Analysis of Trend in Temperature and Rainfall Time Series of an Indian Arid Region: Comparative Evaluation of Salient Techniques

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ABSTRACT

This study investigated trends in 35-year (1979-2013) temperature (maximum, T_{max} and minimum, T_{min}) and rainfall at annual and seasonal (pre-monsoon, monsoon, post-monsoon and winter) scales for 31 grid points in a coastal arid region of India. Box-whisker plots of annual temperature and rainfall depicted systematic spatial gradients. Trends are examined by applying eight tests, such as Kendall rank correlation (KRC), Spearman rank order correlation (SROC), Mann-Kendall (MK), four modified MK tests, and innovative trend analysis (ITA). Trend magnitudes are quantified by Sen's slope estimator, and a new method is adopted to assess significance of linear trends in MK test-statistics. The significant serial correlation is prominent in annual and post-monsoon T_{max} and T_{min}, and pre-monsoon T_{min}. The KRC and MK tests yielded similar results in close resemblance with SROC test. The performance of two modified MK tests considering variance-correction approaches is found superior to KRC, MK, modified MK considering pre-whitening, and ITA test. The performance of original MK test is found poor due to presence of serial correlation, whereas the ITA method is over-sensitive in identifying trends. The significantly increasing trends in T_{min} are more prominent than T_{max}. Further, both the annual and monsoon rainfall have a significantly increasing trend of 9 mm year^{-1}. The sequential significance of linear trend in MK test-statistics is very strong ($R^2 \geq 0.90$) in annual and pre-monsoon T_{min} (90% grid points), and strong ($R^2 \geq 0.75$) in monsoon T_{max} (68% grid points), monsoon, post-monsoon and winter T_{min} (respectively 65, 55 and 48% grid points), as well as in annual and monsoon rainfall (respectively 68 and 61% grid points). Finally, this study recommends use of variance-corrected MK test for precisely identifying trends. It is emphasized that rising T_{max} may hinder crop growth due to enhanced metabolic-activities and shortened crop-duration. Likewise, increased T_{min} may result in lesser crop yields and biomass owing to increased respiration over photosynthesis.

Keywords: Trend analysis; Annual and monsoon rainfalls; Maximum and minimum temperatures; Pre-whitening; Variance correction; Sequential significance.

1. INTRODUCTION

The global warming, caused by the increasing greenhouse gas emissions, has instigated the climate change phenomenon all over the world (Trenberth *et al*., 2007). Temperature and rainfall are the two important climatic variables, which are used to diagnose the impact of climate change in a region (Cannarozzo et al., 2006; Machiwal et al., 2016a). Understanding changes or variability in patterns and/or presence of trends in rainfall and temperature series over different spatial horizons have been the vital aspects in climatological, hydrological and meteorological studies worldwide (Kumar et al., 2010; Jain and Kumar, 2012; Saboohi et al., 2012; Jain et al., 2013; Deka et al., 2013; Goyal, 2014; Rao et al., 2014; Talaee, 2014; Xia et al., 2015; Chatterjee et al., 2016; Tian et al., 2017; Yang et al., 2017). It is revealed from the literature that rainfall and temperature trends have been extensively examined for the semi-arid and humid regions of the world. However, for the arid regions, such studies are still very limited, e.g., Pingale et al. (2014); Talaee (2014); Xu et al. (2015); Machiwal et al. (2016a,b).

In the literature, several studies are available on trend detection methods in climatological, meteorological and hydrological time series. In most studies, trends were detected by parametric and nonparametric methods (Sonali and Kumar, 2013) that include: regression test (Haan, 2002), Kendall rank correlation test (Kendall, 1973), Spearman rank order correlation test (McGhee, 1985), Mann-Kendall (Mann, 1945; Kendall, 1975) test, Sen's slope estimation (Sen 1968; Hirsch et al., 1982), etc. Recently, some studies proposed trend-free pre-whitening (TFPW) and variance correction (VC) approaches prior to applying Mann-Kendall (MK) test to avoid the effect of serial correlation on robustness of the test, e.g. Hamed and Rao (1998); Yue et al. (2002); Yue and Wang (2004). However, not all the studies deals with PW and VC approaches in MK test in the literature. Despite the fact that many studies recommended the use of multiple statistical tests (three or more) for trend identification (Machiwal and Jha, 2008; Sonali and Kumar, 2013; Machiwal and Jha, 2016), this aspect is missing in almost all the studies from Indian subcontinent (Sonali and Kumar, 2013).

The MK test has been extensively used in literature for trend identification in rainfall and temperature data. Martinez et al. (2012) determined significance and magnitude of annual, seasonal and monthly trends in precipitation and temperature for two time periods: (i) 1895-2009 and (ii) 1970-2009 in Florida, USA. Results of MK test indicated significantly decreasing trends in monthly precipitation in October and May for the first and second time periods, respectively. On the other hand, trends in mean, maximum and minimum temperature were generally positive during 1970-2009 period. Jain et al. (2013) examined trends in monthly, seasonal, and annual rainfall (1871-2008) and temperature (1901-2003) in the northeast region of India. Results did not reveal any clear trends in rainfall for the region as a whole although temperature was found to be significantly rising. Ramadan et al. (2013) investigated temperature and precipitation trends during 1900-2008 in the Litani Basin, Lebanon using MK and Sen slope tests. Results revealed a drying trend in the basin without a significant change in temperature. However, the basin grew notably warmer in all seasons during 1970-2008 without being wetter. Kumar et al. (2013) analyzed continental-level (60°S to 60°N) temperature and precipitation trends using MK test for the period 1930-2004 from 19 climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5). Short-term persistence from the data was removed using TFPW technique, and trend magnitude was estimated using Theil-Sen approach. Results suggested that the global land average temperature trend (0.7°C decade^{-1}) based on multi-model ensemble mean captured the corresponding observed trend (0.08°C decade^{-1}) reasonable well. Similarly, the precipitation trends in both models and observations were found to be distributed (spatially) about zero. Asfaw et al. (2017) detected trends in gridded rainfall and temperature (1901-2014) datasets of Woleka sub-basin, northcentral Ethiopia using MK test. Results revealed a significant decline in annual rainfall at a rate of 15 mm decade^{-1}. On the contrary, mean and minimum temperatures were increasing at a rate of 0.046 and 0.067°C decade^{-1}, respectively. Ul Shafiq et al. (2018) analyzed precipitation and temperature trends based on 1980-2014 data for 6 stations of the Kashmir valley, India using MK test. Results suggested that the mean maximum temperature in plain regions is increasing at a rate higher than that in mountainous areas. However, the mean minimum temperature is found increasing at higher rate in mountainous regions. The rainfall showed a decreasing trend with higher rate in mountainous regions.

The significant trend and magnitude of the global warming in the latter half of the 20th century are found matching with the agriculture-based country like India (Pant and Rupa Kumar, 1997). India is the world's third-highest greenhouse gas emitter country (CDIAC, 2013) as well as one of the most vulnerable countries to climate change (INCCA, 2010). The hot arid Indian lands, extending over 32 million ha in Rajasthan and Gujarat (Kar et al., 2009), experience extremely high temperatures and less-frequent rainfall occurrences. Owing to the adverse climatic conditions, the Indian arid lands are very susceptible towards fulfilling the basic needs of food and water. Entire land of Kachchh, the second-largest Indian district, is situated under a hot arid climate of Gujarat (Dayal et al., 2009). Over the whole Indian subcontinent, the highly-intense rainfall events are reported to be increasing (Goswami et al., 2006; Ghosh et al., 2009), which severely affect the agriculture (Revadekar and Preethi, 2010). These high-intensity rainfall events have been observed over the arid land of Kachchh where 38-68% of the annual rainfall occurred in just 2 to 4 consecutive days during 2007-2013 period (Machiwal et al., 2015). Besides, the annual rainfall in two administrative blocks of Kachchh district has been found to be significantly rising (Machiwal et al., 2016b) even though the temperature and rainfall trends at seasonal scale have not been yet investigated in this Indian arid region.

The present study focuses on investigating presence of trends and their significance in temperature (maximum and minimum) and rainfall time series at spatial (31 grid points) and temporal (annual and seasonal) scales in Kachchh, India by employing eight tests including the modified MK tests considering TFPW and VC approaches. Furthermore, performances of all the tests are comparatively evaluated, and a new methodology is adopted to assess statistical significance of the sequential linear trends in the MK test-statistics.

2. MATERIALS AND METHODS

2.1 Study Area and Data

Kachchh district of Gujarat, situated in the western portion of India (Fig. 1), is like an island surrounded by the waterbodies with presence of the Arabian Sea in west, the Gulf of Kachchh in south, and the Great Rann in north, and the Little Rann in east directions. Both, the Great and Little Ranns represent the salty marshlands. It encompasses 45,612 km^2 area and is located from 22^{o}44'08" to 24^{o}41'30" north latitudes and 68^{o}07'23" to 71^{o}46'45" east longitudes. The entire area consists of ten administrative divisions (blocks) namely Bhuj and Nakhatrana (north), Lakhpat and Abdasa (west), Mandvi, Mundra, Anjar and Gandhidham (south), and Bhachau and Rapar (east). There are about 97 rivers/streams in the study area but none of them are perennial. All rivers/streams in the area start from the central portion and flow towards the sea, the Great Rann and the Little Rann.

Climate of the study area is typical arid-coastal with aridity index of more than 40% having almost dry-desert conditions (Prusty, 2012). The 102-year (1901-2002) mean annual rainfall is 341 mm, and the highest mean monthly air temperature ranges from 22.1 to 31.9°C in May, whereas the lowest varies from 8.8 to 22.7°C in January (http://indiawaterportal.org/met_data/). In monsoon season, relative humidity is high (> 80%) in the coastal areas and (> 65%) in inland. However, in dry period (November-May), the relative humidity falls below 25% in afternoon. Potential evapotranspiration (PET) ranges from 1750 mm year^{-1} in coastal areas of Naliya, Mandvi and Mundra to 1900 mm year^{-1} towards inlands of Bhuj and Anjar. The PET values decrease to 1800 mm year^{-1} and less towards the north and northeast portions. The PET is about 4-5 times higher than the rainfall, which leaves large deficit of water availability (Singh and Kar, 1996).

In this study, 35-year (1979-2013) daily data of rainfall, maximum air temperature and minimum air temperature for 31 grid points, located in the study area, were utilized to generate annual and seasonal (pre-monsoon, monsoon, post-monsoon and winter) time series. Location of 31 grid points is shown in Fig. 1. This study considered four seasons in a year, i.e., pre-monsoon (MAM), monsoon (JJAS), post-monsoon (OND) and winter (JF). The daily data were acquired from the National Centers for Environmental Prediction’s Climate Forecast System Reanalysis (NCEP’s CFSR) (Saha et al., 2010). All the procured data were checked for the absence of errors and gaps.

2.2 Comparison between Gridded and Meteorological Stations’ Datasets

An earlier study reported high to very high values of correlations coefficients (ranging from 0.7-0.8) between measured (meteorological stations) and gridded (NCEP-CFSR) datasets of rainfall and temperature for western India where the study area is situated (Shah and Mishra, 2014). Further, accuracy of the NCEP gridded rainfall dataset was evaluated in this study by comparing it with measured dataset recorded at 10 meteorological stations (one in every block of study area) for 1980-2013 period. The gridded rainfall of a certain number of points was averaged for a year depending upon their proximity to the meteorological stations. Thereafter, comparative evaluation of the NCEP data was performed for 10 blocks using three criteria, i.e., correlation coefficient, t-test for similar means, and F-test for similar variances.

