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Hydrological Sciences Journal – Journal des Sciences Hydrologiques

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: https://www.tandfonline.com/loi/thsj20

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To cite this article: Vijay Kumar , Sharad K. Jain & Yatveer Singh (2010) Analysis of long-term rainfall trends in India, Hydrological Sciences Journal – Journal des Sciences Hydrologiques, 55:4, 484-496, DOI: 10.1080/02626667.2010.481373

To link to this article: https://doi.org/10.1080/02626667.2010.481373

Published online: 26 May 2010.

Analysis of long-term rainfall trends in India

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Received 8 April 2008; accepted 8 January 2010; open for discussion until 1 December 2010

Citation Kumar, V., Jain, S. K. & Singh, Y. (2010) Analysis of long-term rainfall trends in India. *Hydrol. Sci. J.* **55**(4), 484–496.

Abstract The study of precipitation trends is critically important for a country like India whose food security and economy are dependent on the timely availability of water. In this work, monthly, seasonal and annual trends of rainfall have been studied using monthly data series of 135 years (1871–2005) for 30 sub-divisions (sub-regions) in India. Half of the sub-divisions showed an increasing trend in annual rainfall, but for only three (Haryana, Punjab and Coastal Karnataka), this trend was statistically significant. Similarly, only one sub-division (Chattisgarh) indicated a significant decreasing trend out of the 15 sub-divisions showing decreasing trend in annual rainfall. In India, the monsoon months of June to September account for more than 80% of the annual rainfall. During June and July, the number of sub-divisions showing increasing rainfall is almost equal to those showing decreasing rainfall. In August, the number of sub-divisions showing an increasing trend exceeds those showing a decreasing trend, whereas in September, the situation is the opposite. The majority of sub-divisions showed very little change in rainfall in non-monsoon months. The five main regions of India showed no significant trend in annual, seasonal and monthly rainfall in most of the months. For the whole of India, no significant trend was detected for annual, seasonal, or monthly rainfall. Annual and monsoon rainfall decreased, while pre-monsoon, post-monsoon and winter rainfall increased at the national scale. Rainfall in June, July and September decreased, whereas in August it increased, at the national scale.

Key words climate change; precipitation; rainfall trend; sub-division; non-parametric test; Mann-Kendall test; India

Analyse des tendances pluviométriques de long terme en Inde

Résumé L'étude des tendances de précipitation est très importante pour un pays comme l'Inde dont la sécurité alimentaire et l'économie dépendent de la disponibilité temporelle de l'eau. Dans ce travail, les tendances des précipitations mensuelles, saisonnières et annuelle ont été étudiées à partir des séries de données mensuelles de 135 années (1871–2005) de 30 sous-divisions (sous-régions) de l'Inde. La moitié de ces sous-divisions présente une tendance croissante de la précipitation annuelle, mais cette tendance n'est statistiquement significative que pour trois d'entre elles (Haryana, Punjab et Karnataka littoral). De même, une seule sous-division (Chattisgarh) présente une tendance décroissante significative parmi les 15 sous-régions qui présentent une tendance décroissante de la précipitation annuelle. En Inde, les mois de mousson de Juin à Septembre contribuent à plus de 80% de la précipitation annuelle. Pendant Juin et Juillet, les sous-divisions sont presque aussi nombreuses à présenter une précipitation croissante ou décroissante. En Août, les sous-divisions présentant une croissance sont plus nombreuses, contrairement à Septembre. La majorité des sous-divisions présente très peu de changement de précipitation pour les mois hors mousson. Cinq régions importantes de l'Inde ne présentent pas de tendance significative pour les précipitations annuelle, saisonnières et mensuelles pour la plupart des mois. Pour l'ensemble de l'Inde, aucune tendance significative n'a été détectée pour les précipitations annuelle, saisonnières ou mensuelles. Les précipitations annuelle et de mousson décroissent, tandis que les précipitations pré-mousson, post-mousson et hivernale augmentent à l'échelle nationale. Les précipitations décroissent en Juin, Juillet et Septembre, et croissent en Août à l'échelle nationale.

Mots clefs changements climatiques; précipitations; tendance pluviométrique; sous-division; test non-paramétrique; test de Mann-Kendall; Inde

INTRODUCTION

Although the subject area of climate change is vast, the changing pattern of rainfall is a topic within this field that deserves urgent and systematic attention, since it affects both the availability of freshwater and food production (Dore, 2005). Based on experimentation

ISSN 0262-6667 print/ISSN 2150-3435 online

doi: 10.1080/02626667.2010.481373
http://www.informaworld.com

at New Delhi, India, Aggarwal (2007) has reported that a 1°C rise in temperature throughout the growing period will reduce wheat production by 5 million tonnes. The global average precipitation is projected to increase, but both increases and decreases are expected at the regional and continental scales (Dore, 2005). Higher or lower rainfall, or changes in its spatial and seasonal distribution would influence the spatial and temporal distribution of runoff, soil moisture and groundwater reserves, and would affect the frequency of droughts and floods. Further, temporal change in precipitation distribution will affect cropping patterns and productivity.

According to the Intergovernmental Panel on Climate Change (IPCC, 2007), future climate change is likely to affect agriculture, increase the risk of hunger and water scarcity, and lead to more rapid melting of glaciers. Freshwater availability in many river basins in India is likely to decrease due to climate change (Gosain *et al.*, 2006). This decrease, along with population growth and rising living standards, could adversely affect many people in India by the 2050s. Accelerated glacier melt is likely to cause an increase in the number and severity of glacier melt-related floods, slope destabilization and a decrease in river flows as glaciers recede (IPCC, 2007). Lal (2001) discussed the implications of climate change on Indian water resources. Gosain *et al.* (2006) have quantified the impact of climate change on the water resources of Indian river systems. Kalra *et al.* (2008) found that the yield of wheat, mustard, barley and chickpea show signs of stagnation or decrease following a rise in temperature in four northern states of India.

Under the conditions of skewed water availability and its mismatch with demand, large storage reservoirs may be needed to redistribute the natural flow of streams in accordance with the requirements of a specific region. The general practice of designing a reservoir is based on the assumption that climate is stationary. Changes in rainfall due to global warming will influence the hydrological cycle and the pattern of streamflows. This will call for a review of reservoir design and management practices in India.

