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Regional changes in extreme monsoon rainfall deficit and excess in India

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ABSTRACT

With increasing concerns about climate change, the need to understand the nature and variability of monsoon climatic conditions and to evaluate possible future changes becomes increasingly important. This paper deals with the changes in frequency and magnitudes of extreme monsoon rainfall deficiency and excess in India from 1871 to 2005. Five regions across India comprising variable climates were selected for the study. Apart from changes in individual regions, changing tendencies in extreme monsoon rainfall deficit and excess were also determined for the Indian region as a whole. The trends and their significance were assessed using non-parametric Mann–Kendall technique. The results show that intra-region variability for extreme monsoon seasonal precipitation is large and mostly exhibited a negative tendency leading to increasing frequency and magnitude of monsoon rainfall deficit and decreasing frequency and magnitude of monsoon rainfall excess.

1. Introduction

The most important climatological feature of the south Asian region is the occurrence of monsoons, the south-west or summer monsoon (June to September) being the principal source of water; and the north-east or winter monsoon (December–February) meets the water needs of the southernmost parts of the Indian peninsula and Sri Lanka. Monsoon rainfall affects millions of lives in India, which is greatly influenced by the shape of the continent, orography, and upper tropospheric conditions

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etc. that are best addressed by a regional approach. Rainfall over India is subject to a high degree of variation leading to the occurrence of extreme monsoon rainfall deficit or excess over extensive areas of the country. Because of large spatial variability of monsoon rainfall, there are occasions when some regions experience floods due to intense rains while at the same time other areas experience severe rainfall deficiency leading to meteorological drought. With more concern about climate change, the need to know about and understand the nature and variability of the modern climate and to evaluate possible future changes becomes increasingly important.

Global Circulation Models (GCM) predict an increase in global rainfall over the oceans and high latitudes as evaporation is enhanced in the warmer climates. To the contrary, drought is projected to rise throughout the 21st century on the tropical land regions that are likely to experience less rainfall (Kruger, 2006), which is due to the mass continuity that requires that the increased vertical mass transfer and associated increased rainfall at some place should be balanced by reduced vertical motion in another place (Bosilovich et al., 2005; Kumar et al., 2004; New et al., 2001). Although no clear evidence on the physical mechanism of this is available yet, the reason for decreasing rainfall in those areas could be because of the increasing trend of atmospheric residence time of the precipitable water and decreasing cloudiness over the tropical land regions (Bosilovich et al., 2005). The changes in local regions can be far more dramatic than changes in global averages. As reported by the IPCC in its most recent synthesis report, the Indian subcontinent will adversely be affected by enhanced variability of climate, rising temperature and substantial reduction of summer rainfall in some parts and water stress by 2020s (Cruz et al., 2007). Population growth makes the stress more unfavourable because this country relies heavily upon rain-fed agriculture and food infrastructures (Fisk, 1997). Monsoon rainfall (summer monsoon) is a major factor for water resources planning and operation in India. Any change or reduction in monsoon rainfall, which contributes to more than 75% of annual rainfall input, may have a great effect on the efficiency and accuracy of such projects affecting the agricultural economy in the country.

Recent research reported a statistical evidence of changing tendency of Indian monsoon rainfall; the findings suggest that the monsoon precipitation variability might be remarkably complex. Inter-regional differences suggest a fairly higher degree of local influence on variability. For example, Goswami et al. (2006) examined the distribution and trend of 'moderate' daily monsoon rainfall over Central India and found a decreasing trend and increasing variability of the same. Soman et al. (1988) noticed a rainfall deficient trend in Kerala, south-west Peninsular India. Sen Roy and Balling (2004) found decline in annual precipitation in the north-eastern states, parts of the eastern Gangetic Plain and Uttaranchal. Sometimes, rainfall distribution expressed in terms of number of rainy days and rainfall intensity also showed changes in some areas (Pal and Al-Tabbaa, 2009; Goswami et al., 2006). Many other similar studies have been taking place in various other parts of the globe, which are also going through decreasing trends of precipitation; for example south-eastern Australia (Murphy and Timbal, 2008; Manton et al., 2001), Italy (Cislaghi et al., 2005) and the UK (Palmer and Raisanen, 2002). However, a gap lies in the detailed study of regional and local climatological changes and its effects on seasonal extreme rainfall 'deficit' and 'excess', which is also true for the Indian monsoon as well.

