Long-Term Rainfall Trends and Change Points in Hot and Cold Arid Regions of India

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Abstract

This study examined trends and change points in long-term annual and seasonal rainfall over hot- and cold-arid regions of India. K-means clustering classified 32 stations into two clusters Coefficient of variation for annual, wet season and dry season rainfall ranged from 19-41%, 22-43% and 30-55%, respectively for Cluster-I and from 25-47%, 31-52%, and 43-142%, respectively for Cluster-II. Short- and long-term persistence was more dominating in Cluster-II (entirely-arid) and Cluster-I (partly-arid), respectively. Sen's method revealed increasing trends for annual and wet season from 0.92-1.35 and 0.77-0.85 mm-year^{-1} for Cluster-II, and from 0.93-1.21 and 0.81-1.13 mm-year^{-1} for Cluster-I, respectively. Dry season rainfall increased with 1.09 mm-year^{-1} in cold-arid region. The significant change points in annual and wet season rainfall mostly occurred during 1941-1955 (hot and cold), and in dry season during 1973-1975 (hot-arid) and 1949 (cold-arid). Moreover, the findings are useful for managing surplus/deficiency of rainwater in the Indian arid region.

Keywords: Arid region, Change point, k-means clustering, Persistence, Trend.

1. INTRODUCTION

Analyzing long-term spatio-temporal patterns of the rainfall is important for detecting climate change/variability (Delitala et al., 2000), studying climate change impacts in water resources planning and management (Haigh, 2004), and understating eco-hydrological processes (Oguntunde et al., 2006). In the recent years, 'extremes of water scarcity and excess' is identified as the greatest threat that climate change will present to South Asia in the 21st century (World Bank, 2013), and hence, it has received an increasing attention (Berrang-Ford et al., 2011). In India, monsoon patterns have changed over the past half century (Bollasina, 2014), and accordingly rainfall in the country has been less frequent but more prone to extremes (Singh et al., 2014). It is further observed that historical rainfall data on global or continental scales are less useful for local or regional scale planning (Brekke et al., 2009; Thornton et al., 2009). Thus, it is emphasized to evaluate long-term historical rainfall records on a regional scale to have more knowledge of the local effects of monsoon variability (Vallebona et al., 2015).

Analysis of rainfall variability at adequate space and time scales using long-term datasets is imperative for arid lands extending over 61 million km^2 on the globe (46% area worldwide) (FAO-AGL, 2003) and experiencing in general a water deficit scenarios mainly due to less frequency and low occurrences of the rainfall. The variability of a rainfall time series is determined by detecting presence/absence of trends, examining persistence, identifying change points, etc. by employing statistical analysis/techniques (Adeloye and Montaseri, 2002). There are several studies reported in the literature where spatial and temporal variations of the rainfall series are examined for humid and/or semi-arid regions (e.g. Kumar et al., 2010; Deka et al., 2013; Goyal, 2014; Talaee, 2014; Machiwal and Jha, 2016); relatively less attempts based on long-term datasets are made solely for the arid regions of the world (Ouarda et al., 2014; Pingale et al., 2014, 2015; Xu et al., 2015; Machiwal et al., 2016). Presently, with availability of the long-term datasets, rainfall trends are increasingly explored for many regions of the world. However, studies dealing with detection of abrupt changes in the long-term rainfall are rare.

In India, arid lands, spreading over 38.7×10^6 ha experience both hot and cold climates (Kar et al., 2009). The major part of the country's hot arid zone occurs in the northwest portion occupying 28.57×10^6 ha, while remaining 3.13×10^6 ha of hot arid lands fall in the southern portion. On the other side, the cold arid region, encompassing 7×10^6 ha land in Jammu & Kashmir and Himachal Pradesh, is situated in the northern portion of the country. Rainfall in the Indian arid region is highly limited, inconstant and unpredictable in nature (Kar et al., 2009). Basistha et al. (2007) investigated spatial trends of rainfall for the period 1872-2005 in India at sub-divisional level. Results indicated decreasing rainfall trends over northern India excluding Punjab, Haryana, Western Rajasthan, and Saurashtra, and increased trends in Southern India excluding Kerala and Central Maharashtra. Their study suggested that a detailed study is essential to identify rainfall trends in the arid regions of India. Therefore, there is a need to understand rainfall variability over space and time in the Indian arid region in order to sustainably manage the scarce availability of water resources. This study focuses on investigating long-term changes in annual and seasonal rainfall time series in hot and cold arid zones of India. This kind of study analyzing regional-scale rainfall variability in Indian arid region using more than 100-year datasets could not be found in the literature. The major objectives of the study are (i) to examine persistence, (ii) to detect and quantify long-term trends, (iii) and to identify single change points in annual and seasonal rainfall. Furthermore, unlike the general approach followed in almost all studies dealing with variations of climatic and hydrologic variables in India, this study adopted more than one method for every analysis in order to obtain the reliable results and to arrive at realistic and precise inferences.

2. MATERIALS AND METHODS

2.1 Study Area and Data

The map depicting 32 rainfall stations in the Indian arid region under hot and cold climates is shown in Fig. 1. In northwest India, the hot arid region is located between 22°30′ and 32°05′ N latitude and 68°05′ to 75°45′ E longitude. The hot arid region is characterized by the low and erratic rainfall, extreme temperatures (-5.7 to 50°C), long sunshine hours (6.6-10 hrs), low relative humidity (30-80%), high wind velocity (9-13 km hr^{-1}) and high potential evapotranspiration (1600-1800 $mm\text{-}year^{-1}$) (Kar et al., 2009). Soils of the region are skeletal and calcareous with alkaline in reaction and low to medium in organic matter content. The Indian cold arid region, covering 5.62% of the country's total area (MoEF, 2009), comes under the trans-Himalayan zone. The cold arid region is confined to Leh and Kargil districts of Jammu & Kashmir State and Lahul & Spiti of Himachal Pradesh State. Leh constitutes 87.4% of total cold arid region of India (Wani et al., 2011). The salient climatic features of the cold arid region are the extremes of temperatures (-40°C in winter and 40°C in summer), low annual rainfall (80-300 mm) mostly in the form of snow, high wind velocity, and low relative humidity (20-40%) (Wani et al., 2011). The soils of the region are coarse-textured, shallow and sandy, with high permeability and low water holding capacity.

In this study, monthly rainfall data of 102-year period (1901-2002) for 32 rainfall stations, located in the individual districts of India with either entirely or partly arid lands experiencing hot and cold climates (Fig. 1), were utilized to generate annual and seasonal (wet and dry) rainfall time series. Details of these 32 districts are given in Table 1; stations of 13 districts are having their major representative area (more than 88%) under the arid climate, whereas districts of 19 stations partly encompass the arid lands. Of the total 32 stations, three, i.e. Leh, Kargil and Lahul & Spiti, are located in cold arid region. Leh, the largest district of the country, encompasses very large proportion of the cold arid region, and hence, this single station may adequately describe rainfall characteristics of a significantly large part of the Indian cold arid region. The wet season has a span of five months from June to October, and the dry season has a spread over November to May months. The rainfall data were collected from the Indian Meteorological Department, Pune, which has made the data available through

India Water Portal (http://indiawaterportal.org/met_data/). All the collected data were checked for absence of errors and gaps.

2.2 Cluster Analysis of Annual Rainfall

In this study, the k-means clustering was performed on annual and seasonal (wet and dry seasons) rainfall with aim of grouping 32 rainfall stations into clusters of similar rainfall regimes in such a manner that within-group variation of the rainfall data is minimized and between-group variation is maximized. The k-means clustering technique is one of the non-hierarchical cluster analysis techniques (Hartigan, 1975), which is relatively robust over other clustering algorithms, e.g. dendrograms, etc.

In this technique, rainfall dataset is partitioned into k mutually-exclusive clusters and each object/station is assigned to the cluster that has the closest center. The clusters were obtained by minimizing the squared-error differences (ϕ) between the rainfall variable and corresponding cluster centroid (IMSL, 1997), defined as:

$$\phi = \sum_{i=1}^{n} \sum_{j=1}^{k} w_{ij} \left\| r_{ij} - \bar{r}_j \right\|^2 \quad (1)$$

Where, ϕ = squared-error criterion function, n = number of data, k = number of clusters, r_{ij} = rainfall at i^{th} data point of j^{th} cluster, $\bar{r}_j$ = j^{th} cluster's centroid, w_{ij} = n×k size pattern association matrix, the element w_{ij} is 1 if r_{ij} belongs to cluster j and 0 otherwise. w_{ij} is defined as:

$$w_{ij} = \begin{cases} 1, & \text{if } \left\| r_{ij} - \bar{r}_j \right\| \le \left\| r_{ij} - \bar{r}_m \right\|, \quad \forall m \ne j \\ 0, & \text{Otherwise} \end{cases} \quad (2)$$

with the properties of $\sum_{j=1}^{k} w_{ij} = 1 \quad i = 1, 2, 3, \ldots, n$ and $\sum_{j=1}^{k} \sum_{i=1}^{n} w_{ij} = n$.

2.3 Computing Statistics of Rainfall in Delineated Clusters

Rainfall distribution pattern of the stations grouped under delineated clusters of annual and seasonal (wet and dry seasons) rainfall series was investigated by drawing box and whisker plots using STATISTICA software. These plots provides pictorial summary of five statistical properties, i.e. median (50^{th} percentile), lower and upper values of box (25^{th} and 75^{th} percentiles), non-outlier range (distance between lower and upper whiskers), and outliers and extremes (Machiwal and Jha, 2012). Further details of the box and whisker plots may be found in USEPA (2006).