The Indian climate is dominated by the southwest monsoon. About 80% of the rainfall in India occurs during the four monsoon months (June–September) with large spatial and temporal variations over the country. Such a heavy concentration of rainfall results in a scarcity of water in many parts of the country during the non-monsoon period. Therefore, for India, where agriculture has a significant influence on both the economy and livelihood, the availability of adequate water for irrigation under changed climatic scenarios is very important. The agricultural output is primarily governed by timely availability of water. In future, population growth along with a higher demand for water for irrigation and industries will put more pressure on water resources.

With the growing recognition of the possibility of adverse impacts of global climate change on water resources, an assessment of future water availability at various spatial and temporal scales is needed. It is expected that the response of hydrological systems, erosion processes and sedimentation could significantly alter due to climate change. An understanding of the hydrological response of a river basin under changed climatic conditions would help solve problems associated with floods, droughts and allocation of water for agriculture, industry, hydropower generation, domestic and industrial use. Scenarios of changes in runoff and its distribution depend on the future climate scenarios.

In India, attempts have been made in the past to determine trends in the rainfall at national and regional scales. Most of the rainfall studies were confined to the analysis of annual and seasonal series for individual or groups of stations. In the present study, a much wider view has been taken, and changes in rainfall have been studied on seasonal and annual scales for 30 subdivisions, and five main regions. Intra-seasonal variability in rainfall has also been studied by analysing the trends in monthly rainfall. Further, the time series of rainfall data used in this study spans more than 100 years. Thus, the present analysis is a significant improvement over the studies carried out previously.

SIGNATURES OF CLIMATE CHANGE OVER INDIA

Studies carried out by several investigators have shown that the trend and magnitude of warming over India/the Indian sub-continent over the last century is broadly consistent with the global trend and magnitude (Hingane, 1995; Pant & Kumar, 1997, Arora *et al.*, 2005, Dash *et al.*, 2007). Pant & Kumar (1997) analysed the seasonal and annual air temperatures from 1881–1997 and have shown that there has been an increasing trend of mean annual temperature, at the rate of 0.57°C per 100 years. Singh *et al.* (2008b) found a warming trend in seven of the nine river basins in northwest and central India.

Some past studies relating to changes in rainfall over India have concluded that there is no clear trend of increase or decrease in average annual rainfall over the country (Mooley & Parthasarathy, 1984; Sarker & Thapliyal, 1988; Thapliyal & Kulshrestha, 1991; Lal, 2001). Though no trend in the monsoon rainfall in India is found over a long period of time, particularly on the all-India scale, pockets of significant long-term rainfall changes have been identified (Koteswaram & Alvi, 1969; Jagannathan & Parthasarathy, 1973; Raghavendra, 1974; Chaudhary & Abhyankar, 1979; Kumar *et al*., 2005; Dash *et al.*, 2007; Kumar & Jain, 2009).

A change detection study using monthly rainfall data for 306 stations distributed across India was attempted by Rupa Kumar *et al*. (1992). They showed that areas of the northeast peninsula, northeast India and northwest peninsula experienced a decreasing trend in summer monsoon rainfall. A widespread increasing trend in monsoon rainfall over the west coast, central peninsula and northwest India was also reported. The decreasing trend ranged between −6 and −8% of the normal per 100 years, while the increasing trend was about 10–12% of the normal per 100 years. Srivastava *et al*. (1998) supported the existence of a definite trend in rainfall over smaller spatial scale. Sinha Ray & De (2003) concluded that all-India rainfall and surface pressure shows no significant trend, except for some periodic behaviour. According to Sinha Ray & Srivastava (1999), the frequency of heavy rainfall events during the southwest monsoon has shown an increasing trend over certain parts of the country, whereas a decreasing trend has been observed during winter, pre-monsoon and post-monsoon seasons. These authors tried to attribute this variation to dynamic and anthropogenic causes. The inter-annual and decadal variability in summer monsoon rainfall over India was examined by Kripalani *et al.* (2003) by using observed data for a 131-year period (1971–2001). They found random fluctuations in annual rainfall and distinct alternate epochs (lasting approximately three decades) of above- and below-normal rainfall for decadal rainfall. They also concluded that this inter-annual and decadal variability appears to have no relationship to global warming. Analysis of rainfall data for the period 1871–2002 indicated a decreasing trend in monsoon rainfall and an increasing trend in the pre-monsoon and post-monsoon seasons (Dash *et al.*, 2007).

Mirza *et al*. (1998) carried out trend and persistence analysis for the Ganges, Brahmaputra and Meghna river basins. They showed that precipitation in the Ganges basin is, by and large, stable. Furthermore, one of three sub-divisions of the Brahmaputra basin shows a decreasing trend, while another shows an increasing trend. Singh *et al.* (2008a) studied the changes in rainfall in nine river basins of northwest and central India and found an increasing trend in annual rainfall in the range of 2–19% of the mean per 100 years.

Recent studies (Khan *et al*., 2000; Shrestha *et al*., 2000; Mirza, 2002; Lal, 2003; Min *et al.*, 2003; Goswami *et al*., 2006; Dash *et al*., 2007) show that, in general, the frequency of more intense rainfall events in many parts of Asia has increased, while the number of rainy days and total annual amount of precipitation has decreased. Goswami *et al.* (2006) used daily rainfall data to show the significant rising trends in the frequency and magnitude of extreme rain events, and a significant decreasing trend in the frequency of moderate events over central India during the monsoon seasons from 1951 to 2000. The frequency of heavy rainfall events during the monsoon season was found to be increasing over the Andaman and Nicobar islands, Lakshadweep, the west coast and some pockets in central and northwest India, whereas it was found to be decreasing in winter, pre-monsoon and post-monsoon seasons over most parts of India (Dash *et al.*, 2007). Mall *et al.* (2007) inferred that there has been a westward shift in rainfall activity over the Indo-Gangetic Plain region. An increase in intense rainfall events leads to more severe floods and landslides. The number of cyclones originating from the Bay of Bengal and the Arabian Sea has decreased since 1970, but their intensity has increased (Lal, 2001). Moreover, the damage caused by intense cyclones has risen significantly in India. In three consecutive years since 2002, there were large floods in the northeastern states of India, on 26–27 July 2005, a record 944 mm of rain fell in Mumbai, but the seasons of 2006 and 2007 saw deficient rainfall. Severe floods were observed in many parts of Gujarat and Rajasthan during the monsoon seasons of 2006 and 2007 (India Meteorological Department, 2006, 2007).

