it is inferred that long spells show a significant decreasing trend over India as a whole while short and dry spells indicate an increasing tendency with 5% significance.

In this study an attempt has been made to investigate the seasonal and annual trends and variations in (i) frequency and magnitude of extreme rainfall intensity and its contribution to total rainfall (ii) highest rainfall events (iii) frequency of extreme rainfall events and days & (iv) frequency of rainfall events and days with daily rainfall above 100 mm and 200 mm in a grid box ($1^\circ \times 1^\circ$) over different homogeneous rainfall regions and over the country as a whole by using the daily gridded rainfall data at $1^\circ \times 1^\circ$ resolution from the India Meteorological Department (IMD).

The information regarding trends and variability of extreme rainfall days /events over different Indian regions is essential requirement for the policy makers for a sustainable economical development, particularly infrastructures, energy and transportation. The damage due to extreme rainfall may be immensely subdued by proper assessment and risk management and by the adaptation and mitigation procedures. In this regard present study may be useful in disaster management.

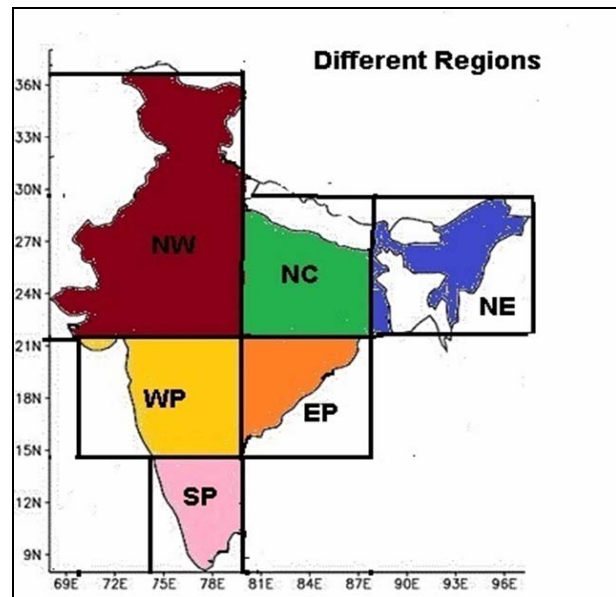


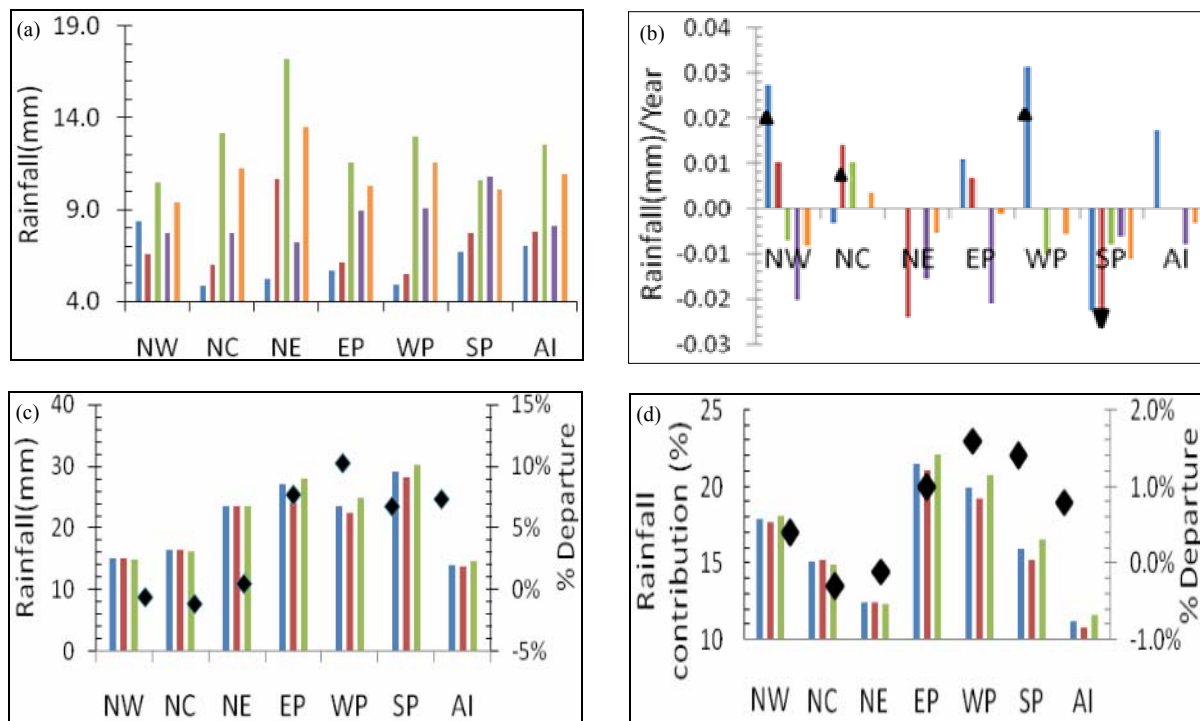
Fig. 1. Different regions over country under study

2. Data and methodology

Daily gridded rainfall data at $1^\circ \times 1^\circ$ resolution from India Meteorological Department (IMD), based on 1803 stations that have at least 90% data availability for the period 1951-2007 are used. The gridded daily data are smoother than the individual station data. The study has also been performed for the periods of 1951-1980 and 1981-2007 separately to check long term changes. Seasonal and annual trends and variability in frequency and intensity of heavy rainfall events are examined for country as a whole and for different regions comprised within the box, *viz.*, (i) North West region; NW (68.5° E - 80.5° E : 36.5° N - 21.5° N) (ii) North Central; NC (80.5° E - 87.5° E : 28.5° N - 21.5° N) (iii) North East; NE (87.5° E - 97.5° E : 28.5° N - 21.5° N) (iv) East Peninsular; EP (80.5° E - 87.5° E : 20.5° N - 14.5° N) (v) West Peninsular; WP (70.5° E - 80.5° E : 20.5° N - 14.5° N) and (vi) South Peninsular; SP (74.5° E - 80.5° E : 13.5° N - 8.5° N). The different regions under study are shown in Fig. 1.

Mean annual highest rainfall intensity over different regions and country as a whole is evaluated by averaging the 10 highest 24 hours total rainfall in each year and its annual contribution to total rainfall in the period of 1951-2007 as well as in the period of 1951-1980 and 1981-2007.

Extreme value theory (Fisher and Tippett, 1928) is used in identifying the extremes of probability distribution



Figs. 2 (a-d). (a) Mean daily rainfall in a grid box in (i) winter season (blue), (ii) Pre-monsoon season (red), (iii) monsoon season (green), (iv) post monsoon (violet) and (v) annual (orange), (b) Trends in mean daily rainfall in a grid box over the country as a whole, \blacktriangle indicate significant trend at 5% significance level during 1951-2007, (c) Mean ten days highest rainfall / grid box over different regions and the country as a whole in the period of (i) 1951-2007 (blue), (ii) 1951-1980 (red), (iii) 1981-2007 (green), \blacklozenge indicate % departure in rainfall in a grid box during the period 1981-2007 compared to 1951-1980 and (d) Same as Fig. 2(c), but for contribution of highest ten days total rainfall to total rainfall

of quantitative data. The generalized extreme value (GEV) distribution is used to determine thresholds for rainfall extremes from the tail of the distribution. The GEV distribution encompasses the three standard extreme value distributions such as Fréchet, Weibull, and Gumbel and is suitable for estimating extreme value percentile thresholds (Klein Tank *et al.*, 2009). GEV distribution is fitted with annual/seasonal highest rainfall events for the period of 1951-1980 and 1980-2007 over the country as a whole to identify the variation in probability of extremes.

Besides choosing any fixed threshold value for the criteria of extreme rainfall intensity (ERI), 95 and 99 percentiles values of long term (1951-2007) daily total rainfall in each season are worked out for all the regions. The days having total rainfall more than the 95 percentile and 99 percentile values are considered as days of extreme rainfall intensity under category 1 and 2 respectively. The time series for the frequency of days of both categories is prepared for the period 1951-2007 for each season/annual over the entire region under consideration. To evaluate the magnitude of extreme rainfall intensity during different

seasons over the regions, contribution of rainfall due to both category of rainfall to the total seasonal rainfall is also worked out.

Frequency of extreme rainfall days is identified by sorting out daily maximum rainfall in each season and over all regions during the period of study. The 95 and 99 percentile of long term (1951-2007) daily maximum rainfall in the regions during each season yields the threshold values for the extreme rainfall under category 1 and category 2 respectively. The threshold values of rainfall during each season are worked out for the entire region under study. The threshold values for extreme rainfall days over the country as a whole in any season is computed by averaging out the threshold values of rainfall of that season in each region. The different threshold values of rainfall over different regions and over country as a whole during different seasons are shown in Figs. 10 (a&b).

The frequency of extreme rainfall days for both categories during each season is worked out by sorting out

the number of days with maximum rainfall in any grid box which were greater than the threshold values of rainfall of that season. The number of days with extreme rainfall for both categories during each season is worked out for all the study regions under the present study. Annual frequency is computed for each region by summing up the frequencies extreme rainfall days of each season. Time series for seasonal and annual frequency of days for extreme rainfall for both categories are prepared for each region and over country as a whole. Similarly, the time series of frequency of extreme rainfall events of both categories over the entire regions during each season is prepared by adding daily total number rainfall events with rainfall more than the threshold values of rainfall in the season.

Frequency of daily rainfall days/events having rainfall higher than 100 mm and 200 mm in a grid box in different region and country as whole is used to prepare the seasonal and annual time series with fixed criteria of rainfall. The Mann-Kendall nonparametric test is applied in order to detect trends and its significance in different extreme parameter. The trends at less than or equal to 5% significance level are considered as statistically significant trend. The magnitude of the trends was estimated using Sen Slope (Sen, 1968).

3. Results and discussion

3.1. Rainfall intensity

3.1.1. Average and maximum rainfall intensity

Averaging over country as a whole, daily mean rainfall in a grid box of $1^\circ \times 1^\circ$ is found to be 8.7 mm on the rainy days, largest during monsoon season (12.5 mm) and lowest in winter (5.1 mm) during the period 1951-2007. Out of six regions, NE region receives highest average daily rainfall of 13.5 mm in a grid box which is due to large rainfall intensity (rainfall/grid box) during pre-monsoon (10.7 mm) and monsoon season (17.2 mm) as shown in Fig. 2(a). Maximum daily average rainfall intensity during winter is observed over NW region (8.4 mm) while in post monsoon season it is observed over SP region (10.8 mm) in a grid box. No significant trend is observed in the average daily rainfall per grid box over the country as a whole. However, it was found to be significantly increased over NW and NC regions during winter and pre monsoon season respectively. Significant decreasing trend in average daily rainfall per grid box is found over SP regions during pre-monsoon season as shown in Fig. 2(b).

