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Evaluation of rainfall extremes. Northeast and West coast regions of India as case study

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Abstract

The response of climate change is the increase in the frequency and intensity of extreme weather events. An attempt has been made to study the trends in heavy rainfall amount and the highest rainfall value in 24 hours over Northeast region (NER) and West coast region (WCR) of India with the period ranging from 1901-2009. A standard statistical analysis concludes that the majority of the stations in NER and WCR indicates increasing trend in annual and monsoon rainfalls. Further, the increasing trends in heavy rainfall were investigated and the associated synoptic conditions were identified. The study reveals that the increase in heavy rainfall over the WCR can be attributed to the synoptic systems namely monsoon trough, cyclonic circulation, depressions and lows.

Keywords: *climate change, monsoon rainfall, trend analysis, synoptic systems*

Rezumat. Evaluarea precipitaţiilor extreme. Studiu de caz: regiunile de coastă nord-estice şi vestice ale Indiei

Ca urmare a schimbărilor climatice, frecvența și intensitatea fenomenelor meteorologice extreme a crescut. Lucrarea de față își propune să analizeze tendințele în evoluția cantității de precipitații torențiale și a cantității de precipitații căzute în 24 ore în Regiunea Nord-Est și Regiunea costieră din vestul Indiei, în perioada 1901-2009. Analiza statistică standard indică faptul că la majoritatea stațiilor meteorologice din cele două regiuni există o tendință de creștere a cantității de precipitații anuale și musonice. Mai mult, tendințele de creștere au fost investigate, fiind identificate condițiile sinoptice. Studiul de față indică faptul că sistemele sinoptice, respectiv musonul, circulația ciclonică, ariile depresionare, contribuie la creșterea cantității de precipitații torențiale în Regiunea costieră din vest.

Cuvinte-cheie: *schimbări climatice, precipitații musonice, analiza tendințelor, sisteme sinoptice*

Introduction

One of the anticipated effects of climate change is the increase in the frequency and intensity of extreme weather events such as cyclones, floods and droughts, heat and cold waves, etc. Public awareness of extreme climatic events has increased in the recent years due to the media reporting catastrophic nature of floods, droughts, storms and heat waves or cold spells. Occurrences of extreme events claim thousands of lives as well as cause extensive damage to national and regional economy. Therefore, possible long term changes in the intensity of such events are of great concern notably in a country like India. About 70% of its population is agrarian; the impact of extreme weather event is a serious matter.

In India, the highest-ever-recorded rainfall in a day was reported at Cherrapunjee (Meghalaya) on the 15–16th of June in 1995 with the rainfall amount of 156.3 cm followed by 116.8 cm at Amini Devi on the 5–6th of May 2004. In Mumbai, on the 26-27th of July 2005, Santa Cruz (Mumbai) received a record-high of 94.4 cm rain. In this event, 927 people perished with loss and damage of property amounting to Rs. 450 crores (Tongdi et al. 2008). There is an alarming concern that extreme events may be changing in frequency and intensity as a result of human influences on climate (IPCC, 2007).

Trends in extreme rainfall days have decreased significantly throughout South Asia, Western and Central south Pacific (Manton et al. 2001). Several studies have revealed an increasing trend of extreme precipitation events in USA and Australia (e.g., Easterling et al., 2000; Haylock and Nicholls, 2000; Groisman et al., 2001; Kunkel, 2003), South-East Asia and Central Pacific (Griffiths et al., 2003). Haylock et al. (2006) have recently addressed the trends in extreme rainfall over South America and their links with sea surface temperatures. Moberg and Jones (2005) found significant increasing trend in extreme daily precipitation in Central and Western Europe while Klein Tank et al. (2006) reported increase in the amount on very wet days in central and south Asia. Recent regional studies on southern South America reported positive trends in the frequency of heavy rainfall (Re, 2009). Further, Choi et al. (2009) found significant trends in extreme precipitation events at fewer than 30 percent weather stations in Asia Pacific region.