STUDY AREA AND DATA USED

Based on meteorological considerations, India has been divided into 36 meteorological sub-divisions (34 on the main land and two on islands). The subdivisions on the mainland are shown in Fig. 1. In this study, rainfall over the whole of India (except the Hilly

Fig. 1 Sub-divisional map of India. Numbers refer to sub-divisions (details in Table 1); dots indicate the location of raingauge stations.

region and islands) was considered. The geographical area of the sub-divisions considered in this study is 2.88×10^6 km^2 (cf. 3.29×10^6 km^2, being the whole of India, excluding islands).

Sub-divisional monthly rainfall data of India prepared by the Indian Institute of Tropical Meteorology (IITM: htpp://www.tropmet.res.in) were used in this study. A network of 306 stations (one representative station per district) over 30 meteorological sub-divisions was used to prepare the sub-divisional data (Fig. 1). The monthly (January–December) area-weighted rainfall series for each of the 30 meteorological sub-divisions were prepared by assigning the district area as the weight for each raingauge station in that sub-division. The station rainfall data were obtained from the India Meteorological Department (IMD). Before releasing the data, the IMD carries out quality checks to ensure that error-free data are used in analysis and design. Thus the quality of this data set is very good and it is one of the most reliable long series of data. The monthly data were available for 135 years (1871–2005) for 30 sub-divisions (Table 1). Rainfall data of six meteorological sub-divisions, namely Jammu and Kashmir, Uttaranchal, Himachal Pradesh, Arunachal Pradesh, Lakshadweep and Andaman & Nicobar islands, were not available. As may be seen from Table 1, the area of studied sub-divisions varies from a minimum of 18 817 km^2 (Coastal Karnataka) to a maximum of 195 086 km^2 (West Rajasthan) with the number of rainfall stations varying from two (Coastal Karnataka) to 26 (East Uttar Pradesh).

The 30 sub-divisions were combined into five homogeneous regions by IITM as detailed in Table 2. The area-weighted monthly rainfall (by assigning the sub-division area as the weight) series of these five regions, along with the combined data of 30 sub-divisions, were available at htpp://www.tropmet.res.in and were also analysed.

Table 1 Meteorological sub-divisions whose data were used and statistical properties of annual rainfall.

Sub-division	Sub-division no.	Area (km^2)	% of 30 sub-divisions	No. of rainfall stations used	Minimum rainfall (mm)	Maximum rainfall (mm)	Mean rainfall (mm)	CV*
Assam & Meghalaya	3	109 096	3.79	10	1790.9	3102.5	2356.4	0.11
Nagaland, Manipur, Mizoram & Tripura	4	70 495	2.45	4	1418.1	2742.1	1993.3	0.12
Sub-Himalayan West Bengal & Sikkim	5	21 625	0.75	5	1705.9	3323.8	2509.0	0.13
Gangetic West Bengal	6	66 228	2.30	11	1083.6	2226.9	1541.0	0.15
Orissa	7	155 842	5.41	13	1008.9	1988.1	1479.1	0.13
Jharkhand	8	79 638	2.76	6	861.8	1862.6	1341.2	0.14
Bihar	9	94 235	3.27	11	648.0	1729.3	1223.6	0.18
East Uttar Pradesh	10	146 509	5.09	26	569.0	1712.9	1027.0	0.20
West Uttar Pradesh	11	96 782	3.36	19	378.7	1304.6	878.4	0.20
Haryana	13	45 698	1.59	12	229.0	997.3	560.3	0.26
Punjab	14	50 376	1.75	10	233.2	1195.6	641.3	0.28
West Rajasthan	17	195 086	6.77	9	36.6	722.2	294.2	0.38
East Rajasthan	18	147 128	5.11	17	275.5	1337.1	686.2	0.25
West Madhya Pradesh	19	175 317	6.09	22	496.6	1420.3	943.2	0.19
East Madhya Pradesh	20	135 156	4.69	15	707.4	1748.5	1261.2	0.16
Gujarat	21	86 034	2.99	11	221.9	1614.3	908.7	0.31
Saurashtra, Kutch & Diu	22	109 950	3.82	7	71.1	1240.5	465.8	0.42
Konkan & Goa	23	34 095	1.18	5	1302.5	3974.3	2525.0	0.19
Madhya Maharashtra	24	115 306	4.00	9	344.5	1107.5	736.1	0.20
Marathwada	25	64 525	2.24	5	283.6	1500.5	831.4	0.26
Vidarbha	26	97 536	3.39	8	444.3	1585.5	1085.5	0.19
Chattisgarh	27	146 138	5.07	6	821.4	2081.5	1361.9	0.17
Coastal Andhra Pradesh	28	93 045	3.23	8	531.5	1501.1	977.7	0.20
Telangana	29	114 726	3.98	9	488.2	1484.1	889.5	0.21
Rayalaseema	30	69 043	2.40	4	225.1	1227.4	718.8	0.22
Tamil Nadu & Pondicherry	31	130 068	4.52	15	527.4	1262.5	924.7	0.16
Coastal Karnataka	32	18 717	0.65	2	2032.7	5552.2	3269.5	0.17
North Interior Karnataka	33	79 895	2.77	6	412.7	1236.1	828.7	0.18
South Interior Karnataka	34	93 171	3.23	11	515.4	1323.1	879.9	0.17
Kerala	35	38 864	1.35	10	1855.4	3944.7	2822.4	0.14
Whole study area		2 880 324	100	306	811.0	1346.8	1087.8	0.09

*CV: Coefficient of variation.

To investigate the changes in rainfall for different seasons, a year was divided into four seasons: winter (December–February), pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–November). Rainfall analysis was carried out for all the seasons as well as the whole year separately. Note that the post-monsoon season contains only two months, while the monsoon season has four months. For the trend analysis, monthly rainfall series were used to form seasonal and annual series of these variables. Basic statistics, such as minimum, maximum, mean and coefficient of variation (CV) of annual rainfall of different data sets are given in Tables 1 and 2. Figure 2 shows the temporal variation of annual rainfall for the five regions and the entire study area. Note that the annual rainfall of the North West India region is about half that of the other regions and its CV is about twice that for the other regions (see Table 2). Low rainfall coupled with a high variation makes this region highly vulnerable to climate change.