2.4 Examining Persistence in Rainfall by Time Domain Approach

Few of the studies established that the presence of serial correlation may lead to the rejection of the null hypothesis of no trends due to inflation of the variance while detecting trends using nonparametric Mann-Kendall (M-K) test (Yue and Wang, 2002). Therefore, the persistence in all three rainfall series (annual, wet season and dry season) was examined by estimating serial autocorrelation at different time lags; details of the test may be found in Haan (2002) and Machiwal and Jha (2012). The main goal of analyzing persistence of the rainfall records in this study was to eliminate effect of presence of serial correlation on the trends identified by the M-K test.

2.5 Detecting and Quantifying Trends in Rainfall Series

Trends may be examined by parametric and nonparametric approaches; former approach is more powerful than later one but the former approach requires fulfilment of normality condition, which is rarely met in hydrological datasets (Machiwal and Jha, 2012). Accordingly, the nonparametric tests, i.e. Kendall's rank correlation (KRC) and M-K tests are customarily applied for detecting trends in rainfall time series (e.g. Guerreiro et al., 2014). This study, in view of need of adequate/multiple statistical tests as recommended in literature (Sonali and Kumar, 2013; Machiwal et al., 2016), employed three nonparametric tests, i.e. KRC, M-K, and Spearman rank order correlation (SROC) tests for identifying trends in the annual and seasonal (wet and dry seasons) rainfall. Moreover, the identified trends were quantified by using Sen's slope estimation and linear regression approaches. Details of these trend tests are available in literature (e.g. Machiwal and Jha, 2012).

2.5.1 Modified Mann-Kendall Test

The serial correlation (r_1) at 1-year time lag was checked in annual and two seasonal rainfall series for all 32 stations by computing r_1 and its significance was examined at level of significance (α) = 5%. Thereafter, the effective sample size (ESS) method proposed by Lettenmaier (1976) was used to remove the influence of serial correlation on the M-K test by replacing the test-statistic z with the modified z* as given by

$$z^* = z\sqrt{\frac{n^*}{n}} \tag{3}$$

where, z and z* = test-statistics of original and modified M-K tests, respectively. The ratio, n*/n is termed as the correction factor, which is computed by using the formula proposed by Matalas and Langbein (1962) for the lag-1 autoregressive process:

$$\frac{n^*}{n} = \frac{1}{1 + 2\dfrac{r_1^{n+1} - n\,r_1^2 + (n-1)\,r_1}{n\,(r_1 - 1)^2}} \tag{4}$$

2.6 Identifying Change Points in Rainfall Time Series and Their Verification

The single change points in the annual and seasonal (wet and dry) rainfall time series were detected by applying widely-used cumulative deviations and Pettitt tests (e.g. Guerreiro et al., 2014; Zhang et al., 2015; Machiwal and Jha, 2016; Mallakpour and Villarini, 2016), and their details are provided below.

The Pettitt test (Pettitt, 1979) is more sensitive to the breaks in the middle of the hydrologic time series and is less sensitive to outliers in the time series causing skewness in the data distribution (Wijngaard et al., 2003). The test-statistic (T_y) is expressed as follows:

$$T_y = 2\sum_{i=1}^{y} r_i - \{y \times (n+1)\}, \text{ where, } y = 1, 2, \ldots, n \tag{5}$$

where, r_i = rank of i^{th} data in the time series and n = size of the series or number of years. The statistically-significant abrupt change (T_{CP}) occurs at a point (or year) in the series where the value of $|T_y|$ is found to be the maximum as defined by:

$$T_{CP} = \max_{1 \le y \le n} |T_y| \tag{6}$$

The cumulative deviations test is based on the adjusted partial sums or cumulative deviations from the mean in the time series (Buishand, 1982). The test-statistic (S_k^*) is expressed as follows (Buishand, 1982):

$$S_k^* = \sum_{t=1}^{k} (x_t - \bar{x}), \qquad k = 1, 2, \ldots, n \tag{7}$$

where, x_t = data of year t and $\bar{x}$ = mean of the series. The significant abrupt change (S_{CP}) occurs at the point (or year) in the time series where the value of $|S_k^*|$ is obtained to be the maximum, as defined below:

$$S_{CP} = \max_{1 \le t \le n} |S_k^*| \tag{8}$$

The earlier-detected change points were further confirmed by applying parametric t-test and nonparametric Mann-Whitney test. For applying t-test, the entire rainfall series was divided at change point into two sub-series of sizes n_1 and n_2. The second sub-series was started from the change point. The details of tests are available in literature (Machiwal and Jha, 2012).

3. RESULTS AND DISCUSSION

3.1 Clusters of Rainfall Stations

The k-means clustering technique rendered 32 rainfall stations into two clusters according to minimum squared error difference among rainfall of the corresponding stations (3264 data points) and clusters' centroids. Two clusters of the rainfall stations are shown in Fig. 2 for the annual, wet season and dry season rainfall series. It is clearly seen that the two clusters have a definite spatial pattern according to more or less their geographical location. It is apparently visible that the stations situated in southern part and/or at southern and eastern edge of the arid region are mostly grouped in Cluster-I whereas the stations located within the western arid region and towards its northern edge are put together in Cluster-II. The number of stations in Cluster-I are 15, 17 and 10 and in Cluster-II are 17, 15 and 22 for the annual, wet season and dry season, respectively. It can be further observed that 12, 10 and 11 of total 13 stations, largely representing the arid lands (more than 80% area), are classified into Cluster-II for the annual, wet season and dry season rainfall, respectively. Hence, it is revealed that the Cluster-II represents the stations mainly characterized by the arid climate, whereas the Cluster-I contains the stations partly depicting the arid lands. Furthermore, it is seen that the clustering of the stations is almost similar for the annual and wet season rainfall; 3 stations of Cluster-II in case of annual rainfall joins Cluster-I of wet season rainfall. However, it is worth-mentioning that the clustering is somewhat different for the dry season rainfall where all stations located in the western arid part constitute Cluster-II, whereas Cluster-I comprises of the stations located in southern hot arid part and in the northern cold arid area.

3.2 Spatial and Temporal Variability of Rainfall Clusters

Box-whisker plots of the annual, wet season and dry season rainfall depict large variations among sites and between two clusters (Fig. 3). An important finding is that median rainfall at all stations of Cluster-II remain lower in comparison to that of Cluster-I for annual as well as seasonal (wet and dry seasons) rainfall, indicating large control of aridity on the rainfall magnitudes. Likewise, the upper whiskers of all stations of Cluster-II, except one and two in case of annual and wet season rainfall, do not cross the lowest upper whisker of Cluster-I (Fig. 3). The coefficient of variation values for the annual, wet season and dry season rainfall is found to range from 19-41%, 22-43% and 30-55%, respectively for Cluster-I and from 25-47%, 31-52%, and 43-142%, respectively for Cluster-II. This indicates relatively more temporal variability in all rainfall series of Cluster-II compared to that of Cluster-I. Also, the largest temporal variations are observed in dry season rainfall, which can also be seen from the presence of extremes in stations of Cluster-II. The long-term mean for annual, wet season and dry season rainfall for Cluster-II is 341, 269 and 38 mm, respectively, which is 303, 244 and 134 mm short of that for Cluster-I. These findings emphasize influence of the entirely arid climate on low-magnitude of annual, wet season and dry season rainfall in Cluster-II in comparison to Cluster-I where the land is partly arid.

The contribution of dry season rainfall to the total annual exceeds by 22% at 8 stations of Cluster-I while the same exceeds by 10% at 12 stations of Cluster-II. Overall, the contribution of dry season rainfall to annual total was relatively less in Cluster-II, except for cold arid region where it accounted for 55% of annual rainfall. The contribution of dry season to annual rainfall in Cluster-I was also the highest for two stations (28 and 44% for Lahul & Spiti and Kargil, respectively) of cold arid region. Thus, the contribution of dry season to annual rainfall may not be overlooked, and therefore, this study included analysis of rainfall in wet and dry seasons separately.

3.3 Presence of Long-Term Persistence in Rainfall Series

Results of the autocorrelation analysis are summarized in Table 2. The coefficients r_k were computed up to 26-year lag. At time lags, where r_k crossed lower/upper critical limits, its deviation was calculated (Table 2). It is discernible that persistence was absent in annual rainfall for 3 stations of Cluster-I and for 2 stations of Cluster-II. Similarly, during wet season, one station of Cluster-I and 4 stations of Cluster-II were free from persistence. However, in dry season, the persistence was absent at only single station of Cluster-II.

In annual rainfall, the persistence mostly occurred at 17-year lag for 9 stations (3 of Cluster-I and 6 of Cluster-II) with 0.03-0.11 deviation of r_k from the non-persistence limits (Table 2). After 17-year lag, the most frequent persistence is observed at 4-year time lag for 6 stations (2 of Cluster-I and 4 of Cluster-II) and for 1-year at 5 stations (2 of Cluster-I and 3 of Cluster-II). The significant persistence ($r_k \geq 0.10$) in annual rainfall was present at three stations, i.e. Kurnool (Cluster-I) and Raichur (Cluster-I) at 13-year lags, and Sangrur (Cluster-II) at 17-year lag (Figs. 4a,g,n). In wet season, the highest frequency of persistence was observed at 17-year lag for 9 stations (4 of Cluster-I and 5 of Cluster-II) with 0.01-0.13 deviation (Table 2). The second and third highest frequency of the persistence appeared at 4-year lag for 6 stations (3 of Cluster-I and 3 of Cluster-II) and at 8-year for 5 stations (2 in Cluster-I and 3 in Cluster-II). The deviation of $r_k \geq 0.10$ in wet season was for two stations, i.e. Chitradurga (Cluster-I) at 12-year lag, Sangrur (Cluster-II) at 8- and 17-year lags (Figs. 4b,k). In dry season, the persistence frequently occurred at 16-year lag for 12 stations (4 in Cluster-I and 8 in Cluster-II) with 0.02-0.07 deviation (Table 2). Followed by the highest frequency, the persistence occurred 8 times at 15-year lag in Cluster-I, 7 times each at 3-year lag (4 in Cluster-I and 3 in Cluster-II) and at 23-year lag in Cluster-II. The significant deviation of r_k (≥ 0.10) for the dry season was observed at 9 stations (Figs. 4c-f,h-j,l,m).