2.2.1 Estimating Correlation Coefficients and Their Significance

Linear relations between the two datasets (gridded and measured data) were evaluated by computing correlation coefficients (r). Furthermore, statistical significance of the r-values was tested by using t-test ():

$$t = r \times \sqrt{\frac{n-2}{1-r^2}} \tag{1}$$

where, n = sample size of the dataset. Critical value of the t-statistic was taken from the t-distribution at level of significance (α) = 0.05 and degree of freedom ‘n-2’.

2.2.2 t-Test for Similar Means

The simple t-test was used to examine the null hypothesis of similar means of two datasets when their standard deviations are also the similar to each other. The test-statistic is defined as (Snedecor and Cochran, 1980):

$$ts = \frac{\left|\bar{x}_2 - \bar{x}_1\right|}{S\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{2}$$

where, $\bar{x}_1$, $\bar{x}_2$, s_1^2 and s_2^2 are the estimated means and variances of the first and second datasets. Critical value of this test-statistic was taken from standard tables of the Student’s t-distribution at α = 0.05 for ‘n-2’ degrees of freedom.

2.2.3 F-Test for Similar Variances

The F-test is used to investigate the null hypothesis of similar variances of two datasets. The test-statistic is defined by the following expression ():

$$F = \frac{s_1^2}{s_2^2} \qquad \text{where } s_1 > s_2 \qquad (3)$$

Critical value of this test-statistic was taken from F-distribution table at $\alpha = 0.05$ for sample size of two datasets defined by n_1 and n_2.

2.3 Investigation of Spatial and Temporal Variability of Temperature and Rainfall Series

Box and whisker plots of the annual maximum temperature, minimum temperature and rainfall time series for 31 grid points were drawn together to depict the temporal pattern of the variables over the study area and to spatially compare them. The box and whisker plot reveal five important characteristics of a time series, i.e., maximum value, minimum value and 25th, 50th and 75th percentiles (USEPA, 2006). It helps understanding temporal distribution of the variable over the given time period, and when plotted together for different points over the space, it also enables spatial comparisons.

2.4 Evaluation of Serial Correlation in Temperature and Rainfall Series

It is recognized in some studies that the presence of serial correlation in time series may lead to the rejection of the true null hypothesis of no trends due to inflation of the variance especially using the MK test (Yue and Wang, 2002). Therefore, this study examined presence of serial correlation in all three time series (maximum temperature, minimum temperature and rainfall) at all time scales (annual, pre-monsoon, monsoon, post-monsoon and winter) by estimating autoregressive process AR(1) at lag-1 or serial correlation coefficient (r_1). The test details may be found in the standard textbooks, e.g. Haan (2002) and Machiwal and Jha (2012). The aim of analyzing serial correlation in the temperature and rainfall series in this study was to see effect of presence of serial correlation on the trends identified by the MK test.

The critical limits (upper and lower) of r_1 were obtained from Anderson (1942), as defined below:

$$(r_1)_{upper} = \{1/(n-1)\}(-1 + z_{1-\alpha/2}\sqrt{n-1-1}) \qquad (4)$$

$$(r_1)_{lower} = \{1/(n-1)\}(-1 - z_{1-\alpha/2}\sqrt{n-1-1}) \qquad (5)$$

where, $z_{1-\alpha/2}$ = standard normal variate at α level of significance (ls). If $(r_1)_{upper} \geq r_1 \geq (r_1)_{lower}$, the null hypothesis ($H_0$) that $r_1 = 0$ is accepted; otherwise, the H_0 is rejected and this indicates that the temperature and rainfall series are not purely random and some serial correlation exists.

2.5 Overview of Trend Tests Used

There exist two approaches for evaluating trends, i.e. parametric and nonparametric. The parametric tests imply the assumption of normality whereas the widely-applied nonparametric MK test may result in erroneous outcome under the presence of serial correlations in data. This study adopted eight nonparametric trend tests such as KRC, SROC, original MK and modified MK tests that considered the effect of serial correlation such as MK-TFPW (von Storch, 1995) and VC approach with MK test, i.e. MK-CF$_1$ (proposed by Yue and Wang, 2004), MK-CF$_2$ (Lettenmaier, 1976) and MK-CF$_3$ (Matalas and Sankarasubramaniam, 2003). In addition, this study considered the innovative trend analysis (ITA) method (Şen, 2015) that is free from the necessary conditions required prior to applying the parametric and nonparametric tests. All the test-statistics are briefly discussed ahead.

2.5.1 KRC Test

The test-statistic, z_{KRC}, of the KRC test is expressed in the following expression (Kendall, 1973):

$$z_{KRC} = \tau \big/ \sqrt{\text{Variance}(\tau)} \tag{6}$$

$$\tau = \left(4\,\underline{p} \big/ n(n-1)\right) - 1 \tag{7}$$

$$\text{and } \operatorname{Var}(\tau) = \left(2\,(2\,n+5)/9\,n\,(n-1)\right) \tag{8}$$

where, $\underline{p}$ = number of times $x_j > x_i$ ($j>i$) is counted in all pairs of (x_i, x_j) in the hydrologic time series, and n = number of data in the series.

2.5.2 SROC Test

Before applying the SROC test, the rank R_{xt} of x_t in the original series arranged in ascending order is computed. Then, difference series $d_t = R_{xt} - t$ is generated; for ties of values, the mean of the ranks is assigned as if there is no tie. Finally, the coefficient of trend (r_s) is computed as follows (McGhee, 1985):

$$r_s = 1 - \left[6 \sum_{t=1}^{n} d_t^2\right] \Big/ \left[n\left(n^2 - 1\right)\right] \tag{9}$$

The test-statistic (t) is defined as (McGhee, 1985):

$$t = r_s \sqrt{(n-2)\big/\left(1 - r_s^2\right)} \tag{10}$$

The computed ‘t’ value is compared with the corresponding critical value the Student’s t-distribution at n-2 degree of freedom and three α levels = 0.01, 0.05 and 0.10. The null hypothesis (H_o) of absence of significant trend is to be rejected if the critical ‘t’ values are found more than the computed ‘t’ values.

2.5.3 MK Test

The test-statistic ‘S’ of the MK test is calculated by using Eqns. 11-13 (Salas, 1993):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{11}$$

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} +1 & \text{if} \quad (x_j - x_k) > 0 \\ 0 & \text{if} \quad (x_j - x_k) = 0 \\ -1 & \text{if} \quad (x_j - x_k) < 0 \end{cases} \tag{12}$$

$$\operatorname{Var}(S) = \left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i (t_i - 1)(2t_i + 5) \right] / 18 \tag{13}$$

where, m = number of tied groups having similar values for a data group, and t_i = number of data in i^{th} tied group. For n>40, the test-statistic is given as follows (Hirsch et al., 1982):

$$z_{MK} = (S + m) \Big/ \sqrt{\operatorname{Var}(S)} \tag{14}$$

where, m = 1 for S<0 and m = -1 for S>0. The z_{MK}-value is considered as zero for S = 0. The H_o of no increasing or decreasing trend is rejected when the computed z_{MK}-value is found to be greater than its critical value taken from the normal distribution at three α levels of 0.01, 0.05 and 0.10.

2.5.4 MK-CF$_1$ Test

In hydrologic time series, presence of positive (negative) serial correlation results in increase (decrease) in variance of ‘S’ statistic of the MK test. To overcome this problem, one of the variance correction approaches was proposed by Yue and Wang (2004), which modified the variance of the MK test-statistic as follows:

$$\operatorname{Var}(S)^* = CF_1 \times \operatorname{Var}(S) \tag{15}$$

where CF_1 = correction factor proposed by Yue and Wang (2004) as defined below.

$$CF_1 = 1 + 2\sum_{k=1}^{n-1} \left(1 - \frac{k}{n} \right) r_k \tag{16}$$

where, r_k = serial correlation coefficient at lag-k, and n = total length of the series. In this study, this test is applied with the assumption of AR(1), e.g., by taking $r_k = r_1$ for the MK-CF$_1$ test.

2.5.5 MK-CF$_2$ Test

This study considered another approach proposed by Lettenmaier (1976) to modify the original MK test-statistic in order to remove the effect of serial correlation on the test. The modified MK test-statistic based on this approach is given as follows:

$$z^* = z \times \sqrt{n^*/n} \tag{17}$$

where, the term n*/n = correction factor computed for the autocorrelation function (r_1), whose value is computed at lag-1 autoregressive (AR) process from the following expression (Matalas and Langbein, 1962):

$$\frac{n^*}{n} = \frac{1}{1 + 2\dfrac{r_1^{n+1} - n\,r_1^2 + (n-1)\,r_1}{n\,(r_1 - 1)^2}} \tag{18}$$

2.5.6 MK-CF$_3$ Test

The variance correction approach proposed by Matalas and Sankarasubramaniam (2003) is also considered in this study, where a bias correction factor B = V(S)/V *(S), is obtained by comparing the theoretical variance for a given H (scaling coefficient or Hurst coefficient) with the estimated variance. The values of B were regressed on both n and H based on 90,000 simulated series from combinations of n = 20 to 200 and H = 0.01 to 0.99. The satisfactory fit of the relationship (R^2 = 0.9996) obtained after investigating several forms of the relationship, is provided in the following equation:

$$B = a_0 + a_1 H + a_2 H^2 + a_3 H^3 + a_4 H^4 \tag{19}$$

where, $a_0 = \dfrac{1.0024n - 2.5681}{n + 18.6693}$; $a_1 = \dfrac{-2.2510n + 157.2075}{n + 9.2245}$; $a_2 = \dfrac{15.3402n - 188.6140}{n + 5.8917}$;

$$a_3 = \frac{-31.4258n + 549.8599}{n - 1.1040}; \text{and } a_4 = \frac{20.7988n - 419.0402}{n - 1.9248} \tag{20-24}$$

2.5.7 MK-PW Test

The PW or TFPW approach, proposed by von Storch (1995) to remove impact of serial correlation on the performance of MK test, was utilized in this study to generate a new series as follows:

$$x_t^{'} = x_t - r_1 x_{t-1} \tag{25}$$

where, r_1 is the lag-1 serial correlation coefficient of data series. The serial correlation coefficient (r_1) at lag-1 can be estimated for the series by computing autocorrelation function (Salas et al., 1980). This kind of PW method has been used in many trend detection studies to remove an AR(1) process from original data series, e.g. Douglas et al. (2000), Zhang et al. (2000, 2001), Hamilton et al. (2001), Burn and Elnur (2001).

2.5.8 ITA Test

In order to apply this graphical test, first half of the entire time series is plotted against the second half. If the plotted scatter points lie on 1:1 line (45° straight line), it means there is no trend in the time series. On contrary, scatter points above or below the 1:1 line indicate increasing or decreasing monotonic trends, respectively. In this test, slope (s) of the trend is calculated according to the following expression (Şen, 2015):

$$s = \frac{2(\bar{y}_2 - \bar{y}_1)}{n} \tag{26}$$

where, $\bar{y}_1$ and $\bar{y}_2$ = arithmetic means of the first and second halves of the time series, and n = number of data in the series.

The confidence limits (CL) of the trend slope can be estimated at α significance level based on confidence limits (s_{cri}) for a standard normal probability density function with zero mean and standard deviation from the following expression (Şen, 2015):

$$CL_{(1-\alpha)} = 0 \pm s_{cri}\sigma_s \tag{27}$$

where, σ_s = slope standard deviation, which is computed as follows (Şen, 2015).

$$\sigma_s = \frac{2\sqrt{2}}{n\sqrt{n}}\sigma\sqrt{1-\rho_{\bar{y}_1\bar{y}_2}} \tag{28}$$

Where, $\rho_{\bar{y}_1\bar{y}_2}$ = cross-correlation coefficient between the ascending sorted two halves' means of the series.

If slope value (s) of each point falls outside of the lower and upper CL values, then the null hypothesis of no significant trend is to be rejected at α significance level.