METHODOLOGY

The magnitude of the trend in the time series was determined using Sen's estimator (Sen, 1968). This method has been widely used for determining the magnitude of trend in hydro-meteorological time series, and details are available in Lettenmaier *et al.* (1994); Yue & Hashino (2003) and Partal & Kahya (2006). The statistical significance of the trend in monthly, seasonal and annual series was analysed using the non-parametric Mann-Kendall (MK) test

Table 2 Details of regions and statistical properties of annual rainfall.

Region name	Sub-divisions forming the region	Area (km^2)	% of all regions	No. of rainfall stations used	Minimum (mm)	Maximum (mm)	Mean (mm)	CV*
North East India	3,4,5,6	267 444	9.29	30	1576.0	2625.9	2070.52	0.09
Central North East India	7,8,9,10,11	573 006	19.89	75	827.3	1605.2	1200.28	0.11
North West India	13,14,17,18,21,22	634 272	22.02	66	175.3	1057.2	544.39	0.25
West Central India	19,20,23,24,25,26,27,29,33	962 694	33.42	85	593.2	1442.7	1073.04	0.13
Peninsular India	28,30,31,32,34,35	442 908	15.38	50	704.9	1445.1	1159.31	0.11
Whole study area		2 880 324	100	306	811.0	1346.8	1087.82	0.09

*CV: Coefficient of variation.

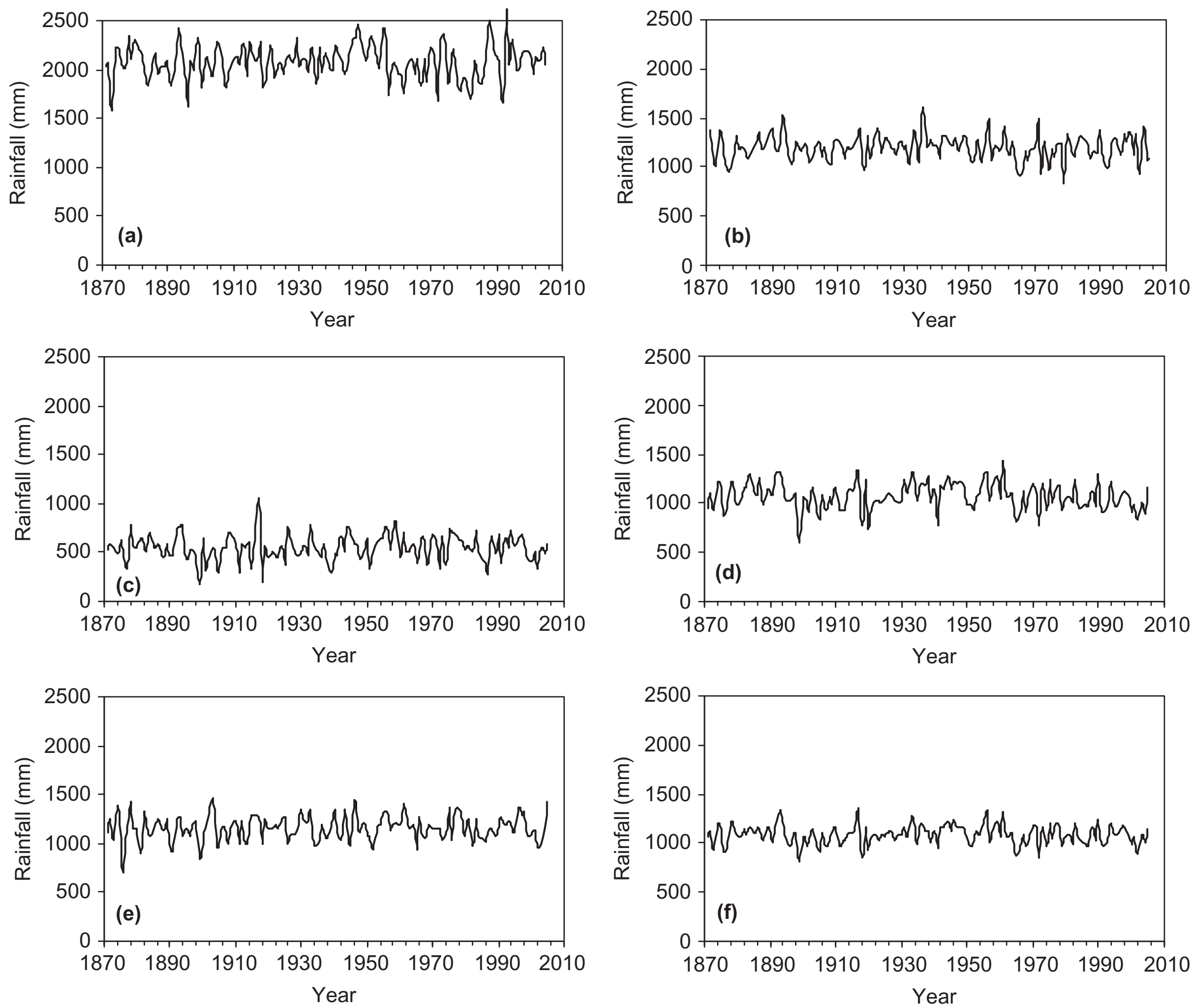

Fig. 2 Temporal variation of annual rainfall for (a) North East, (b) Central North East, (c) North West, (d) West Central, (e) Peninsular, and (f) all-regions.

(Mann, 1945; Kendall, 1975). The MK test has been employed by a number of researchers (e.g. Yu *et al.*, 1993; Douglas *et al.*, 2000; Yue *et al.*, 2003; Burn *et al.*, 2004; Singh *et al.*, 2008a,b) to ascertain the presence of statistically significant trend in hydrological climatic variables, such as temperature, precipitation and streamflow, with reference to climate change. The MK test checks the null hypothesis of no trend *versus* the alternative hypothesis of the existence of increasing or decreasing trend. Following Bayazit & Onoz (2007), no pre-whitening of the data series was carried out, as the sample size was large ($n \geq 50$) and the slope of trend was high (>0.01). Details of this method are available in the papers cited above.