Overall, it is seen that significant persistence (deviation of $r_k \geq 0.10$ from critical limits) in annual, wet season and dry season rainfall mostly occurred in Cluster-I representing partly-arid climate. In Cluster-II, except at five stations, the rainfall at rest of the stations is found free from the significant persistence. The presence of long-term persistence in annual (2 of Cluster-I and 1 of Cluster-II), wet season (1 in each cluster) and dry season (5 of Cluster-I and 4 of Cluster-II) rainfall may influence performance of the M-K test. Therefore, the modified M-K test was performed to eliminate the effect of long-term persistence on the trend results.

3.4 Trends in Annual and Seasonal Rainfall

3.4.1 Presence of Serial Correlation at One-Year Lag

Values of serial correlation (r_1) for annual and seasonal rainfall are given in Table 3. It is seen that r_1 in annual rainfall crosses either upper limit (0.15) or lower limit (-0.17) at five stations (2 in Clusters-I and 3 in Cluster-II). Likewise, r_1 goes beyond the critical limits in wet and dry season rainfall at two (one station in each cluster) and five rainfall stations (1 in Cluster-I and 4 in Cluster-II), respectively. This reveals that the serial correlation is present at 17, 7 and 17% stations in annual, wet season and dry season rainfall, respectively, and the serial correlation is present at more number of stations of Cluster-II in comparison to that of Cluster-I. This clearly indicates that short-term persistence was more dominating in Cluster-II whereas the long-term persistence was more prominent in Cluster-I.

3.4.2 Increasing/Decreasing Rainfall Trends

Results of three trend tests depicting stations with positive and negative trends of annual, wet season and dry season rainfall at α = 1, 5 and 10% are shown in Fig. 5. It is seen that the significant positive/negative rainfall trends identified by KRC and M-K tests are identical to each other, and are preferred over the SROC test as sign of the former test-statistics is indicative of nature (increasing/decreasing) of trend. The similar findings have been reported in the earlier studies also dealing with rainfall of arid, semi-arid and humid regions of India (Machiwal and Jha, 2008; Machiwal and Jha, 2016).

It can be seen from Fig. 5(a,c) that the significant positive trends in annual rainfall are present at 3 (9%), 10 (31%) and 13 (41%) stations at α = 1, 5 and 10%, respectively. Figs. 5(d,f) depict the significant positive trends in wet season rainfall at α = 1, 5 and 10% for 2 (6%), 6 (19%) and 12 (38%) stations, respectively. Also, the significant positive trends at α = 1, 5 and 10% are apparent in dry season rainfall of 1 (3%), 1 (3%) and 4 (13%) stations, respectively (Fig. 5g,i). On the contrary, none of the negative trends observed in annual, wet season and dry season rainfall were found statistically-significant for any of the station at α = 1, 5 and 10%.

Furthermore, it is well discernible from Figs. 5(a-f) that the most significant positive trends (α=1%) of annual and wet season rainfall exist at two stations (Bhatinda and Sangrur) of Punjab State in India (Cluster-II) situated in the northern portion of the hot arid region. Similar findings are reported by Sinha Ray and Srivastava (2000). Likewise, the increasing rainfall trends in the arid part of Rajasthan State are also reported in earlier studies (Basistha et al., 2007; Kharol et al., 2013). Few studies reported contrasting results for some of the stations in arid western Rajasthan (e.g. Pingale et al., 2014), which may be due to less number of data used in their study and several other anthropogenic activities at local scale. In cold arid region, the annual and dry season rainfall showed increasing trends at all three stations with statistically-significant trends in annual rainfall of Kargil station (α=5%) and in dry season rainfall of Leh (α=10%) and Kargil (α=1%) stations (Fig. 5a-c,g-i). However, none of the increasing or decreasing rainfall trends in wet season rainfall could be found statistically-significant in the cold arid region (Fig. 5d-f). Likewise, statistically-significant positive trends (α=0.10) of dry season rainfall can be observed at two rainfall stations of hot arid region (Cluster-II) at α=10% and two stations of cold arid region (Cluster-I) at α=1 and 10% (Fig. 5g,i). Whereas, the negative trends (not significant) in annual, wet season and dry season rainfall are mostly dominating in Cluster-I [Figs. 5(a,c,d,f,g,i)]. Furthermore, spatial pattern of the increasing/decreasing rainfall is more or less similar for annual and wet season while it slightly differs for the dry season (Fig. 5). The above results clearly reveal that the annual and wet season rainfall in Cluster-II (entirely arid land) is significantly increasing especially in the northern portion; the increasing trends of rainfall are relatively less prominent in Cluster-I. On the other hand, the dry season rainfall in Cluster-II is not significantly increasing/decreasing; the significantly increasing rainfall is seen in Cluster-I. These findings are in agreement with Guhathakurta and Rajeevan (2006) where increasing but not significant trends at sub-divisional level were found in the Indian arid zone. The long-term increasing rainfall trends are likely to be associated with increasing trends of sea surface temperatures (Goswami et al., 2006) and surface latent heat flux over the tropical Indian Ocean (Rajeevan et al., 2008). The increasing trends of the dry season rainfall over the Indian arid region, may most likely be driven by factors of higher atmospheric greenhouse gas concentration, large number of hygroscopic particles and anthropogenic drivers, among others (Bollasina et al., 2008, 2011; Lacombe and McCartney, 2014). A detailed investigation may be undertaken in a future study to find out the exact causes for the possible significant trends in the dry season rainfall.

3.4.3 Mean Annual Trend Magnitudes of Rainfall

Results of the Sen's slope estimator and linear regression are shown in Table 3. At annual scale, results of the linear regression were found more or less similar to that of the Sen's slope estimation. Regression test resulted in statistically-significant (α=0.05) and positive trend magnitudes of annual rainfall in Cluster-I varying from 0.82 to 1.31 mm-year^{-1} whereas the significant positive trends in Cluster-II ranged from 0.81 to 1.25 mm-year^{-1}. In wet season rainfall, magnitude of the significant positive trend (α=0.05) was found ranging from 0.69 to 0.83 mm-year^{-1} for Cluster-I while magnitude for the significant positive trends varied between 0.72 and 1.07 mm-year^{-1} in Cluster-II. In dry season, one of the positive trends was found significant (α=0.05) in Cluster-I; none of the positive trends were found significant in Cluster-II. Nevertheless, it is important to note from Table 3 that 4 of the total 5 stations showing negative trends (though not significant) ranging from -0.005 to -0.29 mm-year^{-1} are situated in Cluster-I representing the partly arid lands under hot climate. It also worth-mentioning that the dry season depicted a statistically-significant positive trend of 1.09 mm-year^{-1} at Kargil station of cold arid land.

Magnitudes of the statistically-significant (α=0.05) increasing trends in the annual rainfall as revealed from the Sen's slope method varied from 0.93 to 1.21 mm-year^{-1} for Cluster-I and from 0.92 to 1.35 mm-year^{-1} (Table 3). In wet season, the magnitude of the significantly rising (α=0.05) trends ranged from 0.77 to 0.85 mm-year^{-1} and from 0.81 to 1.13 mm-year^{-1} for Cluster-I and Cluster-II, respectively. In dry season, the Sen's slope method determined magnitude of the significantly-increasing (α=0.05) rainfall trend as 1.09 mm-year^{-1} at Kargil station (Cluster-I) of cold arid region.

Overall, it is revealed that number of stations having increasing rainfall trends is relatively high for Cluster-II entirely representing the arid lands in comparison to that for Cluster-I partly reflecting the arid region. Guhathakurta and Rajeevan (2008) also reported an increasing trend in annual mean rainfall of the arid regions in India. Furthermore, magnitude of increasing rainfall trends is more in Cluster-II as compared to that in Cluster-I. The increasing magnitude of rainfall is predominantly controlled by the increased atmospheric moisture content (Lacombe and McCartney, 2014). This emphasizes the need of proper management of water resources and adequate drainage facilities to avoid flooding in the area. The dry season rainfall is significantly increasing at one station, i.e. Kargil of arid region situated in hot climate; however, it is somewhat decreasing in wet season for cold arid region. The partly-arid region experiences both positive and negative trend magnitudes in the dry season but those are not found to be statistically-significant.

3.5 Change Points in Long-Term Rainfall Time Series

Results of cumulative deviations and Pettitt tests along with test-statistics of t-test (t_s) and Mann-Whitney test (u_c) are presented in Table 4. It is seen that change points detected by two tests are matching at 12 (80%), 13 (76%) and 9 (90%) of total 15, 17 and 10 stations in Cluster-I of annual, wet season and dry season rainfall, respectively. Likewise, similar change points are identified by the two tests at 11 (65%), 8 (53%) and 17 (77%) of total 17, 15 and 22 stations in Cluster-II for the annual, wet season and dry season rainfall, respectively. Thus, results of two tests are in agreement for most stations, and consistency between their results reduces in order of dry-season>wet-season>annual and Cluster-I>Cluster-II.

