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Trend analysis of climatic variables in an arid and semi-arid region of the Ajmer District, Rajasthan, India

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Abstract

In the present study, trends and variations in climatic variables (i.e. rainfall, wet day frequency, surface temperature, diurnal temperature, cloud cover, and reference and potential evapotranspiration) were analyzed on seasonal (monsoon and non-monsoon) and annual time scales for the Ajmer District of Rajasthan, India. This was done using non-parametric statistical techniques, i.e. the Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests, over a period of 100 years. The MK test with prewhitening (MK–PW) of climatic series was also applied to climatic variables and the results were compared to those obtained through the MK and MMK tests in order to assess the performance of trend detection methods. The Pettitt–Mann–Whitney (PMW) test was applied to detect the temporal shift in climatic series. The trend analysis revealed that annual and seasonal rainfall did not show any statistically significant trend at a 10% significant level. A noticeable trend increase was found in wet day frequency, surface temperature and reference evapotranspiration (*ET*) during the non-monsoon season from the three non-parametric statistical tests at a 10% significance level. A statistically significant decrease in maximum temperature was found during the non-monsoon season by the MK–PW test alone. This analysis of several climatic variables at the district scale is helpful for the planning and management of water resources and the development of adaptation strategies in adverse climatic conditions.

Key words: *Mann–Kendall test, modified Mann–Kendall test, Pettitt–Mann–Whitney test, Rajasthan, Sen's slope, trends*

INTRODUCTION

The effects of climate change on precipitation occurrence, distribution, intensity, quality and quantity are resulting in noticeable changes in the hydrologic cycle. While the International Panel on Climate Change (IPCC) has projected an increase in global precipitation due to the effects of climate change, both increases and decreases in precipitation have been projected at the regional scale [IPCC 2007]. The later part of the 20th century experienced an average temperature increase of 0.6°C and by the end of the 21st century, temperatures are expected to increase dramatically by 1.4°C to 5.4°C based on various climate prediction models [IPCC 2001]. The AR4 synthesis report showed that changes in precipitation has been more spatially variable than temperature change and demonstrated that climate change assessment is needed at sub-national (i.e. state or province) and local scales. Therefore, there is a need to study the climate change at regional and local scales [IPCC 2007; NAPCC 2008] to assess the impacts of climate change on various sectors.

In India, seasonal and annual air temperature has been increasing at the rate of 0.57°C every hundred years, as estimated using data from 1881 to 1997 [PANT, KUMAR 1997]. In most previous studies, efforts were made to assess trends in selected climatic variables at regional and local scales using different trend analysis techniques (e.g. YOON, LEE [2003]; DE, RAO 2004; ARORA *et al.* 2005; BASISTHA *et al.* 2007; PINGALE *et al.* 2014]) and only a few studies assessed different climatic variables at the district scale [GOWDA *et al.* 2008]. GOWDA *et al.* [2008] analyzed the climatic parameters (i.e. rainfall, relative humidity, maximum temperature, minimum temperature, sunshine hours and wind speed) for the Devangere district of India to assess local scale climate change over a period of 32 years. While the results showed a mild trend in climate change in and around the Devangere region, it was also evident that a small data set might not provide an accurate portrayal of climate change and that long term data is often required. However, the study was based solely on statistical analyses and trends and shifts in climatic variables were not assessed. GHOSH *et al.* [2009] observed a varied trend in Indian summer monsoon season rainfall that was not only affected by global warming but also by local changes resulting from rapid urbanization, industrialization, and deforestation. DUHAN and PANDEY [2013] explored the spatial and temporal variability of precipitation in 45 districts in Madhya Pradesh (MP), India on an annual and seasonal basis. The Mann–Kendall (MK) test and Sen's slope estimator test were used for trend detection. An increase and decrease in the precipitation trend was found in the districts of MP on an annual and seasonal basis, respectively. However, the study only assessed precipitation and a comparative study of different climatic variables using different statistical techniques was not performed.