Unlike extreme rainfall excess that can result from small scale features such as individual thunderstorm systems, extreme rainfall deficit result from persistence, large scale and organised features of weather and climate which act to suppress rain producing systems that may be expected to occur in monsoon season and in a particular region. A study of the behaviour of departures of monsoon rainfall from long-period temporal means and local-scale spatial means is therefore necessary and informative for the regional water resource developments, which is not yet done for India. In view of that, this study examines the changes in frequency and magnitude of extreme monsoon rainfall deficit and excess from 1871 to 2005 in various Indian regions.

2. Data and methodology

India has high spatially variable climate and therefore the amount of rainfall in the monsoon season is highly variable, spatially ranging from 160 to 1800 mm/year from the north-west to the north-east and from the north to the far south (peninsular). Although India has several meteorological subdivisions, many are found to be very similar to their neighbourhoods. Therefore, spatially coherent

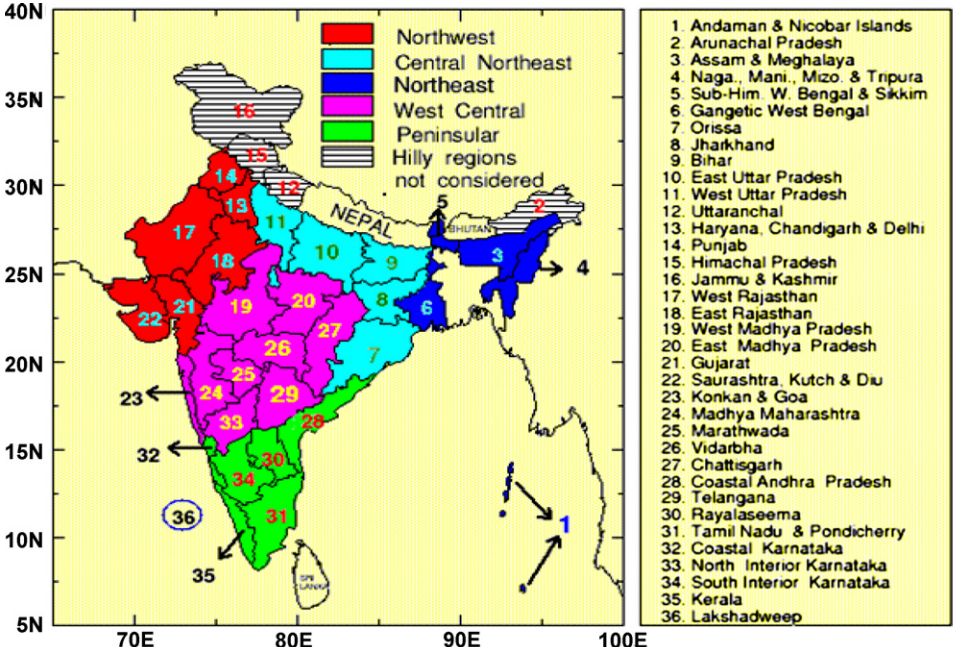

Fig. 1. Study regions in India except the northern-most hilly region. ALLIN, NWIN, WCIN, CNEIN, NEIN and PENIN denotes all-India, north-west India, west-central India, central north-east India, north-east India and peninsular India respectively.

monsoon regions, when aggregated, result in five homogeneous regions covering 90% of the whole of India (except hilly regions in the extreme north of India), which are being considered here. The monthly time series of rainfall data was collected for north-west India (NWIN), west-central India (WCIN), central north-east India (CNEIN), north-east India (NEIN) and peninsular India (PENIN), and also a spatial and temporal average rainfall for the whole of India (ALLIN) from the Indian Institute of Tropical Meteorology (http://www.tropmet.res.in). The study regions are shown in Fig. 1. The rainfall data set consists of monthly totals for all the regions above from 135 years (1871–2005) of record. The study regions were determined to be distinct with respect to the interannual variability of rainfall. The seasonal cycle of rainfall in each region is shown in Fig. 2. The cycles are significantly different, suggesting different mechanisms of variability. This study considers only the south-west monsoon rainfall, i.e., the accumulated rainfall from June to September.