2.6 Quantifying Trend Magnitudes

In this study, trend magnitudes of the annual temperature (maximum and minimum) and rainfall series at 31 grid points were quantified by using Sen's slope test-statistic (Sen, 1968; Hirsch et al., 1982) given by the slope (β) as follows:

$$\beta_k = \text{median}\left[\left(x_{ik} - x_{jk}\right)/\left(i - j\right)\right] \quad \text{for all } i<j \qquad (29)$$

where, x_{ik} and x_{jk} = data at time i and j (j>i), and k = data point. The positive and negative β-values indicate the increasing and decreasing trends, respectively.

2.7 Linear Trend Significance of MK Test-Statistics

This study adopted a new methodology, originally proposed by Machiwal et al. (2016a), to assess statistical significance of linear trend in MK test-statistic values over different time periods increasing sequentially from a selected base period (1979-2000) up to entire length of time series (1979-2013). Salient steps of the methodology are explained below.

(i) Choose a base period of adequate length starting from beginning of time series with total number of n data, and compute the MK test-statistic (z_{MK}) by using Eqn. (14).

(ii) Add one more year's data in the base period, and compute the MK test-statistic value. Repeat this process till the last n^{th} data is included in the series, and z_{MK} is computed.

(iii) Plot bar charts for the computed z_{MK} values against their corresponding time periods sequentially increasing from the base period up to the total length of the time series.

(iv) Explore statistical significance of the presence of linear trends in the bar charts by fitting trend line through least square method, and determine value of goodness-of-fit criterion, i.e., coefficient of determination (R^2).

Examining the statistical significance of the linear trends over sequential periods in climatologic time series is imperative due to the fact that sometimes the trends of a climatologic parameter over a fixed period may not reveal statistically-significant trends but test-statistic values may be having the significantly increasing/decreasing trends. This indicates that the trends are not significant currently, but may be significant in the near future.

3. RESULTS AND DISCUSSION

3.1 Validation of Gridded Dataset

Results of statistical tests comparing gridded annual rainfall data with dataset of 10 meteorological stations are presented in Table 1. It is seen that r-values range from 0.4-0.7 for the stations, which indicate moderate to good relationships between the two sets of data. It is further apparent that the r-values are found to be statistically significant at α = 0.05 for all the stations except one station, i.e., Gandhidham, where the non-significant r-value may likely be due to relatively less availability of the measured rainfall dataset (1998-2013) of the meteorological stations. In addition, results of t-test (α = 0.05) suggested similar means of the average gridded and meteorological stations' datasets as the null hypothesis of similar means could not be rejected for most of the stations except one. Moreover, results of F-test revealed that the variances of the gridded rainfall dataset are similar to that of the measured rainfall dataset for most of the meteorological stations. The coherence in the findings of three criteria at most of the stations validated the accuracy of the gridded rainfall dataset used in this study.

3.2 Temperature and Rainfall Variability

The box and whisker plots of the annual maximum temperature, minimum temperature and rainfall time series for 31 grid points (Figs. 2a-c) reveal their temporal distribution over the space. It is apparent from Figs. 2a-c that there exists a systematic spatial variation in patterns of maximum temperature, minimum temperature and rainfall. The median of the annual maximum temperature generally gets inclined on moving from western to eastern and from southern to northern directions (Fig. 2a). On the other hand, the annual minimum temperature initially declines when moving from first grid point to third grid point in west-east direction, and then it inclines when moving towards rest of the grid points (Fig. 2b). However, the annual rainfall has a downward gradient towards eastern portion for the points 1 to 5, and an upward west-east gradient for rest of the points (Fig. 2c). The rainfall magnitudes are mostly decreasing in south-north direction. Overall, an increase in the maximum temperature and a decrease in the minimum temperatures are observed when moving away from the western and southern coastal boundaries of the area.

3.3 Serial Correlation in Rainfall and Temperature Series

The r_1 values at lag-1 for the annual and seasonal (pre-monsoon, monsoon, post-monsoon and winter seasons) maximum temperature, minimum temperature and rainfall are presented in Tables 2-4. The Anderson's critical limits of the r_1 for sample size of 35-year period ranged from -0.31 to 0.25, and any value outside this range indicates the presence of the serial correlation in the series.

It is seen from Table 2 that the significant serial correlation at lag-1 is present in annual, pre-monsoon, monsoon and post-monsoon maximum temperature series of 30 (97%), 19 (61%), 11 (35%) and 31 (100%) grid points, respectively. However, both the positive (18 grid points) and negative (13 grid points) serial correlations in the maximum temperature of the winter season are not significant. In case of the minimum temperature, the r_1 values crossed the critical limits for 31 (100%), 29 (94%), 25 (81%) and 9 (29%) grid points in annual, pre-monsoon, post-monsoon and winter seasons, respectively (Table 3). Whereas, the serial correlation at none of the grid points goes beyond the non-critical region for the monsoon season's minimum temperature series. The r_1 values in annual rainfall time series of 10 grid points (32%) are found to be larger than the upper critical limit (0.25) (Table 4), and thus, it indicates presence of the statistically-significant serial correlation. Similarly, the r_1 values of 11 grids (35%) in the monsoon season rainfall series indicate the presence of the significant serial correlation.

It is inferred from the above discussion that serial correlation is prominent in annual and post-monsoon season data series of both the maximum and minimum temperatures, and additionally in pre-monsoon minimum temperature series. However, the serial correlation is either completely absent or present at less than 35% of the grid points in the other temperature series and both the rainfall series. Presence of the serial correlation in temperature and rainfall series at annual and seasonal scales are taken care by the modified MK tests with PW and VC approaches adopted in this study.

3.4 Trends in Maximum Temperature Series

Results of eight trend tests for the maximum temperature of annual and seasonal (pre-monsoon, monsoon, post-monsoon and winter) time series in the area are depicted in Fig. 3. It is seen that the trends identified by the SROC test showed some resemblance with the results of KRC and MK tests; however, this test did not indicate whether the trend is increasing or decreasing. The MK-PW test results exhibited the most disagreement to the findings of other tests for all time series except for monsoon and winter seasons; nevertheless, the MK-CF_1 and MK-CF_2 tests showed more or less similar results in all the time series. The maximum temperature is having increasing trends whether significant or non-significant at all the grids in all the time series except during monsoon season when the maximum temperature is observed to be the declining over the entire area.

It is seen from Fig. 3 that the annual maximum temperature is having significantly-increasing trends at 6 (19%) of total 31 grids as revealed by both the KRC and MK tests at $\alpha=0.10$. However, none of the modified MK tests could reveal the detected trend to be the statistically-significant at $\alpha=0.10$, 0.05 and 0.01. On the contrary, the ITA test resulted statistically-significant trends for 20 (65%) and 23 (74%) grids at $\alpha=0.01$ and 0.10, respectively. In pre-monsoon maximum temperature series, the KRC and MK tests found statistically-significant trends ($\alpha=0.10$) for 2 grids (6%), whereas the MK-CF_1 and MK-CF_2 tests confirmed significant trends at only 1 grid point at the similar significance level. In contrast, trends at 18 grids (58%) were the highly-significant ($\alpha=0.01$) as revealed by the ITA test. In monsoon season, the maximum temperature was found to be non-significantly decreasing by almost entire tests except the ITA test (Fig. 3), which suggested significantly-increasing trends for 14 (45%) and 20 (64%) grids at $\alpha=0.01$ and 0.05, respectively. The maximum temperature in the post-monsoon season was found to be significantly increasing for 10 (32%), 10 (32%), 2 (6%) and 1 (3%) grids by the KRC, MK, MK-CF_1 and MK-CF_2 tests at $\alpha=0.10$ (Fig. 3). However, the significance of rising trends at 22 grids (71%) was relatively high ($\alpha=0.01$) for the ITA test. The KRC and MK tests indicated significant trends in the winter season temperature series of 2 grids (6%) each at $\alpha=0.01$ while at the similar significance level, the MK-CF_1 and MK-CF_2 tests revealed trends to be significant for 4 grids (13%) each. The ITA test resulted the statistically-significant trends for 31 grids (100%) at $\alpha=0.01$.

It is apparent from the above results that the trend results are exactly similar for KRC and MK tests, and number of the grids having significant trends (α=0.10) reduces in order of the tests MK-CF$_1$, MK-CF$_2$ and MK-CF$_3$ except during winter season when the MK-CF$_1$ and MK-CF$_2$ tests detected trends at 2 additional grids in comparison to that identified by the KRC and MK tests. This finding clearly suggests that the MK test revealed the significantly increasing trends in the annual and post-monsoon season maximum temperature due to presence of serial correlation. Moreover, the significantly increasing maximum temperature trends were mostly present in the southern or southwest portions of the area (Fig. 3) where coastal boundaries are situated in close proximity. Therefore, the rising trends in the maximum temperature are likely to be associated with increase in sea surface temperature (Rao and Vivekanandan, 2008). It is important to mention that the ITA test is highly sensitive in detecting trends in the maximum temperature series in comparison to the MK-CF$_1$ and MK-CF$_2$ tests. Hence, the results of the ITA test may not be considered adequate for the maximum temperature time series in the area. The significantly increasing maximum temperature during the post-monsoon season may result in higher evaporation, crop transpiration and evapotranspiration losses from the water-short arid region, and consequently, the aridity will be increased. Furthermore, rise in the maximum temperature in the southern and southwest portions in the study area may shorten the crop duration due to increased metabolic activities inside the plants. This may further reduce biomass and yield because of increased respiration, reduced photosynthesis and cellular energy in the crop plants of the arid regions.

3.5 Trends in Minimum Temperature Series

Results of trend tests for the minimum temperature of 31 grids are geographically shown in Fig. 4. In annual minimum temperature series, the KRC, MK, SROC and ITA tests identified statistically-significant increasing trends for all 31 grids (100%) at α=0.01. However, the MK-CF$_1$, MK-CF$_2$, MK-CF$_3$ and MK-PW tests revealed trends for 31 (100%), 30 (97%), 28 (90%) and 28 (90%) grids, respectively, at α=0.05, and 28 (90%), 15 (48%), 19 (61%) and 13 (42%) grids, respectively, at α=0.01 (Fig. 4).

In case of pre-monsoon season (Fig. 4), the KRC, MK, SROC and ITA tests evidenced the significant trends in the minimum temperature series of 30 (97%), 30 (97%), 30 (97%) and 31 (100%) grids, respectively, at α=0.01. Whereas, the MK-CF$_1$, MK-CF$_2$, MK-CF$_3$ and MK-PW tests confirmed presence of the statistically-significant trends for 30 (97%), 21 (67%), 28 (90%) and 17 (55%) grids at α=0.05, and for 28 (90%), 10 (32%), 1 (3%) and 0 (0%), respectively, at α=0.01. The minimum temperature series in monsoon season exhibited the significantly increasing trends (α=0.05) for 29 (94%), 31 (100%), 29 (94%), 25 (81%), 25 (81%), 20 (64%), 21 (67%) and 31 (100%) grids based on the results of the KRC, SROC, MK, MK-CF$_1$, MK-CF$_2$, MK-CF$_3$, MK-PW and ITA tests, respectively (Fig. 4). At α=0.01, the KRC, SROC, MK, MK-CF$_1$, MK-CF$_2$, MK-CF$_3$, MK-PW and ITA tests revealed the significant trends for 21 (68%), 27 (87%), 21 (68%), 21 (68%), 20 (65%), 10 (32%), 15

(48%) and 31 (100%) grids, respectively. During post-monsoon, the minimum temperature trends are found to be significantly increasing at $\alpha=0.05$ over the entire 31 grids from results of the KRC, SROC and MK tests, and at $\alpha=0.01$ from the ITA test (Fig. 4). The significant trends are revealed from the MK-CF$_1$, MK-CF$_2$, MK-CF$_3$ and MK-PW tests at $\alpha=0.01$ for 30 (97%), 19 (61%), 26 (84%) and 17 (55%) grids, respectively. The statistically-significant rising trends ($\alpha=0.05$) of the minimum temperature in winter season are perceived from the results of the KRC, SROC, MK, MK-CF$_1$, MK-CF$_2$, MK-PW and ITA tests for 27 (88%), 30 (97%), 26 (84%), 27 (87%), 27 (87%), 24 (77%) and 31 (100%) grids, respectively (Fig. 4). Among these rising trends, the most significant trends at $\alpha=0.01$ are present for 20 (65%), 23 (74%), 20 (65%), 11 (35%), 10 (32%) and 31 (100%) grids detected by the KRC, SROC, MK, MK-CF$_1$, MK-CF$_2$ and ITA tests, respectively.