There is need to analyze additional parameters within the political boundaries of countries, to clearly assess and understand climate change [ADAMOWSKI *et al.* 2012; ARAGHI *et al.* 2015; BELAYNEH *et al.* 2014; CAMPISI *et al.* 2012; HAIDARY *et al.* 2013; TIWARI, ADAMOWSKI 2014]. Micro-scale studies are required to assess climate change and to identify its real causes for the proper planning and management of water resources [ADAMOWSKI *et al.* 2012; ADAMOWSKI, PROKOPH 2013; HALBE *et al.* 2013; SAADAT *et al.* 2011]. No studies have been reported in the literature that have investigated climate in terms of inter-seasonal and inter-annual variation in temperature, precipitation, number of rainy days, humidity, cloud cover, evaporation and evapotranspiration along with seasonal shifts for the Ajmer District for the State of Rajasthan, India. Ajmer is an important holy place in the central part of the State of Rajasthan. The effects of climate change are evident in the uneven rainfall pattern and temperature increases, and may due to increased population and developmental activities in Ajmer [PINGALE *et al.* 2015]. Therefore, the statistical analysis should be extended to analyze additional climatic parameters and their relationships with water resources, land use/cover change, urbanization, etc. Given this, the present study was undertaken with the objective to analyze representative meteorological parameters (i.e. rainfall, wet day frequency, temperature, cloud cover, reference and potential evapotranspiration) using non-parametric statistical tests (i.e. Mann–Kendall (MK) test, modified Mann–Kendall (MMK) test, MK test with prewhitening of series (MK–PW) and Pettitt–Mann–Whitney (PMW) test) to observe the trends and shifts in these climatic variables in the Ajmer District of Rajasthan, India. Also, a comparative assessment of the different trend detection techniques was performed to analyze trends and shifts in the selected climatic variables. Such information can be useful to allow stakeholders to plan and manage water resources in a more sustainable manner [BUTLER, ADAMOWSKI 2015; HALBE *et al.* 2014; INAM *et al.* 2015; KOLINJIVADI *et al.* 2014a, b; STRAITH *et al.* 2014].

MATERIALS AND METHODOLOGY

STUDY AREA AND DATA USED

Ajmer District is located between 25°38' to 26°58'N latitude and 73°54' to 75°22'E longitude (Fig. 1) in India. It is situated almost in the heart of Rajasthan, and it is bordered by the Nagaur district to the north, the Jaipur and Tonk districts to the east, the Bhilwara district to the south, and the Pali district to the west. To the north of Ajmer city is a large artificial lake called Anasagar, which is adorned with a marble structure called Baradari. The Ajmer District has an area of 8,481 km^2 and a population of 2,584,913 [Registrar General, India 2011]. It is situated 486 m above mean sea level (msl), has a hot climate characterized by extremely hot summers and receives a fairly large amount of rainfall.

In the present study, 0.5°×0.5° gridded meteorological data (i.e. monthly rainfall, wet day frequency, surface temperature, cloud cover, reference evapotranspiration and potential evapotranspiration) from the Ajmer District of Rajasthan were utilized from the year 1903 to 2002. These data sets were obtained from the Indian water portal web, developed from the Climate Research Unit TS 2.1 dataset [MITCHELL, JONES 2005], UK and GIS software GRASS (Geographic Resources Analytical Support System). The meteorological data of 100 years (1903 to 2002) was selected to assess climate change trends and variations