The trends of climatological variables suggest the tendency of change in spite of intermittent fluctuations. So, long-term trends were assessed for monsoon excess and deficits over the study period, which would also provide an idea of the changing pattern of the same. All those trends and their significance were determined using non-parametric Mann–Kendall (MK) technique (Luo et al., 2008; Onoz and Bayazit, 2003; Wilks, 1995). Since there are chances of outliers to be present as the extreme rainfall events, non-parametric Mann–Kendall test is useful because its statistic is based on the sign of differences, not directly on the values of the random variable and therefore the trends determined is less affected by the outliers. The Mann–Kendall test is applicable to the detection of a monotonic trend in a time series with no seasonal or other cycle. The test is based on the statistic S, which is calculated using the formulae:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \quad (1)$$

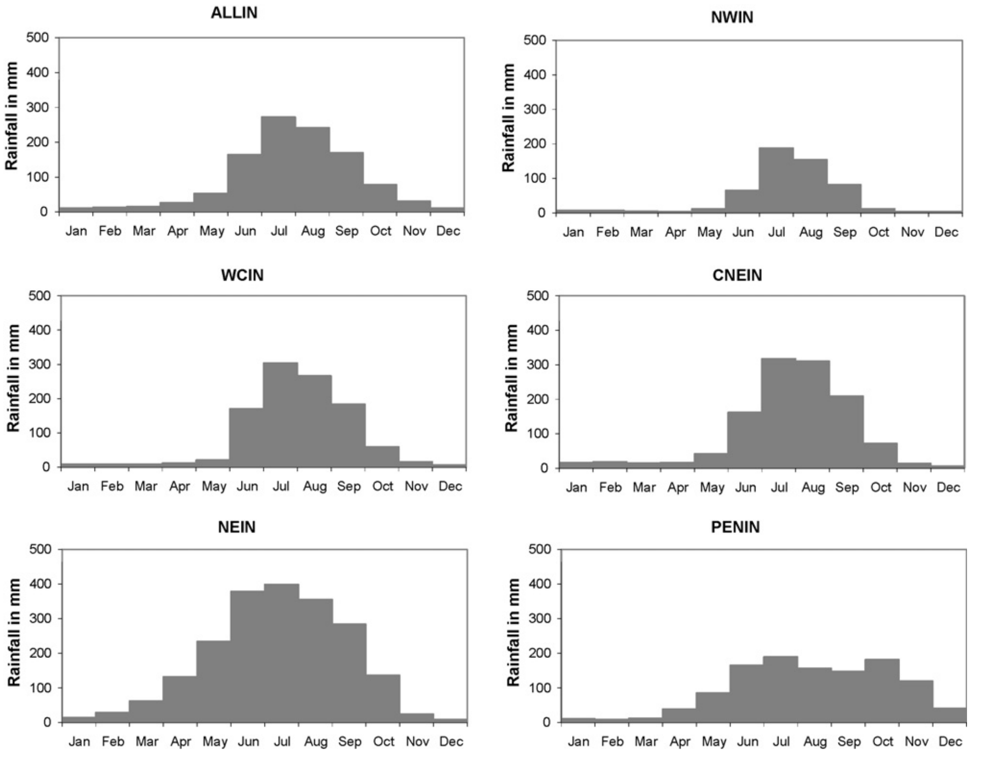

Fig. 2. The seasonal cycle of rainfall in various study regions in India.

$$sgn(x_j - x_k) = \begin{Bmatrix} +1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{Bmatrix} \quad (2)$$

where n is the number of observed data series, x_j and x_k are the values in periods j and k respectively, $j > k$. For $n \geq 10$, the sampling distribution of S is as in Eq. (1). Z (the area under the standard normal curve) follows the standard normal distribution where:

$$Z = \begin{Bmatrix} \dfrac{S-1}{\sqrt{\mathrm{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{VAR}(S)}} & \text{if } S < 0 \end{Bmatrix} \quad (3)$$

VAR(S) is determined as:

$$\mathrm{VAR}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \quad (4)$$

where q is the number of tied groups and t_p is the number of data values in the pth group. A positive value of Z indicates an upward trend and a negative value of Z indicates a downward trend. To determine the statistical significance, calculated Z-score values are used in Standard Normal Table.