Sen Roy and Balling (2004) found increasing trends in precipitation extremes over India. Francis and Gadgil (2006) reported that probability of intense rainfall events is high during mid-June and mid-August over the WCR. They established that organized convection over a large scale zonal belt, off-shore convective systems, mid-tropospheric cyclone (MTC) and an off-shore vortex were the features that caused heavy rainfall events. The orographic features over the west coast and northeast India, and the movement of synoptic scale systems from the Bay of Bengal region to the central parts of India (Sikka, 2006; Pattanaik, 2007) contribute to heavy rainfall events. In a warming environment there is a significant rising trend in the frequency and magnitude of extreme rain events over central India (Goswami et al. 2006). A study by Sen Roy (2009) reveal an increasing trend in extreme hourly precipitation over north-western Himalaya, Indo-Gangetic basin and northern parts of WCR. However, the southern west coast has been associated with a declining trend. Kishtawal et al. (2009) concluded that increasing trend in the frequency of heavy rainfall events over Indian monsoon region is likely where urbanization is faster. There is an increasing trend in heavy rainfall during summer monsoon (Ghosh et al. 2009) and its contribution to the seasonal rainfall shows significant increasing trend (Pattanaik et al. 2010). Guhathakurta et al. (2011) found decreasing trend in frequency of heavy rainfall events over major parts of central and north India while they are increasing in peninsular, east and north east India.

Looking at the extreme weather events, India stands prominently and has witnessed many such episodes. For a country that has more than 70% of its population relying on agriculture directly or indirectly, the impact of extreme weather event is critical. In India, a significant number of persons live on the bank of the rivers, low lying areas and coastal regions that are vulnerable to meteorological disasters. Furthermore, unplanned urbanization and growth of slums due to migration from rural to urban areas aggravate the problems. In the context of climate change, it is pertinent to ascertain whether the trends in heavy rainfall and the highest rainfall in 24-hour over these regions are also changing. Whether the extreme weather events are becoming more frequent or are region specific. In order to seek answers to the above-mentioned questions, it is necessary to examine the annual and monsoon extreme in rainfall over the study areas by using 26 stations during the last century.

Research Methods

In the NER, it was not possible to include a greater number of stations due to paucity of data series. As a result, two stations from the neighbouring state of West Bengal were included in this study. The daily rainfall data during the period ranging from 1901-2009 were acquired from the Indian Meteorological Department (IMD) Pune (Table 1.a, 1.b). There are two types of data; one data signifying the highest rainfall value in 24 hours in a month (26 stations) while the other data (16 stations) signifies the threshold amount of rainfall ranging from 6.5 to 12.5 cm, 12.5 to 25 cm and 25 to 9999.9 cm.

Table 1.a. Meteorological stations along with the data period (data period signifying the highest rainfall value in 24 hours in a month)

NER	Data period	Elevation (m)	WCR	Data period	Elevation (m)
Pasighat	1958-1992	157 m	Mumbai	1901-2006	11 m
Dibrugarh	1970-2000	111m	Alibag	1939-2002	7 m
Lakhimpur	1955-1992	102 m	Harnai	1970-2002	20 m
Tezpur	1939-1998	79 m	Ratnagiri	1901-2005	67 m
Guwahati	1903-2000	54 m	Panjim	1964-2003	60 m
Dhubri	1946-1993	35 m	Marmagoa	1970-2001	62 m
Silchar	1951-1993	29 m	Karwar	1915-2003	4 m
Gantok	1970-2000	1812 m	Honavar	1939-2002	26 m
Shillong	1903-2000	1500 m	Mangalore	1901-2001	22 m
Cherrapunjee	1903-2000	1313 m	Calicut	1901-2000	5 m
Imphal	1954-1998	781 m	Cochin	1970-2000	3 m
Kailashahar	1959-1996	29 m	Alleppey	1944-2000	4 m
Agartala	1970-2000	16 m	Trivandrum	1901-2004	64 m