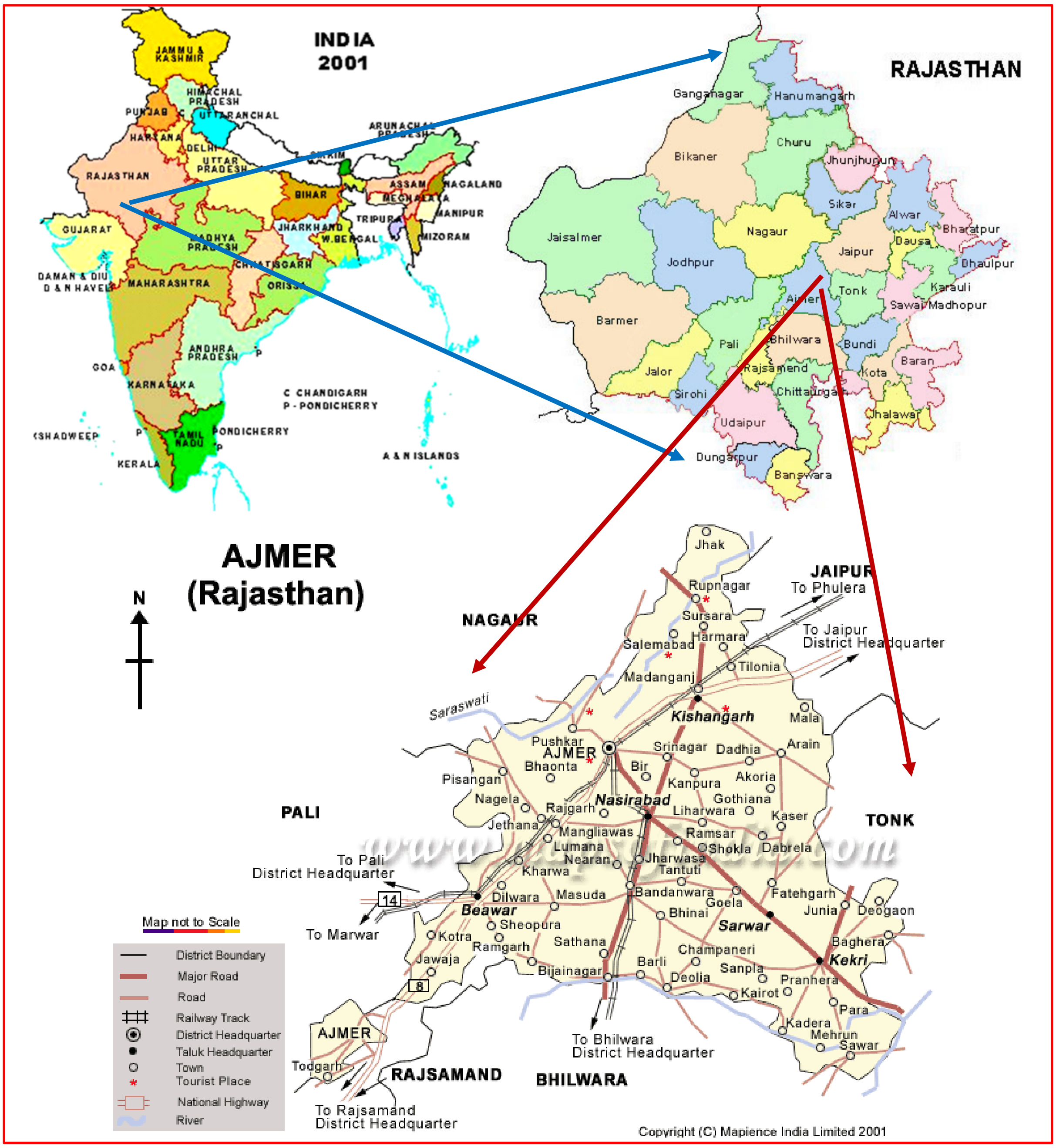

Fig. 1. Index map of Ajmer District; source: Mapience India Ltd.

on seasonal and annual scales for the Ajmer District. The monsoon season runs for the months of June to September, and the non-monsoon season represents the months of October to May.

METHODOLOGY

Assessment of climate change for the Ajmer District was carried out on seasonal (monsoon and non-monsoon) and annual time scales using the non-parametric (MK, MK–PW, MKK and PMW test), statistical analyses. The derived reference and potential evapotranspiration from the FAO-56 manual [ALLEN *et al.* 1998] were also analyzed for the Ajmer District over the period of 100 years.

Normalisation and autocorrelation analysis of time series

Normalized climatic time series were used to test for the presence of outliers, which were obtained from the following relationship [PINGALE *et al.* 2014; 2015; RAI *et al.* 2010]:

$$X_t = (x_t - \bar{x})/\sigma \tag{1}$$

Where X_t is the normalized anomaly of the series, x_t is the observed time series, $\bar{x}$ and σ are the long-term mean and standard deviation of annual/seasonal time series.

The autocorrelation (serial coefficients) test was performed to check the randomness and periodicity in the time series [Modarres, Silva 2007]. If lag-1 serial coefficients were not statistically significant then the MK test was applied to the original time series [Karpouzos *et al.* 2010; Luo *et al.* 2008; Pingale *et al.* 2015]. The MMK test was applied to the statistically significant time series after removing the effect of serial correlation. The serial correlation coefficients of normalized climatic series were computed for lags $L = 0$ to k, where k is the maximum lag (i.e. $k = n/3$), and n is the length of the series. The autocorrelation coefficient r_k of a discrete time series for lag-k was estimated as follows:

$$r_k = \frac{\sum_{k=1}^{n-k}(X_t - \overline{X}_t)(X_{t+k} - \overline{X}_{t+k})}{\left[\sum_{k=1}^{n-k}(X_t - \overline{X}_t)^2(X_{t+k} - \overline{X}_{t+k})^2\right]^{0.5}} \qquad (2)$$