RESULTS AND DISCUSSION

Magnitude of trend

The magnitude of the trend in the time series, as determined using the Sen estimator, is given in Tables 3 and 4. As expected, the analysis of trends of rainfall variations by sub-division shows a large variability in the magnitude and direction of trend from one sub-division to another. Monthly analysis of sub-divisional rainfall indicated that the majority of the sub-divisions have very little or no change in non-monsoon months of January, February, March, November and December (Table 3). The remaining three non-monsoon months (April, May and October) witnessed (small) increasing rainfall in the majority of sub-divisions. Sixteen sub-divisions experienced decreasing rainfall in the monsoon months of June and July. The maximum reduction was found for Kerala (−0.97 mm/year) in June and East Madhya Pradesh (−0.70 mm/year) in July. The maximum increase out of 12 sub-divisions was experienced by Coastal Karnataka in June and sub-Himalayan West Bengal & Sikkim (out of 14 sub-divisions) in July. In August, the maximum increase, out of 21 sub-divisions showing positive trend, was witnessed by Konkan & Goa (1.04 mm/year), whereas the maximum reduction, out of nine sub-divisions showing negative trend, was experienced by Nagaland, Manipur, Mizoram & Tripura sub-division (−0.52 mm/year). For September, 22 sub-divisions showed decreasing rainfall, with the maximum reduction for Marathwada (−0.50 mm/year), and eight sub-divisions experienced increasing rainfall with maximum increase for Gangetic West Bengal (0.35 mm/year).

Seasonal analysis of sub-divisional rainfall showed that pre-monsoon rainfall increased over 23 sub-divisions; monsoon rainfall increased over 10; post-monsoon rainfall increased over 27; and winter rainfall increased over 20. Five sub-divisions (West Rajasthan, Saurashtra Kutch & Diu, Madhya Maharashtra, Tamil Nadu & Pondicherry, and North Interior Karnataka) showed very little trend in monsoon rainfall. The maximum increase in monsoon rainfall was of the order of 1.81 mm/year for Coastal Karnataka followed by Konkan & Goa and Punjab, whereas the maximum decrease was for Chattisgarh (−1.29 mm/year) followed by Kerala and Nagaland, Manipur, Mizoram & Tripura sub-divisions. While analysing the rainfall data for the 1871–2003 period, Dash *et al.* (2007) also found the same three sub-divisions showing the maximum increase in monsoon rainfall, whilst they found maximum decrease in Nagaland, Manipur, Mizoram & Tripura followed by East Madhya Pradesh and Orissa. In seasons other than monsoon, the magnitude of change was quite small; as rainfall in these seasons is much smaller than in the monsoon season.

Nearly half of the sub-divisions have shown an increasing trend in annual rainfall and the remaining have shown the opposite trend (Table 4). The increase in annual rainfall over the sub-divisions varied between 0.03 mm/year (for South Interior Karnataka) to 2.37 mm/year (for Coastal Karnataka). Similarly, the decrease in annual rainfall was found to be maximum for East Madhya Pradesh (−0.76 mm/year) and minimum for Madhya Maharashtra (−0.04 mm/year). The changes in annual rainfall for six sub-divisions, namely sub-Himalayan West Bengal & Sikkim, West Rajasthan, Saurashtra Kutch & Diu, Madhya Maharashtra, Tamil Nadu & Pondicherry, and South Interior Karnataka, were found to be comparatively small.

When the data were analysed on a regional scale, four regions experienced rainfall reduction in the monsoon months of June and July. Three regions in August and two regions in September showed increasing rainfall. All five regions experienced increasing rainfall during pre-monsoon and post-monsoon seasons. During the monsoon season, all regions except Peninsular India showed a decreasing trend. The change in monsoon rainfall for the North West India and Peninsular India regions is small. West Central India and Peninsular India experienced an increasing trend in winter and all the other three regions experienced a decreasing trend. The West Central India region, which covers the maximum area among the regions, and the North East region, which received the maximum mean annual rainfall, showed a decreasing trend in annual rainfall. Annual rainfall indicated an increasing trend for North West India (0.08 mm/year) and Peninsular India (0.22 mm/year) and a decreasing trend in the remaining three regions with a maximum decrease for West Central India (−0.30 mm/year).

On an all-India basis, February, April, August, October and November experienced increasing rainfall, whereas June, July and September showed

Table 3 Sen estimator of slope (mm/year) for monthly rainfall.