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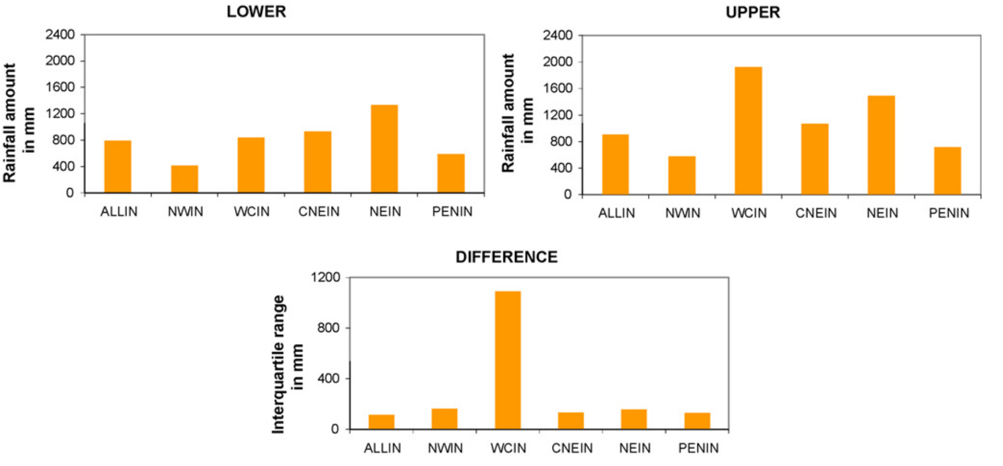

Fig. 3. Lower and upper quartiles of 135 years (1871–2005) monsoon rainfall in various study regions in India.

3. Analyses and results

This study looks at regional monsoon rainfall changes by assessing the trends and their significance of frequency and magnitudes of regional extreme monsoon rainfall deficit and excess based on 135 years (1871–2005) quartiles. Since the frequency and magnitudes of extreme monsoon rainfall deficit and excess in India consisted of single sample values per year, their changes in distributions and the corresponding graphs would be complicated or even confusing if they were not grouped in certain interval. Therefore, to eliminate such unnecessary details in trend assessment, 135 years were subdivided into nine sub-intervals having 15-years length.

3.1. Changes in 'frequency' of extreme monsoon rainfall deficit and excess

The first step in the analysis was to determine frequencies of extreme monsoon rainfall deficit and excess based on lower and upper quartiles of 135-year (1871–2005) monsoon rainfall and thereafter to assess their trends using MK technique. Fig. 3 shows variation of upper and lower quartiles of monsoon rainfall in different regions in India and including an all-India average. Fig. 3 depicts a great difference in upper and lower quartiles while WCIN was found to be having the greatest inter quartile range.

Fig. 4 displays variation of the frequencies of extreme monsoon rainfall deficit and excess occurred in 15 years interval starting in 1871. The figure shows large regional variations. Fig. 5 shows tendencies in regional frequencies of extreme monsoon rainfall deficit and excess in Fig. 4. Fig. 5 shows four panel maps where all the regional changes are captured including ALLIN (small all-India maps inside every panel). The figure (Fig. 5, panel I) reveals that ALLIN is undergoing an increasing tendency in frequency of monsoon rainfall deficient years. All northern Indian regions show increasing tendencies while PENIN shows no tendency. However, as noted in Fig. 4, that the frequency of extreme monsoon rainfall deficient years has a steady increase in the decades after 1940s in WCIN, CNEIN and NEIN and also in PENIN.

Although the panel II in Fig. 5 indicates tendencies in extreme monsoon rainfall excess frequencies in 1871–2005, it is noted that the tendencies are not simply the opposite of the results corresponding to frequencies of extreme monsoon rainfall deficits. Panel II also shows that extreme monsoon rainfall excess frequency in ALLIN and all the other regions except NWIN is decreasing. Based on panels I and II in Fig. 5, NWIN is the most vulnerable in terms of both extreme monsoon rainfall deficit and excess frequencies. ALLIN and WCIN showed a steady decrease in monsoon rainfall excess frequency since 1930s and until current decade and so did happen in CNEIN and NEIN until 1990, as seen in Fig. 4.