The above interpretation clearly suggested that the KRC and MK tests yielded exactly similar results, which are in close agreement to the results of the SROC test that does not convey about the nature of trend (positive or negative). Furthermore, it is clearly seen that either number of grid points having statistically-significant trends or their statistical-significance decreases in case of modified MK tests (MK-CF$_1$, MK-CF$_2$, MK-CF$_3$ and MK-PW) in comparison to those identified by MK and KRC tests (Fig. 4), which is attributed to the effect of serial correlation on the power of the MK test. On the other hand, the results of the ITA test are thoroughly similar to the results of KRC and MK tests for the minimum temperature series of annual, pre-monsoon and post-monsoon seasons. However, there is disagreement between the results of the ITA and MK tests for monsoon and winter seasons (Fig. 4). The ITA test is found to be the over-sensitive in detecting the trend significance due to detection of the statistically-significant trends at all the grids at $\alpha=0.01$. In most cases, the significant trends detected by the MK-CF$_1$ and MK-CF$_2$ tests are found in close agreement to each other, which may also be considered as the precise in identifying the actual trends. Therefore, use of the modified MK tests based on variance correction approach, i.e. MK-CF$_1$ and MK-CF$_2$ is recommended for trend detection in the climatologic time series.

In comparison to the maximum temperature, the increasing trends are more significant and prominent in the minimum temperature at relatively large number of grid points in the area. An increase in the minimum temperature causes respiration to overtake the photosynthesis process in crop plants, which restricts the plant growth and development leading to reduction in dry matter accumulation and crop yields.

3.6 Trends in Annual and Monsoon Rainfall Series

Results of all trend tests indicating significant and non-significant trends in annual and monsoon season rainfall are presented in Fig. 5. In annual rainfall time series, the significantly increasing trends at $\alpha=0.10$ are evident for 27 (87%), 31 (100%), 27 (88%), 22 (71%), 14 (45%) and 26 (82%) grids from the results of the KRC, SROC, MK, MK-CF$_1$, MK-CF$_2$ and MK-PW tests, respectively (Fig. 5). However, at $\alpha=0.05$, 22 (71%), 28 (91%), 20 (65%), 3 (10%) and 9 (29%) grids were having significantly increasing trends based on the results of the KRC, SROC, MK, MK-CF$_1$ and MK-PW tests, respectively. The ITA is the only test that resulted in the most-significant (α=0.01) rising trends at 31 (100%) grids in the area.

Likewise, the statistically-significant rising trends at α=0.10 are unveiled in the monsoon season rainfall for 27 (87%), 30 (97%), 27 (87%), 12 (38%), 9 (29%) and 19 (58%) grids from the results of the KRC, SROC, MK, MK-CF$_1$, MK-CF$_2$ and MK-PW tests, respectively. (Fig. 5) Whereas, the significantly increasing trends at α=0.05 reduced to 14 (45%), 29 (94%), 14 (45%), 1 (3%), 0 (0%) and 1 (3%) according to results of the KRC, SROC, MK, MK-CF$_1$, MK-CF$_2$ and MK-PW tests, respectively. The increasing trends at all 31 grids were found to be the most-significantly increasing at α=0.01 from the results of the ITA test.

Here, it is further confirmed that the results of the KRC and MK tests are almost similar (Fig. 5), which is also observed in case of minimum and maximum temperature series. These findings are also reported in the literature for the rainfall time series in arid and semi-arid regions of India (Machiwal and Jha, 2016; Machiwal et al., 2016b). The results obtained from the MK-CF$_3$ test depicted that the increasing trends in both the annual and monsoon season rainfall are non-significant at all the grids, which is in sharp contrast to the highly-sensitive ITA test indicating very significantly rising trends (α=0.01) at all the grids (Fig. 5). Also, number of the significantly increasing trends identified by the MK-CF$_1$ and MK-CF$_2$ tests decreased as compared to those detected by the MK test. Hence, the presence of serial correlation affected the performance of the MK test also in case of annual and monsoon season rainfall. Therefore, two modified MK tests, i.e. MK-CF$_1$ and MK-CF$_2$ that consider the variance correction approach are suggested to be certainly employed among the more than two tests for identifying the correct trends in the hydrologic and/or climatologic time series in future studies. Furthermore, the significant increase in the rainfall during the monsoon season is mainly due to climate variability resulting high-intensity and short-duration rainy events in the area (Vivekanandan et al., 2008). The significant rise in rainfall may also be due to cyclones with increased intensity hitting to the coastal land (GEC, 2011), rising sea surface temperature (Rao and Vivekanandan, 2008), and/or cosmic influence on the sun-earth environment (Mukherjee, 2008). Besides, natural disaster like earthquake frequently-occurring in this seismic-prone zone is also reported to be a likely cause for increasing rainfall trends (Trivedi et al., 2014). The significantly increasing rainfall trends are also reported in few earlier studies for the arid regions of Rajasthan (Basistha et al., 2007; Kharol et al., 2013) as well as for other arid lands of India (Guhathakurta and Rajeevan, 2006). The runoff generated from such rainy events easily escape out of the area, and therefore, suitable rainwater harvesting techniques need to be implemented in order to harvest that rainwater and use it for providing supplemental irrigation to winter season crops. Also, in increasing rainfall areas, long duration and high-yielding crop varieties may be suggested.

3.7 Magnitudes of Temperature and Rainfall Trends

The magnitudes of the increasing/decreasing trends in the annual and seasonal time series of minimum temperature, maximum temperature and rainfall computed from the Sen's slope test are presented for 31 grids in Tables 1-3. It is seen from Table 1 that the annual maximum temperature is increasing at a rate ranging from 0.016 to 0.023 degree year^{-1} with the mean value of 0.021 degree year^{-1}. Whereas, the maximum temperature in the pre-monsoon, monsoon, post-monsoon and winter seasons is increasing at rates varying from 0.013-0.024, -0.032-0.001, 0.017-0.031 and 0.024-0.042 degree year^{-1}, respectively with their corresponding mean values of 0.018, -0.018, 0.026 and 0.033 degree year^{-1}, respectively. It is noticed that the maximum temperature has negative magnitudes in the monsoon season at 30 of total 31 grid points, which indicate that the trends area decreasing in monsoon season.

Similarly, the annual minimum temperature is found to be inclining at a mean rate ranging from 0.028 to 0.060 degree year^{-1} with the mean value of 0.046 degree year^{-1} (Table 2). Likewise, the magnitudes of the minimum temperature are observed to be the increasing in the pre-monsoon, monsoon, post-monsoon and winter seasons within 0.028-0.063, 0.015-0.044, 0.034-0.069 and 0.032-0.089 degree year^{-1} with the mean rates of 0.049, 0.028, 0.054 and 0.058 degree year^{-1}, respectively.

Moreover, the annual rainfall in the area is increasing at a magnitude of 4-13 mm year^{-1} with the mean increment of 9 mm year^{-1} whereas the monsoon rainfall is increasing at a rate ranging from 3-13 mm year^{-1} with the mean value of 9 mm year^{-1} (Table 3).

3.8 Trend Significance in Sequential Temperature and Rainfall Time Series

The MK test-statistic values (z) were determined for the maximum temperature, minimum temperature and rainfall series of the sequential time periods ranging from 22 to 35 years for the annual and all seasons. The test-statistic values, plotted in the form of bar charts against the sequentially increasing time periods for all 31 grid points, were fitted with straight lines and R^2 values were computed. The computed R^2 values of all kind of temperature and rainfall time series for 31 grids are summarized in Table 4. Also, the bar charts of MK test-statistic values drawn at the annual and seasonal scales for the temperature and rainfall series are illustrated in Fig. 6, as an example, for the selected grid point having the maximum R^2 value.

It is observed from Table 4 that the R^2 value for the annual maximum temperature ranges from 0.001 to 0.48. Likewise, the R^2 value for the pre-monsoon, monsoon, post-monsoon and winter season varied from 0.10-0.56, 0.05-0.93, 0.0003-0.55 and 0.04-0.33, respectively. Furthermore, in monsoon season, the sequential significance of the linear trend in z-statistic values was found to be strong ($R^2 \geq 0.75$) at 21 (68%) grids and moderate ($R^2 \geq 0.50$) at 4 (13%) grids. However, the linear trends of moderate nature ($R^2 \geq 0.50$) were seen for single grid in case of pre-monsoon season and for 9 (29%) grids in post-monsoon season. None of the grid could reveal moderately linear trend in annual and winter season maximum temperature as R^2 value was always less than 0.50.

The R^2 value for the annual minimum temperature varies from 0.50-0.99 whereas for the pre-monsoon, monsoon, post-monsoon and winter seasons, it ranges from 0.62-0.98, 0-0.97, 0.50-0.90 and 0.19-0.81, respectively (Table 4). In annual series, all the grid points evidenced either very strong sequential significance ($R^2 \geq 0.90$ at 28 grids) or moderate significance ($R^2 \geq 0.50$ at 3 or 10% grids) of the linearly increasing trend in the z-statistic values over time. The very similar pattern of R^2 values is seen in case of the pre-monsoon season. In monsoon season, the sequential trend significance is strong ($R^2 \geq 0.75$) at 20 (65%) grids and moderate ($R^2 \geq 0.50$) at one grid point while the sequential significance is strong ($R^2 \geq 0.75$) at 17 (55%) grids and moderate ($R^2 \geq 0.50$) at 14 (45%) grids in post-monsoon season. In winter season, the sequential z-statistic values showed strong ($R^2 \geq 0.75$) and moderate ($R^2 \geq 0.50$) statistical significance at 15 (48%) and 8 (26%) grids, respectively.

The statistical significance of sequential z-statistics of the annual rainfall is strong ($R^2 \geq 0.75$) at 21 (68%) grids and moderate ($R^2 \geq 0.50$) at 7 (23%) grids (Table 4). Almost similar pattern is observed for the monsoon season rainfall where sequential z-statistics showed strongly significant trends ($R^2 \geq 0.75$) at 19 (61%) grids and moderate significant trends ($R^2 \geq 0.50$) at 10 (32%) grids.

The strong and moderate R^2 values in the z-statistic values at most of the grid points for the temperature and rainfall series indicate that the presence of the significantly linear increasing trends. Hence, it is evident that not only the trends in the temperature series of the Kachchh arid region are increasing but also the statistical significance of the increasing trends is inclining significantly.

This study presented the spatial patterns of the variability and trends of two climatic factors, i.e., temperature and rainfall, in an arid region of India. It is apparent from the findings of this study that climate is significantly changing in the area, which may have substantial impacts on agricultural production and food security. The climate variability is more prominent towards the coastal areas making it difficult to predict future climate scenarios and manage agricultural practices. The spatial locations identified in this study should be taken into consideration by the policymakers and planners when formulating strategies to manage agricultural production under climate change in the region. Furthermore, looking at the more complex climate dynamics in the coastal areas than the inland areas, more meteorological stations should be deployed in the weather-sensitive coastal region to improve accuracy of climate predictions.