Where r_k is the lag-k serial correlation coefficient. The hypothesis of serial independence was then tested by the lag-1 autocorrelation coefficient as $H_0 : r_1 = 0$ against $H_1 : |r_1| \geq 0$ using the test of significance of serial correlation [Rai *et al.* 2010; Yevjevich 1972]:

$$(r_k)_{t_g} = \frac{-1 \pm t_g(n-k)^{0.5}}{n-k} \qquad (3)$$

Where $(r_k)_{tg}$ is the normally distributed value of r_k, t_g is the normally distributed statistic at 'g' level of significance. The values of t_g are 1.645, 1.965 and 2.326 at significance levels of 0.10, 0.05 and 0.01, respectively. If $|r_k| \geq (r_k)_{tg}$, the null hypothesis about serial independence was rejected at significance level α (0.05 in this study). For non-normal series, the MK test is an appropriate choice for trend analysis [Basistha *et al.* 2009; Yue, Pilon 2004]. Therefore, the MK test was used in the present study where autocorrelation was found to be non-significant at the 5% level of significance.

Mann–Kendall test

The MK test is a non-parametric test used to detect trends in a time series [Mann 1945]. The non--linear trend and the turning point can be derived from Kendall test statistics [Kendall 1975]. This method searches for a trend in a time series without specifying whether the trend is linear or nonlinear. It has been found to be an excellent tool for trend detection and many researchers have used this test to assess the significance of trends in hydro-climatic time series such as water quality, stream flow, temperature and precipitation (e.g. Ludwig *et al.* [2004]; Zhang *et al.* [2004]; McBean, Motiee [2008]; Adamowski *et al.* [2009]; Basistha *et al.* [2009]; Adamowski *et al.* [2010]; Rai *et al.* [2010]; Nalley *et al.* [2012]; Patra *et al.* [2012]; Nalley *et al.* [2013]; Pingale *et al.* 2015]. The MK test can be applied to a time series x_i ranked from $i = 1, 2 \dots n\text{–}1$ and x_j ranked from $j = i + 1, 2 \dots n$. Each data point x_i is used as a reference point and is compared with all other data points x_j such that:

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1 & \mathit{if}\ (x_j - x_i) > 0 \\ 0 & \mathit{if}\ (x_j - x_i) = 0 \\ -1 & \mathit{if}\ (x_j - x_i) < 0 \end{cases} \qquad (4)$$

The Kendall test statistic (S) is given as:

$$S = \sum_{k=1}^{n-1} \operatorname{sgn}(x_j - x_k) \qquad (5)$$

Where $\operatorname{sgn}(x_j - x_k)$ is the signum function. The test statistic (S) has been assumed to be asymptotically normal, with $E(S) = 0$ for sample size $n \geq 8$ and variance as follows:

$$V(S) = \frac{[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)]}{18} \qquad (6)$$

Where t denotes number of ties up to sample i. The standardized MK test statistics (Z_{mk}) can be estimated as follows:

$$Z_{mk} = \begin{cases} \dfrac{S-1}{\sqrt{V(S)}} & \mathit{if}\ S > 0 \\ 0 & \mathit{if}\ S = 0 \\ \dfrac{S+1}{\sqrt{V(S)}} & \mathit{if}\ S < 0 \end{cases} \qquad (7)$$

The standardized MK test statistics (Z_{mk}) follows the standard normal distribution with a mean of zero and variance of one. If $\pm Z_{mk} \leq Z_{\alpha/2}$ (here $\alpha = 0.1$), then the null hypothesis for no trend is accepted in a two sided test for trend and the null hypothesis for no trend is rejected if $\pm Z_{mk} \leq Z_{\alpha/2}$. Failing to reject H_0 (i.e. null hypothesis) does not mean that there is no trend. Rather, it is a statement that the evidence available is not sufficient to conclude that there is a trend [Helsel, Hirsch 2002]. A positive value of Z_{mk} indicates an 'upward trend' and a negative value indicates a 'downward trend'.

Mann–Kendall test with pre-whitening of series

The prewhitening of time series involves the computation of serial correlation and removing the correlation if the calculated serial correlation is significant at a significance level of 0.05 [Burn, Elnur 2002]. The pre-whitening of the time series is accomplished as follows:

$$X_t^{'} = (x_{k+1} - rx_k) \qquad (8)$$

Where x_k is the original time series with autocorrelation for time interval k; X'_t is the pre-whitened time series; and r is the lag-1 autocorrelation coefficient. This pre-whitened series is then subjected to the MK test for detecting the trend.