Averaging the rainfall of ten highest rainfall days of each year, mean rainfall in a grid box is 14.1 mm during

the period 1951-2007 over the country as whole and it is increased by approximately 1.0 mm/grid box during the period of 1981-2007 as compared to the intensity during the period 1951-1980. Ten highest rainfall days in the year over the country as a whole contribute 11.2% of annual total rainfall in the study period. Over the regions, mean rainfall of ten highest rainfalls in a grid box is highest over SP region (29.2 mm) and lowest in NW region (15.1 mm). The intensity is predominantly increased over peninsular India during 1981-2007 by approximately 2.0 mm in a grid box, Fig. 2(c). Contribution of rainfall from ten highest rainfall days to annual total rainfall is seen increased by about 1% during the period 1981-2007 over peninsular India and over country as whole while a decrease is seen over NC and NE regions, Fig. 2(d).

3.1.2. Annual frequency of days with extreme rainfall intensity over country as a whole

Based on the criteria described in section 2 for the consideration of extreme rainfall intensity days, it is found that on an average 18.3 days in a year meet with the criteria of extreme rainfall intensity (ERI) of category 1 and 3.7 days in a year meet with the criteria of ERI of category 2 with their inter annual variability of 36% and 74% days respectively over the country as a whole, Figure not shown. Working out the magnitude of extreme rainfall intensity ERI, the mean annual contribution from category 1 rainfall to total rainfall is 19% during the period 1951-2007. It is increased by 0.9% during 1981-2007 over the country as a whole, as compared to the period 1951-1980. The decade 1953-1962 is observed to be largest intensity rainfall decade over the country when mean contribution from category 1 ERI rainfall to total annual rainfall was nearly 23%. Very heavy rainfall intensity is worked out through contribution of category 2 ERI rainfall to total annual rainfall. On an average, annually 4.9% rainfall is contributed by category 2 rainfall over the country as a whole and on an average, it is increased by 0.4% during 1981-2007 as compared to 1951-1980.

3.1.3. Annual frequency of days with extreme rainfall intensity over the regions

The largest annual number of days with ERI of category 1 is found to be 14.6 and 14.2 days over SP and NW regions respectively. For category 2 ERI days, these are observed to be maximum over SP region (2.95 days). The lowest annual frequency for category 1 and 2 ERI days is observed over WP region with 11.7 and 2.33 days respectively. No significant trend in annual frequency of days with extreme rainfall intensity is observed over the country as a whole and also over any region except over WP region where nearly significant increasing trend is observed during the study period, Figure not shown.

The analysis also shows that the annual frequency of days with ERI of category 1 is seen decreased only over SP region during 1981-2007. Remarkable increase (2 to 3 days) in mean annual frequency is found over EP and WP regions. Annually, very high intensity of rainfall (due to category 2) in the northern India is mostly observed over the NW region, contributing 6% of total annual rainfall. Similarly, over EP and SP regions in peninsular and southern India the annual contribution of rainfall from category 2 ERI days to total annual rainfall is found to be 7.7% and 7.6% of respectively.

The magnitude of very high intensity of rainfall due to category 2 rainfall is increased in the second half of the study period mostly over WP and SP regions by 4 to 5% and over NW and EP by 1 to 2%. On the other hand there is a decrease in magnitude of contribution of very high annual intensity of rainfall over NC and NE regions by 1.0% and 0.2% respectively during the period of 1981-2007 as compared to 1951-1980.

3.1.4. *Seasonal frequency of days with extreme rainfall intensity over country as a whole*

Seasonal frequency of days with ERI of both categories was maximum during monsoon season over country as a whole. But magnitude of extreme rainfall intensity in terms of contribution of rainfall due to category 1 and 2 to total seasonal rainfall is found to be largest during winter and post-monsoon seasons, contributing 29.7 and 25.7% respectively. This contribution was only 10.6% and 17.6% during monsoon and pre-monsoon seasons respectively during 1951-2007. The contribution of rainfall due to ERI of category 1 to total seasonal rainfall is largely increased during winter season by 7.3% and decrease was observed in post monsoon season by 0.3% over the country as a whole during 1981-2007 as compared to 1951-1980. Similarly, rainfall on ERI days of category 2 contributed 9.2% of total seasonal rainfall during winter season which is also a largest contribution out of all seasons. This contribution of extreme rainfall under category 2 is largest increased during winter season by 2.2% and decreased during post monsoon season by 2.2% in the second half of study period (1981-2007). This result reveals that most of the rainfall during winter season is due to events of high intensity rainfall over country as a whole.

3.1.5. *Seasonal frequency of days with extreme rainfall intensity over regions*

3.1.5.1. *Winter season*

Maximum frequency of ERI days under both categories during winter season is found over NW region

and minimum over WP region. No statistically significant trends in frequency of ERI days under both categories are observed over any region during period of study. Although, there was an increase in frequency with category 1 ERI days over all the regions during the period of 1981-2007 as compared to 1951-1980. The largest increase (by 150%) in ERI days under category 1 is seen over EP and WP regions during the second half of the study period as compared to the first half. Mean frequency of ERI days with category 2 in winter is noticed to be largely increased over WP and decreased over NC regions during the period of 1981-2007.

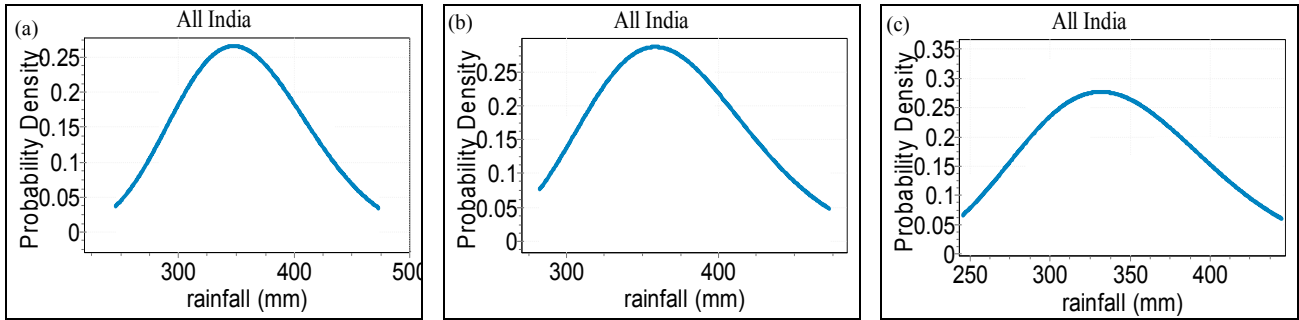
About 61% of total seasonal rainfall over NW region is seen contributed by the rainfall of category 1 during winter season which is observed to be the largest contribution to total seasonal rainfall among the entire regions during the period 1951-2007. This contribution was lowest over NE region, contributing only 29.7% to total seasonal rainfall during the period 1951-2007. The contribution due to category 1 rainfall to the total seasonal rainfall was largely increased over WP region by 27.9% and decreased over NC region by -2.4% during the period of 1981-2007 as compared to 1951-1980.

3.1.5.2. *Pre-monsoon season*

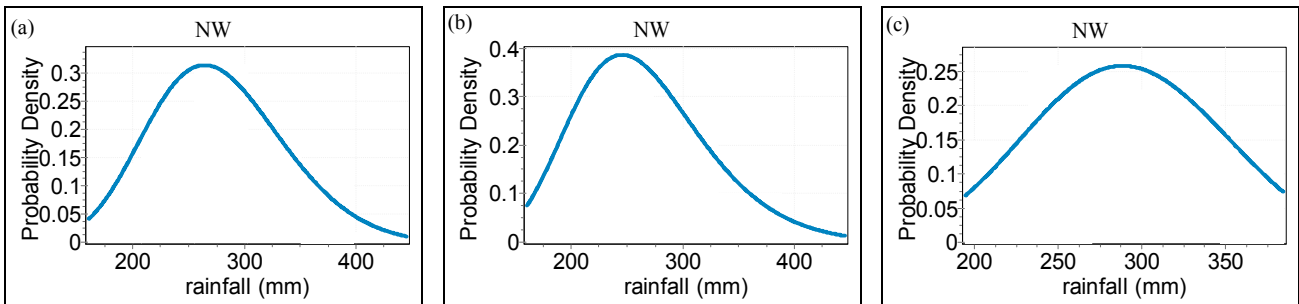
A significant increasing trend (0.4 days/decade) in frequency of category 1 ERI days was found during pre-monsoon season over NC region and significant decreasing trend was noted over NE region (0.5days/decade), figure not shown. Mean frequency of ERI days under category 1 declined over NE, WP and SP regions during 1981-2007 as compared to 1951-1980 while ERI days with category 2 decreased only over NE and SP regions. The contribution of rainfall due to category 1 ERI days to the total seasonal rainfall was highest over peninsular India (36%). This contribution of rainfall is largely increased over EP region by 9.8% and decreased over NE and WP regions by 4.1 and 2.5% respectively in the latter half of the study period.

3.1.5.3. *Monsoon season*

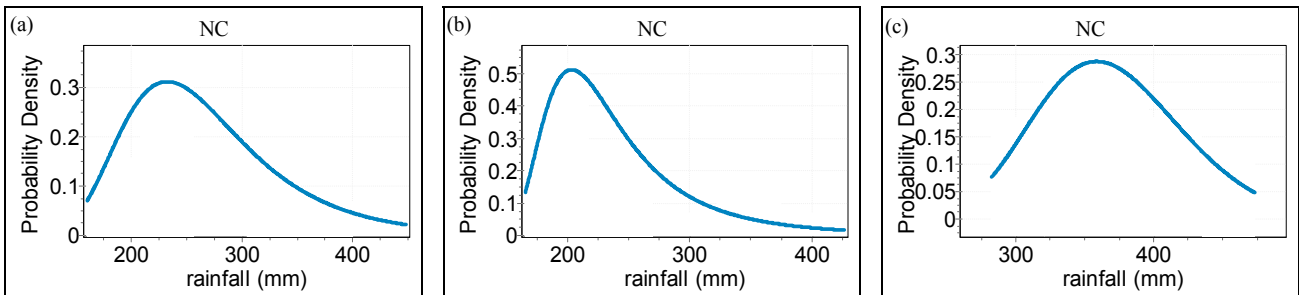
No significant trend in the frequency of days under category 1 and category 2 ERI is observed over any region during the season. However, the frequency of days under category 1 ERI days is observed to be increased largest over EP (29%) followed by WP region (20%) during 1981-2007 as compared to 1951-1980. A downfall in frequency is observed over NC and NE regions (by 15% for both) in the same period. Similarly, category 2 ERI rainfall days are highly increased over WP and SP regions by 268% and 150% respectively during 1980-2007. Highest contribution of rainfall due ERI days of