Sub-division/Region	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Sub-divisions												
Assam & Meghalaya	−0.03	0.03	−0.14	0.01	−0.14	−0.16	0.22	**−0.48**	−0.19	0.32	0.03	0.01
Nagaland, Manipur, Mizoram & Tripura	−0.01	−0.03	−0.11	0.06	0.14	−0.24	−0.11	**−0.52**	−0.21	0.06	0.02	0.00
Sub-Himalayan West Bengal & Sikkim	0.00	0.00	−0.01	0.12	0.04	**−0.69**	**0.87**	−0.27	−0.26	**0.35**	**0.02**	0.00
Gangetic West Bengal	0.01	0.00	0.02	0.07	−0.09	−0.13	0.10	0.11	**0.35**	0.19	0.02	0.00
Orissa	0.01	0.02	0.01	0.09	−0.03	−0.11	−0.20	0.18	−0.15	−0.04	0.00	0.00
Jharkhand	0.01	−0.01	0.00	0.04	−0.03	−0.06	−0.29	−0.31	0.06	0.11	0.00	0.00
Bihar	0.00	0.00	0.00	0.03	0.06	−0.23	0.07	−0.32	−0.04	0.09	0.00	0.00
East Uttar Pradesh	0.02	0.01	0.00	**0.02**	0.00	0.00	−0.27	−0.28	0.32	0.04	0.00	0.00
West Uttar Pradesh	−0.02	0.01	0.00	0.01	0.01	0.01	−0.23	0.03	0.07	0.03	0.00	0.00
Haryana	0.00	0.02	0.02	**0.01**	0.01	0.06	0.15	**0.43**	−0.03	0.00	0.00	0.00
Punjab	−0.03	0.05	**0.07**	0.02	0.01	0.13	0.26	0.25	0.12	0.01	0.00	0.00
West Rajasthan	0.00	0.00	0.00	0.00	0.00	0.04	0.12	−0.05	−0.05	0.00	0.00	0.00
East Rajasthan	−0.01	0.00	0.00	0.01	−0.01	−0.02	−0.09	0.08	−0.12	0.00	0.00	0.00
West Madhya Pradesh	0.00	0.00	0.00	0.00	0.00	**−0.30**	−0.19	0.40	−0.28	0.03	0.00	0.00
East Madhya Pradesh	0.01	0.00	0.00	0.01	0.00	−0.39	**−0.70**	0.22	−0.10	0.01	0.00	0.00
Gujarat	0.00	0.00	0.00	0.00	0.00	0.13	−0.47	0.20	−0.17	0.00	0.00	0.00
Saurashtra, Kutch & Diu	0.00	0.00	0.00	0.00	0.00	0.07	−0.36	0.16	−0.02	0.00	0.00	0.00
Konkan & Goa	0.00	0.00	0.00	0.00	0.01	0.33	0.13	**1.04**	−0.05	0.15	0.00	0.00
Madhya Maharashtra	0.00	0.00	0.00	−0.01	0.00	0.13	−0.23	**0.25**	−0.17	0.05	−0.01	0.00
Marathwada	0.00	0.00	0.00	0.00	0.02	−0.03	0.04	0.28	**−0.50**	**0.21**	0.00	0.00
Vidarbha	0.01	0.01	0.01	0.01	−0.01	−0.13	**−0.40**	0.40	**−0.45**	0.10	0.00	0.00
Chattisgarh	0.01	−0.01	0.00	0.03	0.00	−0.35	**−0.61**	−0.24	−0.14	0.01	0.00	0.00
Coastal Andhra Pradesh	0.01	0.00	0.00	0.03	−0.05	0.04	0.18	0.09	−0.06	0.23	−0.08	0.00
Telangana	0.00	0.00	0.00	0.02	0.05	0.08	0.21	**0.35**	**−0.36**	**0.29**	−0.01	0.00
Rayalaseema	0.00	0.00	0.00	0.04	0.01	0.05	0.20	0.05	−0.10	0.09	−0.01	0.00
Tamil Nadu & Pondicherry	−0.01	0.00	−0.01	0.01	−0.05	−0.06	0.07	−0.13	0.07	−0.07	0.14	0.07
Coastal Karnataka	0.00	0.00	0.00	0.00	0.12	0.78	0.08	**1.03**	−0.33	0.17	−0.01	0.00
North Interior Karnataka	0.00	0.00	0.00	0.03	0.09	0.00	−0.15	0.22	−0.07	0.05	−0.05	0.00
South Interior Karnataka	0.00	0.00	−0.01	0.07	−0.12	−0.06	−0.13	0.09	0.19	0.06	−0.02	0.00
Kerala	0.01	0.04	0.04	0.17	0.02	**−0.97**	−0.66	0.31	0.23	0.29	0.28	−0.02
Regions												
North East India	−0.01	0.00	−0.09	0.05	−0.03	−0.21	0.16	**−0.31**	−0.05	0.25	0.04	0.01
Central North East India	0.01	0.01	0.01	**0.04**	0.01	−0.16	−0.17	−0.10	0.03	0.03	0.00	0.00
North West India	0.00	0.01	0.01	0.01	0.00	0.07	−0.09	0.11	−0.07	0.01	0.00	0.00
West Central India	0.01	0.01	0.01	0.01	0.01	−0.22	**−0.31**	0.25	−0.28	0.12	−0.01	0.00
Peninsular India	0.00	0.01	−0.01	0.07	−0.03	−0.09	−0.02	0.08	0.04	0.06	0.03	0.01
Whole study area	0.00	0.01	0.00	0.04	0.00	−0.12	−0.13	0.08	−0.10	0.10	0.01	0.00

*Bold values indicate statistical significance at 95% confidence level as per the Mann-Kendall test (+ for increasing and – for decreasing).

decreasing rainfall. The months of January, March, May and December showed little or no change in rainfall. The monsoon rainfall showed a decreasing trend and all other seasons' rainfall showed an increasing trend. The maximum magnitude of trend was found in the monsoon season (negative), and the minimum in the winter season (positive). Annual rainfall showed a decreasing trend on an all-India basis, although it was not statistically significant.

The El Niño Southern Oscillation (ENSO) phenomenon and the Himalayan/Eurasian snow cover are two external factors which impact on the Asian monsoon, and these have a negative correlation with the Indian monsoon (Kripalani *et al*., 2003). The warm phase (El Niño) is associated with weakening of the Indian monsoon, while the cold phase (La Niña) is associated with the strengthening of the Indian monsoon (Kripalani *et al.*, 2003). Similarly, excessive snow during the preceding winter is unfavourable for the subsequent summer monsoon; conversely, deficient snow is favourable. The analysis of monsoon rainfall with Darwin Pressure Tendency (DPT) (an index of ENSO) by Kripalani *et al*. (2003) indicated that the relationship has changed sign around 1990 and showed maximum positive relationship during the 1990s. The relationship of monsoon rainfall with snow over western Eurasia has also weakened in recent times (Kripalani *et al*., 2003). Khola (2004) reported that the sea-surface temperature (SST) anomalies over the three El Niño regions of the Pacific Ocean, on a monthly scale, showed an oscillatory type of

Table 4 Sen estimator of slope (mm/year) for annual and seasonal rainfall.