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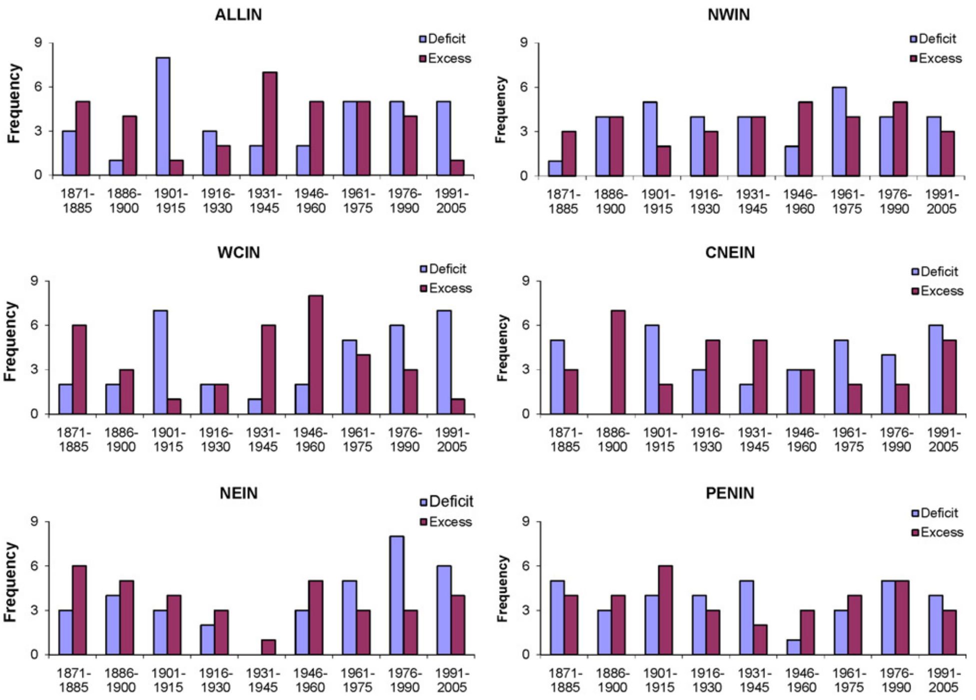

Fig. 4. Variation of frequencies of extreme monsoon rainfall deficit and excess in 15 years interval based on data from 1871 to 2005 in various regions in India.

PENIN has been going through a continuous increase in monsoon rainfall excess frequency from 1930s to 1990 and then a sudden drop in the current most decades, as in Fig. 4.

Table 1 shows percentage significance of the trends in panels I and II in Fig. 5 determined using MK method. It is noticed in Table 1 that the highest significance is noticed in NEIN, which experiences highest monsoon rainfall every year. Therefore, increase in monsoon deficient years in this region is greatly affecting ALLIN monsoon rainfall average as well. Table 1 also shows that the northern Indian regions have highly significant trends in extreme monsoon rainfall deficit and excess frequencies in 1871–2005.

3.2. Changes in 'magnitude' of extreme monsoon rainfall deficit and excess

Values of the magnitudes of extreme monsoon rainfall deficit and excess with respect to long-term lower and upper quartiles of monsoon rainfall are estimated. These are the rainfalls in each

Table 1
Significance corresponding to trends in extreme monsoon rainfall deficit and excess frequency in various regions in India in 1871–2005.

Region	Percent significance (based on *Z*-score calculated by MK)	
	Extreme monsoon deficient frequency	Extreme monsoon excess frequency
ALLIN	59.34%	46.48%
NWIN	39.7%	70.16%
WCIN	78.88%	31.82%
CNEIN	59.34%	46.48%
NEIN	78.88%	78.88%
PENIN	–	24.34%