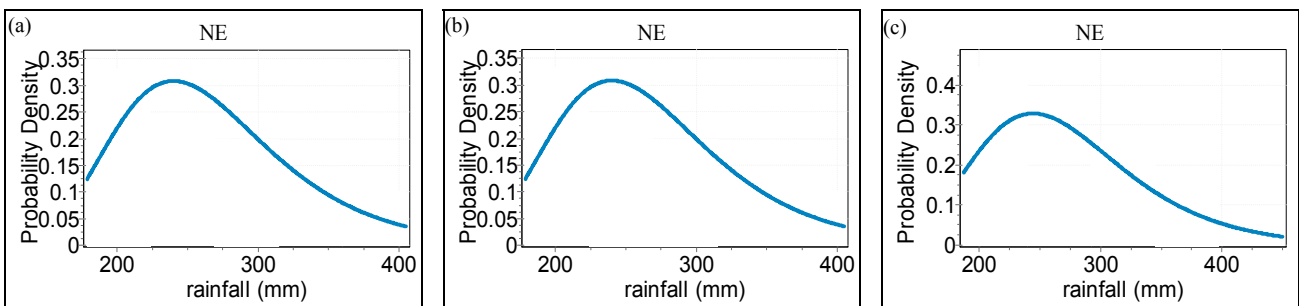
Figs. 3(a-c). Variations in the generalized extreme value probability distribution function for annual highest rainfall over country as whole in a grid box (in 24 hours) (a) during 1951-2007, (b) 1951-1980 and (c) 1981-2007



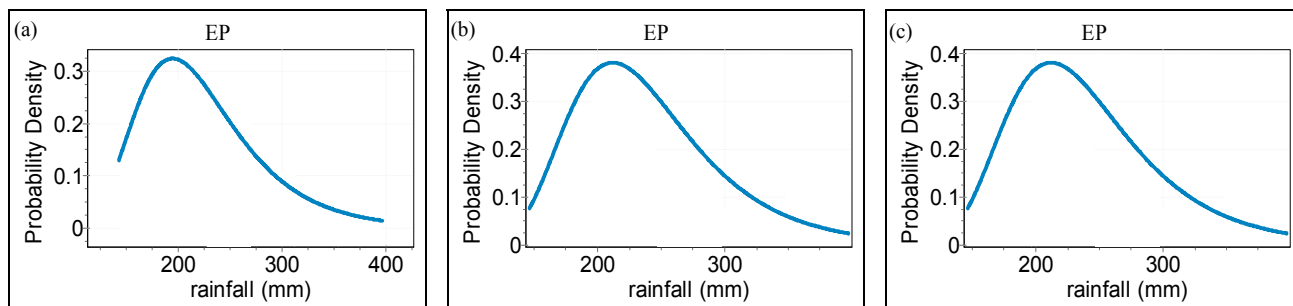
Figs. 4(a-c). Same as Figure 3 except for NW region



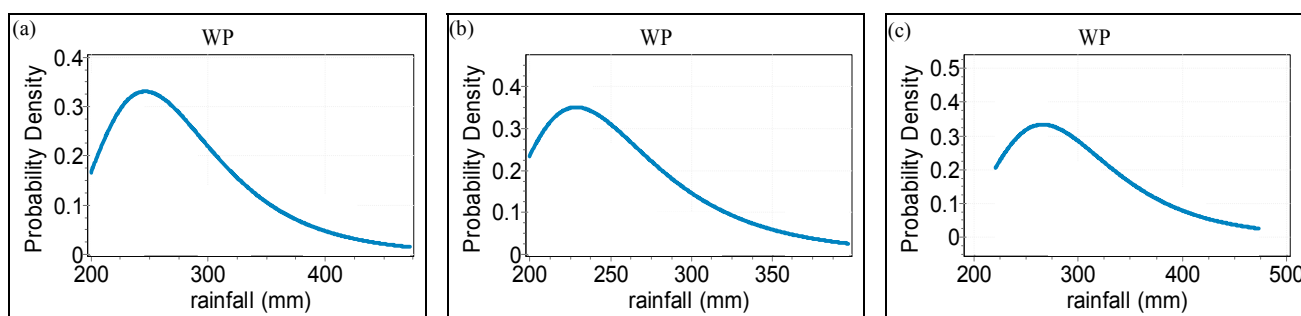
Figs. 5(a-c). Same as Figure 3 except for NC region



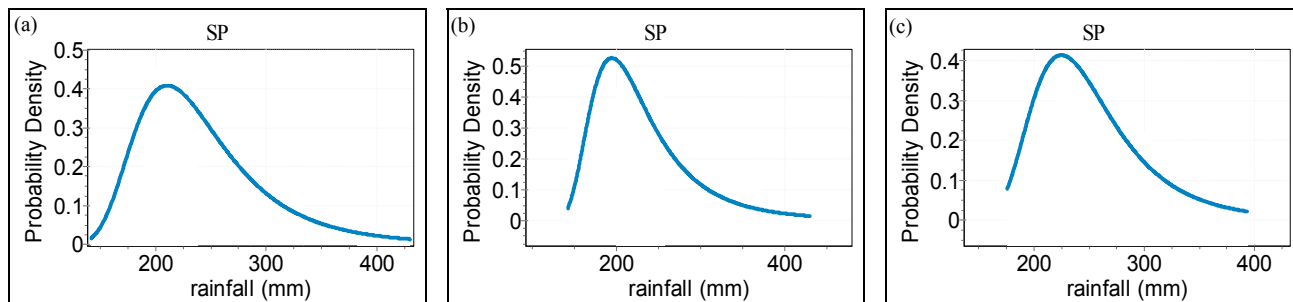
Figs. 6(a-c). Same as Figure 3 except for NE region



Figs. 7(a-c). Same as Figure 3 except for EP region



Figs. 8(a-c). Same as Figure 3 except for WP region



Figs. 9(a-c). Same as Figure 3 except for SP region

category 1 to total seasonal rainfall during monsoon season is observed over southern parts of the country, EP (19%), WP (14%) and SP (20.9%). Similarly, this contribution was largest over NW region in northern part of the country, contributing 15% rainfall to total seasonal rainfall. The magnitude of intensity in respect of contribution of rainfall from category 1 has declined over NW and NC regions by -1.1 and -1.5% respectively and sharply increased over EP and WP regions by 5.1% and 3.8% respectively during the period of 1981-2007 as compared to 1951-1980.

The contribution of rainfall from category 2 ERI days to total seasonal rainfall is seen highest over EP and

SP regions during the study period, contributing 5.4 and 6.3% of total seasonal rainfall respectively. This contribution of rainfall is found to be increased largest over SP region by 6.6% and decreased over NC region during 1981-2007 as compared to 1951-1980.

3.1.5.4. Post-monsoon season

No significant trend in the frequency of category 1 and category 2 ERI days is observed over any region during the season. The ERI days under category 1 are found to be maximum over EP region where on an average 47% of total seasonal rainfall is contributed by category 1 ERI days. Over the north India heavy intensity

of rainfall is mainly observed over NW region where category 1 rainfall contributed 41% of total seasonal rainfall during the period of 1951-2007. The magnitude of extreme intensity is decreased over NW and NC regions in the second half of study period 1981-2007. The increase in frequency under category 1 ERI rainfall days are observed only over peninsular India (EP, WP and SP regions) during the period 1981-2007 as compared to 1951-1980. The maximum frequency of extreme intensity of rainfall days under category 2 is observed over SP region and lowest over NC region. However, intensity of rainfall from category 2 ERI days is observed largest over NW and EP regions, contributing 15% of total seasonal rainfall during the period of 1951-2007. The largest increase in magnitude of rainfall from category 2 ERI days is seen over WP region (3.3%) during the period of 1981-2007. It was found to decrease over NC and EP regions during the same period.

3.2. *Spatial and temporal variation of highest rainfall events*

3.2.1. *Annual highest rainfall events*

The analysis of data in the present study shows that mean annual 24 hours highest rainfall event in any grid box over the country is 345.6 mm with an inter-annual variability 15.6% during 1951-2007. Insignificant trend in magnitude of annual 24 hours highest rainfall event is found over the country as a whole. On the other hand, there is a significant increasing trend observed in magnitude of 24 hours highest rainfall in a grid box over all regions under consideration except NE and SP regions, figure not shown. Over the last ten years period of the present study, mean 24 hours highest rainfall in a grid box is seen largest over WP region. Magnitude of mean annual highest rainfall events in any grid box over NW, NC, NE, EP, WP and SP regions is observed to be 276.8 mm, 270.5 mm, 270.0 mm, 224.7 mm, 283.3 mm & 244.8 mm respectively with inter-annual variability of 22 to 27% during the study period. Most of annual 24 hours highest rainfall events over the country in the period of 1951-2007 were observed over NW (14 times) followed by WP (13 times) and NC (12 times). The number of highest rainfall events over the country occurring over NC region is seen to increase sharply (200%) and decrease over the NE region (57%) in the second half of the study period.

Generalized extreme value (GEV) distribution is applied to get most probable annual and seasonal highest rainfall event over the country as a whole and over different Indian region during (i) 1951-2007, (ii) 1951-1980 and (iii) 1981-2007. The most probable annual highest rainfall event during 1951-2007 over the country as a whole is observed to be 334.1 mm in a grid box in 24

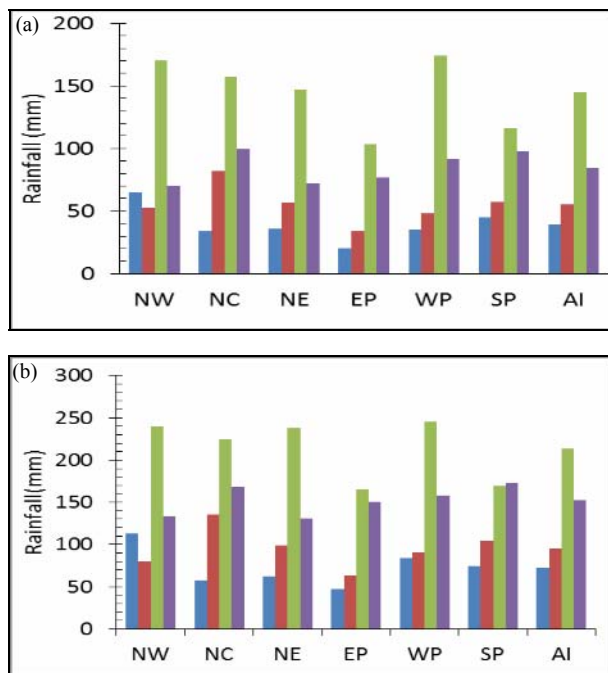
hours; it was only 320.0 mm during 1951-1980 and increased upto 348.5 mm during 1981-2007 [Figs. 3(a-c)]. Similarly, over the regions, most probable magnitude of highest rainfall event during 1951-2007 is observed to be 253.1 mm, 234.9 mm, 240.2 mm, 195.6 mm, 249.8 mm, 214.8 mm, over NW, NC, NE, EP, WP and SP regions respectively. Comparing the magnitude of most probable annual highest rainfall event in a grid box over different region between 1951-1980 and 1981-2007, it is clearly observed that there is an increase in magnitude of rainfall by 30 mm over NW, EP, WP and SP regions. Largest increase of more than 50 mm is observed over NC region. Almost no change is seen over NE region. The variations in probability density functions (PDFs) in the annual highest rainfall in a grid box over country as a whole and over the different regions are shown in Figs. 3(a-c) to Figs. 9(a-c). A shift in the mean of PDF from left to right indicates an increase in magnitude of highest rainfall events. Minimum change is noticed in the PDF over NE region, whereas maximum change is noticed over NC region. It implies an increase in magnitude of most probable 24 hours highest rainfall in a grid box during second half of the study period over NC region. The increase of area under the right tail of the PDF indicates an increase in amount of highest rainfall events as well as the severity of extremes. The area under right tail is seen largest increase in NW, NC and WP regions and least increase is seen over NE region. This result reveals that there is an increase in probability for the higher magnitude and frequency of 24 hours highest rainfall events during the period of 1981-2007 as compared to 1950-1980 over NW, NC and WP regions.