4. CONCLUSIONS

This study comparatively evaluated performance of eight statistical tests to identify significant trends in rainfall and temperature series at annual and seasonal scales of 31 grid points in arid Kachchh district of India. The trends are examined by applying eight trend tests including Kendall rank correlation (KRC), Spearman rank order correlation (SROC), Mann-Kendall (MK) and modified MK considering pre-whitening (PW) and three variance correction (VC) approaches along with innovative trend analysis (ITA) method. The box and whisker plots of the annual rainfall and temperature depicted systematic spatial gradients. The median values of the maximum temperature increases while moving from west to east and from south to north directions, whereas the minimum temperature initially declines from west to east for 3 grids, and afterwards, it generally inclines from west to east. On the other hand, the annual rainfall decreases from west to east for the southern coastal boundary, and then on moving towards northern inland, it increases from west to east. The significant serial correlation is prominent in both the maximum temperature and minimum temperature of annual (97 and 100% grids, respectively) and post-monsoon season (100 and 81% grids, respectively), and in pre-monsoon season (94% grids) minimum temperature data. In contrast to temperatures, the serial correlation is present at relatively less number of sites in case of annual and monsoon season rainfall, i.e. 32 and 35% of the grids, respectively. Results of the KRC and MK tests are exactly similar to each other with great coherence to the results of the SROC test. The number of significant trends identified by the MK test in temperature and rainfall series decreases in case of the modified MK tests with PW and VC approaches, which suggests that the MK test does not perform adequately in presence of the serial correlation. Hence, it is emphasized to include the modified MK tests with variance correction approaches, i.e. MK-CF$_1$ and MK-CF$_2$ to take care for the presence of serial correlation in the hydrologic and/or climatologic time series. The significantly increasing trends in the maximum temperature were mostly visible in the southern and southwest portions having the coastal boundary. The ITA method did not perform satisfactorily in this study as revealed from the most significant trends in almost all the temperature and rainfall time series at all the grid points due to its over-sensitiveness in detecting trends. Comparatively, the significantly increasing trends are more apparent in the minimum temperature than in the maximum temperature. The trend magnitudes in the maximum temperature ranged from 0.016-0.023, 0.013-0.024, -0.032-0.001, 0.017-0.031 and 0.024-0.042 degree year^{-1}, respectively for the annual, pre-monsoon, monsoon, post-monsoon and winter seasons. Likewise, the minimum temperature is increasing at rates varying from 0.028 to 0.060, 0.028-0.063, 0.015-0.044, 0.034-0.069 and 0.032-0.089 degree year^{-1}, respectively during the annual, pre-monsoon, monsoon, post-monsoon and winter seasons. The rainfall is found to increase at the rate within 4-13 mm year^{-1} and 3-13 mm year^{-1} in annual and monsoon season series with the mean rate of 9 mm year^{-1}. The sequential values of the MK test-statistics are found to have a strongly significant linear trend in the monsoon season maximum temperature at 21 (68%) grids as revealed from the values of coefficient of determination ($R^2 \geq 0.75$). In case of minimum temperature, the significance of sequential linear trend is very strong ($R^2 \geq 0.90$) in annual and pre-monsoon series for 28 (90%) grids, strong ($R^2 \geq 0.75$) in monsoon, post-monsoon and winter seasons for 20 (65%), 17 (55%) and 15 (48%) grids, respectively. On the contrary, the linear trend in the MK test-statistics over sequential periods is observed to be the strongly significant in the annual and monsoon rainfall series at 21 (68%) and 19 (61%) grids, respectively. This finding clearly indicates that the statistical significance of the rising trends in the temperature and rainfall is increasing in the arid Kachchh region, which suggests that the trends may be more significant in the coming years.

Based on the findings of this study, it is emphasized that water resources and agriculture both are at the great risk under the changing climate of arid Kachchh region of India. The rise in the maximum temperature may enhance metabolic activities of the plants and shorten the crop duration, which may ultimately leads to reduced crop yields. Likewise, the inclining minimum temperature may boost crop respiration with reduced photosynthesis that may result in poor biomass and grain yield. On the other hand, the areas experiencing the surplus rainfall will need to have adequate rainwater harvesting structures in order to store large quantities of runoff water generated from the high-intensity rainfall storms in the water-scarce region, and to use the stored water as supplemental irrigation during dry periods. Moreover, the findings of this study is useful for the regional scientific and international scientific communities for formulating appropriate strategies in order to mitigate with the scenario of changing climate in the arid regions of India and other parts of the world.

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Table 1. Results of statistical tests comparing gridded data of annual rainfall with that of meteorological stations in Kachchh (1980-2013)

Test	**Blocks Represented by Meteorological Stations**									
	Abdasa	**Anjar**	**Bhachau**	**Bhuj**	**Gandhidham**	**Lakhpat**	**Mandvi**	**Mundra**	**Nakhatrana**	**Rapar**
Correlation Coefficient (r)	0.5	0.6	0.5	0.5	0.4	0.4	0.7	0.6	0.5	0.7
t-Test for significance of ‘r’	3.36	4.12	3.47	3.05	1.58[a]	2.17	4.84	4.07	3.30	6.16
t-Test (Critical)	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
t-Test for Similar Means	-0.89	-1.67	-1.81[b]	-1.08	-1.44	0.41	-1.56	-0.53	-0.75	-1.45
t-Test (Critical)	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
F-Test for Similar Variances	1.61	2.33[c]	1.49	1.04	2.39[c]	1.30	1.06	1.50	1.46	1.88[c]
F-Test (Critical)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8

Note: [a] indicates ‘r’ is non-significant; [b] indicates dissimilar means; and [c] indicates dissimilar variances.

Table 2. Serial correlation and trend magnitudes in maximum temperature (1979-2013) at 31 stations

Station	**Annual**		**Pre-Monsoon**		**Monsoon**		**Post-Monsoon**		**Winter**	
	r_1	**Q_{med} (degree year^{-1})**	**r_1**	**Q_{med} (degree year^{-1})**	**r_1**	**Q_{med} (degree year^{-1})**	**r_1**	**Q_{med} (degree year^{-1})**	**r_1**	**Q_{med} (degree year^{-1})**
1	0.40*	0.021	0.39*	0.015	0.07	0.001	0.59*	0.022	-0.03	0.024
2	0.35*	0.022	0.21	0.017	0.07	-0.008	0.47*	0.030	-0.03	0.031
3	0.34*	0.020	0.18	0.016	0.09	-0.015	0.44*	0.030	-0.02	0.035
4	0.35*	0.020	0.24	0.015	0.09	-0.020	0.46*	0.030	-0.01	0.034
5	0.30*	0.020	0.19	0.015	0.07	-0.023	0.39*	0.031	-0.02	0.038
6	0.46*	0.020	0.50*	0.016	0.11	-0.001	0.69*	0.020	-0.01	0.027
7	0.26*	0.019	0.10	0.018	0.03	-0.008	0.42*	0.030	-0.03	0.037
8	0.28*	0.021	0.09	0.021	0.07	-0.016	0.41*	0.031	-0.01	0.039
9	0.29*	0.021	0.09	0.020	0.09	-0.024	0.43*	0.029	-0.002	0.038
10	0.27*	0.021	0.11	0.022	0.07	-0.023	0.41*	0.030	-0.002	0.041
11	0.24	0.022	0.12	0.024	0.05	-0.022	0.35*	0.030	-0.01	0.042
12	0.26*	0.023	0.12	0.024	0.06	-0.026	0.34*	0.031	-0.01	0.041
13	0.42*	0.019	0.34*	0.013	0.11	-0.032	0.48*	0.026	0.004	0.036
14	0.64*	0.023	0.68*	0.013	0.33*	0.005	0.80*	0.017	0.08	0.024
15	0.48*	0.021	0.50*	0.014	0.16	-0.006	0.67*	0.024	-0.001	0.029
16	0.39*	0.016	0.31*	0.015	0.12	-0.014	0.56*	0.027	0.0003	0.029
17	0.34*	0.021	0.18	0.017	0.09	-0.021	0.51*	0.028	0.01	0.033
18	0.32*	0.020	0.13	0.018	0.08	-0.024	0.51*	0.027	0.01	0.032
19	0.42*	0.023	0.28*	0.017	0.13	-0.028	0.60*	0.023	0.03	0.035
20	0.64*	0.022	0.61*	0.018	0.32*	-0.027	0.74*	0.024	0.12	0.035
21	0.49*	0.022	0.40*	0.018	0.16	-0.028	0.58*	0.027	0.04	0.035
22	0.40*	0.022	0.28*	0.016	0.09	-0.029	0.47*	0.029	0.01	0.035
23	0.68*	0.023	0.69*	0.016	0.43*	-0.002	0.79*	0.021	0.11	0.025
24	0.68*	0.020	0.68*	0.019	0.44*	-0.008	0.80*	0.025	0.12	0.024
25	0.68*	0.017	0.67*	0.019	0.43*	-0.020	0.80*	0.021	0.12	0.025
26	0.70*	0.018	0.67*	0.018	0.46*	-0.024	0.81*	0.024	0.15	0.027
27	0.69*	0.019	0.66*	0.020	0.45*	-0.022	0.81*	0.023	0.15	0.029
28	0.65*	0.020	0.61*	0.019	0.36*	-0.025	0.79*	0.023	0.13	0.030
29	0.69*	0.022	0.66*	0.018	0.41*	-0.022	0.80*	0.023	0.16	0.032
30	0.68*	0.022	0.66*	0.019	0.38*	-0.027	0.77*	0.027	0.15	0.035
31	0.63*	0.022	0.60*	0.018	0.28*	-0.026	0.70*	0.028	0.09	0.036

Note: r1 is serial correlation coefficient at lag-1; Q_{med} is trend magnitude by Sen's slope estimator; * indicates presence of significant serial correlation.

Table 3. Serial correlation and trend magnitudes in minimum temperature (1979-2013) at 31 stations

Station	Annual		Pre-Monsoon		Monsoon		Post-Monsoon		Winter	
	r_1	Q_{med} (degree year^{-1})	r_1	Q_{med} (degree year^{-1})	r_1	Q_{med} (degree year^{-1})	r_1	Q_{med} (degree year^{-1})	r_1	Q_{med} (degree year^{-1})
1	0.51*	0.046	0.47*	0.044	0.14	0.034	0.54*	0.051	0.05	0.045
2	0.44*	0.036	0.32*	0.038	0.12	0.022	0.38*	0.046	0.01	0.034
3	0.39*	0.029	0.27*	0.035	0.11	0.016	0.00	0.040	-0.01	0.032
4	0.39*	0.032	0.32*	0.041	0.11	0.017	0.27*	0.040	-0.02	0.033
5	0.39*	0.034	0.33*	0.042	0.11	0.018	0.23	0.044	-0.03	0.033
6	0.57*	0.051	0.56*	0.051	0.17	0.036	0.61*	0.064	0.10	0.055
7	0.45*	0.037	0.27*	0.035	0.14	0.025	0.38*	0.051	0.02	0.038
8	0.40*	0.030	0.23	0.029	0.14	0.018	0.28*	0.039	0.01	0.034
9	0.38*	0.028	0.24	0.028	0.14	0.017	0.22	0.034	0.01	0.032
10	0.37*	0.028	0.26*	0.035	0.13	0.017	0.19	0.038	-0.01	0.037
11	0.37*	0.032	0.29*	0.038	0.12	0.018	0.20	0.041	-0.02	0.042
12	0.36*	0.032	0.27*	0.036	0.11	0.015	0.20	0.043	-0.03	0.043
13	0.44*	0.045	0.36*	0.048	0.10	0.015	0.40*	0.060	0.05	0.063
14	0.67*	0.052	0.70*	0.053	0.20	0.040	0.71*	0.062	0.23	0.069
15	0.57*	0.055	0.52*	0.055	0.18	0.035	0.57*	0.066	0.10	0.061
16	0.51*	0.051	0.41*	0.052	0.16	0.029	0.47*	0.063	0.06	0.056
17	0.47*	0.048	0.39*	0.049	0.16	0.025	0.41*	0.058	0.04	0.051
18	0.44*	0.046	0.41*	0.049	0.15	0.022	0.37*	0.057	0.03	0.051
19	0.51*	0.054	0.53*	0.055	0.15	0.025	0.48*	0.061	0.10	0.071
20	0.65*	0.056	0.68*	0.062	0.17	0.033	1.00*	0.062	0.32*	0.079
21	0.51*	0.050	0.50*	0.055	0.13	0.019	0.46*	0.058	0.12	0.066
22	0.43*	0.045	0.39*	0.050	0.11	0.015	0.35*	0.054	0.04	0.059
23	0.69*	0.057	0.72*	0.058	0.23	0.044	0.70*	0.065	0.28*	0.081
24	0.70*	0.060	0.73*	0.061	0.24	0.043	0.70*	0.069	0.30*	0.088
25	0.69*	0.060	0.73*	0.063	0.23	0.041	0.70*	0.065	0.30*	0.089
26	0.71*	0.060	0.76*	0.063	0.24	0.041	0.72*	0.064	0.36*	0.089
27	0.70*	0.058	0.75*	0.063	0.22	0.039	0.72*	0.060	0.37*	0.085
28	0.65*	0.056	0.71*	0.061	0.18	0.036	0.67*	0.059	0.29*	0.078
29	0.68*	0.054	0.73*	0.061	0.19	0.037	0.69*	0.058	0.36*	0.073
30	0.67*	0.052	0.71*	0.058	0.17	0.034	0.68*	0.056	0.35*	0.072
31	0.60*	0.049	0.63*	0.057	0.14	0.030	0.60*	0.058	0.23	0.072