When change points detected by the two tests differed for a station, both the identified change points were tested for the verification. Furthermore, u_c test-statistic was preferred over the t_s test-statistic due to nonparametric nature of the former one. Similarly, the year associated with the large value of u_c test-statistic was chosen as the final change point in case two different years were identified and verified as likely change points. Results of the verification tests confirmed presence of significant change points (α=0.05) in annual rainfall of 6 stations in Cluster-I and of 10 stations in Cluster-II (Table 4). Similarly, the significant change points in wet and dry seasons' rainfall were confirmed at 9 and 3 station(s) in Cluster-I, respectively and at 6 and 5 stations in Cluster-II, respectively. It is seen from Table 3 that the Pettitt test and cumulative deviations test identified the years 1901-1907 as change points in the annual, wet season and dry season rainfall at 4, 3 and 3 stations, respectively (Table 4). Presence of the change points at very early years of the study may not be considered adequate due to uncertainty associated with lack of the preceding years while testing their significance by the confirmation tests. This tendency of other statistical tests to identify the change points at the beginning or end of the data series is reported by other researchers (e.g. Martínez et al., 2009; Machiwal and Jha, 2016). Hence, the change points at very beginning of the rainfall series were not considered in this study.

Geographical distribution of the significant change points in annual, wet season and dry season rainfall over the arid region of India is shown in Fig. 6. It is well-discernible from Fig. 6a that of the total 14 significant change points in annual rainfall, 10 stations experienced significant change during the period 1941-1955 (3 in 1941, 1 in 1942, 2 in 1945, 1 in 1947, 1 in 1949, 1 in 1954, 1 in 1955). Similarly, Fig. 6b depicts that most of the significant change points in wet season rainfall occurred during the period 1941-1952 (5 in 1941, 2 in 1942, 3 in 1947, 1 in 1948 and 2 in 1952). Also, it is revealed that the stations having significant change points are more or less similar for the annual and wet season rainfall. This is due to the fact that the major portion of annual rainfall is contributed by the wet season rainfall in a large tract of the Indian arid region. Similar findings indicating the major contribution of seasonal rainfall to annual rainfall is also observed in earlier study in the same area (Pingale et al., 2015) and in Iran (Tabari and Talaee, 2011). In contrary to the results of annual and wet season rainfall, the significant change points in the dry season rainfall were identified in the year 1975 at 4 stations and in year 1973 at one station of hot arid region. However, in cold arid region, the significant change points were confirmed at two (Kargil and Lahul & Spiti) of total three stations in the year 1949.

It is clearly revealed from the above discussion that the number of stations with established change points were relatively more in Cluster-II (representing entirely arid climate over the land area) in comparison to that in Cluster-I (experiencing arid climate over a part of land). It is worth-mentioning that existence of the change points in the rainfall over the Indian arid lands, completely encompassing the country's great desert, may be due to increasing frequency of wet days in this area as reported by Guhathakurta et al. (2011). It is also apparent that most of the significant change points in the annual and wet season rainfall occurred during the period 1941-1955, which may have linkages with increasing sea surface temperatures and very heavy rain events. The frequency of very heavy rain events was below average during two decades, i.e. from 1940-1950 and from 1950-1960 (Rajeevan et al., 2008). During the period from 1940-1960, the decreasing frequency of very heavy rain events was attributed to the cooling phase of sea surface temperatures as evident from IPCC (2007) over the equatorial Pacific Ocean, and after 1960s, the increasing trend of very heavy rain events was linked to the warming phase of sea surface temperature.

Moreover, frequency of the change points in the dry season rainfall is quite less in comparison to that in the annual and wet season rainfall. In dry season, the major cause for occurrence of the rainy events in the arid regions of India is low pressure systems, which may be characterized as lows, depressions, cyclonic storms, etc. depending upon their intensity (Mooley, 1987). It is reported that since 1970, there is a decreasing trend in the number of depressions in the country (Kumar and Dash, 2001). Therefore, it is most-likely that the change points detected during early 1970s in dry season rainfall of the Indian arid region may somewhat related to changes in low pressure systems in the area. Detailed investigations in this direction may be undertaken in future studies in order to further enhance the knowledge on exact factors/causes responsible for change point occurrences in the rainfall of the arid region.

4. CONCLUSIONS

This study aimed at detection of long-term trends and their quantification, and identification of change points in annual and seasonal rainfall in hot and cold arid regions of India. The k-means clustering technique rendered 32 stations into two clusters for annual, wet season and dry season rainfall; Cluster-I with 15, 17 and 10 stations, respectively representing arid climate over a part of land and Cluster-II having 17, 15 and 22 stations, respectively illustrating arid climate over the entire land area.

Coefficient of variation and box-whisker plots clearly indicated the influence of arid climate on low-magnitude and high variability of the annual rainfall in Cluster-II representing arid region entirely. The annual, wet season and dry season rainfall is found persistent mostly at time-lags of 17-year (9 stations), 17-year (9 stations) and 16-year (12 stations), respectively. The significant persistence (>0.10) was observed at 3, 2, and 9 stations at time scales of annual, wet season and dry season, respectively. The significant persistence was more prominent in Cluster-I than that in Cluster-II. Results of the trend tests revealed significantly increasing trends in annual and wet season rainfall in arid region, which is most-likely due to increased atmospheric moisture content. The dry season rainfall is found to be significantly increasing in the cold arid region. The mean increasing rates of annual rainfall were computed by the Sen's slope method as 0.93-1.21 mm-year^{-1} (Cluster-I) and as 0.92-1.35 mm-year^{-1} (Cluster-II). On the other hand, less rates of increasing rainfall were observed for the wet season (0.77-0.85 mm-year^{-1} in Cluster-I and 0.81-1.13 mm-year^{-1} in Cluster-II). In dry season, the rainfall was increasing at Kargil station of cold-arid region at a rate of 1.09 mm-year^{-1}. It was found that abrupt changes of annual rainfall at 10 of total 14 stations, having significant change points, occurred during 1941-1955. Similarly, the change period identified in the hot arid region for wet and dry seasons was from 1941-1952 and from 1973-1975, respectively. However, in the cold arid region, the significant change point in dry season rainfall was found in the year 1949 at two stations. The period of change points for the annual and wet season rainfall may be attributed to decreasing trends of very high rainfall events from 1940-1960, which was due to the cooling phase of sea surface temperatures.

Overall, the findings of this study suggest the statistically-significant increasing trends of annual rainfall over both hot and cold arid regions, significantly-increasing trends of wet season rainfall over hot arid region, and significantly-increasing trends of the dry season rainfall in cold arid region of India. The findings are very much useful to the planners and policy makers to develop appropriate strategies for utilization and management of the surplus/meagre quantities of the water received from the increased/decreased rainfall in both the hot and cold arid regions of the country.

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Table 1. Details of 32 stations/districts of India having lands under either entirely arid or partly arid climate

S. No.	Station or District (State)	Climate	Proportion of Arid Land Area (%)
1	Anantpur (Andhra Pradesh)	Hot arid	67
2	Banaskantha (Gujarat)	Hot arid	18
3	Barmer (Rajasthan)	Hot arid	100
4	Bellary (Karnataka)	Hot arid	25
5	Bhatinda (Punjab)	Hot arid	88
6	Bikaner (Rajasthan)	Hot arid	100
7	Chitradurga (Karnataka)	Hot arid	4
8	Churu (Rajasthan)	Hot arid	100
9	Cuddapa (Andhra Pradesh)	Hot arid	9
10	Firozpur (Punjab)	Hot arid	77
11	Ganganagar (Rajasthan)	Hot arid	100
12	Hanumangarh (Rajasthan)	Hot arid	100
13	Hisar (Haryana)	Hot arid	90
14	Jaisalmer (Rajasthan)	Hot arid	100
15	Jalor (Rajasthan)	Hot arid	88
16	Jhunjhunu (Rajasthan)	Hot arid	69
17	Jodhpur (Rajasthan)	Hot arid	100
18	Kachchh (Gujarat)	Hot arid	100
19	Kurnool (Andhra Pradesh)	Hot arid	31
20	Mahendragrah (Haryana)	Hot arid	9
21	Mahesana (Gujarat)	Hot arid	7
22	Nagaur (Rajasthan)	Hot arid	96
23	Pali (Rajasthan)	Hot arid	48
24	Raichur (Karnataka)	Hot arid	39
25	Rajkot (Gujarat)	Hot arid	6
26	Sangrur (Punjab)	Hot arid	8
27	Sikar (Rajasthan)	Hot arid	65
28	Solapur (Maharashtra)	Hot arid	Very less
29	Surendranagar (Gujarat)	Hot arid	29
30	Leh (Jammu & Kashmir)	Cold arid	100
31	Kargil (Jammu & Kashmir)	Cold arid	Very less
32	Lahul & Spiti (Himachal Pradesh)	Cold arid	Very less

Table 2. Summary of autocorrelation analysis indicating presence of persistence in annual and seasonal rainfall time series