3.2.2. *Seasonal highest rainfall events*

3.2.2.1. *Winter season*

Mean seasonal highest 24 hours rainfall event in a grid box during winter season over India as a whole is found to be 99.5 mm during 1951-2007 with an inter-annual variability of 43%. The most probable 24 hours highest rainfall in a grid box which fitted with GEV distribution is observed as 88.6 mm during the period 1951-2007. It has been found to be increase by 10 mm during the period on 1981-2007 as compared to 1951-1980.

The magnitude of the highest 24 hours rainfall event in a grid box is observed to be significantly increasing at the rate of 6.1 mm/decade during the winter season over country as a whole. Most of the highest 24 hours rainfall events in a grid box during the winter season are found to be occurred over NW region (63% times) during the period of present study. Simultaneously, mean 24 hours highest rainfall in a grid box in winter season is found to



Figs. 10 (a&b). (a) Long term 95 percentile value of daily maximum rainfall (i) winter season (blue) (ii) pre-monsoon season (red) (iii) monsoon season (green) (iv) Post monsoon (violet) and (b) Same as Fig. 10(a) but for 99 percentile value of daily maximum rainfall

be 93.8 mm over NW region during the study period which was largest among all the regions. Significant increasing trend in magnitude of highest rainfall event is observed only over EP region at the rate of 4.7 mm/decade. Decreasing trend is seen only over NE region at the rate of 0.8 mm/decade but it is statistically insignificant.

3.2.2.2. Pre-monsoon season

Mean highest 24 hours rainfall in a grid box during pre-monsoon season over India as a whole is 159.2 mm with an inter-annual variation of 44%. Probability distribution function of highest 24 hours rainfall in a grid box over all India indicate most probable highest rainfall of 133.1 mm during the season and it is observed to be increased by 10 mm in the period on 1981-2007 as compared to the period from 1951-1980. Out of the six regions, most probable highest rainfall which fitted GEV distribution was largest over NE (136.3 mm) and lowest over EP region (77.6 mm). Nearly significant increasing trend in magnitude of highest rainfall is observed over NW and NC regions. About 50% highest 24 hours rainfall events in a grid box in the season are mainly found to occur over NE region in the country during the study period.

3.2.2.3. Monsoon season

During the monsoon season which is the major rain giving season over the country, the mean highest 24 hours rainfall in a grid box is found to be 329.0 mm with an inter-annual variation of 16%. Most probable highest 24 hours rainfall in a grid box over the country during 1951-1980 is observed to be 299.0 mm and it is increased to 344 mm during the period 1981-2007. The mean of highest 24 hours rainfall in a grid box was largest over WP region (278 mm) and lowest over EP region (196.3 mm). Seasonal mean highest rainfall in a grid box over the country as a whole is observed to be significantly increasing at the rate of 12.2 mm/decade.

Regarding region wise distribution, the magnitude of highest 24 hours rainfall event in a grid box during the season was sharply and significantly increasing over the NW region at the rate of 16 mm/decade and over WP region it was increasing at the rate of 12 mm/decade. It is clear from the analysis that during the last ten years of the study period most of the highest 24 hours rainfall events in a grid box over the country are observed over WP region and hence this region showed the largest mean highest 24 hours rainfall among the entire regions during this period. Significant increasing trend in magnitude of highest 24 hours rainfall in a grid box is also observed over NC region at the rate of 9.0 mm/decade.

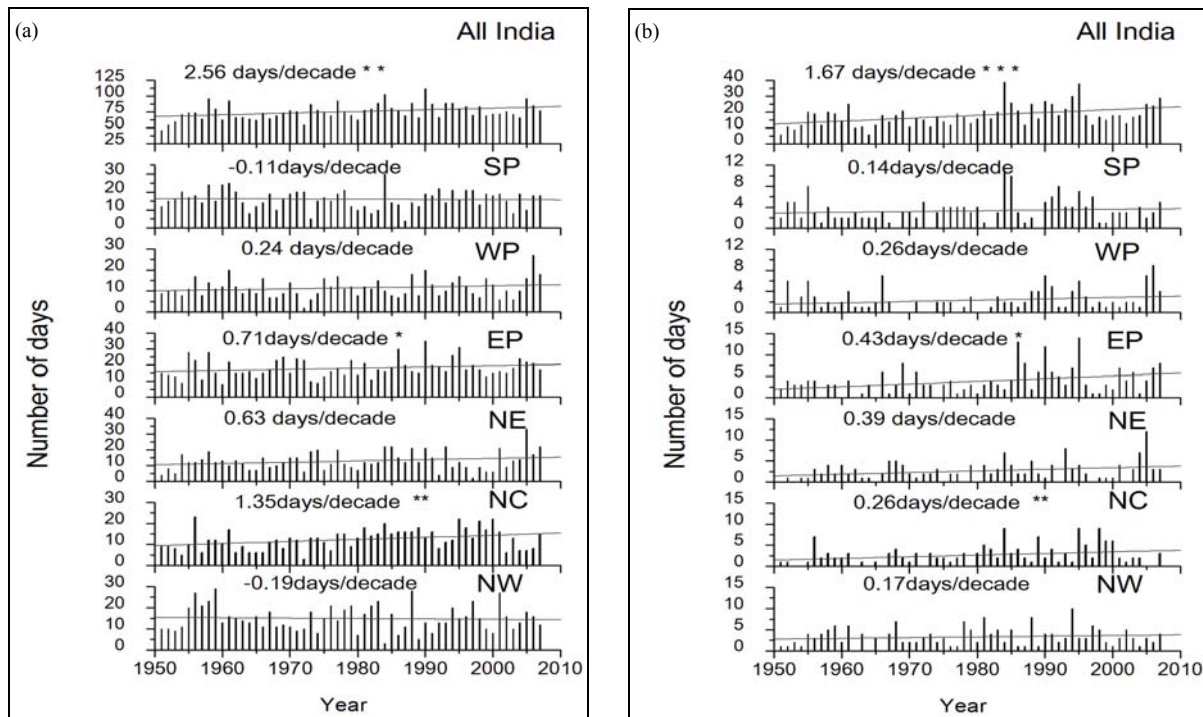
3.2.2.4. Post-monsoon season

Mean 24 hours highest rainfall in a grid box over the country in the post monsoon is found to be 243.7 mm and it showed a decreasing trend during the period 1951-2007. GEV distribution fitted with highest rainfall over the country as a whole country during the post monsoon season indicates that the most probable highest rainfall in a grid box was 203.8 mm during the period of 1951-1980 and no change is observed in the second half of the study period. Regarding regional distribution, mean 24 hours highest rainfall event in a grid box is seen largest over SP (187.1 mm), the next higher over EP region (179.0 mm) and lowest over NW region (116.6 mm). Significant decreasing trend in the magnitude of rainfall in the highest event is observed only over NW region at the rate of 16.2 mm/decade, while all other regions showed very insignificant increasing trend during the period 1951-2007.

3.3. Frequency of extreme rainfall days

3.3.1. Annual frequency

Analyzing the number of days with an event of extreme rainfall over the country as a whole



Figs. 11 (a&b). (a) Trends in annual frequency of extreme rainfall days of category 1, * significant at 5%, ** significant at 1%, *** significant at 0.1% and (b) Same as Fig. 11(a) but for extreme rainfall of category 2

during 1951-2007, it is observed that 21% of the days during the year meet the criteria of extreme rainfall of category 1 while only 4.9% of days in a year meet the criteria of extreme rainfall days of category 2. A significant increasing trend (2.56 days/decade) is observed in the annual frequency of days under category 1 extreme rainfall Fig. 11(a), while a significant increasing trend (1.67 days/decade) is seen in category 2 extreme rainfall days Fig. 11(b) over the country as a whole. Inter-annual variation of category 1 and category 2 rainfall days is observed to be 16% and 38% respectively. The years 1984 and 1990 were the biggest years for annual extreme rainfall days of category 1. The years 1984 and 1995 were the biggest years for category 2 over the country when positive anomaly of more than 2 is observed in frequency of extreme rainfall days. Decade of the largest annual frequency of category 1 rainfall days is found in the period of 1982-1991 while that of category 2 is observed in the period of 1986-1995.

Annual mean frequency of days for both category of rainfall over the regions is found to be largest observed over EP region with 18.1 and 3.8 days for category 1 and category 2 extreme rainfall days respectively. Next to EP region, annual mean frequency of days for extreme rainfall of category 1 is seen over SP and NW 15.2 and 14.8 days respectively, while extreme rainfall days of

category 2 is found to be 3.28 days and 3.0 days over NW and SP regions respectively. Inter-annual variation in frequency of category 1 rainfall days over all regions ranges from 30 to 46%, highest over NE region (46%) while that for category 2 rainfall days ranges from 65 to 90%, highest over WP region (90%).

Significant increasing trend in annual frequency of extreme rainfall days of both categories is observed over NC and EP regions, Figs. 11(a&b). Annual frequency of days accompanied with category 1 and category 2 extreme rainfall over the NC region is observed to be significantly increasing at the rate of 1.35 days/decade and 0.26 days/decade respectively. Similar, significant increasing trend in annual frequency of category 1 and category 2 extreme rainfall days is found over the EP region at the rate of 0.71 days/decade and 0.43 days/decade respectively.

The mean annual frequency of category 1 and 2 extreme rainfall days over country as a whole is increased by 13% and 47% respectively during the period of 1981-2007 as compared to 1951-1980. Mean annual frequency of days with extreme rainfall of category 1 is increased largest over NC region by 42% followed by NE region showed an increase of 22% in the period of 1981-2007 as compared to 1951-1980. A slight decrease in annual

frequency of days accompanied with extreme rainfall days under category 1 is seen over NW and SP regions during the same period. As far as, extreme rainfall days under category 2 is concerned, a substantial increase in mean annual frequency of days (more than 90%) is found over NC and EP regions during the period of 1981-2007 as compared to 1951-1980.

3.3.2. Seasonal frequency

On an average, one fourth days (25% days) during monsoon season over the country as a whole showed an event of extreme rainfall of category 1 which is largest out of all the seasons while lowest frequency is observed during winter and post monsoon seasons where 17% and 16% days of the season respectively showed an event of extreme rainfall of category 1. Inter-annual variation in frequency of days is observed maximum during winter (47%) and least during the monsoon season (23%). Similarly, number of days with extreme rainfall of category 2 is also seen largest during monsoon season (6.2% days of the season) over the country as a whole. It was least during winter and post monsoon season where 3.9% and 3.6% days of the season accompanied with extreme rainfall of category 2 respectively. The inter-annual variation in category 2 extreme rainfall days ranges from 56 to 88%, being largest during winter (88%) and lowest during the monsoon season (56%) over country as a whole.