Table 1.b. Meteorological stations along with the data period (data period signifying heavy rainfall ranging from 6.5 - 12.5, 12.5 - 25 and >25 cm)

NER	Data period	Elevation (m)	WCR	Data period	Elevation (m)
Agartala Aero	1953-2005	14 m	Bombay Coloba	1901-2006	4 m
Cherrapunjee	1902-2005	1313 m	Bombay SC	1950-2006	11 m
Mohanbari Aero	1949-2005	110 m	Karwar	1882-2005	4 m
Gantok	1971-2005	1812 m	Ahmadabad Aero	1901-2006	53 m
Alipur	1901-2005	14 m	Ratnagiri	1901-2006	67 m
Dumdum	1951-2005	11 m	Trivandrum	1901-2005	64 m
Guwahati	2003-2005	54 m	Trivandrum Aero	1955-2005	4 m

Note: Aero-aerodrome, SC-Santa Cruz

The extreme value has been computed focusing on monsoon season and annual scales. In order to determine the trend, linear regression coefficients and Student's t-test was applied to find out its significance at 0.05 and 0.01 level. Time series were plotted for the entire record.

Linear regression has been used by various climatologists (Sen Roy and Balling, 2004; Ali et al., 2007) for studying the rainfall and temperature patterns. This method (linear trend), i.e., the slope of the simple least square regression line with time as the independent variable, is found to be very useful in studying the secular trend in rainfall and temperature data. This is a simple model which is expressed in the form of an equation:

$$Y = a + bx$$

Where:

- Y is the dependent variable
- a is the intercept
- b is the slope or regression coefficient
- X is the independent variable (or covariate)

The equation will specify the average magnitude of the expected change in Y given a change in X. Statistical significance was determined by the t-test in the following way.

$$t = \sqrt{\frac{r^2(N-2)}{1(1-r^2)}}$$

Where 'r^2' is squared correlation coefficient and 'N' is the number of observations. The obtained value of 't' is compared with its table value. If the computed value is greater than table value at the desired level of significance then the correlation is significant. The results are presented in the forthcoming paragraphs.

In the light of the above discussions two extreme regions in the country namely the west coast and northeast region of India (Fig. 1) have been selected to study the trend in extreme rainfall. These two regions have some unique physical characteristics different from the rest of the country. Both regions have rugged terrain, receiving copious rainfall but vary in distribution patterns. More than 80% of the rainfall over the west coast is concentrated during the four months of the southwest monsoon while for northeast 25% of the annual rainfall occurs from March to May and 65% during the south west monsoon period. There is a general increase in precipitation with altitude in northeast region while precipitation in west coast region increases from the coast towards the interior. The mountain ranges of the northeast (Himalayas, Meghalaya plateau and Purvanchal ranges) and the west coast regions receive heavy rainfall due to the orographic effect. Both regions receive mean annual rainfalls of more than 100 cm. With this in view, an attempt is being made to investigate the changing patterns of this climatic element over these two regions.