Station	Presence of Persistence at Time-Lags					
	Cluster	Annual Rainfall	Cluster	Wet Season Rainfall	Cluster	Dry Season Rainfall
Anantpur	I	1-yr (0.02), 12-yr (0.05)	I	1-yr (0.09), 12-yr (0.07)	I	15-yr (0.04), 17-yr (0.12)
Banaskantha	I	17-yr (0.03)	I	17-yr (0.04)	II	3-yr (0.05), 26-yr (0.07)
Barmer	II	17-yr (0.05)	II	17-yr (0.03)	II	13-yr (0.04), 22-yr (0.02)
Bellary	I	10-yr (0.06), 12-yr (0.01), 18-yr (0.03), 21-yr (0.03)	I	8-yr (0.03), 10-yr (0.04), 12-yr (0.08)	I	15-yr (0.17), 22-yr (0.05)
Bhatinda	II	2-yr (0.04), 8-yr (0.03), 14-yr (0.01), 17-yr (0.03)	II	8-yr (0.05), 17-yr (0.07), 19-yr (0.03)	II	1-yr (0.01), 23-yr (0.04)
Bikaner	II	4-yr (0.02)	II	4-yr (0.03), 20-yr (0.01)	II	14-yr (0.01), 16-yr (0.03)
Chitradurga	I	7-yr (0.07), 10-yr (0.08), 12-yr (0.09), 16-yr (0.04), 23-yr (0.02)	I	7-yr (0.08), 8-yr (0.06), 10-yr (0.05), 12-yr (0.12), 15-yr (0.01)	I	5-yr (0.03), 15-yr (0.10), 22-yr (0.01)
Churu	II	4-yr (0.05)	II	1-yr (0.01), 4-yr (0.08)	II	16-yr (0.03)
Cuddapa	I	13-yr (0.04), 19-yr (0.08)	I	11-yr (0.01), 14-yr (0.08), 24-yr (0.01)	I	1-yr (0.01), 5-yr (0.09), 16-yr (0.03), 17-yr (0.03)
Firozpur	II	1-yr (0.01), 2-yr (0.06), 5-yr (0.04), 8-yr (0.04)	II	5-yr (0.01), 8-yr (0.05), 17-yr (0.03), 18-yr (0.01), 19-yr (0.01)	II	1-yr (0.02), 13-yr (0.02), 19-yr (0.01)
Ganganagar	II	1-yr (0.01)	II	No persistence	II	No persistence
Hanumangarh	II	1-yr (0.01)	II	No persistence	II	23-yr (0.01)
Hisar	II	17-yr (0.01)	II	17-yr (0.03)	II	23-yr (0.06)
Jaisalmer	II	17-yr (0.02)	II	19-yr (0.01)	II	11-yr (0.02), 14-yr (0.01), 20-yr (0.03), 22-yr (0.03)
Jalor	II	17-yr (0.03)	I	17-yr (0.02)	II	23-yr (0.11)
Jhunjhunu	II	4-yr (0.05)	I	4-yr (0.05)	II	16-yr (0.03), 23-yr (0.02)
Jodhpur	II	No persistence	II	No persistence	II	3-yr (0.01), 16-yr (0.07)
Kachchh	II	3-yr (0.04)	II	3-yr (0.05)	II	1-yr (0.08), 2-yr (0.05), 3-yr (0.12)
Kurnool	I	13-yr (0.11), 15-yr (0.02)	I	14-yr (0.03)	I	5-yr (0.04), 15-yr (0.02)

Mahendragarh	I	4-yr (0.04)	I	4-yr (0.03)	II	16-yr (0.02), 23-yr (0.05)
Mahesana	I	17-yr (0.09)	I	17-yr (0.09)	II	3-yr (0.12), 10-yr (0.02), 12-yr (0.02)
Nagaur	II	No persistence	II	No persistence	II	3-yr (0.06), 16-yr (0.07)
Pali	I	No persistence	I	21-yr (0.03)	II	12-yr (0.01), 16-yr (0.06), 25-yr (0.02), 26-yr (0.07)
Raichur	I	1-yr (0.01), 10-yr (0.01), 13-yr (0.12), 18-yr (0.04)	I	11-yr (0.04), 13-yr (0.01)	I	2-yr (0.01), 5-yr (0.04), 15-yr (0.11), 19-yr (0.01), 24-yr (0.04)
Rajkot	I	No persistence	I	No persistence	II	3-yr (0.17), 19-yr (0.02)
Sangrur	II	2-yr (0.04), 5-yr (0.04), 8-yr (0.07), 14-yr (0.07), 17-yr (0.11), 19-yr (0.07)	II	8-yr (0.10), 14-yr (0.02), 17-yr (0.13), 19-yr (0.05)	II	1-yr (0.02), 23-yr (0.08)
Sikar	II	4-yr (0.03)	I	4-yr (0.01)	II	16-yr (0.04)
Solapur	I	No persistence	I	6-yr (0.01)	I	7-yr (0.01), 15-yr (0.03), 16-yr (0.02)
Surendranagar	I	14-yr (0.01), 17-yr (0.05)	I	14-yr (0.02), 17-yr (0.02)	II	3-yr (0.07), 10-yr (0.01)
Leh	II	21-yr (0.07), 25-yr (0.01)	II	2-yr (0.01), 13-yr (0.03)	I	16-yr (0.02)
Kargil	I	2-yr (0.03), 3-yr (0.03), 9-yr (0.04)	II	4-yr (0.02)	I	2-yr (0.11), 6-yr (0.03), 8-yr (0.02), 9-yr (0.09), 15-yr (0.08), 16-yr (0.05), 24-yr (0.04)
Lahul & Spiti	I	4-yr (0.03), 13-yr (0.02), 15-yr (0.01), 19-yr (0.07),	I	4-yr (0.03), 13-yr (0.02)	I	2-yr (0.05), 15-yr (0.01)

Note: yr is the year. Bracketed figures indicate deviation from the non-persistence limit.

Table 3. Results of trend analysis for annual and seasonal rainfall (1901-2002) at 32 stations

S. No.	Rainfall Station	Annual			Wet Season			Dry Season		
		r1	Trend magnitude (mm yr^{-1})		r1	Trend magnitude (mm yr^{-1})		r1	Trend magnitude (mm yr^{-1})	
			Q_{med}	b		Q_{med}	b		Q_{med}	b
1	Anantpur	-0.19*	0.69	0.67	-0.26*	0.55	0.67	-0.13	0.01	-0.005
2	Banaskantha	-0.11	-0.39	-0.39	-0.12	-0.49	-0.46	0.15	0.02	0.07
3	Bellary	-0.04	0.06	-0.05	-0.13	0.21	0.16	0.02	-0.26	-0.21
4	Chitradurga	-0.09	-0.24	-0.35	-0.13	0.05	-0.06	0.04	-0.31	-0.29
5	Cuddapa	-0.11	0.93[a]	0.82[a]	-0.13	0.81	0.80	-0.18*	0.10	0.01
6	Kurnool	0.10	1.09[a]	0.96[a]	-0.03	0.85[a]	0.83[a]	-0.01	0.13	0.13
7	Mahesana	-0.07	-0.37	-0.26	-0.08	-0.42	-0.29	0.09	-0.05	0.03
8	Pali	0.02	0.42	0.21	0.03	0.40	0.21	-0.02	0.01	0.001
9	Raichur	0.16*	0.88	0.68	0.11	0.77[a]	0.69[a]	-0.06	-0.07	-0.01
10	Rajkot	0.02	0.46	0.56	-0.01	0.37	0.49	0.04	-0.01	0.07
11	Solapur	0.15	1.03[a]	0.91[a]	0.04	0.95	0.87	0.15	0.00	0.05
12	Surendranagar	-0.07	-0.12	-0.01	-0.10	-0.26	-0.04	0.12	-0.02	0.04
13	Barmer	-0.06	0.14	0.13	-0.06	0.15	0.13	0.15	0.01	0.01
14	Bhatinda	0.14	1.03[a]	0.91[a]	0.09	0.85[a]	0.77[a]	0.16*	0.10	0.15
15	Bikaner	0.14	0.10	-0.02	0.14	0.01	-0.05	0.08	0.07	0.03
16	Churu	0.15	0.40	0.31	0.16*	0.30	0.21	0.11	0.11	0.10
17	Firozpur	0.16*	0.92[a]	0.89[a]	0.11	0.81[a]	0.77[a]	0.17*	0.09	0.12
18	Ganganagar	0.16*	0.25	0.17	0.14	0.20	0.11	0.12	0.09	0.06
19	Hanumangarh	0.16*	0.50	0.40	0.14	0.45	0.29	0.14	0.11	0.11
20	Hisar	0.09	1.05[a]	0.89[a]	0.06	0.87[a]	0.72[a]	0.15	0.13	0.18
21	Jaisalmer	-0.04	-0.03	-0.01	-0.05	-0.03	0.01	0.07	0.00	-0.01
22	Jalor	-0.07	-0.02	-0.02	-0.09	-0.05	-0.09	0.12	0.03	0.06
23	Jhunjhunu	0.10	0.89	0.75	0.12	0.69	0.59	0.11	0.16	0.16
24	Jodhpur	0.05	0.33	0.22	0.08	0.35	0.20	0.02	0.03	0.02
25	Kachchh	-0.09	-0.03	0.01	-0.11	-0.14	-0.08	0.23*	0.02	0.08
26	Mahendragarh	0.05	1.21[a]	1.01[a]	0.06	0.90	0.83	0.12	0.17	0.18
27	Nagaur	0.09	0.85	0.56	0.12	0.76	0.51	0.01	0.08	0.06
28	Sangrur	0.11	1.35[a]	1.25[a]	0.04	1.13[a]	1.07[a]	0.17*	0.15	0.18
29	Sikar	0.10	1.11[a]	0.81[a]	0.13	0.96	0.70	0.07	0.13	0.12
30	Leh	-0.12	0.24	0.36	0.01	-0.07	-0.02	-0.09	0.25	0.39

31	Kargil	-0.03	1.14[a]	1.31[a]	-0.09	0.16	0.22	0.08	1.04[a]	1.09[a]
32	Lahul & Spiti	-0.04	0.22	0.36	0.04	-0.17	-0.13	-0.02	0.36	0.49

Note: r1 is serial correlation coefficient at lag-1; Q_{med} is trend magnitude by Sen's slope estimator; b is the trend magnitude by slope of linear regression; yr is year; * indicates that modified MK test was applied; [a] indicates significant trends at $\alpha = 0.05$.