Significant increasing trend in frequency of days of both categories of extreme rainfalls is seen only in monsoon season at the rate of 2.3 days/decade for category 1 and 1.2 days/decade for category 2 respectively over the country as a whole, figure not shown. There was a largest increase in mean frequency of extreme rainfall days of both categories during the monsoon season in the period 1981-2007 as compared to 1951-1980 over the country as a whole. This increase was 26% in frequency of extreme rainfall days of category 1 and almost 100% for category 2 extreme rainfall days. Next to monsoon season, frequency of extreme rainfall days of both categories is seen much increased during the winter season in the same period.

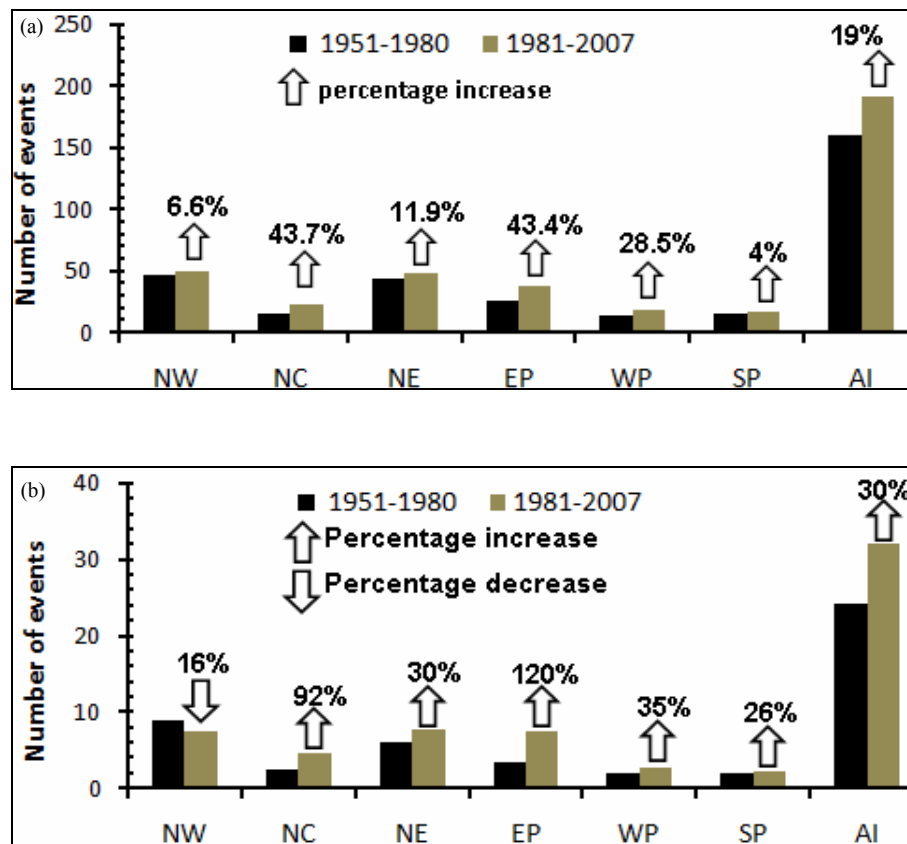
Seasonal analysis of extreme rainfall days over different regions showed that the mean frequency of both categories of extreme rainfall days during the winter season were largest over NW and EP regions. Nearly 5% days of the winter season was accompanied with category 1 rainfall over NW region and 3.8% days over EP regions. Similarly 1.0% and 0.8% days of the season accompanied with category 2 rainfalls over NW and EP regions respectively. Frequency of days under both category of extreme rainfall is noticed lowest over WP region where

1.2% and 0.3% days of the season is accompanied with category 1 and category 2 extreme rainfall respectively. Inter-annual variation in frequency of days with extreme rainfall of category 1 and category 2 during winter season is found to be largest over WP and lowest over EP region. No significant trend is seen over any region in the frequency of days with extreme rainfall of both categories during the winter season. Mean frequency of extreme rainfall days of category 1 and category 2 during the winter season is generally increased over all the regions during the period of 1981-2007 except for the fact that mean frequency of extreme rainfall days of category 2 is found to be decreased over the NW region. Maximum increase in both, *i.e.*, category 1 and category 2, extreme rainfall days in the season are observed over EP region.

During the pre-monsoon season, maximum frequency of extreme rainfall days of both categories is observed over EP and NW regions with 5.1% and 4.2% of season's days is accompanied with category 1 extreme rainfall and 1.0% and 0.88% of season's days accompanied with category 2 extreme rainfall respectively. The lowest frequency of days is seen over WP region for both categories of extreme rainfall. Inter-annual variation in frequency of days with extreme rainfall of category 1 and category 2 during pre-monsoon season is largest over WP region. It was lowest over EP region for category 1 and over NW region for category 2 extreme rainfall.

None of the regions showed any significant trend in the frequency of extreme rainfall days under category 2. While significantly increasing trend in frequency of days with extreme rainfall of category 1 is observed over NC region only at the rate of 0.48 days/decade during the period 1951-2007. Except over the WP and SP regions, there was a general increase in mean frequency of extreme rainfall days of both categories during the second half of study period. A substantial increase by 52% in extreme rainfall days of both categories during pre monsoon season is found over the NC region in the period of 1981-2007 as compared to 1951-1980.

Maximum frequency of extreme rainfall days of both categories during monsoon season are observed over NW and EP regions when 5.1% and 4.7% of seasons days are accompanied with category 1 rainfall and 1.21% and 1.12% of season's days with category 2 rainfall respectively. Inter-annual variation in frequency of days with extreme rainfall of category 1 during monsoon season is found to be largest over NW and lowest over the EP region and for category 2, largest variation is observed over NC and lowest over the NW region. No significant trend is seen over any region in the frequency of days with extreme rainfall of category 2 while significant increasing



Figs. 12 (a&b). (a) Variation in mean number of extreme rainfall events (category 1) over different region and India as a whole during 1981-2007 as compared to 1951-1980 and (b) Same as Fig. 12(a) but for extreme rainfall events of category 2

trend in frequency of days with extreme rainfall of category 1 is observed over NC, EP and WP regions at the rate of 0.58, 0.47 and 0.42 days/decade respectively during the season and there was an insignificant decreasing trend over NW region. The mean number of days with extreme rainfall of category 1 during monsoon season is largest increased over NC region (67%) and it is decreased only over NW region during the period 1981-2007 as compared to 1951-1980. Similarly, frequency of extreme rainfall days of category 2 is found to be increased over all regions, maximum over NC (198%) and then slightly lower increase over EP (150%) and WP regions (122%).

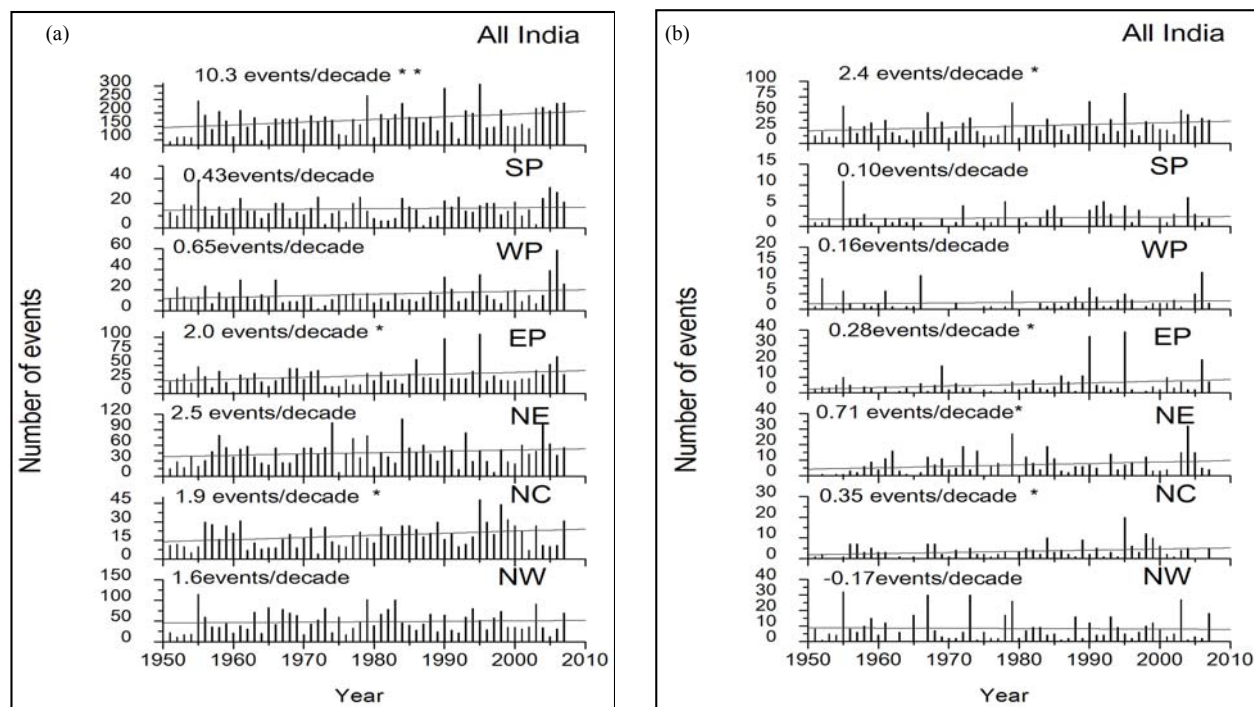
Maximum frequency of extreme rainfall days of both categories during post monsoon season is observed over SP and EP regions where 5.0% season's days are accompanied with category 1 extreme rainfall and 0.93% season's days with category 2 extreme rainfall respectively. Inter annual variability in frequency of days with extreme rainfall of category 1 and category 2 during

post monsoon season is found to be largest over NW and lowest over SP region. No significant trend is seen over any region in the frequency of days with extreme rainfall of both categories. Although, frequency of extreme rainfall days of category 1 rainfall is increased only over WP and SP regions by 14.3% and 3.7% days respectively while it is decreased over NW, NC, NE and EP regions during the period 1981-2007 as compared to 1951-1980. Mean frequency of extreme rainfall days under category 2 is seen decreased only over NW region by 19.2% during the period 1981-2007 as compared to 1951-1980. Largest increase of extreme rainfall days under category 2 is seen over EP and SP regions by 69% in the season during the same period.