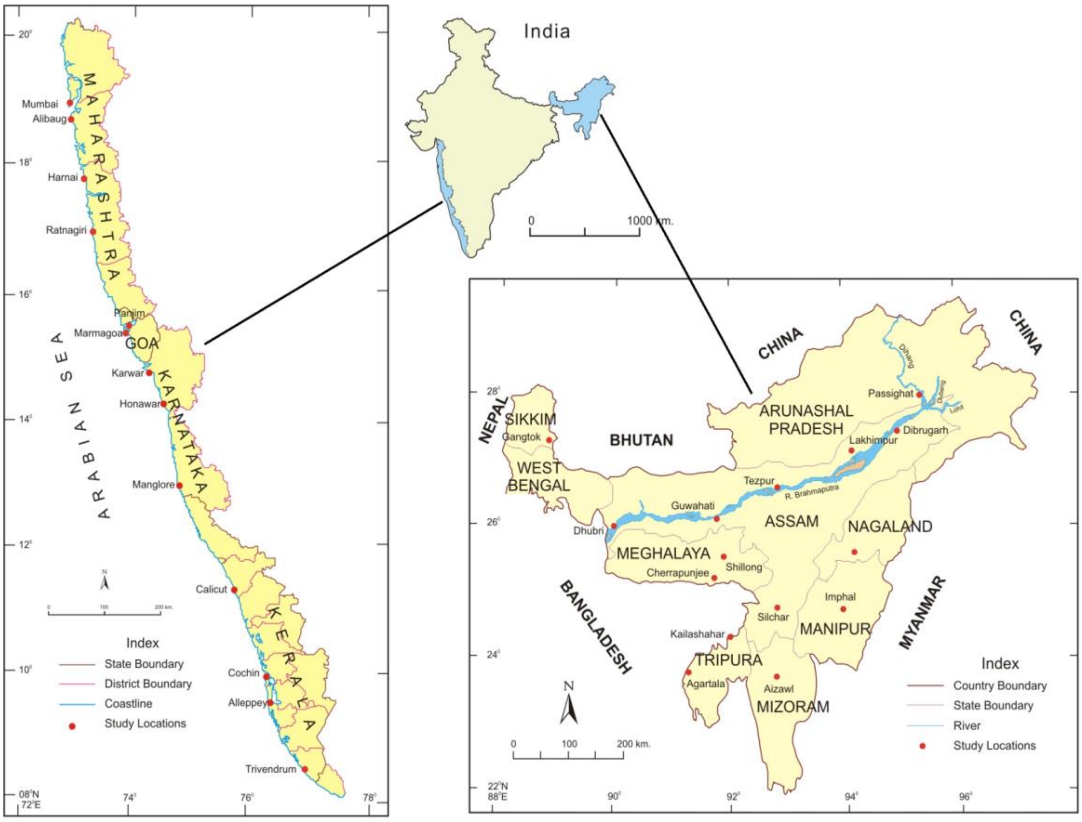

Fig. 1: Study Area

Source: Jamir et al., 2015, Geoadria, 20/1, 1-11

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Results

Trends in extreme rainfall (6.5 - 12.5 cm, 12.5 - 25 cm and >25 cm)

The trends in the extreme rainfall for the study regions are shown in Table 2. Therefore, to assess long-term trends, heavy rainfall events that exceed certain thresholds for 7 stations representing the NER were used.

Table 2 Trends in heavy rainfall

Stations	6.5 to 12.5 cm		12.5 to 25 cm		25 to 9999.9 cm	
NER	**Annual**	**MON**	**Annual**	**MON**	**Annual**	**MON**
Agartala Aero	**-1.428x**	**-1.574x**	**-0.703x**	**-0.673x**	~	~
Cherrapunjee	**-4.586x**	**-4.147x**	**3.427x**	0.575x	**7.039x**	**5.752x**
Mohanbari Aero	**1.776x**	**1.956x**	**1.073x**	0.117x	~	~
Gantok	**5.667x**	**1.956x**	~	~	~	~
Alipur	**1.042x**	**0.716x**	**-0.526x**	**-0.741x**	~	~
Dumdum	**2.032x**	0.148x	**1.288x**	**1.046x**	~	~
Guwahati	**0.743x**	**0.148x**	**0.261x**	**0.155x**	~	~
WCR						
Bombay Coloba	**1.689x**	**1.774x**	**1.542x**	**1.411x**	**1.119x**	**1.119x**
Bombay Santa Cruz	**-1.701x**	**-1.934x**	**-0.285x**	**-1.188x**	0.585x	0.585x
Karwar	**4.609x**	**4.165x**	**0.736x**	**0.621x**	0.048x	0.048x
Ahmadabad Aero	**0.617x**	**0.533x**	**0.257x**	**0.144x**	~	~
Ratnagiri	**2.667x**	**2.541x**	**2.969x**	**2.912x**	**0.737x**	0.162x
Trivandrum	0.069x	**0.384x**	**-0.206x**	**-0.291x**	~	~
Trivandrum Aero	**0.814x**	**0.703x**	~	~	~	~