Table 4. Results of change detection and confirmation tests applied to 102-year annual and seasonal rainfall series of 32 stations

S. No.	Rainfall Station	Identified Change Points in Rainfall Time Series											
		Annual				Wet Season				Dry Season			
		T_{CP}	S_{CP}	t_s	u_c	T_{CP}	S_{CP}	t_s	u_c	T_{CP}	S_{CP}	t_s	u_c
1	Anantpur	1952	1952	1.611	-1.60	1952	1952	**2.050**	-1.85	1914	1914	0.855	-0.88
2	Banaskantha	1959	1959	0.842	0.83	1959	1961[a]	1.179	1.11	1975	1975	0.293	0.28
3	Bellary	1945[a]	1975	0.548	-0.83	1946	1946	1.118	-1.23	1982	1982	0.016	-0.18
4	Chitradurga	1964	1964	1.197	1.09	1990[a]	1917	0.803	-0.97	1980	1980	0.414	0.49
5	Cuddapa	1955	1955	**2.649**	**-2.80**	1952	1952	**2.407**	**-2.27**	1903[a]	1914	0.490	-0.39
6	Kurnool	1942	1945[a]	**2.914**	**-2.97**	1942[a]	1948	**2.703**	**-2.74**	1975	1973[a]	**1.709**	-1.74
7	Mahesana	1959	1959	0.689	0.88	1963[a]	1959	1.115	1.17	1973	1948[a]	0.534	0.71
8	Pali	1925	1925	0.855	-1.50	1925	1925	0.984	-1.43	1920	1920	0.657	-1.22
9	Raichur	1942	1942	**2.228**	**-2.59**	1948	1948	**2.482**	**-2.49**	1901	1982[a]	0.666	-0.77
10	Rajkot	1952	1952	1.210	-0.94	1942	1942	1.162	-0.88	1975[a]	1982	0.621	-0.76
11	Solapur	1945	1945	**2.509**	**-2.93**	1942	1942	**2.429**	**-2.58**	1913	1913	1.040	-1.34
12	Surendranagar	1981	1981	1.392	1.60	1981	1981	1.139	1.20	1982	1982	1.287	1.40
13	Barmer	1905	1906[a]	**2.097**	**-2.22**	1906[a]	1907	**2.067**	**-2.01**	1975	1975	0.417	-0.33
14	Bhatinda	1947	1974[a]	**3.581**	**-3.14**	1952	1947[a]	**2.908**	**-2.84**	1978	1975[a]	**3.133**	**-2.83**
15	Bikaner	1905[a]	1983	1.489	-1.78	1983	1983	1.138	0.91	1920[a]	1965	0.051	-0.45
16	Churu	1941	1941	1.121	-1.24	1941	1941	1.188	-1.23	1978	1965[a]	0.367	-0.47
17	Firozpur	1974	1974	**3.741**	**-3.19**	1952	1947[a]	**2.828**	**-2.78**	1978	1975[a]	**3.418**	**-3.11**
18	Ganganagar	1969	1973[a]	1.531	-1.56	1970	1972[a]	1.199	-1.50	1978	1965[a]	0.433	-0.79
19	Hanumangarh	1953	1973[a]	**1.856**	-1.87	1941	1941	1.417	-1.67	1978	1965[a]	0.734	-1.11
20	Hisar	1954	1954	**2.824**	**-2.87**	1941	1941	**2.393**	**-2.63**	1978	1975[a]	**2.067**	**-2.25**
21	Jaisalmer	1905	1905	1.428	-1.38	1906	1906	**1.995**	**-1.99**	1907[a]	1975	**1.939**	-1.88
22	Jalor	1905	1906[a]	**2.311**	**-2.44**	1906	1906	**2.206**	**-2.30**	1975	1975	0.247	-0.34
23	Jhunjhunu	1941	1941	**1.943**	**-2.19**	1941	1941	**1.927**	**-2.10**	1975	1975	1.123	-0.98
24	Jodhpur	1941	1941	0.906	-1.17	1941	1941	1.030	-1.28	1920[a]	1975	0.525	-0.92
25	Kachchh	1981	1981	0.877	0.94	1981[a]	1961	0.953	1.09	1975[a]	1956	0.031	-0.07
26	Mahendragarh	1941	1941	**2.314**	**-2.41**	1941	1941	**2.252**	**-2.43**	1975	1975	1.195	-1.12
27	Nagaur	1941	1941	1.412	-1.96	1941	1941	1.526	**-2.11**	1975	1975	0.802	-0.82
28	Sangrur	1947	1947	**3.742**	**-3.52**	1947	1947	**3.468**	**-3.48**	1976	1975[a]	**3.330**	**-2.99**
29	Sikar	1941	1941	**1.961**	**-2.46**	1941	1941	**2.035**	**-2.52**	1975	1975	1.098	-1.15
30	Leh	1949	1949	**2.238**	-1.68	1988[a]	1970	0.817	1.03	1949	1949	0.269	0.46

31	Kargil	1947	1947	**2.926**	**-2.66**	1970	1971[a]	1.449	-1.15	1949	1949	**4.334**	**-3.91**
32	Lahul & Spiti	1970	1974[a]	1.454	-1.10	1986	1986	1.185	1.26	1949	1949	**2.908**	**-2.23**

Note: T_{CP} is change point by Pettit test; S_{CP} is change point by cumulative deviation test; t_s is test-statistic of t-test; u_c is test-statistic of Mann-Whitney test; [a] indicates change point with relatively high u_c at a station where change point differs for two tests; and bold face figures indicate presence of significant change point ($\alpha = 0.05$).

Figure Caption

Fig. 1. Map showing hot and cold, arid and semi-arid regions of India along with rainfall stations of two clusters

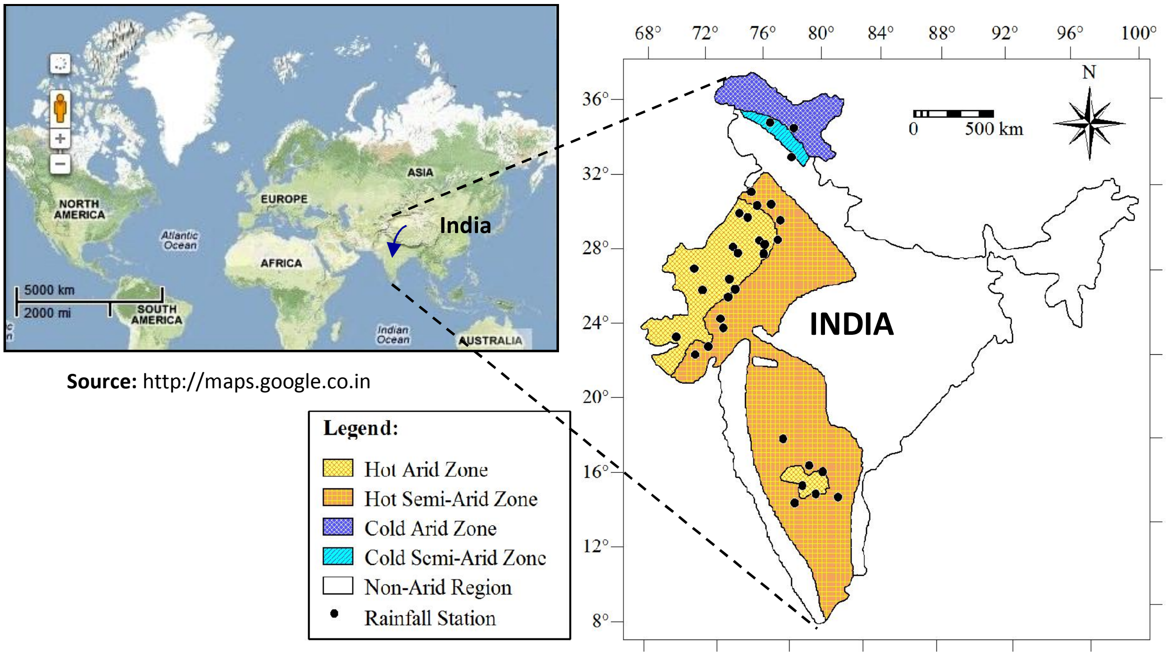
Fig. 2. Two clusters of stations for (a) annual rainfall (b) wet season rainfall, and (c) dry season rainfall

Fig. 3. Box-whisker plots of stations grouped into two clusters for (a) annual rainfall (b) wet season rainfall, and (c) dry season rainfall

Fig. 4. Autocorrelograms showing significant persistence with auto-regressive (AR) coefficient (r_k) values more than 0.10 in annual, wet season and dry season rainfall

Fig. 5. Significant positive and negative trends revealed by Kendall rank correlation (KRC), Spearman rank order correlation (SROC) and Mann-Kendall (MK) tests in long-term (1901-2002) data of (a-c) annual, (d-f) wet season, and (g-i) dry season rainfall

Fig. 6. Significant change points identified in (a) annual, (b) wet season, and (c) dry season rainfall



Source: http://maps.google.co.in

Source : modified from Rao et al. (1998)