3.4. Frequency of extreme rainfall events

3.4.1. Annual frequency of extreme rainfall events

Analysis of the annual frequency of extreme rainfall events over the country as a whole shows that, there



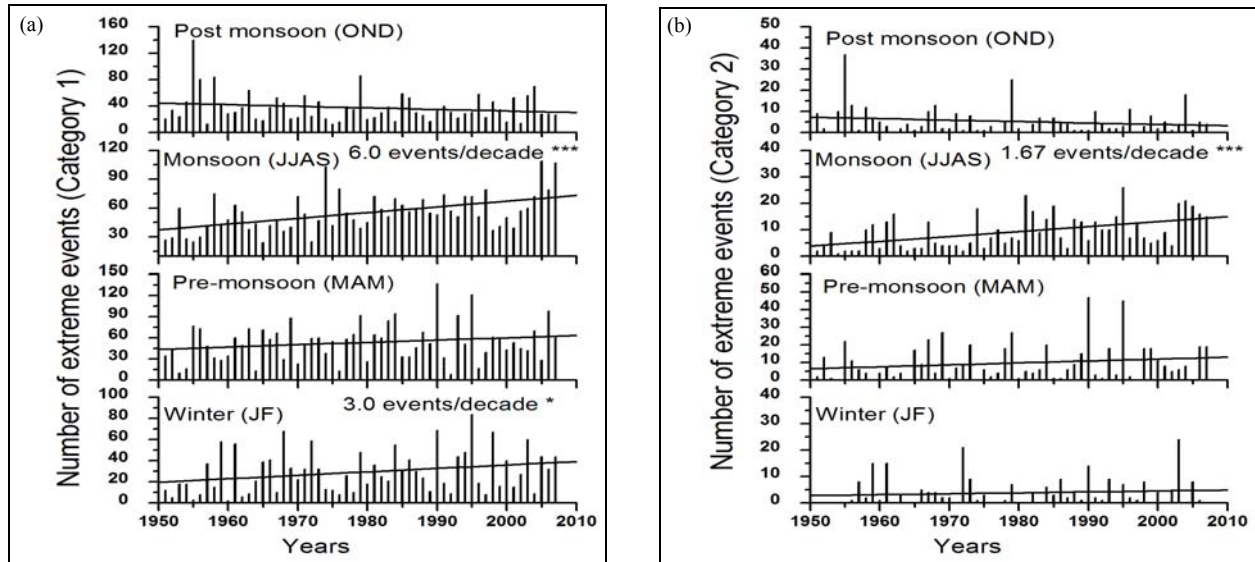
Figs. 13 (a&b). (a) Trends in annual frequency of extreme rainfall events (category 1), * significant at 5%, ** significant at 1%, *** significant at 0.1% and (b) Same as Fig. 13(a) but for extreme rainfall events (category 2)

are 48 extreme rainfall events of category 1 and 8 events of category 2 is found in every 100 days of the year during the period 1951-2007. Comparing the frequency of extreme rainfall events during 1981-2007 with respect to 1951-1980, there is a 19% increase in the frequency of extreme rainfall events of category 1 and about 30% increase are noted in frequency of extreme rainfall events with category 2. Inter-annual variation of 27% is observed in annual frequency of extreme rainfall events of category 1 and 52% variation is observed in category 2 extreme rainfall events over the country as whole. Significant increasing trend is observed in annual frequency of extreme rainfall events of category 1 and category 2 at the rate of 10.3 event and 2.4 event /decade respectively over country as a whole, Figs. 13(a&b).

Analysis over the regions indicate that about 12-13 events of extreme rainfall of category 1 have occurred in each 100 days of the year over NW and NE regions, 9 over EP and 4 to 5 over NC, WP and SP regions. There was an increase in the annual frequency of extreme rainfall events of both categories over almost all the regions during period 1981-2007 as compared to 1951-1980, Figs. 12(a&b). Decrease in frequency is observed only over NW region (16%) in category 2 extreme rainfall events during the period 1981-2007, Fig. 12(b). Largest

increase in annual frequency of extreme rainfall events is observed over NC and EP regions in both categories of events during the period of 1981-2007 as compared to 1951-1980. Annual frequency of extreme rainfall events of category 1 is increased by 43.7% and 43.4% over NC and EP regions respectively, Fig. 12(a). A substantial increase by 92% and 120% in annual frequency of category 2 extreme rainfall events is also found over NC and EP region respectively, Fig. 12(b). Inter-annual variation in annual frequency of extreme rainfall events over different regions for category 1 rainfall ranges from 47% to 59%. It is largest over WP region and lowest over SP region. Similarly, inter annual variation is observed in annual frequency of extreme rainfall events over different region for category 2 rainfall ranges from 99% to 140%. It is largest over EP region and lowest over NW region.

Significant increasing trend is observed in annual frequency of extreme rainfall events of category 1 over NC and EP regions at the rate of 1.9 and 2.0 events/decade respectively, Fig. 13(a). Annual frequency of extreme rainfall events of category 2 is observed to be nearly significantly increasing over NC, NE and EP regions at the rate of 0.35, 0.71 and 0.28 events/decade respectively, Fig. 13(b).



Figs. 14 (a&b). (a) Trends in seasonal frequency of extreme rainfall events (category 1) over country as a whole, * significant at 5%, ** significant at 1%, *** significant at 0.1% and (b) Trends in seasonal frequency of extreme rainfall events (category 2) over country as a whole, * significant at 5%, ** significant at 1%, *** significant at 0.1%

3.4.2. Seasonal frequency of extreme rainfall events

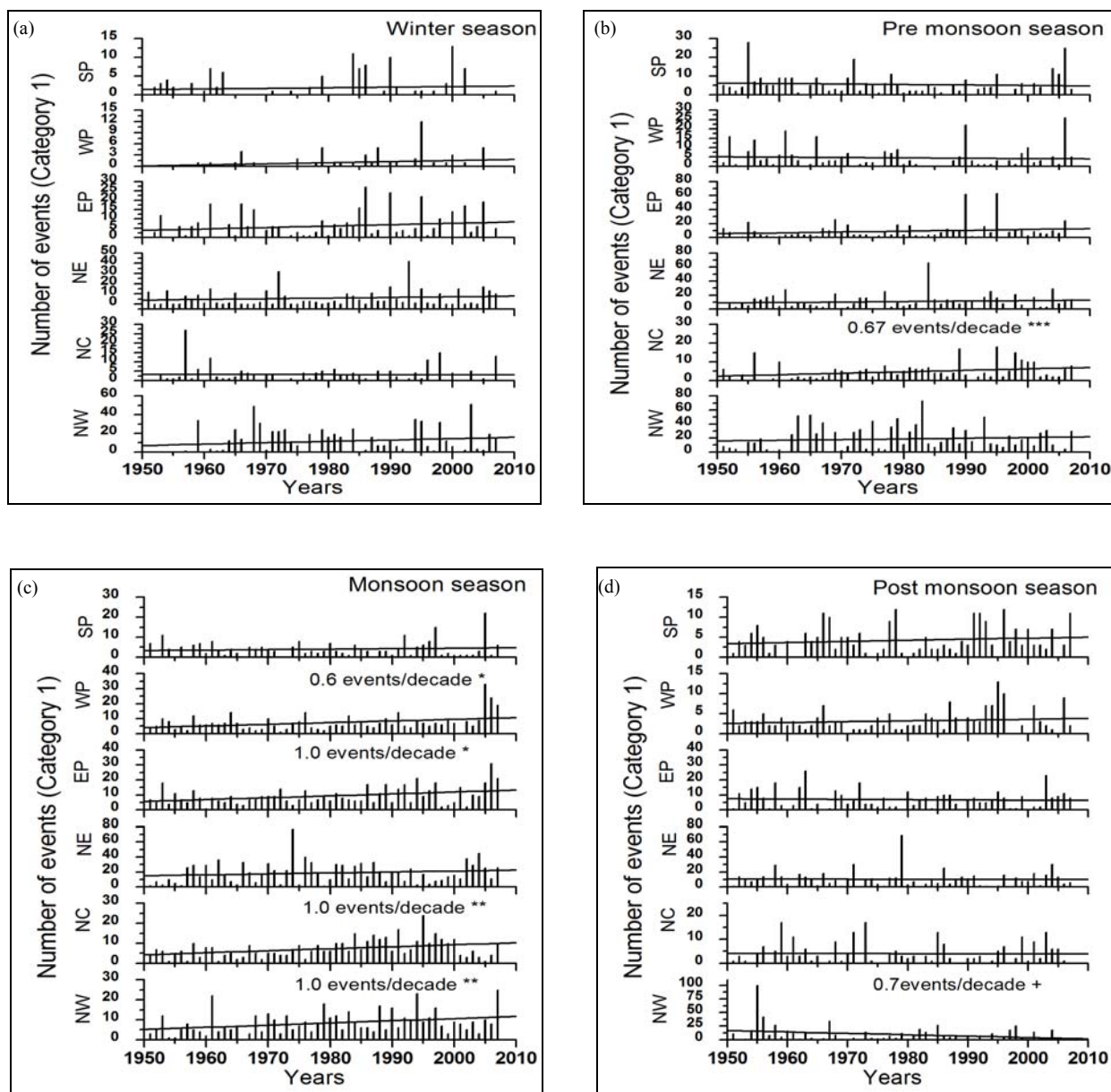
There are 5 extreme rainfall events of category 1 observed over the country in each 10 days of winter season during the period 1951-2007, while 5.8, 4.5 and 4.1 extreme rainfall events of category 1 per 10 days are seen during pre-monsoon, monsoon and post monsoon seasons. The frequency of category 2 extreme rainfall events during winter, pre-monsoon, monsoon and post monsoon season is observed at an average of 0.7, 1.0, 0.7 and 0.6/10 days respectively. The number of extreme rainfall events of category 1 over the country as a whole is observed to be increased during winter (by 39%), pre-monsoon (by 23%) and monsoon season (by 36%) and decreased during post monsoon season (by 15%) during the period of 1981-2007 as compared to 1951-1980. Similarly mean frequency of category 2 extreme rainfall events is increased by more than 100% in monsoon season and by 23% and 32% during winter and pre-monsoon season respectively. There is a decrease in frequency of category 2 extreme rainfall events during post monsoon season during the period 1981-2007. Largest inter-annual variation in frequency of extreme rainfall events of category 1 and category 2 is observed over country as a whole during winter season and lowest during monsoon season.

Significant increasing trend in the frequency of extreme rainfall events of category 1 at the rate of 6 and 3 events/decade is observed in monsoon and winter season

respectively during the period 1951-2007 over the country as a whole, Fig. 14(a). Frequency of extreme rainfall events of category 2 were significantly increasing only during monsoon season at the rate of 1.67 events /decade, Fig. 14(b) over the country as a whole during the period 1951-2007.

Extreme rainfall events of both categories during winter season are found to be largest in number over NW region during the period of present study. On an average, there were 11 events of category 1 and 1.3 event of category 2 extreme rainfall observed over NW region. Other regions such as NE and EP showed relatively less number of extreme rainfall events (6 events of category 1 and at least 1 event of category 2) during the season. A large increase in mean frequency of extreme rainfall events of both categories is observed during winter season over WP, EP and SP regions during the period 1981-2007 as compared to 1951-1980. Decrease in frequency of extreme rainfall events of category 2 is observed over NW and NE region during the winter season in the same period.

Mean frequency of extreme rainfall events of category 1 during pre-monsoon season is maximum over NW region (19 events) followed by lesser number of events over NE and EP region with 11 and 9 events respectively. For category 2 extreme rainfall events, mean frequency of extreme rainfall was found to be 3.4, 2.4 and 1.5 events over NW, EP and NE region respectively.