Note: MON-monsoon, Aero-aerodrome, ~-few occasions; Bold-significant

From the above table, it can be concluded that, for the NER, there is a significant increase in rainfall at Mohanbari Aero, Gangtok, Alipur, Dumdum and Guwahati. However, two stations namely Agartala and Cherrapunjee show significant decrease in rainfall. The rate of increase in annual amounts varies from 5.66 cm/year at Gangtok to 0.74 cm/year at Guwahati. While the rate of decrease ranges from -1.42 cm at Agartala Aero to -4.58 cm at Cherrapunjee. Further, the study was extended to examine, whether the contribution of monsoon rainfall to annual shows any significant trend. The results suggest that the increase/decrease during the monsoon seasons except for Dumdum is not significant. The rate of decrease during the monsoon season is high at Cherrapunjee (-4.14 cm/year) whereas the maximum rate of increase is observed at Gangtok and Dibrugarh Aero (1.95 cm/year).

Whereas, for the WCR (Table 2), the stations - Bombay Coloba, Karwar, Ahmedabad Aero, Ratnagiri and Trivandrum Aero indicate significant increase in rainfall. The same situation is noticed during the monsoon season also. However, Bombay-Santa Cruz shows significant decrease in annual amount as well as during the monsoon season. The rate of increase in annual amounts varies from 0.06 cm/year at Trivandrum to 4.6 cm/year at Karwar. Among the stations selected for this study only Bombay Santa Cruz show decrease at the rate of -1.70 cm/year. During the monsoon season, the rainfall varies from -1.93 cm/year at Bombay Santa Cruz to a high of 4.16 cm/year at Karwar. Thus, it can be said that maximum stations experiencing significant increasing trend in rainfall for both regions during annual as well as monsoon season. The increase in rainfall over the NER and WCR is consistent with Sinha Ray et al. (1999), on their study on frequencies of heavy rainfall > 7cm show increasing trend in the WCR. Our findings are also in agreement with Sinha Ray and De (2003); Sen Roy and Balling (2004). Among the stations in the NER used for the study of heavy rainfall trend only Agartala Aero and Cherrapunjee show significant decrease in rainfall. The decrease in rainfall shows similarity with the finding of Sontakke and Singh (2001), their study concluded that there is a decreasing trend in monsoon rainfall at Cherrapunjee. The summer monsoon rainfall was decreased by 8 mm/year significant at 10% level. Similarly, orographic lifting over the northeast parts of the country causes heavy rainfall events over the region (Rao, 1976).

For the trends in extreme rainfall of 12.5 cm to 25 cm in the NER (Table 2), the stations Mohanbari Aero, Alipur, Dumdum and Guwahati report significant increase in annual rainfall while during the monsoon season it is not significant at Mohanbari Aero. Only one station viz., Agartala Aero shows significant decrease in annual and monsoon rainfall. The rate of increase/decrease in annual amounts varies from -0.70 cm/year at Agartala Aero to 3.42 cm/year at Cherrapunjee. During the monsoon season, the rainfall rate range from -0.67 cm/year at Agartala Aero to 1.04 cm/year at Dum

Dum. Gangtok rainfall data was insufficient and hence it was not used. The rainfall above 25 cm for the NER reveals that, Cherrapunjee reported significant increase in annual and monsoon rainfall, the rest of the stations reported less rainfall amount so the data was not analysed. The rate of increase in annual is 7.03 cm/year to 5.75 cm/year during the monsoon season.