Figure 1

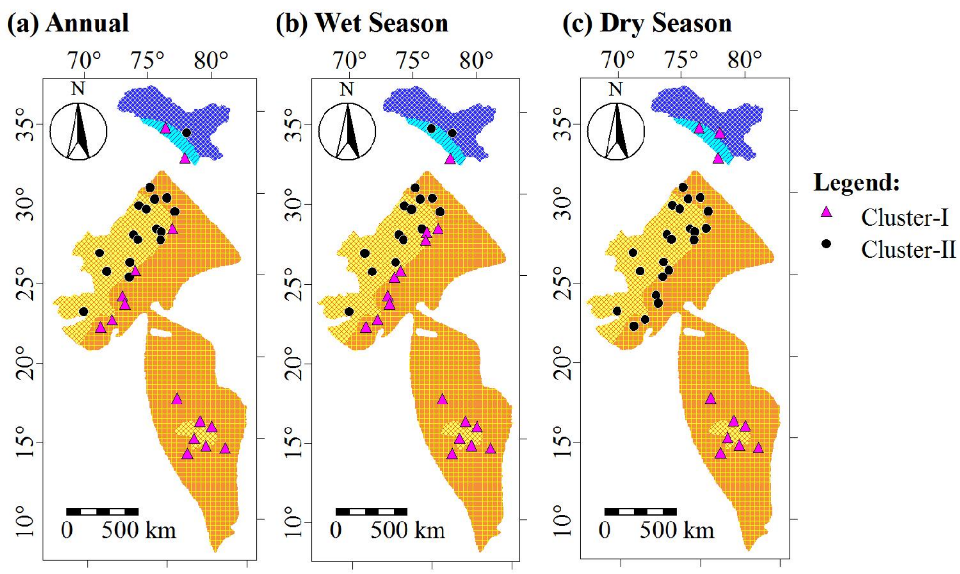

(a) Annual
(b) Wet Season
(c) Dry Season
70°
75°
80°
35°
30°
25°
20°
15°
10°
N
0 500 km
Legend:
Cluster-I
Cluster-II

Figure 2

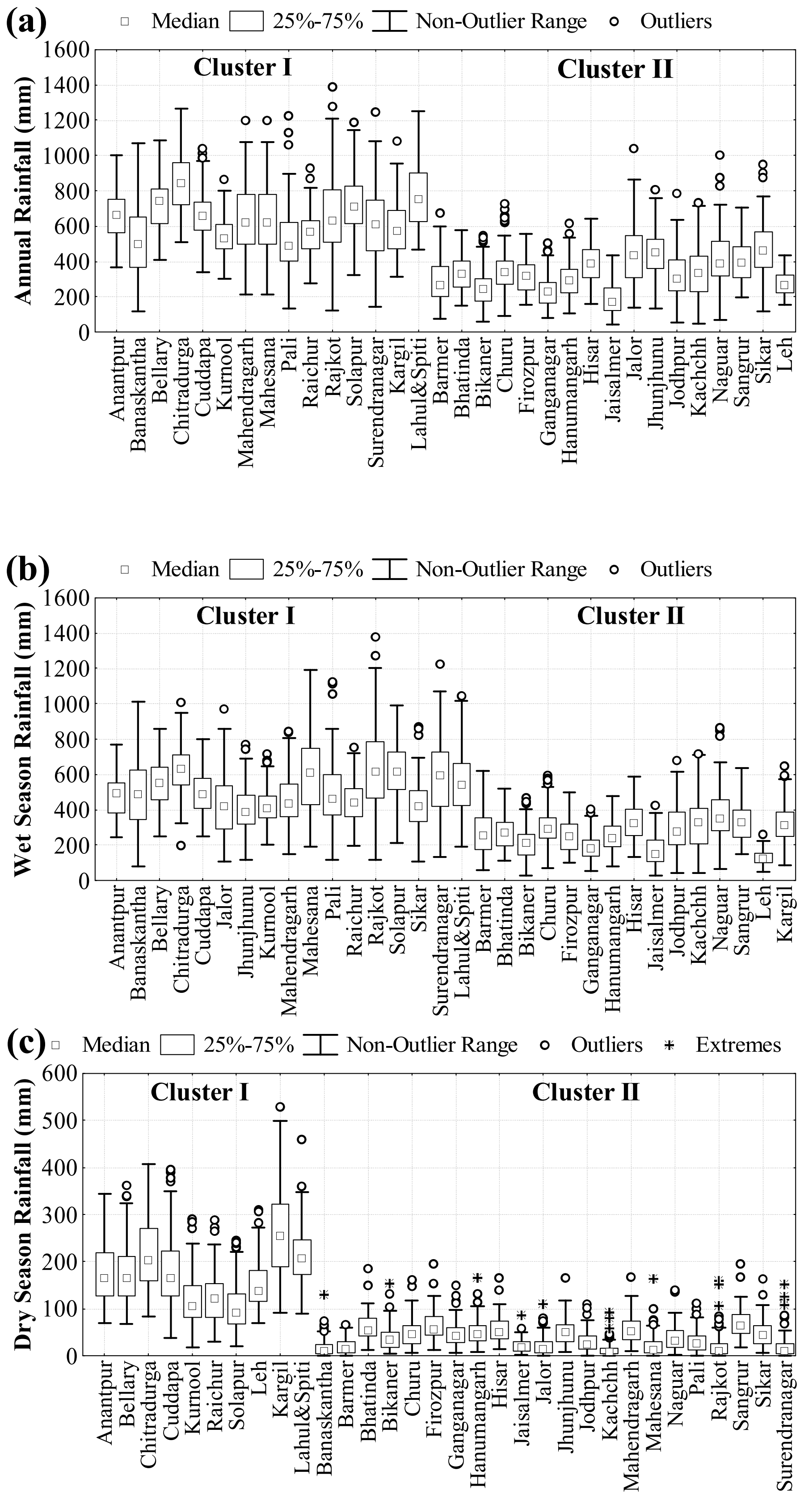

(a)
Median
25%-75%
Non-Outlier Range
Outliers
Annual Rainfall (mm)
Cluster I
Cluster II
Anantpur Banaskantha Bellary Chitradurga Cuddapa Kurnool Mahendragarh Mahesana Pali Raichur Rajkot Solapur Surendranagar Kargil Lahul&Spiti Barmer Bhatinda Bikaner Churu Firozpur Ganganagar Hanumangarh Hisar Jaisalmer Jalor Jhunjhunu Jodhpur Kachchh Naguar Sangrur Sikar Leh
(b)
Median
25%-75%
Non-Outlier Range
Outliers
Wet Season Rainfall (mm)
Cluster I
Cluster II
Anantpur Banaskantha Bellary Chitradurga Cuddapa Jalor Jhunjhunu Kurnool Mahendragarh Mahesana Pali Raichur Rajkot Solapur Sikar Surendranagar Lahul&Spiti Barmer Bhatinda Bikaner Churu Firozpur Ganganagar Hanumangarh Hisar Jaisalmer Jodhpur Kachchh Naguar Sangrur Leh Kargil
(c)
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Dry Season Rainfall (mm)
Cluster I
Cluster II
Anantpur Bellary Chitradurga Cuddapa Kurnool Raichur Solapur Leh Kargil Lahul&Spiti Banaskantha Barmer Bhatinda Bikaner Churu Firozpur Ganganagar Hanumangarh Hisar Jaisalmer Jalor Jhunjhunu Jodhpur Kachchh Mahendragarh Mahesana Naguar Pali Rajkot Sangrur Sikar Surendranagar