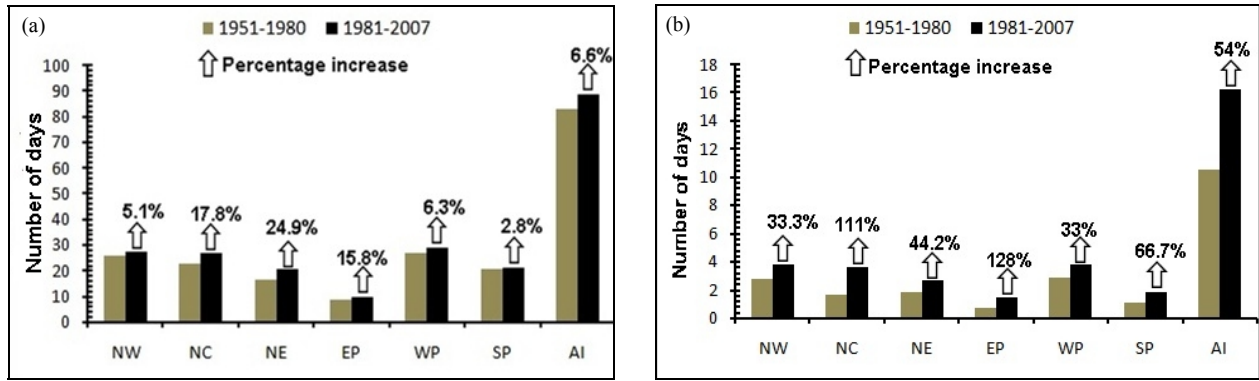


Figs. 15 (a-d). (a) Trends in seasonal frequency of extreme rainfall events (category 1) over different Indian region during winter season, * significant at 5%, ** significant at 1%, *** significant at 0.1%, (b) Same as Fig. 15(a) except for pre monsoon season, (c) Same as Fig. 15(a) except for monsoon season and (d) Same as Fig. 15(a) except for post monsoon season

Maximum inter-annual variation in number of extreme rainfall events is observed over EP and WP regions. Significant increasing trend in frequency of extreme rainfall events of category 1 is observed over NC region at the rate of 0.6 event/decade, Fig. 15(b). Mean frequency of extreme rainfall event of category 1 is increased largest over NC and NE regions by 78% and 64% respectively during the period of 1981-2007 as compared to 1951-1980. Largest increase in category 2 extreme rainfall

events is found over NE and EP regions 130% and 120% respectively. Decrease in mean frequency of extreme rainfall event of both categories is observed over WP and SP region during the period 1981-2007.

The extreme rainfall events are found to be most abundant during monsoon season over NE region during the period 1951-2007. On an average 19 extreme rainfall event of category 1 and 3 extreme rainfall events of



Figs. 16 (a&b). Variation in mean number of days with rainfall greater than (a) 100 mm in a grid box in 24 hours over different regions and India as a whole during 1981-2007 as compared to 1951-1980 and (b) 200 mm in a grid box in 24 hours over different region and India as a whole during 1981-2007 as compared to 1951-1980

category 2 occurred during the season over NE region. Number of extreme rainfall event of category 1 varies from 7 to 9 over NW, NC, EP and WP regions during the season while only 4 events occurred over SP region. Largest inter-annual variation in the number of category 1 extreme rainfall events is observed over SP region (100%) and lowest over EP (62%) during monsoon season. Number of category 2 extreme rainfall events during the season is observed to be varying from 1.95 to 1.42 over NW, NC and EP region and only 0.6 events were found over WP and SP regions. Variability in the number of category 2 extreme rainfall events is largest over SP region and least over NW region.

Significant increasing trend is observed in number of extreme rainfall events of category 1 during monsoon season over NW, NC, and EP at the rate of 1 event/decade and over the WP region at the rate of 0.6 event/decade, Fig. 15(c). There was an increase in the mean frequency of extreme rainfall event of category 1 over all regions during the period 1981-2007 as compared to 1951-1980 with largest increase over NC region (86%) and least over NE region (10%). Similarly, largest increase in mean frequency of extreme rainfall events of category 2 is seen over WP, NC and EP region by 313%, 249%, 239% respectively during the period 1981-2007 as compared to 1951-1980 while least increase is observed over NE region (45%).

During the post monsoon season, the maximum occurrence of extreme events of both categories is found over NW and NE regions. On an average, 10 events of extreme rainfall of category 1 while 1.6 and 1.3 events of category 2 is found over NW and NE respectively. Inter-annual variation of frequency of extreme events of category 1 is found to be highest over NW region (161%)

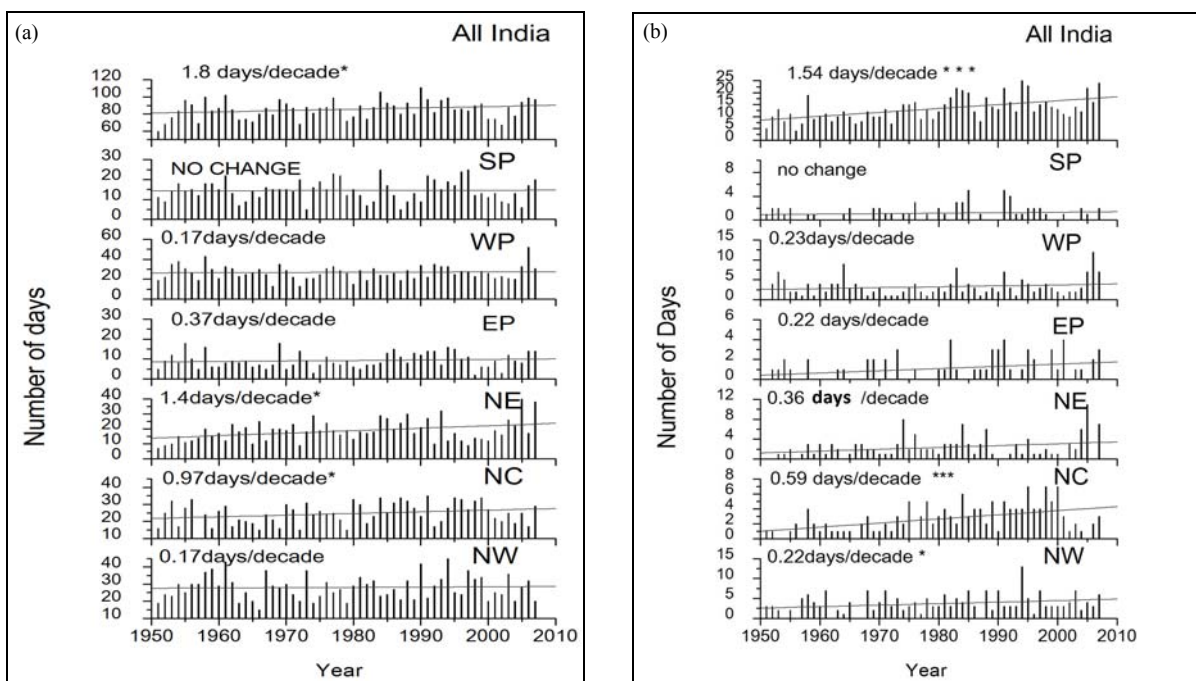
and lowest variability is observed over EP, WP and SP regions (approximately 85%). Inter-annual variation in the frequency of extreme events of category 2 during post monsoon was higher over the regions in northern parts of India as compared to southern parts of India. No significant trend in frequency of extreme event of both categories is observed over any region, although nearly significant decreasing trend in frequency of extreme events of category 1 is found only over NW region at the rate of 0.7 event/decade, Fig. 15(d).

The analysis shows a decrease in frequency of category 1 events over all the regions except WP and SP regions in period of 1981-2007 as compared to the period 1951-1980 during the post monsoon season. Largest decrease in the frequency of category 1 events is found over NW and NE regions by 39% and 22% respectively and largest increase by 43% is observed over WP region during the period 1981-2007 as compared to the period 1951-1980. Similarly, frequency of extreme event of category 2 is decreased largest over NW region by 81% followed by NE region (by 24%). Largest increase by 55% in frequency of extreme event of category 2 is found over WP region in the same period.

3.5. Annual frequency of daily rainfall above 100 mm and 200 mm in any grid box

3.5.1. Annual frequency of rainfall days with rainfall above 100 mm and 200 mm in any grid box

It was conspicuously observed that on an average there were 23% days in a year accompanied with at least one event of rainfall above 100 mm in any grid box in 24 hours over the country as a whole, with an inter-annual



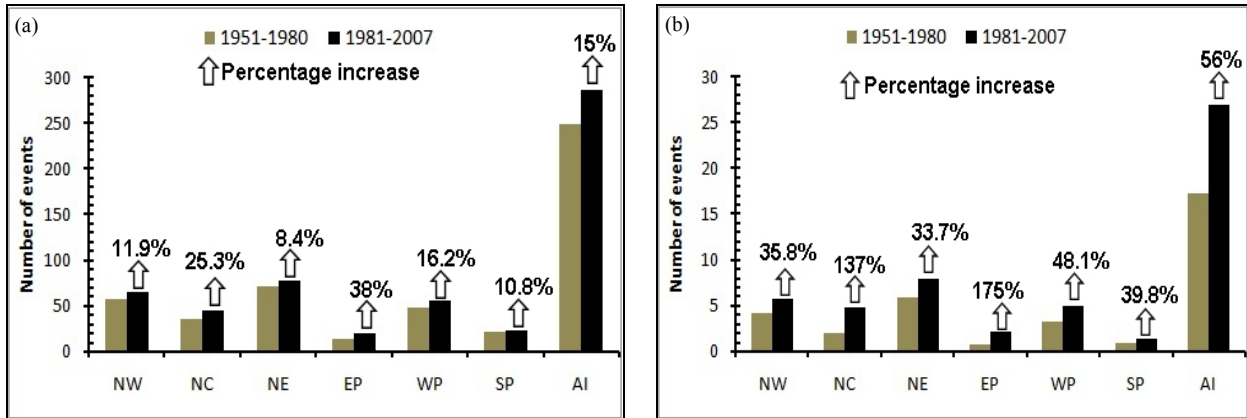
Figs. 17 (a&b). Trends in annual frequency of extreme rainfall days with rainfall greater than (a) 100 mm in a grid box in 24 hours, * significant at 5%, ** significant at 1%, *** significant at 0.1% and (b) 200 mm in a grid box in 24 hours, * significant at 5%, ** significant at 1%, *** significant at 0.1%

variation of 13% days during the period 1951-2007. In the same way an event of daily rainfall above 200 mm in any grid box occurred during 3.6% days in a year with an inter-annual variation of 30% days. Significant increasing trends in number of days with an event of rainfall above 100 mm and 200 mm in any grid box in 24 hours is observed at the rate of 1.8 and 1.54 days/decade respectively, Figs. 17(a&b). There was 6.6% increase in the annual mean frequency of days with an event of rainfall above 100 mm and 54% increase with an event of rainfall above 200 mm in any grid box in 24 hours is observed during the period 1981-2007 as compared to 1951-1980, Figs. 16(a&b).