Note: r1 is serial correlation coefficient at lag-1; Q_{med} is trend magnitude by Sen's slope estimator; * indicates presence of significant serial correlation.

Table 4. Serial correlation and trend magnitudes in rainfall (1979-2013) at 31 stations

Station	**Annual**		**Monsoon**	
	r_1	**Q_{med} (mm year^{-1})**	**r_1**	**Q_{med} (mm year^{-1})**
1	0.15	9	0.18	8
2	0.25	11	0.28*	11
3	0.35*	12	0.37*	11
4	0.36*	11	0.38*	12
5	0.33*	11	0.35*	12
6	0.16	7	0.16	6
7	0.19	9	0.21	9
8	0.34*	11	0.35*	12
9	0.40*	12	0.41*	11
10	0.35*	13	0.36*	12
11	0.32*	11	0.32*	13
12	0.35*	13	0.34*	13
13	0.32*	12	0.32*	11
14	0.15	5	0.11	3
15	0.16	6	0.13	5
16	0.18	9	0.17	8
17	0.22	10	0.21	9
18	0.21	9	0.23	9
19	0.24	10	0.25	10
20	0.27*	12	0.27*	12
21	0.25	12	0.25	12
22	0.20	10	0.20	10
23	0.14	4	0.12	3
24	0.16	5	0.12	5
25	0.16	5	0.14	5
26	0.15	6	0.13	6
27	0.18	7	0.17	7
28	0.16	8	0.16	8
29	0.11	7	0.11	8
30	0.10	7	0.10	8
31	0.12	7	0.12	8

Note: r1 is serial correlation coefficient at lag-1; Q_{med} is trend magnitude by Sen's slope estimator; * indicates presence of significant serial correlation.

Table 5. Values of coefficient of determination (R^2) indicating significance of sequential trends in the MK test-statistics

Station	Maximum Temperature					Minimum Temperature					Rainfall	
	Annual	Pre-Monsoon	Monsoon	Post-Monsoon	Winter	Annual	Pre-Monsoon	Monsoon	Post-Monsoon	Winter	Annual	Monsoon
1	0.28	0.10	0.23	0.51#	0.30	0.98*	0.97*	0.93*	0.78*	0.63#	0.92*	0.89*
2	0.39	0.14	0.83*	0.47	0.29	0.98*	0.95*	0.88*	0.75*	0.68#	0.89*	0.84*
3	0.43	0.10	0.87*	0.34	0.20	0.90*	0.91*	0.09	0.63#	0.65#	0.88*	0.84*
4	0.42	0.12	0.89*	0.25	0.12	0.94*	0.93*	0.10	0.64#	0.67#	0.92*	0.90*
5	0.41	0.20	0.93*	0.07	0.07	0.95*	0.91*	0.13	0.66#	0.62#	0.93*	0.91*
6	0.10	0.15	0.15	0.52#	0.33	0.98*	0.98*	0.94*	0.86*	0.65#	0.84*	0.81*
7	0.33	0.31	0.71#	0.50#	0.09	0.98*	0.95*	0.89*	0.90*	0.58#	0.85*	0.80*
8	0.42	0.38	0.83*	0.38	0.12	0.74#	0.70#	0.21	0.81*	0.31	0.89*	0.85*
9	0.48	0.35	0.88*	0.31	0.11	0.50#	0.62#	0.01	0.63#	0.19	0.85*	0.84*
10	0.42	0.40	0.88*	0.10	0.08	0.72#	0.76*	0.03	0.61#	0.49	0.85*	0.86*
11	0.40	0.47	0.93*	0.0003	0.04	0.93*	0.89*	0.01	0.73#	0.65#	0.94*	0.92*
12	0.35	0.56#	0.92*	0.002	0.06	0.92*	0.87*	0.00007	0.78*	0.75*	0.97*	0.95*
13	0.38	0.22	0.93*	0.05	0.11	0.93*	0.90*	0.001	0.74	0.79*	0.96*	0.94*
14	0.001	0.21	0.09	0.51#	0.25	0.99*	0.97*	0.95*	0.83*	0.76*	0.64#	0.66#
15	0.10	0.22	0.17	0.53#	0.25	0.99*	0.97*	0.96*	0.85*	0.81*	0.74#	0.67#
16	0.16	0.22	0.71#	0.53#	0.22	0.99*	0.97*	0.95*	0.84*	0.78*	0.76*	0.69#
17	0.30	0.25	0.82*	0.40	0.17	0.99*	0.96*	0.87*	0.83*	0.71#	0.78*	0.73#
18	0.31	0.33	0.87*	0.24	0.17	0.98*	0.93*	0.77*	0.80*	0.70#	0.81*	0.81*
19	0.31	0.23	0.89*	0.20	0.16	0.97*	0.92*	0.86*	0.77*	0.76*	0.76*	0.83*
20	0.29	0.20	0.90*	0.16	0.13	0.96*	0.92*	0.93*	0.73#	0.77*	0.85*	0.89*
21	0.30	0.17	0.92*	0.11	0.10	0.95*	0.90*	0.60#	0.71#	0.76*	0.94*	0.92*
22	0.33	0.16	0.91*	0.06	0.11	0.94*	0.90*	0.05	0.50#	0.79*	0.94*	0.93*
23	0.02	0.16	0.05	0.54#	0.21	0.99*	0.97*	0.97*	0.84*	0.77*	0.52#	0.53#
24	0.01	0.23	0.18	0.51#	0.15	0.99*	0.97*	0.97*	0.86*	0.78*	0.42	0.45
25	0.09	0.24	0.57#	0.55#	0.19	0.99*	0.97*	0.96*	0.82*	0.77*	0.57#	0.56#
26	0.23	0.29	0.66#	0.42	0.18	0.99*	0.95*	0.96*	0.75*	0.78*	0.48	0.52#
27	0.16	0.24	0.79*	0.37	0.16	0.98*	0.92*	0.95*	0.78*	0.72#	0.50#	0.47
28	0.20	0.24	0.82*	0.24	0.20	0.97*	0.91*	0.94*	0.70#	0.71#	0.62#	0.64#
29	0.26	0.20	0.84*	0.23	0.15	0.96*	0.92*	0.94*	0.69#	0.75*	0.71#	0.74#
30	0.29	0.17	0.86*	0.18	0.14	0.94*	0.90*	0.90*	0.62#	0.73#	0.77*	0.77*
31	0.33	0.14	0.83*	0.14	0.17	0.93*	0.86*	0.83*	0.55#	0.75*	0.68	0.72#

Note: * indicates presence of strongly significant ($R^2 \geq 0.75$) linear trend; # indicates presence of moderately significant ($R^2 \geq 0.50$) linear trend.

Figure Caption

Fig. 1. Location map of study area along with data stations

Fig. 2. Box-whisker plots of 35-year (a) annual maximum temperature, (b) annual minimum temperature and (c) annual rainfall for 31 stations

Fig. 3. Results of eight trend identification tests showing presence of non-significant (ns) and significant increasing/decreasing trends in annual and seasonal maximum temperature at three level of significance (ls) for 31 stations

Fig. 4. Results of eight trend identification tests showing presence of non-significant (ns) and significant increasing/decreasing trends in annual and seasonal minimum temperature at three level of significance (ls) for 31 stations

Fig. 5. Results of eight trend identification tests showing presence of non-significant (ns) and significant increasing/decreasing trends in annual and monsoon rainfall at three level of significance (ls) for 31 stations

Fig. 6. Barcharts of the Mann-Kendall test-statistic values over sequential periods and fitted linear trend line for the annual and seasonal temperature (maximum and minimum) and rainfall for the stations showing the highest coefficient of determination (R^2) values