Figure 3

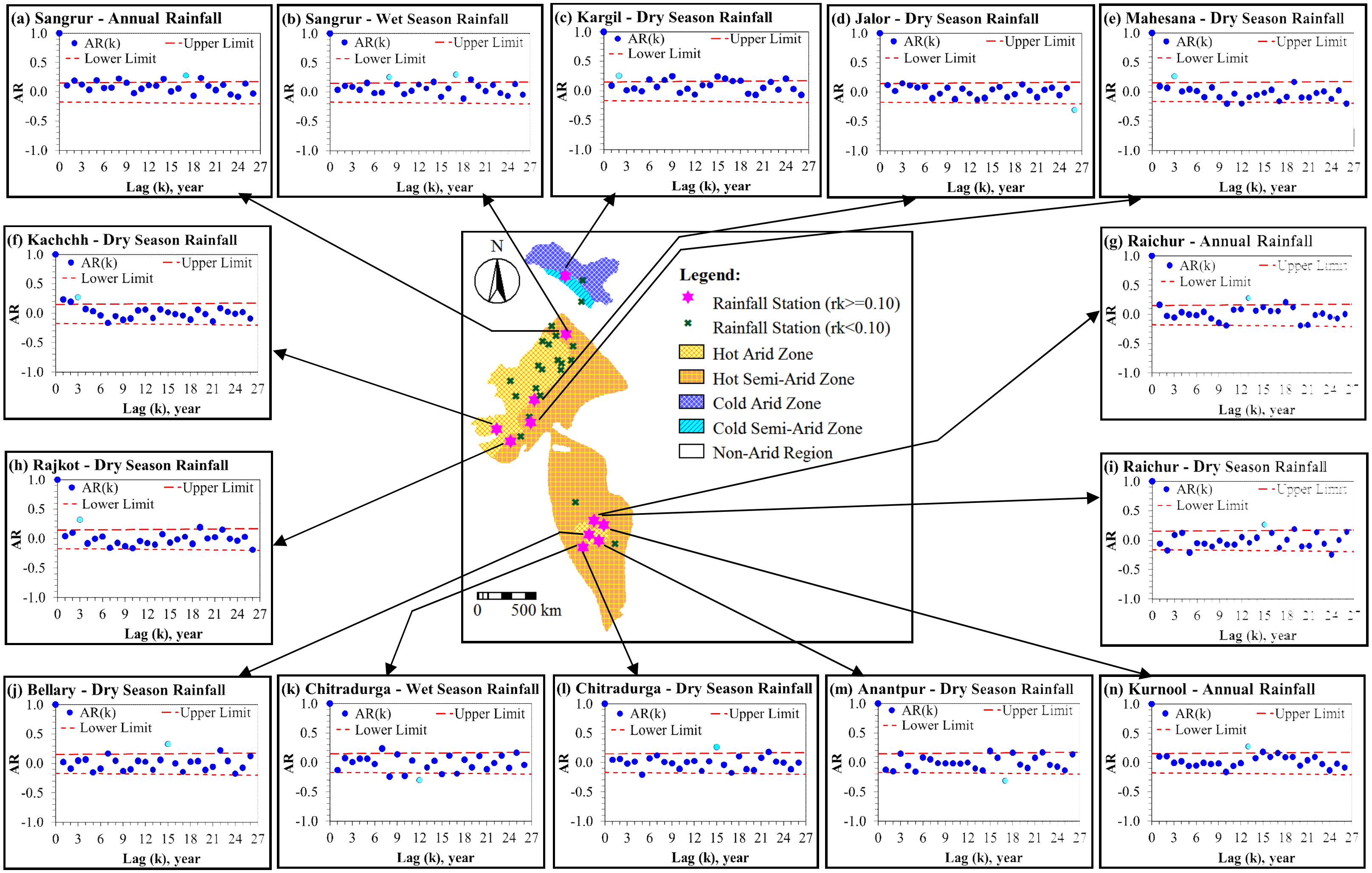
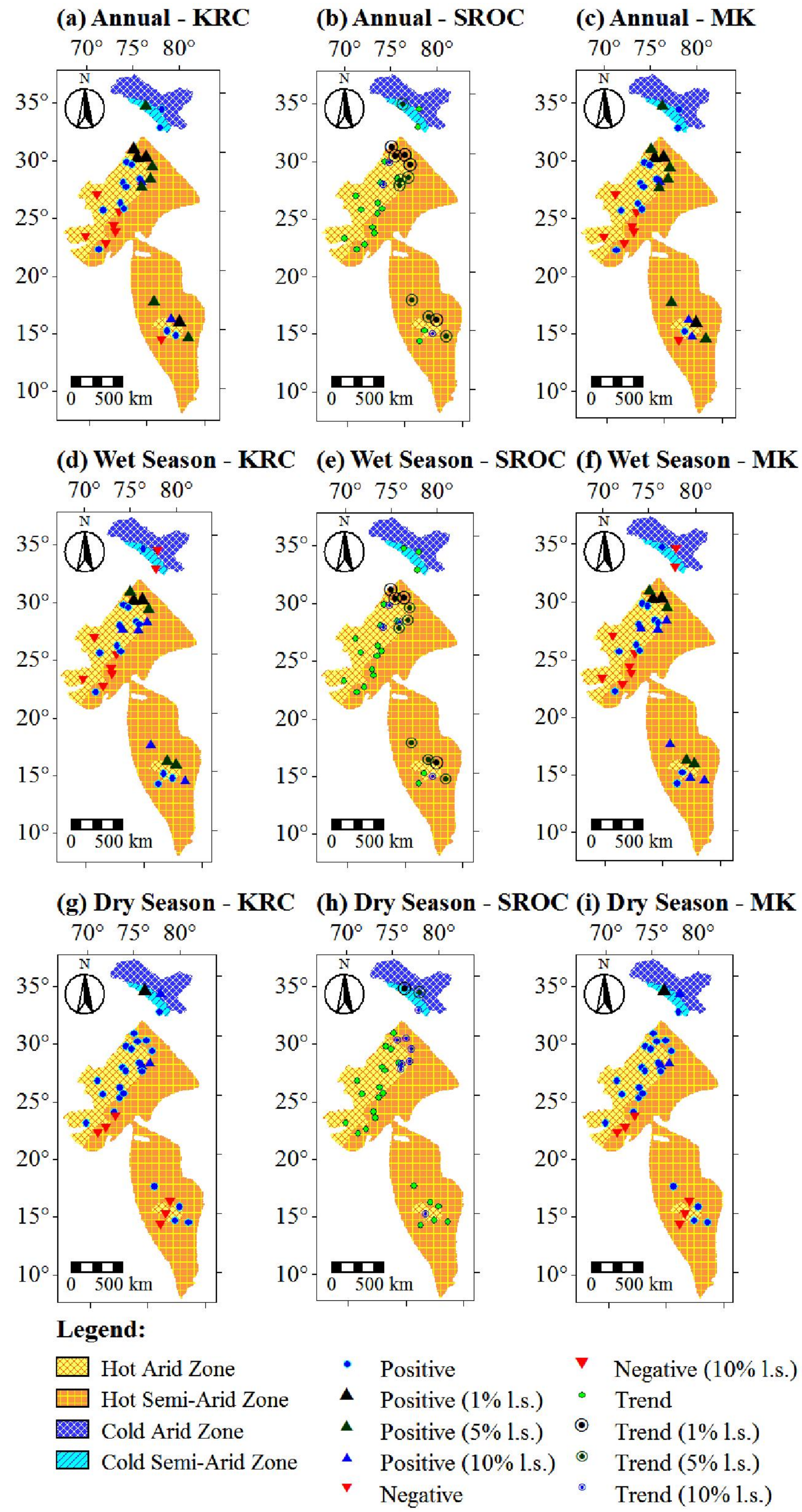
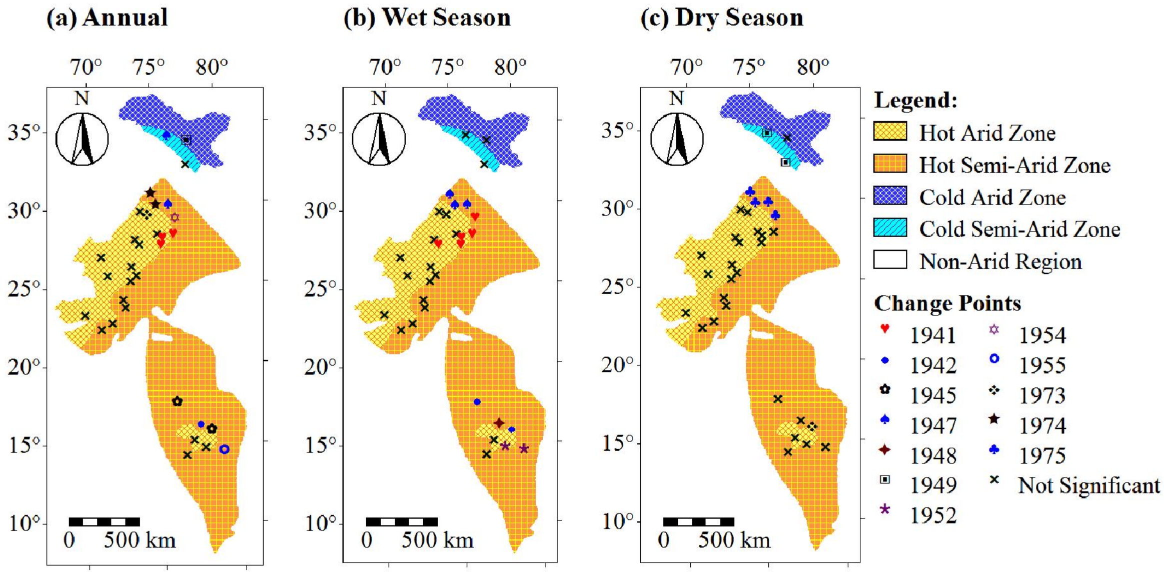

(a) Sangrur - Annual Rainfall
(b) Sangrur - Wet Season Rainfall
(c) Kargil - Dry Season Rainfall
(d) Jalor - Dry Season Rainfall
(e) Mahesana - Dry Season Rainfall
(f) Kachchh - Dry Season Rainfall
(g) Raichur - Annual Rainfall
(h) Rajkot - Dry Season Rainfall
(i) Raichur - Dry Season Rainfall
(j) Bellary - Dry Season Rainfall
(k) Chitradurga - Wet Season Rainfall
(l) Chitradurga - Dry Season Rainfall
(m) Anantpur - Dry Season Rainfall
(n) Kurnool - Annual Rainfall
AR(k)
Upper Limit
Lower Limit
AR
Lag (k), year
N
0
500 km
Legend:
Rainfall Station (rk>=0.10)
Rainfall Station (rk<0.10)
Hot Arid Zone
Hot Semi-Arid Zone
Cold Arid Zone
Cold Semi-Arid Zone
Non-Arid Region

Figure 4



(a) Annual - KRC
(b) Annual - SROC
(c) Annual - MK
(d) Wet Season - KRC
(e) Wet Season - SROC
(f) Wet Season - MK
(g) Dry Season - KRC
(h) Dry Season - SROC
(i) Dry Season - MK
70° 75° 80°
35° 30° 25° 20° 15° 10°
N
0 500 km
Legend:
Hot Arid Zone
Hot Semi-Arid Zone
Cold Arid Zone
Cold Semi-Arid Zone
Positive
Positive (1% l.s.)
Positive (5% l.s.)
Positive (10% l.s.)
Negative
Negative (10% l.s.)
Trend
Trend (1% l.s.)
Trend (5% l.s.)
Trend (10% l.s.)

Figure 5



(a) Annual
(b) Wet Season
(c) Dry Season
70° 75° 80°
35° 30° 25° 20° 15° 10°
N
0 500 km
Legend:
Hot Arid Zone
Hot Semi-Arid Zone
Cold Arid Zone
Cold Semi-Arid Zone
Non-Arid Region
Change Points
1941
1942
1945
1947
1948
1949
1952
1954
1955
1973
1974
1975
Not Significant

Figure 6