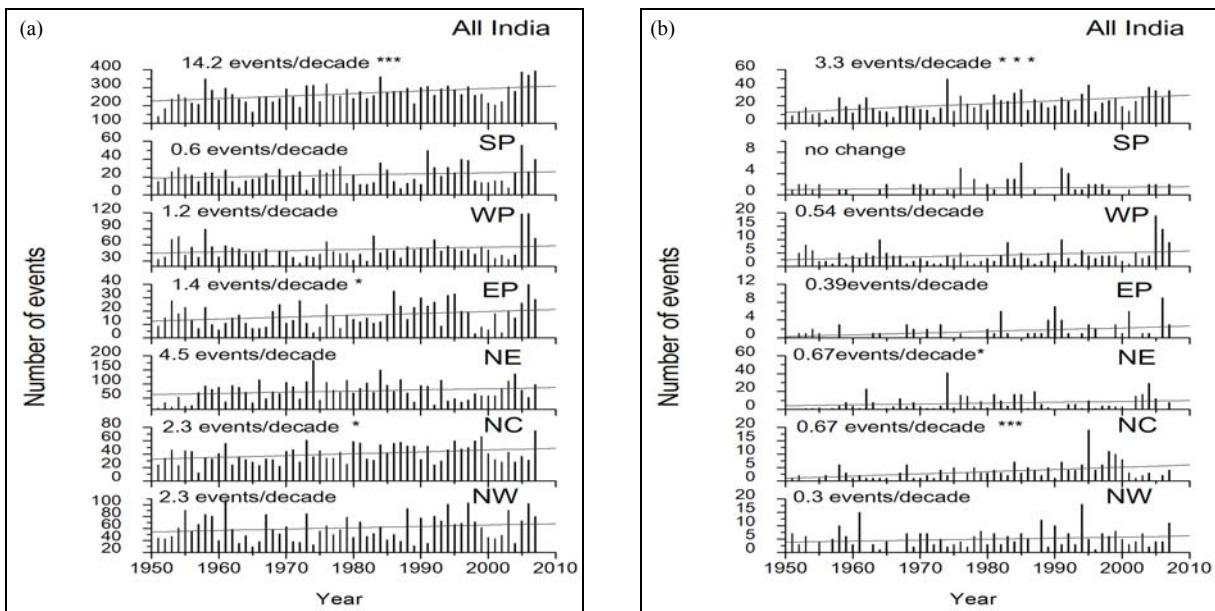
Regarding regional distributions, most frequent occurrence of an event of rainfall above 100 mm in any grid box in 24 hours is observed over WP region followed by NW region. On an average 7.7% and 7.3% days in a year were accompanied with an event of rainfall above 100 mm in any grid box in 24 hours over WP and NW region respectively. Similarly, maximum number of days in a year with rainfall above 200 mm in any grid box in 24 hours is also observed over these two regions (WP and NW). Both of the regions showed 1% days in a year with rainfall above 200 mm in any grid box in 24 hours. Least number of days in the year with an event of rainfall above

100 mm (2.5% days) and above 200 mm (0.3% days) in 24 hours is observed in any grid box over EP region. Inter-annual variation in number of days for occurrence of an event of rainfall above 100 mm in any grid box in 24 hours is observed to be ranging from 25% to 40% in different regions, being maximum over EP and NE regions (40%) and minimum over NW and WP regions (25%). Similarly, variability in number of days of occurrence of an event of rainfall above 200 mm in any grid box in 24 hours was ranging from 65% to 113% days, being largest over EP and SP (113%) and lowest over NW (65%).

Annual frequency of days with 24 hours rainfall above 100 mm in any grid box was seen increasing significantly only over NC and NE regions at the rate of 0.97 and 1.4 days/decade respectively during the period 1951-2007, Fig. 17(a). Frequency of days with rainfall above 200 mm is observed to be significantly increasing over NW and NC regions at the rate of 0.22 and 0.59 days/decade in the same period, Fig. 17(b). During second half period (1981-2007), annual frequency of days with 24 hours rainfall above 100 mm in any grid box was found to be highly increased over the NC and NE regions by 17.8%, 24.9% respectively with respect to the frequency during the period of 1951-1980, Fig. 16(a).



Figs. 18 (a&b). Variation in mean number of events with rainfall greater than (a) 100 mm in a grid box in 24 hours over different regions and India as a whole during 1981-2007 as compared to 1951-1980 and (b) 200 mm in a grid box in 24 hours over different regions and India as a whole during 1981-2007 as compared to 1951-1980



Figs. 19 (a&b). Trends in annual frequency of extreme rainfall events with rainfall greater than (a) 100 mm in a grid box in 24 hours, * significant at 5%, ** significant at 1%, *** significant at 0.1% and (b) 200 mm in a grid box in 24 hours, * significant at 5%, ** significant at 1%, *** significant at 0.1%

Large increase in annual frequency of days with 24 hours rainfall above 200 mm in any grid box is observed over NC and EP region where it became more than double as compared to the frequency the period of 1951-1980. Annual frequency of days with 24 hours rainfall above 200 mm in any grid box is found to be increased by 111% over NC region and by 128% over EP region during the period 1981-2007 as compared to the period 1951-1980, Fig. 16(b).

3.5.2. Annual frequency of rainfall events with rainfall above 100 mm and 200 mm in any grid box

Annual mean frequency of rainfall events with rainfall above 100 and 200 mm in any grid box in 24 hours over country as a whole was found to be 249 and 18 respectively during the period 1951-2007. No large inter-annual variation in the events above 100 mm rainfall

was found (only 18%) while 50% inter-annual variation were seen in the frequency of events above 200 mm rainfall during the period 1951-2007 over the country as a whole. Mean frequency of rainfall events with rainfall above 100 mm and 200 mm in any grid box in 24 hours over country as a whole was found to be increasing most significantly at the rate of 14.2 and 3.3 events/decade respectively during the period 1951-2007, Figs. 19(a&b). The mean frequency of rainfall events with 24 hours above 200 mm rainfall in any grid box is increased by 56% during the period of 1981-2007, while frequency of rainfall events above 100 mm is increased only by 15% in the later half with respect to first half of the study period, Figs. 18(a&b).

Regarding regional distribution, the maximum frequency of rainfall events with above 100 mm rainfall in 24 hours in any grid box mostly concentrated over NE region, which had about 74 events in a year during 1951-2007, while 61 and 51 number of events was observed on an average over NW and WP regions respectively. Its frequency was lowest over EP region (17 events). The mean annual frequency of rainfall events above 200 mm rainfall in 24 hours in any grid box is also found to be maximum over NE (6.8 events) followed by NW region where 4.9 events is observed during the same period. Inter-annual variation in annual frequency of rainfall events with above 100 mm rainfall in any grid box in 24 hours over different region were ranging from 33 to 53% of events with maximum variability observed over EP region and lowest over NC and NW regions. Similarly highest variability for rainfall events with above 200 mm rainfall in 24 hours is observed over EP region (140%) and lowest over NW (74%) and WP (82%) regions. Statistically significant increasing trend in the frequency of rainfall events above 100 mm rainfall in any grid box in 24 hours is mostly found over NC and EP regions at the rate of 2.3 and 1.4 event/decade respectively, Fig. 19(a). However, largest increasing rate was observed (4.4 events/decade) over NE region, but not statistically significant. The frequency of rainfall events of above 200 mm rainfall in 24 hours in any grid box were found to be significantly increasing over NC and NE regions at the rate of 0.67 event/decade Fig. 19(b). Comparing the frequency of rainfall events in second half period (1981-2007) with respect to 1951-1980, there were large jumps in the frequency of rainfall events with above 100 mm rainfall in any grid box in 24 hour over EP and NC region by 38 and 25.3% respectively, Fig. 18(a). Similarly frequency of rainfall events above 200 mm rainfall in any grid box in 24 hour were also found to be increased maximum over EP and NC region by 175% and 137% respectively, Fig. 18(b).

4. Conclusions

In this study seasonal/annual trends and variations in the occurrence of extreme rainfall over India as a whole and over different Indian regions are analyzed on the basis of various parameters. Based on the analysis, following conclusion can be given.

Averaging over country as a whole, daily mean rainfall in a grid box of $1^\circ \times 1^\circ$ is found to be 8.7 mm on the rainy days. North east region receives highest average daily rainfall of 13.5 mm per grid box out of all six regions. Daily mean rainfall in a grid box is found to be significantly increasing during winter over North west region and during pre monsoon over North central region. Significant decreasing trend was found over SP regions during pre-monsoon season. Averaging the rainfall of ten highest rainfall days of each year, mean rainfall in a grid box is 14.1 mm during the period 1951-2007 over the country as a whole. It is found to be increased over the country as a whole and over peninsular India by approximately 1.0 mm/grid box and 2 mm/grid box respectively during the period of 1981-2007 as compared to 1951-1980. It is decreased mainly over North central and North east region during latter half of study period (1981-2007).

The annual frequency of extreme rainfall intensity (ERI) days has increased by 3% for category 1 and 7% for category 2 during 1981-2007 compared to 1951-1980 over country as a whole. Mean frequency of days with ERI of category 1 is found increased largest during winter season (33%) while for very high intensity rainfall days (ERI days of category 2), a massive increase in frequency by 100% is seen during pre monsoon season of over country as a whole in the second half period as compared to first half of the study period. The magnitude of intensity of category 1 and category 2 in terms of contribution of rainfall to total seasonal rainfall is largely increased during winter season by 7.3% and 2.2% respectively in the period of 1981-2007 as compared to 1951-1980 over country as a whole.

Nearly significant increasing trend in annual frequency of days with extreme rainfall intensity is observed only over west peninsular region during study period. On seasonal scale, significant increasing trend (0.4 days/decade) in frequency of category 1 ERI rainfall days is seen during pre-monsoon over North central region and significant decreasing trend in North east region (0.5 days/decade). Comparing the mean frequency of days for category 1 ERI days during 1981-2007 as compared to 1950-1980, a large increase is found over east and west peninsular India during winter, monsoon and post monsoon season whereas during pre-monsoon

the largest increase is seen over north central India. Similarly, very high intensity of rainfall days (category 2 ERI days) is found to be substantially increased over whole peninsular India during winter season, over east peninsular and north central India in pre monsoon season, west peninsular India during monsoon and post monsoon season.

The magnitude of ERI in both categories in respect of contribution of rainfall to total seasonal rainfall is observed to be largest increased over west peninsular region in the latter half of study period (1981-2007) during all the seasons except in the pre monsoon season.

The most probable annual highest rainfall event during 1951-2007 over the country as a whole is observed to be 334.1 mm in a grid box in 24 hours, it was only 320.0 mm during 1951-1980 and increased up to 348.5 mm during 1981-2007. A significant increasing trend observed in magnitude of 24 hours highest rainfall in a grid box over all regions under consideration except over north east and south peninsular regions. Generalized extreme value (GEV) distribution is fitted to highest rainfall events indicate the higher probability for an increase in amount and frequency of highest rainfall events over north west, north central and west peninsular regions and least over north east region during the period of 1981-2007 as compared to 1950-1980.

Annual frequency of days and events with extreme rainfall of both categories is increased most significantly over country during the period of present study. Only monsoon season over the country showed significant increasing trends in frequency of days with extreme rainfall of both categories while extreme rainfall events showed increasing trends during monsoon season along with winter season. Significant increase in annual frequency of days and events for both categories also observed over North central and east peninsular region.

Number of days and events with daily rainfall above 100 mm and 200 mm in any grid box is observed to be significantly increased over the country. Over the regions, significant increase in annual number of days with rainfall above 100 mm is observed over north central and north east regions and above 200 mm, increase is observed over northwest and north central regions. Significant increase in number of events above 100 mm is seen over north central and east peninsular regions while for events above 200 mm increase is seen over north central and northeast region.

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