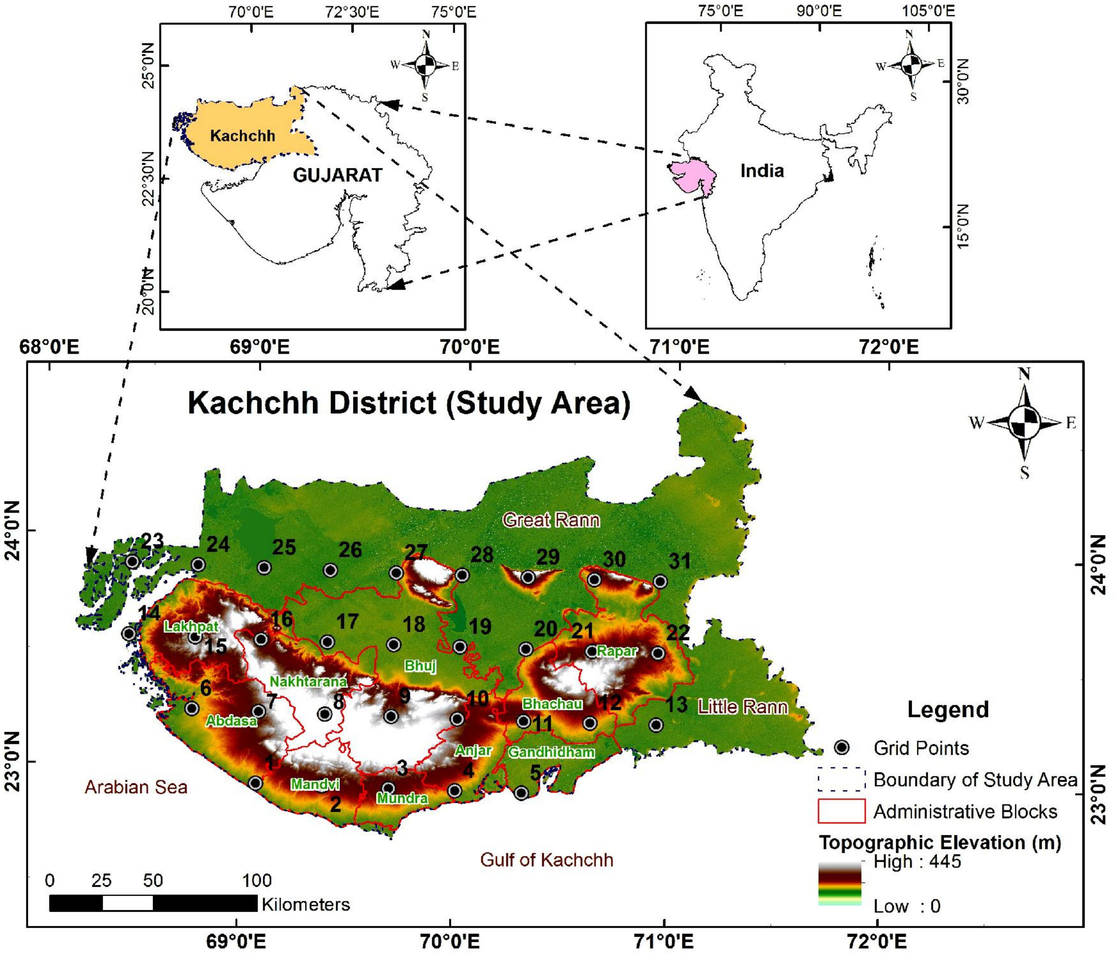

70°0'E
72°30'E
75°0'E
25°0'N
22°30'N
20°0'N
Kachchh
GUJARAT
N
W
E
S
75°0'E
90°0'E
105°0'E
30°0'N
15°0'N
India
68°0'E
69°0'E
70°0'E
71°0'E
72°0'E
24°0'N
23°0'N
Kachchh District (Study Area)
Great Rann
Little Rann
Arabian Sea
Gulf of Kachchh
Lakhpat
Nakhtarana
Bhuj
Abdasa
Mandvi
Mundra
Anjar
Bhachau
Gandhidham
Rapar
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
Legend
Grid Points
Boundary of Study Area
Administrative Blocks
Topographic Elevation (m)
High : 445
Low : 0
0
25
50
100
Kilometers

Figure 1

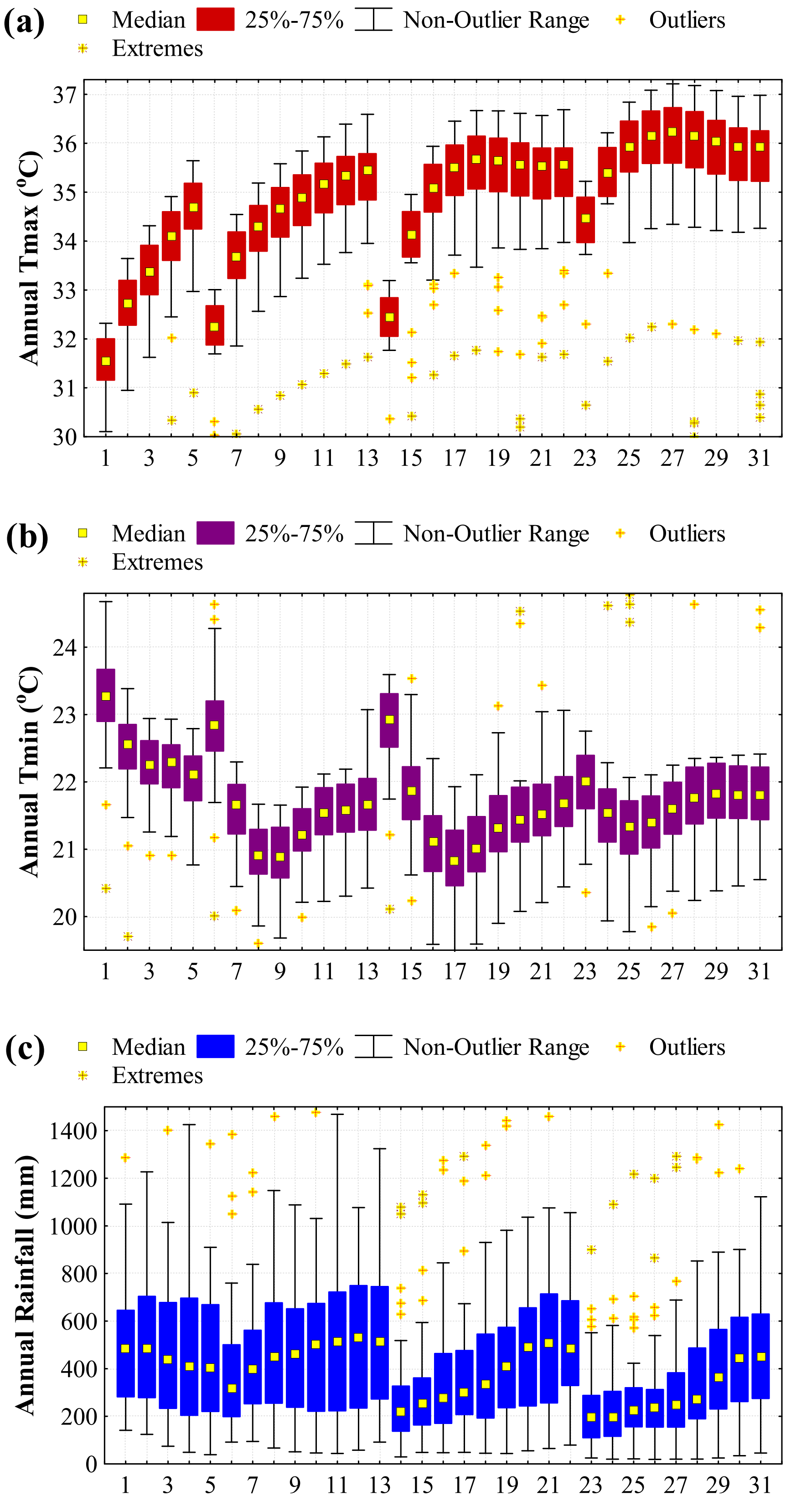

(a)
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Annual Tmax (ºC)
30
31
32
33
34
35
36
37
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
(b)
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Annual Tmin (ºC)
20
21
22
23
24
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
(c)
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Annual Rainfall (mm)
0
200
400
600
800
1000
1200
1400
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31

Figure 2

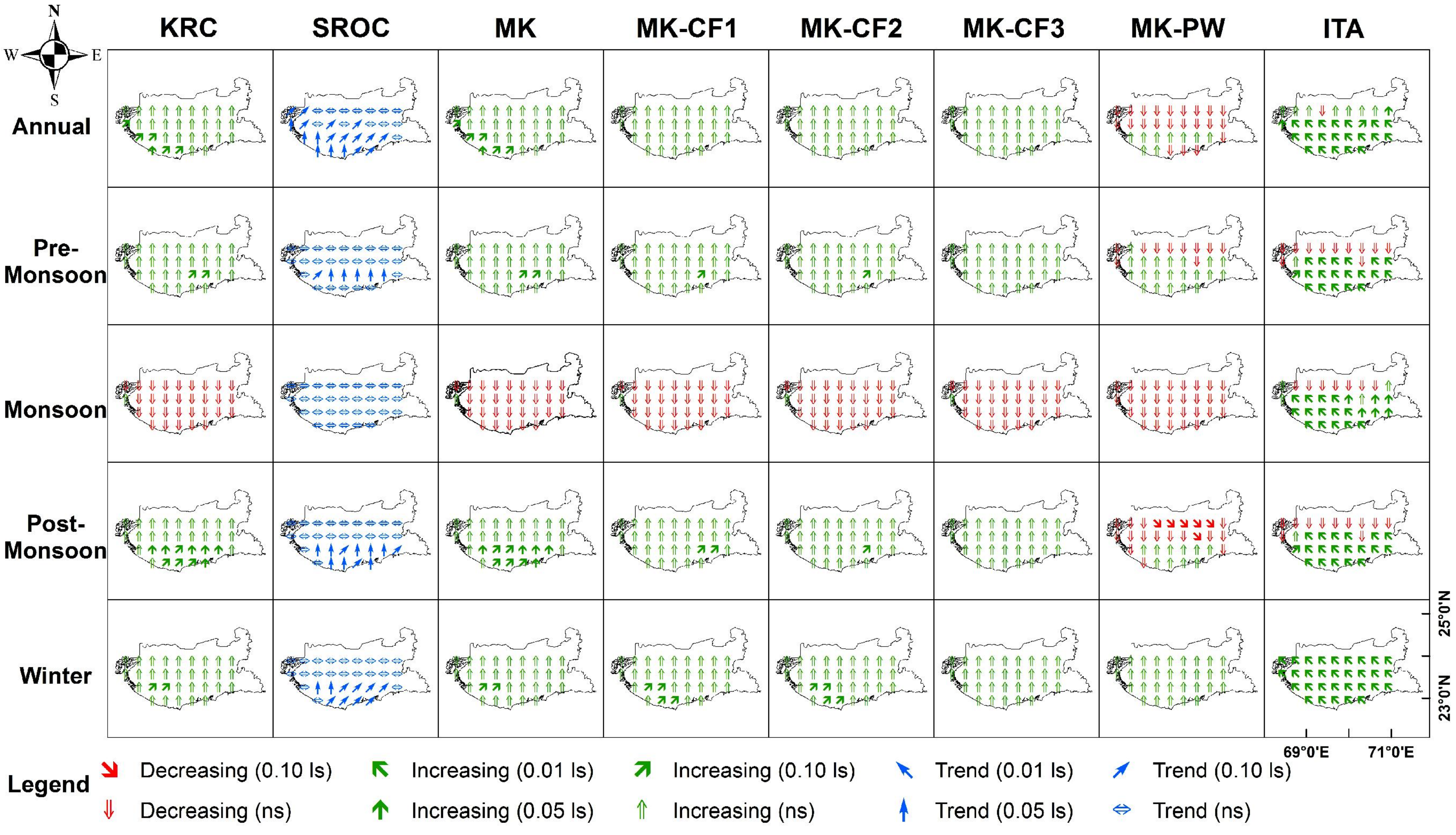

N
W
E
S
KRC
SROC
MK
MK-CF1
MK-CF2
MK-CF3
MK-PW
ITA
Annual
Pre-Monsoon
Monsoon
Post-Monsoon
Winter
25°0'N
23°0'N
69°0'E
71°0'E
Legend
Decreasing (0.10 ls)
Decreasing (ns)
Increasing (0.01 ls)
Increasing (0.05 ls)
Increasing (0.10 ls)
Increasing (ns)
Trend (0.01 ls)
Trend (0.05 ls)
Trend (0.10 ls)
Trend (ns)