For the WCR, annual rainfall over Bombay Coloba, Karwar, Ahmedabad Aero, Ratnagiri and Trivandrum witnessed significant increase (Table 2). The increase in annual rainfall is attributed by significant increase in monsoon rainfall. Only two stations that is, Bombay Santa Cruz and Trivandrum show decrease in annual rainfall but it is significant only at Trivandrum however during the monsoon season it is significant at 95% and 99%. The rate of increase in annual rainfall varies from 0.25 cm/year at Ahmedabad Aero to 2.96 cm/year at Ratnagiri. While the rate of decrease at Bombay Santa Cruz and Trivandrum is almost the same that is -0.20 cm/year at Santa Cruz to -0.28 cm/year at Trivandrum. The rate of increase during monsoon is high at Ratnagiri (2.91 cm/year) to -1.18 cm/year at Bombay Santa Cruz. The stations that receive rainfall above 25 cm for the WCR reveal increasing trend in annual rainfall at Bombay Coloba, Bombay Santa Cruz, Karwar and Ratnagiri; however it is significant at Bombay Coloba and Ratnagiri. The increase in annual rainfall is attributed to the increase in monsoon rainfall. The rate of increase in annual rainfall is 1.11 cm/year at Mumbai Coloba to 0.04 cm/year at Karwar whereas during the monsoon season it varies from 0.04 cm/year at Karwar to 1.11 cm/year at Mumbai Coloba. However, the station Karwar does not show statistical significance. The rest of the stations reported fewer rainfall amounts which are not possible to compute. IPCC (2007) also stated that there will be substantial increase in heavy precipitation (95^{th} Percentile) in many land regions.

The above studies concluded that there is an increasing trend in heavy rainfall over both the regions however significant at majority of the stations. As these are the two regions in the country that receive copious rainfall throughout the year, in the following paragraph, the highest rainfall in 24 hours in a month in all the 26 stations for both the regions will be examined. Therefore, it makes sense to assess the heavy rainfall frequency at the regional level, because these events are more likely to be revealed by several observations than by a single station.

Trends in the highest rainfall in 24 hours

The trends in extreme rainfall for the NER are examined and the results are shown in Table 3.

Table 3 Trends in rainfall extremes

NER			**WCR**		
Stations	**Annual**	**MON**	**Stations**	**Annual**	**MON**
Pasighat	2.037x	1.08x	Mumbai	**0.832x**	**0.836x**
Dibrugarh	2.259x	1.574x	Alibag	**1.313x**	**1.374x**
Lakhimpur	0.677x	0.982x	Harnai	-0.729x	-0.729x
Tezpur	0.362x	0.353x	Ratnagiri	**0.573x**	**0.619x**
Guwahati	0.106x	0.018x	Panjim	1.685x	**1.733x**
Dhubri	0.102x	0.631x	Marmagoa	1.881x	1.830x
Silchar	-0.497x	-0.211x	Karwar	0.443x	**0.455x**
Gantok	-0.739x	0.024x	Honavar	**1.472x**	**1.356x**
Shillong	0.188x	0.167x	Mangalore	**0.303x**	**0.473x**
Cherrapunjee	0.766x	0.855x	Calicut	0.087x	-0.028x
Imphal	0.161x	0.326x	Cochin	-0.621x	0.468x
Kailashahar	0.385x	0.096x	Alleppey	-0.395x	-0.312x
Agartala	-2.849x	0.541x	Trivandrum	-0.075x	-0.086x

Note: MON-monsoon; Bold-significant

Although there is a predominant positive trend in annual as seen from the Table 3 at the majority of the stations in the NER, it does not exhibit any statistical significance while Silchar, Gangtok and Agartala depict decrease in the extreme values. Thus, in order to detect the presence of trends monsoon rainfall was analysed. During the monsoon season, ten stations reported increasing trend significant only at Lakhimpur. The rate of increase in annual amounts varies from 0.10 cm/year at Dhubri and Guwahati to 2.03 and 2.25 cm/year at Pasighat and Dibrugarh. The rate of decrease varies from -0.49 cm/year at Silchar to -2.84 cm/year at Agartala. The rate of increase/decrease during the monsoon season, varies from -0.21 cm/year at Silchar to 1.57 cm/year at Dibrugarh. Thus, considering the annual results it can be stated that monsoon rainfall influenced annual trend.