Modified Mann–Kendall test

The MK–PW test is used to detect trends in a time series in the presence of autocorrelation [CUNDERLIK, BURN 2004]. However, pre-whitening reduces the detection rate of significant trends in the MK test [YUE, HASHINO 2003]. Therefore, the MMK test is employed for trend detection of an auto-correlated series [HAMED, RAO 1998]. Only significant values of ρ_k are used to calculate the variance correction factor n/n^*_s (equation 9) as the variance of S is underestimated when the data are positively autocorrelated.

$$n/n_s^* = 1 + \\ + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\rho_s(i) \tag{9}$$

Where n is the actual number of observations, n^*_s is considered as the 'effective' number of observations to account for autocorrelation in data, and $\rho_s(i)$ is the autocorrelation function of the ranks of the observations which is given as follows [KENDALL 1955]:

$$\rho_s(i) = \sin^{-1}\left(\frac{\rho(i)}{2}\right) \tag{10}$$

Where $\rho(i)$ is the parent autocorrelation function of rank of the observation. The corrected variance is then computed as:

$$V^*(S) = V(S) \cdot n/n_s^* \tag{11}$$

Where $V(S)$ is obtained from equation (6). The remaining process of trend analysis is included in the MK test by incorporating the corrected variance in equation (7). A significance level of 10% was used for the autocorrelation of rank $\rho_s(i)$, which produces the best overall empirical significance level. The advantage of using corrected variance is that there is no need to either normalize data or their autocorrelation function [RAI *et al.* 2010].

Sen's estimator of slope and percentage change over a period

If a linear trend is present in a time series, then the true slope of trend can be estimated using a simple non-parametric procedure [SEN 1968; THEIL 1950] that is computed as:

$$Q_i = \text{median}\left(\frac{x_j - x_k}{j-k}\right) \quad \forall k \le j \tag{12}$$

Where x_j and x_k are data values at times j and k ($j > k$), respectively. The median of N values of Q_i is Sen's estimator of slope. If N is odd, then Sen's estimator is computed by $Q_{med} = Q_{(N+1)}/2$ and if is even, then Sen's estimator is computed by $Q_{med} = (Q_{(N)}/2 + Q_{(N+2)}/2)/2$. Finally, Q_{med} is tested by a two-sided test at a $100(1 - \alpha)$% confidence interval.

The percentage change (%) is estimated assuming a linear trend in which magnitude by Theil and Sen's median slope and mean are used [BASISTHA *et al.* 2009; YUE, HASHINO 2003]. The %changes over a period is expressed as follows:

$$\%\text{change} = \left(\frac{\text{median slope} \cdot \text{length of period}}{\text{mean}}\right) \tag{13}$$

Pettitt–Mann–Whitney (PMW) test for shift detection

The PMW test is used for the determination of shift in climatological time series [PETTITT 1979]. This test was performed using the evaluation version of Xlstat 2011 software. This test can be briefly described using PMW statistics [BASISTHA *et al.* 2009; KIELY *et al.* 1998] where T is the length of the time series and τ is the year of the most likely change point. Considering the time series as two samples represented by $X_1 \ldots X_\tau$ and $X_{\tau+1} \ldots X_T$, the index V_τ is defined as:

$$V_\tau = \sum_{j=1}^{T} \text{sgn}(X_\tau - X_j) \quad \text{for any } \tau \tag{14}$$

Let a further index U_τ be defined as:

$$U_\tau = \sum_{i=1}^{\tau} \sum_{j=1}^{T} \text{sgn}(X_i - X_j) \tag{15}$$

A plot of U_τ against τ for a time series with no change point would result in a continually increasing value of $|U_\tau|$. However, if there is a change point (even a local change point), then $|U_\tau|$ would increase up to the change point and then begin to decrease. The most significant change point τ can be identified as the point where the value of $|U_\tau|$ is a maximum and can be found using equation (16).

$$K_T = \max_{1 \le \tau \le T} |U_\tau| \tag{16}$$

The probability of a change point being at a year where $|U_\tau|$ is the maximum, is approximated by:

$$p = 1 - \exp\left[\frac{-6K_T^2}{T^3 + T^2}\right] \tag{17}$$

Further for $1 \le \tau \le T$, the series

$$\hat{U}(\tau) = |U_\tau| \tag{18}$$

is introduced and defined as:

$$p(\tau) = 1 - \exp\left[\frac{-6U(\tau)^2}{T^3 + T^2}\right] \tag{19}$$

In this way, series consisting of probabilities of the change point at each year are obtained for the shift detection in the time series of annual and seasonal rainfall and temperature over a period of time.