Sub-division/Region	Annual	Pre-Monsoon	Monsoon	Post-Monsoon	Winter
Sub-divisions					
Assam & Meghalaya	−0.53	−0.19	−0.64	**0.34**	−0.02
Nagaland, Manipur, Mizoram & Tripura	−0.63	0.13	**−1.00**	0.16	−0.07
Sub-Himalayan West Bengal & Sikkim	0.07	0.15	−0.58	**0.40**	0.02
Gangetic West Bengal	0.95	0.09	0.58	0.26	0.03
Orissa	−0.31	0.07	−0.45	−0.08	0.04
Jharkhand	−0.37	−0.01	−0.44	0.13	0.01
Bihar	−0.27	0.13	−0.52	0.10	0.03
East Uttar Pradesh	−0.17	0.03	−0.13	0.05	0.02
West Uttar Pradesh	−0.30	0.06	−0.39	**0.07**	−0.03
Haryana	**0.73**	0.06	0.57	0.02	−0.01
Punjab	**0.96**	0.10	**0.85**	**0.03**	0.00
West Rajasthan	0.06	0.03	−0.03	0.00	−0.01
East Rajasthan	−0.39	0.01	−0.54	0.02	−0.03
West Madhya Pradesh	−0.35	0.02	−0.49	0.06	0.00
East Madhya Pradesh	−0.76	0.02	−0.89	0.01	0.07
Gujarat	−0.17	−0.01	−0.28	0.02	0.00
Saurashtra, Kutch & Diu	0.08	0.00	−0.05	0.01	0.00
Konkan & Goa	1.97	0.03	1.56	0.21	0.00
Madhya Maharashtra	−0.04	−0.01	0.00	0.05	−0.01
Marathwada	0.14	0.03	−0.21	**0.30**	0.00
Vidarbha	−0.53	0.02	−0.58	0.11	0.07
Chattisgarh	**−1.33**	0.00	**−1.29**	−0.02	0.01
Coastal Andhra Pradesh	0.70	0.00	0.37	0.00	0.06
Telangana	0.82	0.09	0.30	**0.28**	0.05
Rayalaseema	0.47	0.11	0.21	0.03	−0.02
Tamil Nadu & Pondicherry	0.05	−0.07	−0.02	−0.05	0.08
Coastal Karnataka	**2.37**	0.25	1.81	0.14	0.00
North Interior Karnataka	0.16	0.10	−0.06	0.03	0.00
South Interior Karnataka	0.03	−0.11	0.18	0.01	0.00
Kerala	−0.37	0.21	−1.28	**0.66**	0.07
Regions					
North East India	−0.10	0.03	−0.48	0.33	−0.01
Central North East India	−0.10	0.06	−0.30	0.04	0.01
North West India	0.08	0.04	−0.07	0.02	−0.01
West Central India	−0.30	0.04	−0.43	0.11	0.02
Peninsular India	0.22	0.01	0.08	0.09	0.05
Whole study area	−0.03	0.04	−0.25	0.12	0.02

*Bold values indicate statistical significance at 95% confidence level as per the Mann-Kendall test (+ for increasing and – for decreasing).

lagged correlation with the summer monsoon rainfall over some homogeneous regions of India.

The monsoon rainfall is associated with multiple spells of active and break-monsoon phases. The phenomenon of "monsoon break" is of great interest because long intense breaks are often associated with a pronounced decrease in rainfall in the major part of India. Such breaks have a large impact on rainfed agriculture and prolonged breaks create drought conditions. Examination of daily rainfall over India for the period 1951–2007 by Ramesh Kumar *et al.* (2009) revealed that there has been a significant increase in the incidence of prolonged monsoon breaks during the core monsoon rainy months of July and August in recent decades. Monsoon depressions are the main rainfall-producing synoptic weather system over India. Studies on the occurrence of monsoon depressions using the data of 1889–2002 showed a significant decrease in their seasonal frequency, with a maximum decrease in July, followed by August and September (Dash *et al.*, 2004).

Trends and magnitude of change in annual rainfall in the study area, in terms of percentage of the mean per 100 years, are shown in Figs 3 and 4. Punjab and Haryana, which are said to be the granaries of India, have witnessed a large increasing trend in this value. Many sub-divisions in South East Peninsular India such as Telangana, Coastal Andhra Pradesh, Coastal

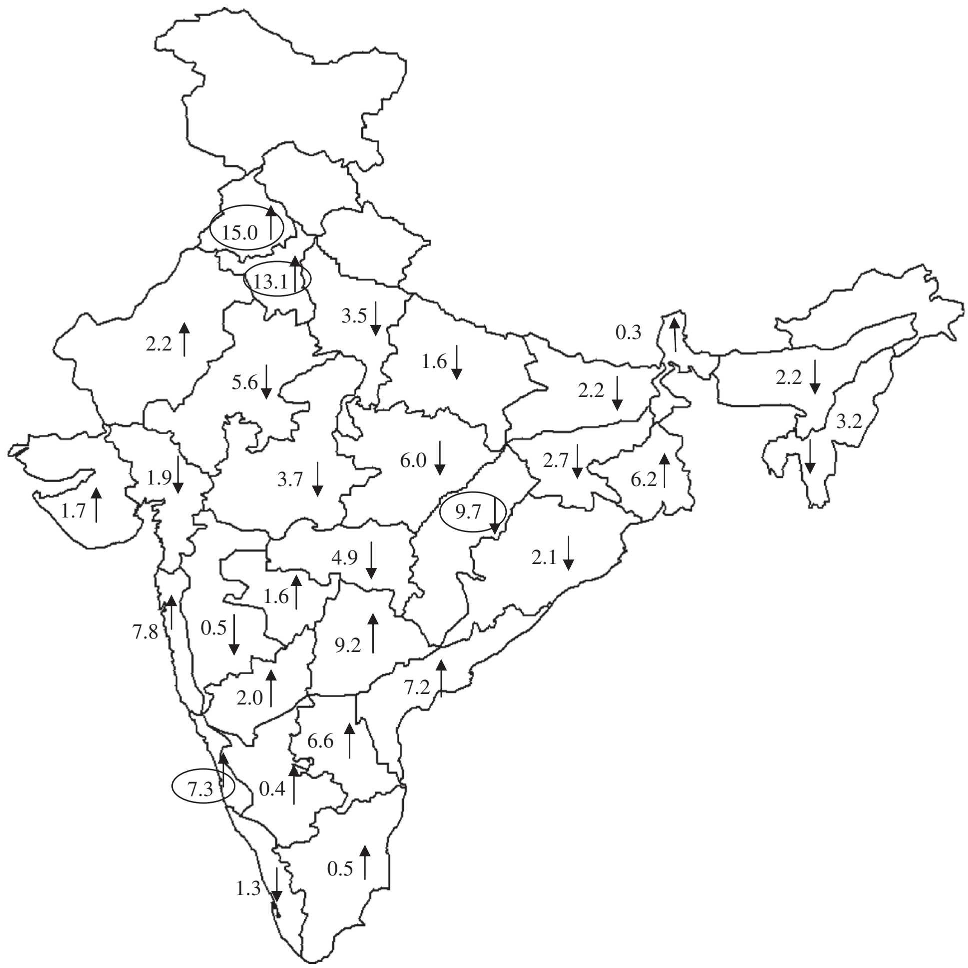

Fig. 3 Trends and magnitude of changes in annual rainfall (% of mean/100 years) for different sub-divisions in the study area. The symbol ↑ indicates increase and ↓ indicates decrease in rainfall. Circles around values indicate sub-divisions having significant trend.