The results for the WCR are shown in the Table 3. When analysed on the annual basis, nine stations show increasing trend statistically significant at Mumbai, Alibag, Ratnagiri, Honavar and Mangalore

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while Harnai, Cochin, Alleppey and Trivandrum report decrease in extreme rainfall. The rate of increase ranges from 0.08 cm/year at Calicut to 1.88 cm/year at Marmagoa. The rate of decrease varies from -0.07 cm/year at Trivandrum to -0.72 cm/year at Harnai. During the monsoon season, the rate of decrease ranges from -0.02 cm/year at Calicut to 1.83 cm/year at Marmagoa. The seasonal trend reveals that during the monsoon season, ten stations demonstrate significant increase at five stations, viz., Mumbai, Alibag, Ratnagiri, Honavar and Mangalore at 95% and 99% levels of significance, respectively. Three stations – Harnai, Alleppey and Trivandrum show decreased rainfall. Therefore, it can be concluded that in this region extreme rainfall have increased over the last century.

The increase in rainfall trend over the WCR shows similarities with the finding of Francis and Gadgil (2006); Pattanaik et al. (2010), which show increase in extreme rainfall events over the WCR during the monsoon months.

Extreme rainfall events and associated synoptic conditions

When considering the highest rainfall in the months that were available, the trends of annual and seasonal heavy rainfall in both the region were by large positive during the study period. Similarly, changes in the frequency of rainfall over certain thresholds (6.5 cm to 12.5 cm, 12.5 cm to 25 cm and 25 cm to 9999.9 cm) were predominantly positive in majority of the series. These two copious rainfall receiving regions of India have witnessed positive changes in rainfall extremes; however, statistical significance was reported only from the West coast region. It is difficult to justify the direct causes of the changes in rainfall extremes, but some attributes have been put forward in this study. It is not the intention of the article to identify all the physical causes of the observed upward trends in the indices of heavy precipitation. For establishing the physical causes in the increase in heavy rainfall over the west coast for all the stations during the last century, it is beyond the scope of this paper. However, the issue deserves a brief discussion in the context of synoptic system for some main events during the monsoon season in the WCR during the period 1901-2005.

So, in this section, extreme rainfall events in the WCR were investigated with the help of synoptic systems which may be useful to explain the corresponding changes in the rainfall pattern. This paper attempts to find out the synoptic component associated with heavy rainfall occurring at certain places and accordingly the synoptic system had been identified. For this, data related to extreme rainfall events during the last 105 year (1901-2005) over the WCR were acquired from IMD (Indian Meteorological Department), Pune. The data related to synoptic systems were noted from IMD publications - Mausam and Indian Daily Weather Report. WCR witnessed increasing trend in heavy rainfall amount significant at the majority of the stations in annual as well as during the monsoon season. It is a well-known fact that the extreme rainfall were caused either by cyclonic circulations, lows, cyclones and depressions, monsoon troughs, north-south troughs, east-west troughs, etc. In order to understand the causative factor for these trends in heavy rainfall the data related to various synoptic systems were collected and their frequencies during the last 104 years have been worked out. The date of occurrence, duration and amount of rainfall in mm were taken into account.