RESULTS AND DISCUSSION

In the present study, assessment of climate change (i.e., trends, shifts and variability) for the Ajmer District was carried out at seasonal (monsoon and non-monsoon) and annual time scales through the MK, MK–PW, MMK and PMW non parametric statistical tests. Sen's slope estimator and percentage change was also estimated. The rainfall, wet day frequency, surface temperature (minimum, average and maximum), cloud cover, reference evapotranspiration (*ET*) and potential evapotranspiration (*PET*) were assessed for the Ajmer District over the period of 100 years.

NORMALISATION AND AUTOCORRELATION ANALYSIS

Initially autocorrelation analysis was performed to identify the suitable trend analysis method for the original and normalized series of climatic variables. The results of autocorrelation analysis up to the 20th lag are shown in Table 1 and Fig. 2 to 4 for the climatic variables (i.e. rainfall, wet day frequency, temperature (minimum, average and maximum), cloud cover, reference *ET* and *PET*) for the monsoon season, non-monsoon season and annual scale. The upper and lower boundaries were decided by the 95% confidence interval to test the limits of the autocorrelation coefficient [PINGALE *et al.* 2015]. The significant autocorrelation in climatic variables at lag-1 was observed for the monsoon season, non-monsoon season and annual scale at the 0.05 significance level. For auto-correlated series at lag-1, the MK test was applied for non-significant climatic variables while the MMK test was used for the significant climatic variables. The autocorrelation coefficient at lag-1 was selected because WAGESHO *et al.* [2013] found that the dependence of physical systems on past values is likely to be strongest for the most recent past.

Table 1. Summary of autocorrelation analysis at lag-1 for climatic variables

Parameters	Monsoon season	Non-monsoon season	Annual
Rainfall	0.060	0.008	0.041
Wet day frequency	0.007	0.123	0.024
Minimum temperature	0.024	**0.220**	0.166
Average temperature	0.016	**0.229**	0.165
Maximum temperature	0.008	**0.235**	0.165
Diurnal temperature	**0.310**	**0.298**	**0.384**
Cloud cover	0.102	**0.490**	**0.549**
Reference *ET*	–0.007	**0.206**	0.150
PET	0.048	**0.311**	**0.384**

Explanations: *ET* = evapotranspiration; *PET* = potential evapotranspiration;: highlighted bold values indicates significant autocorrelation at the 0.05 significance level.
Source: own study.

Based on the autocorrelation analysis, the MMK test was applied for the diurnal temperature for the monsoon season, non-monsoon season and annual scale. For the annual scale the MMK test was applied for *PET* and cloud cover while for the non-monsoon season the MMK test was applied for the temperature, cloud cover, reference *ET* and *PET*. For the remaining variables, the MK test was applied for the monsoon season, non-monsoon season and annual scale (Tab. 1). The MK and MMK tests were applied at the 10% significance level for the trend analysis of the monsoon season, non-monsoon season and annual time scale. However, the MK, MK–PW and MMK test were also applied for all climatic variables for the monsoon season, non-monsoon season and annual scale. This was done in order to compare the results and accurately estimate the trends in climatic variables over the period of 100 years.

TREND ANALYSIS

The climatic variables were analyzed for the monsoon season, non-monsoon season and annual scale using the MK, MK–PW and MMK trend tests. The MMK and MK–PW test were used for the series that had significant lag-1 autocorrelation at the 0.05 level of significance. The results of the three trend tests were derived for all climatic variables and compared at the 10% significance level. The test statistics (S) and Z_{mk} derived for the monsoon season, non-monsoon season and annual scale are presented in Tables 2 to 4 for both the significant and non-significant climatic variables. The positive values of Z_{mk} statistics indicated increasing trends in climatic variables while negative values of Z_{mk} showed decreasing trends for the significant and non-significant climatic variables.