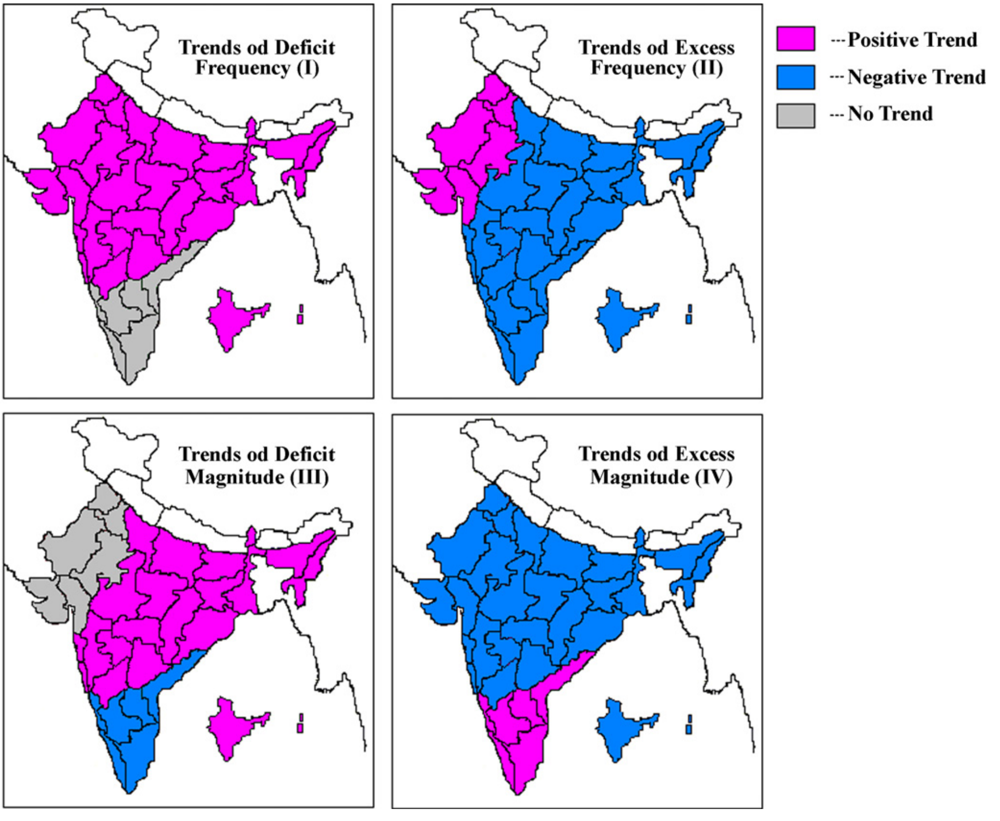

Fig. 5. Regional trends in extreme monsoon rainfall deficit and excess in India in 1871–2005.

year differenced from the lower/upper quartile values and averaged over the 15 years. Those magnitudes are then averaged over the 15 years interval from 1871 to 2005 in order to look at how the average magnitudes of extreme monsoon rainfall deficits and excesses are changing over the 135 years. Fig. 6 depicts the variations of those magnitudes over the study period. As noticed in panel III, Fig. 5, magnitudes of extreme monsoon rainfall deficiencies have been increasing in every region except north-west (NWIN) and peninsular India (PENIN). Although extreme monsoon deficiency magnitudes in PENIN decreased from the previous decades to mid 1970s, it has been increasing thereafter, as in Fig. 6. Increase in magnitude and frequency (Section 3.1) of extreme monsoon rainfall deficit in NEIN, WCIN and CNEIN make these regions very much vulnerable to water shortage.

Panel IV, Fig. 5 shows the trends in magnitude of extreme monsoon rainfall excess in various regions in India and including an all-India average. It is noted in Fig. 5 that the magnitude of extreme monsoon rainfall excess has been decreasing over the years in northern India (NEIN, NWIN, WCIN, and CNEIN); however, an increase in magnitude of extreme monsoon rainfall excess in NEIN is noticed in the most current decade in study (1991–2005), which, along with lesser number of extreme monsoon deficit years from the previous decade (Fig. 4) and increase in magnitude and frequency of extreme monsoon rainfall excess (Figs. 4 and 6) might have caused some of the severe flood events in the recent decade in NEIN.