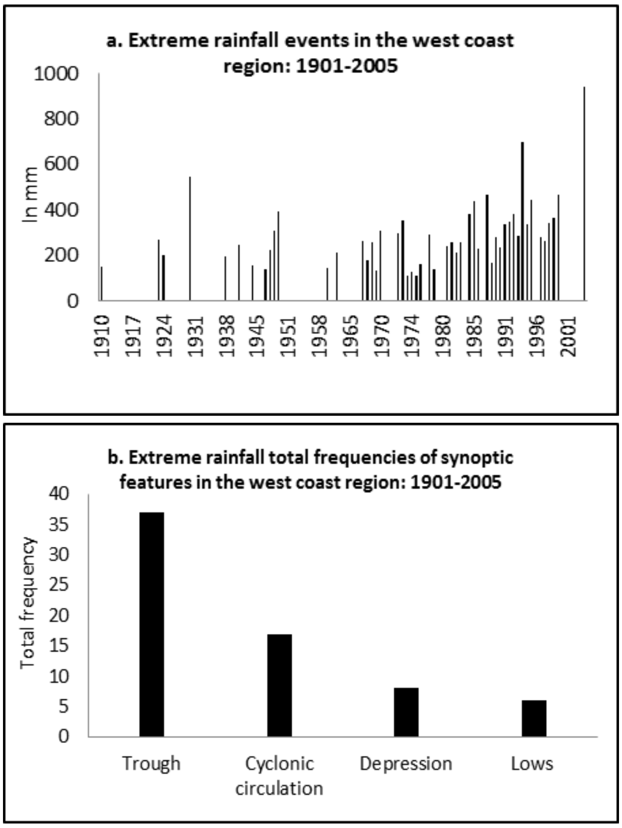

Fig. 2 Extreme rainfall events and frequencies of synoptic features in the west coast region: 1901-2005

Fig. 2 (a and b) concludes that heavy rainfall in the WCR were caused by monsoon trough (37), followed by cyclonic circulations (17), depressions (8) and lows (6); wherein 54% of heavy rainfall events were caused by monsoon trough, 25% by cyclonic circulation, while 12% and 9% were contributed by depressions and lows. The above figure (2 a and b) clearly indicates that synoptic conditions over the Arabian Sea during the study period were the main factors leading to the heavy rainfall.

Nearly half of active to vigorous monsoon situations in Konkan and three quarters of such occasions in CK are associated with troughs off the west coast region (Rao, 1976). In their study on intense rainfall events over the WCR, Francis and Gadgil (2006) found that the probability of intense rainfall events is high between the period mid-June and mid-August over the WCR. They attributed the cause in heavy rainfall to organized convection over a large scale zonal belt, off-shore convective systems, mid-tropospheric cyclone (MTC) and an off-shore vortex. Investigating on the Indian summer monsoon rainfall during the recent years Jadhav (2006) found that the west coast trough becomes more prominent. Even though the systems are not intensifying, they give sufficient rainfall over southern part of the country. Jenamani et al. (2006) investigated the Mumbai rain of 2005, and they found that the rain band/low pressure system positioned over the Western Ghats interacted with meso-scale processes to create the heavy rain event. Vaidya and Kulkarni (2006) independently confirmed a similar conclusion and found that a cloud burst phenomenon was the main reason for the heavy rain. Kishtawal et al. (2009) found very heavy and extreme rainfall events showed increasing trends over urban centres of Indian where the pace of urbanization is faster.

Conclusion

This study reveals noticeable changes in the extreme rainfall events that occurred over the WCR in the past century. The non-parametric test as well as the linear trend analysis identified increasing trends in the heavy rainfall amount and extreme rainfall over the study regions. However, the significance is higher for the WCR on annual and monsoon scale with a threshold of 6.5 - 12.5 cm, 12.5 - 25 cm. The majority of the stations over the WCR, namely, Konkan/Goa and Coastal Karnataka reported significant increase in annual and monsoon rainfall extremes (the highest rainfall in 24 hours) but not significant for the NER. Further, the synoptic systems associated with this rainfall were identified and it was found that the extreme rainfall events for the WCR were due to the increased formation of the synoptic systems like monsoon trough, cyclonic circulations, depressions and lows.

Our results are in general agreement with the increase in extreme precipitation events over the country (Goswami et al. 2006) in a global warming environment given with the increase in greenhouse gases over the study areas (Tongdi Jamir and De. 2012). Further, an increase in the frequency of intense precipitations events in many parts of South Asia for the period 2080-2099 with the control period 1980-1999 is well documented by IPCC 2007. Hence, changes in heavy rainfall events will increase proportionally in the future. The result of this analysis shows that regional planning and preparedness should be initiated as there is greater risk of flood related events over the study regions.

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