Karnataka and Rayalaseema, have shown an increasing trend of nearly 7–9% of mean per 100 years. However, Chattisgarh, Vidarbha, and East Madhya Pradesh have experienced a decreasing trend of nearly 5–10% of mean per 100 years. On a regional basis, West Central India shows a decreasing trend, while Peninsular India has an increasing trend (Fig. 4). For the whole study area, the annual rainfall shows a decreasing trend of 0.3% of mean per 100 years.

Significance of trend

The results of the Mann-Kendall test, applied to ascertain the significance of trends in monthly rainfall (Table 3), indicated that, during the non-monsoon months, the increasing rainfall at only seven sub-divisions was found statistically significant: Punjab in March; East Uttar Pradesh and Haryana in April; sub-Himalayan West Bengal, Marathwada and Telangana in October, and sub-Himalayan West Bengal in November. The decreasing trends in sub-divisional rainfall during non-monsoon months were found not significant. During the monsoon months of June, July, August and September, significant trends (both positive and negative) were detected for sub-divisional rainfall. Significant decreasing trend was detected for: sub-Himalayan West Bengal, West Madhya Pradesh and Kerala (three sub-divisions) during June; for East Madhya Pradesh, Vidarbha and Chattisgarh (three sub-divisions) during July; for Assam, Nagaland, Manipur, Mizoram & Tripura (two sub-divisions) during August; and for Marathwada, Vidarbha, and Telangana (three sub-divisions) during September. An increasing trend for sub-Himalayan West Bengal in July, Haryana, Konkan & Goa, Madhya Maharastra, Telangana, and Coastal Karnataka in August; and

Fig. 4 Trends and magnitude of changes in annual rainfall (% of mean/100 years) for different regions in the study area. The symbol ↑ indicates increase and ↓ indicates decrease in rainfall. The trend was not statistically significant in any region.

Gangatic West Bengal in September was found significant. The increasing and decreasing trends in pre-monsoon and winter season rainfall were found not significant for all sub-divisions. Monsoon rainfall indicated a negative significant trend in East Madhya Pradesh, Chattisgarh, and Nagaland Manipur Mizoram & Tripura sub-divisions, and an increasing significant trend only in Punjab. Seven sub-divisions (Assam & Meghalaya, sub-Himalayan West Bengal & Sikkim, West Uttar Pradesh, Punjab, Marathwada, Telangana and Kerala) indicated a significant increasing trend in post-monsoon rainfall. Out of the 30 sub-divisions studied, the annual rainfall of only four sub-divisions showed a significant trend: that of Haryana, Punjab and Coastal Karnataka showed a positive trend, whilst that of Chattisgarh showed a negative trend.

Monthly analysis of regional rainfall showed that only increasing rainfall in the Central North East region in April, and decreasing rainfall in the West Central region in July and in the North East Region in August were statistically significant. Seasonal and annual rainfall was found not significant for all five regions. It can be noted from Tables 3 and 4 that no statistically significant trend was detected in monthly, seasonal and annual rainfall on an all-India basis. It is pertinent to note that there are problems associated with significance testing (Cohn & Lins, 2005), particularly when the underlying process shows long-term persistence.

CONCLUSIONS

The present study has examined trends in the monthly, seasonal and annual rainfall on the meteorological sub-division scale, the regional scale, and for the whole of India. A large data set was used, consisting of 306 stations with the length of data series of 135 years. As expected, the sub-divisional rainfall trends show a large variability – nearly half of the sub-divisions have shown an increasing trend in annual rainfall and the remainder have shown the opposite trend. The maximum increase was 2.37 mm/year and the maximum decrease was –0.76 mm/year. Region-wise, annual rainfall indicated a small increasing trend for the North West and Peninsular India and a decreasing trend in the remaining three regions. On an all-India basis, the annual rainfall showed a small decreasing trend.

Seasonal analysis showed that pre-monsoon rainfall increased over 23 sub-divisions and all regions; monsoon rainfall increased over 10 sub-divisions and one region; post-monsoon rainfall increased over 27 sub-divisions and all regions; and winter rainfall increased over 20 sub-divisions and three regions. Pre-monsoon, post-monsoon and winter rainfall has increased and monsoon rainfall decreased on an all-India basis. As for annual rainfall, nearly half of the sub-divisions experienced an increasing trend in June and July monthly rainfall, and the remaining months showed an opposite trend. In August, about 75% of sub-divisions witnessed an increasing trend, whereas in September about 75% sub-divisions experienced a decreasing trend. In terms of percentage of mean per 100 years, Punjab and Haryana witnessed a large increasing trend in annual rainfall. Many sub-divisions in South East Peninsular India showed an increasing trend of nearly 7–9% of mean per 100 years, but Chattisgarh, Vidarbha, and East Madhya Pradesh experienced a decreasing trend of nearly 5–10% of mean/100 years in annual rainfall. On an all-India basis, the annual rainfall has decreased by 0.3% of the mean/100 years.

Significance testing showed that the monsoon rainfall had negative significant trend in East Madhya Pradesh, Chattisgarh and Nagaland Manipur Mizoram & Tripura sub-divisions, and increasing significant trend only in Punjab. The majority of sub-divisions and all the regions show neither increasing nor decreasing significant trends in seasonal rainfall. No statistically significant trend was detected in annual rainfall in any of the five regions, nor on an all-India basis.

The study indicated large spatial and temporal variability in the rainfall trends over India and no clear pattern was detected. Strong intra-seasonal variability was analysed for the majority of sub-divisions, regions and the whole of India. The annual and monsoon rainfall indicated the same direction of trend for the majority of the sub-divisions and regions, including all of India. All regions except Central North East India indicated non-homogeneity in rainfall trend. For annual rainfall within the West Central India region, five sub-divisions experienced increasing trend and four experienced decreasing trend with a decreasing trend for the region. A follow-up work to this study could be a review of hydrological and agricultural practices in the light of trends in hydroclimatic variables for the different regions/sub-divisions of the country.

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