Figure 3

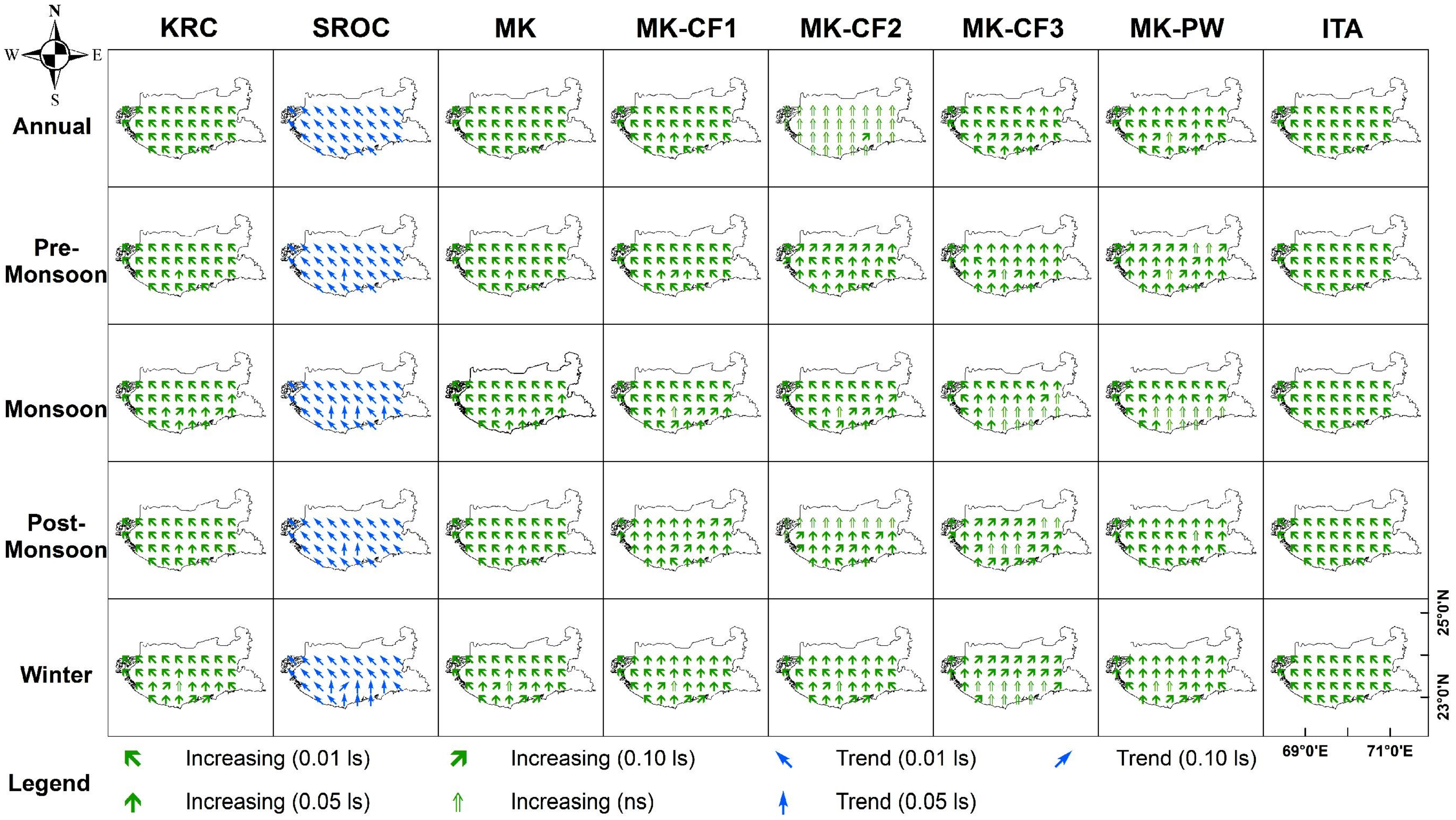

N
W
E
S
KRC
SROC
MK
MK-CF1
MK-CF2
MK-CF3
MK-PW
ITA
Annual
Pre-Monsoon
Monsoon
Post-Monsoon
Winter
25°0'N
23°0'N
69°0'E
71°0'E
Legend
Increasing (0.01 ls)
Increasing (0.10 ls)
Trend (0.01 ls)
Trend (0.10 ls)
Increasing (0.05 ls)
Increasing (ns)
Trend (0.05 ls)

Figure 4

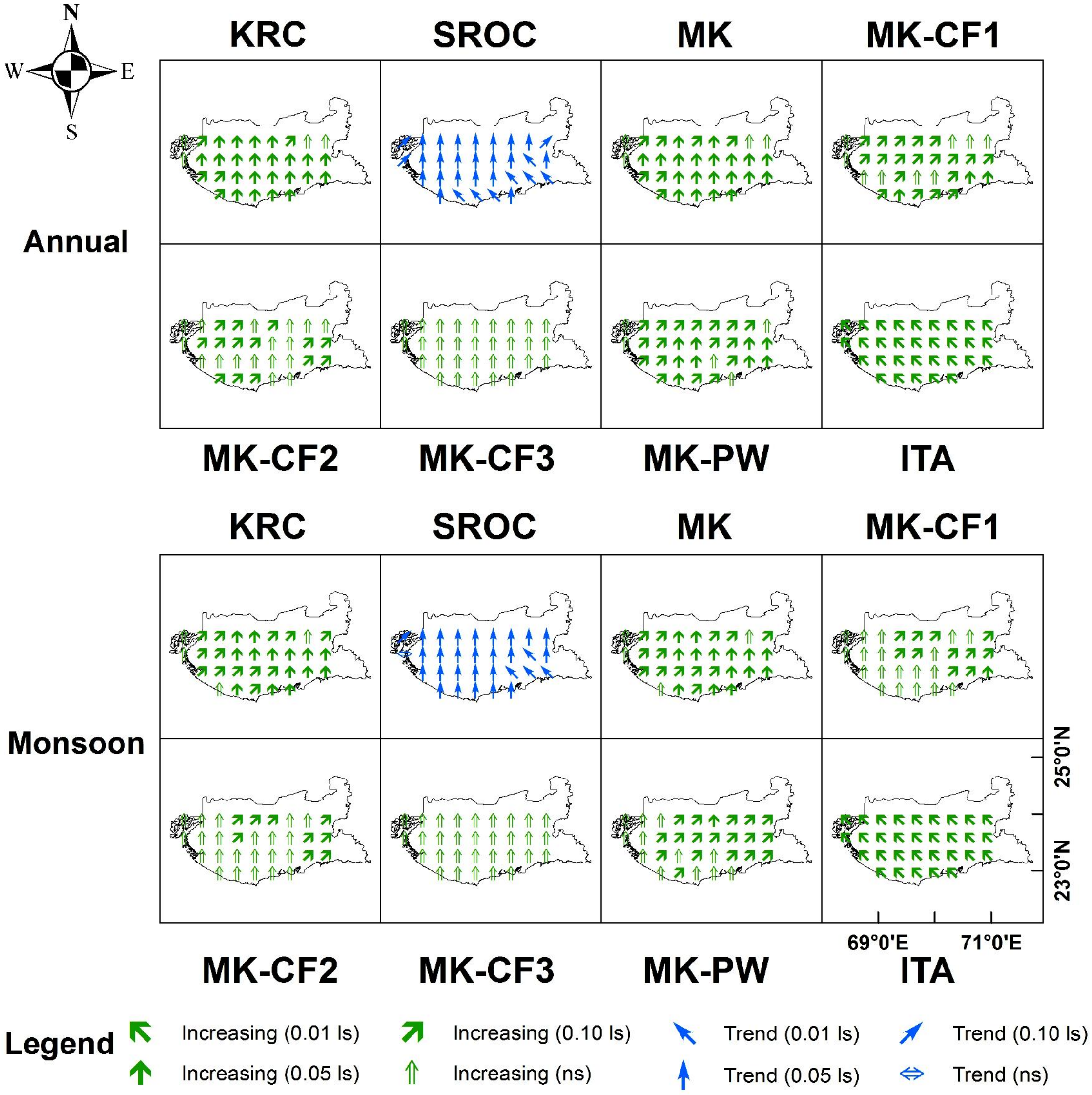
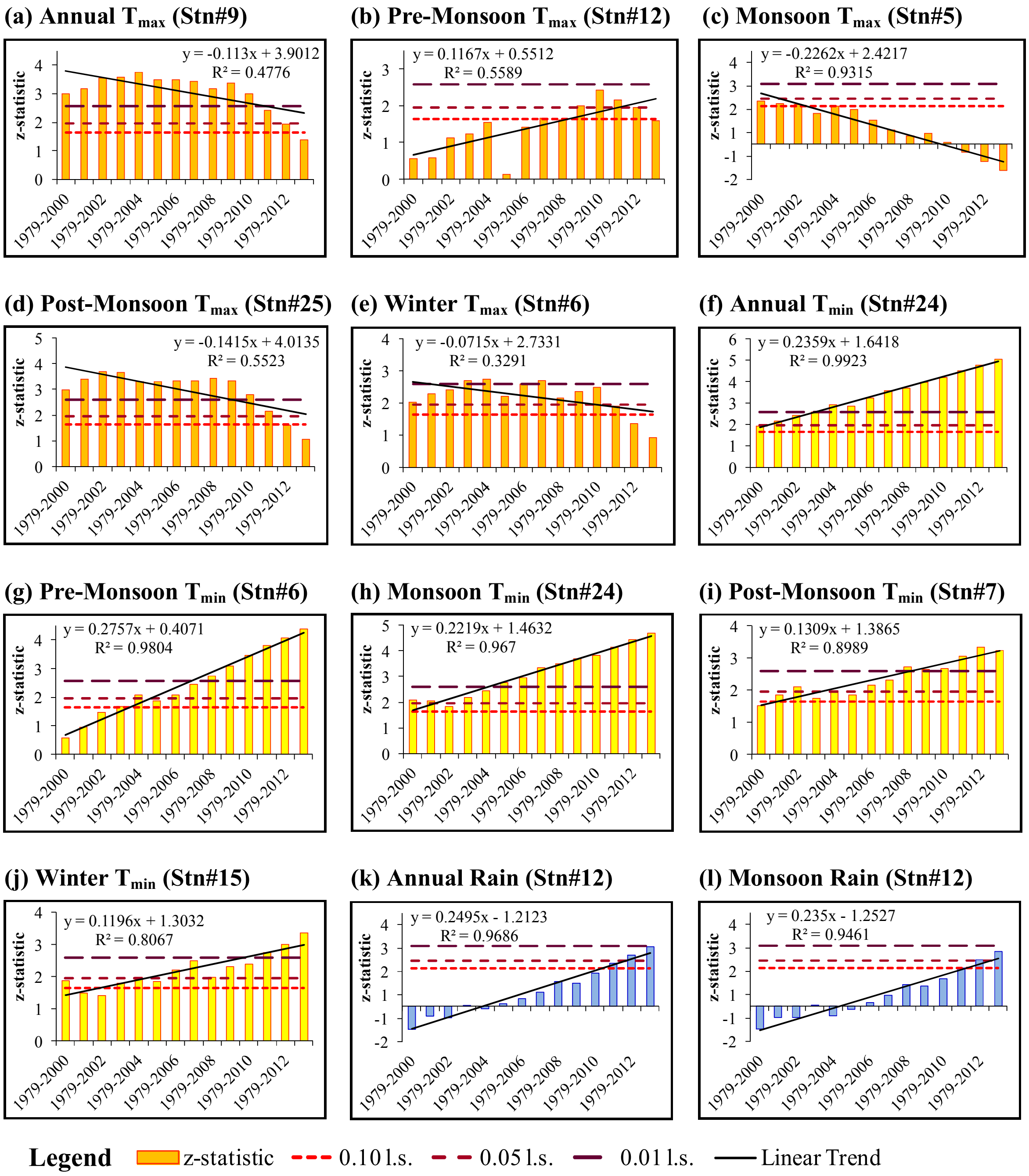

N
W
E
S
KRC
SROC
MK
MK-CF1
Annual
MK-CF2
MK-CF3
MK-PW
ITA
KRC
SROC
MK
MK-CF1
Monsoon
25°0'N
23°0'N
69°0'E
71°0'E
MK-CF2
MK-CF3
MK-PW
ITA
Legend
Increasing (0.01 ls)
Increasing (0.10 ls)
Trend (0.01 ls)
Trend (0.10 ls)
Increasing (0.05 ls)
Increasing (ns)
Trend (0.05 ls)
Trend (ns)

Figure 5


(a) Annual T_{max} (Stn#9)

(b) Pre-Monsoon T_{max} (Stn#12)

(c) Monsoon T_{max} (Stn#5)

(d) Post-Monsoon T_{max} (Stn#25)

(e) Winter T_{max} (Stn#6)

(f) Annual T_{min} (Stn#24)

(g) Pre-Monsoon T_{min} (Stn#6)

(h) Monsoon T_{min} (Stn#24)

(i) Post-Monsoon T_{min} (Stn#7)

(j) Winter T_{min} (Stn#15)

(k) Annual Rain (Stn#12)

(l) Monsoon Rain (Stn#12)

Figure 6