Table 2 shows percentage significance of the trends in panels III and IV in Fig. 5 determined using MK method. It is noticed in Table 2 that the highest significance is found for NEIN again for the case

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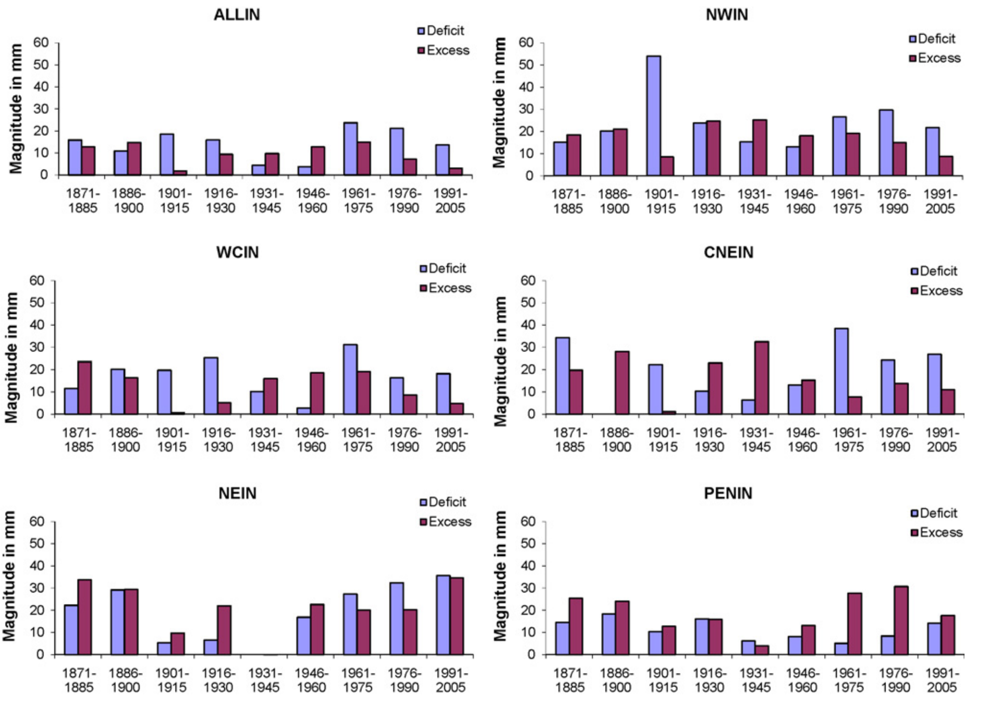

Fig. 6. Variation of magnitudes of extreme monsoon rainfall deficit and excess in 15 years interval based on data from 1871 to 2005 in various regions in India.

of magnitude of extreme monsoon deficit. Since this region receives large amount of rainfalls in monsoon season, it could be concluded that the changes in NEIN rainfalls in monsoon season is greatly affecting ALLIN monsoon rainfall average, like frequency in Table 1. Table 2 also shows that CNEIN has comparatively higher significance both in trends of extreme monsoon rainfall deficit and excess magnitudes in 1871–2005.

All the results discussed in Sections 3.1 and 3.2 collectively show that, probability of extreme monsoon deficiency is generally increasing in India, which is the highest in northern India while changing tendencies are quite variable in the country and especially north–south wise. Therefore, based on these observations it could be concluded that while extreme monsoonal climate is changing in all the regions in India, the changes are very distinct and as a result, a study based in one particular region may not adequately represent the whole of India.

Table 2
Significance corresponding to trends in extreme monsoon rainfall deficit and excess magnitudes in various regions in India in 1871–2005.

Region	Percent significance (based on *Z*-score calculated by MK)	
	Extreme monsoon deficient magnitude	Extreme monsoon excess magnitude
ALLIN	8%	40%
NWIN	39.7%	53%
WCIN	–	40%
CNEIN	64.76%	64.76%
NEIN	82.3%	8%
PENIN	74.58%	24.34%

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4. Conclusion

In this paper, climatic changes over the period of 1871–2005 were analysed based on assessing long-term trends of extreme monsoon rainfall deficit and excess in Indian regions using non-parametric Mann–Kendall technique. The paper presents an insight of the temporal evolution of extreme monsoon rainfall in India as resulting from the analysis of five regions covering 90% of India. Rainfall deficiencies are found to occur in most parts, except peninsular Indian region. However, the magnitudes of the regional differences in the results are very high. The deficiency is relatively strong in the north-east, west-central and central north-east India, the regions of usual maximum monsoon rainfall, making the north India most vulnerable to summer droughts.

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