After the MK test, the Sen's estimator of slope was employed to find out the change per unit time of the trends observed in the time series of all climatic variables. The corresponding results are presented in Table 5. The Sen's slope estimates with upper and lower bounds for statistically significant upward slopes for wet day frequency, surface temperature and downward slope of reference *ET* are shown in Fig. 5. The percentage changes in climatic variables over the 100 year period of study for the statistically significant climatic variables are presented in Table 5 for monsoon season, non-monsoon season and annual scale. The mean and standard deviation of all the nine

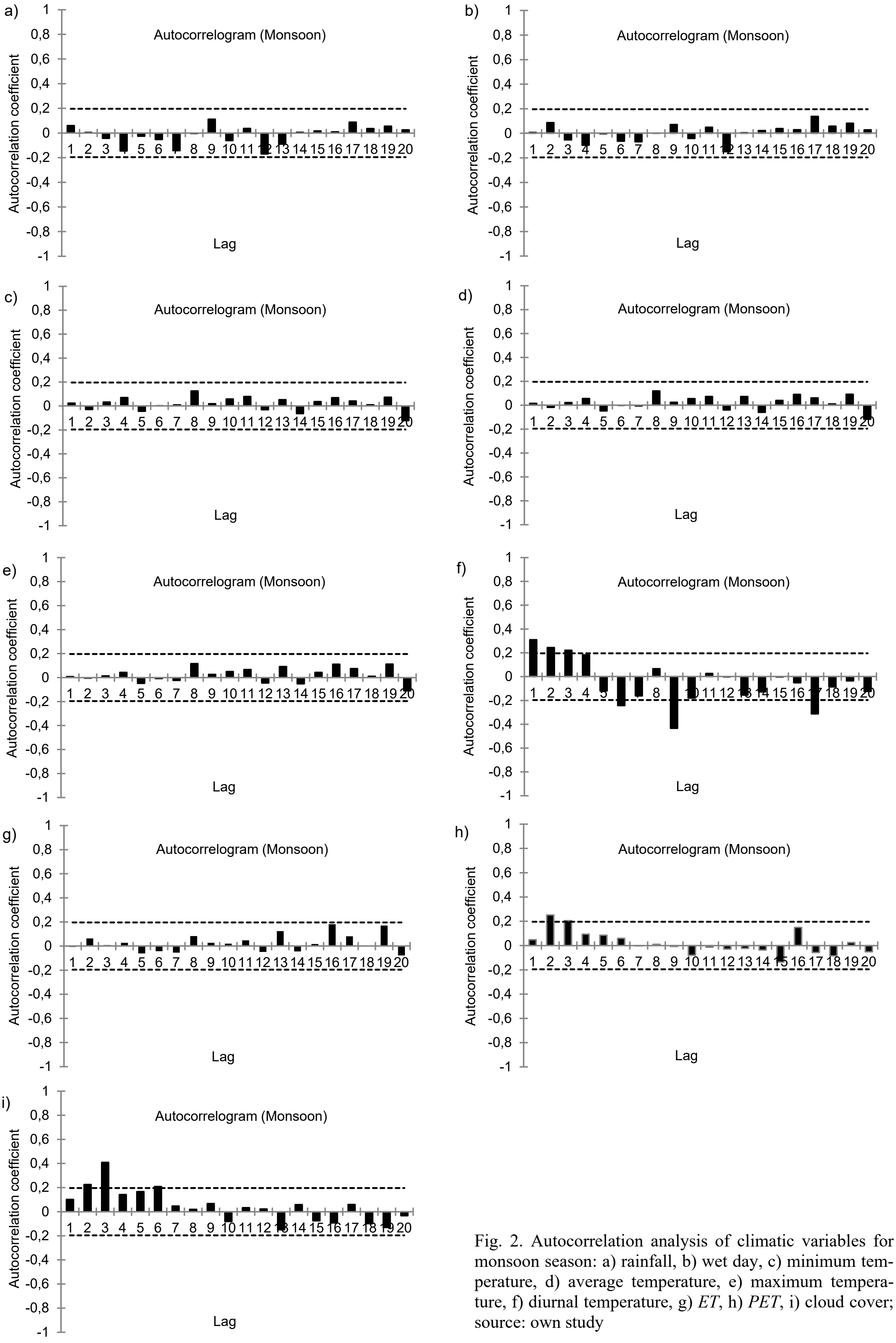

Fig. 2. Autocorrelation analysis of climatic variables for monsoon season: a) rainfall, b) wet day, c) minimum temperature, d) average temperature, e) maximum temperature, f) diurnal temperature, g) *ET*, h) *PET*, i) cloud cover; source: own study

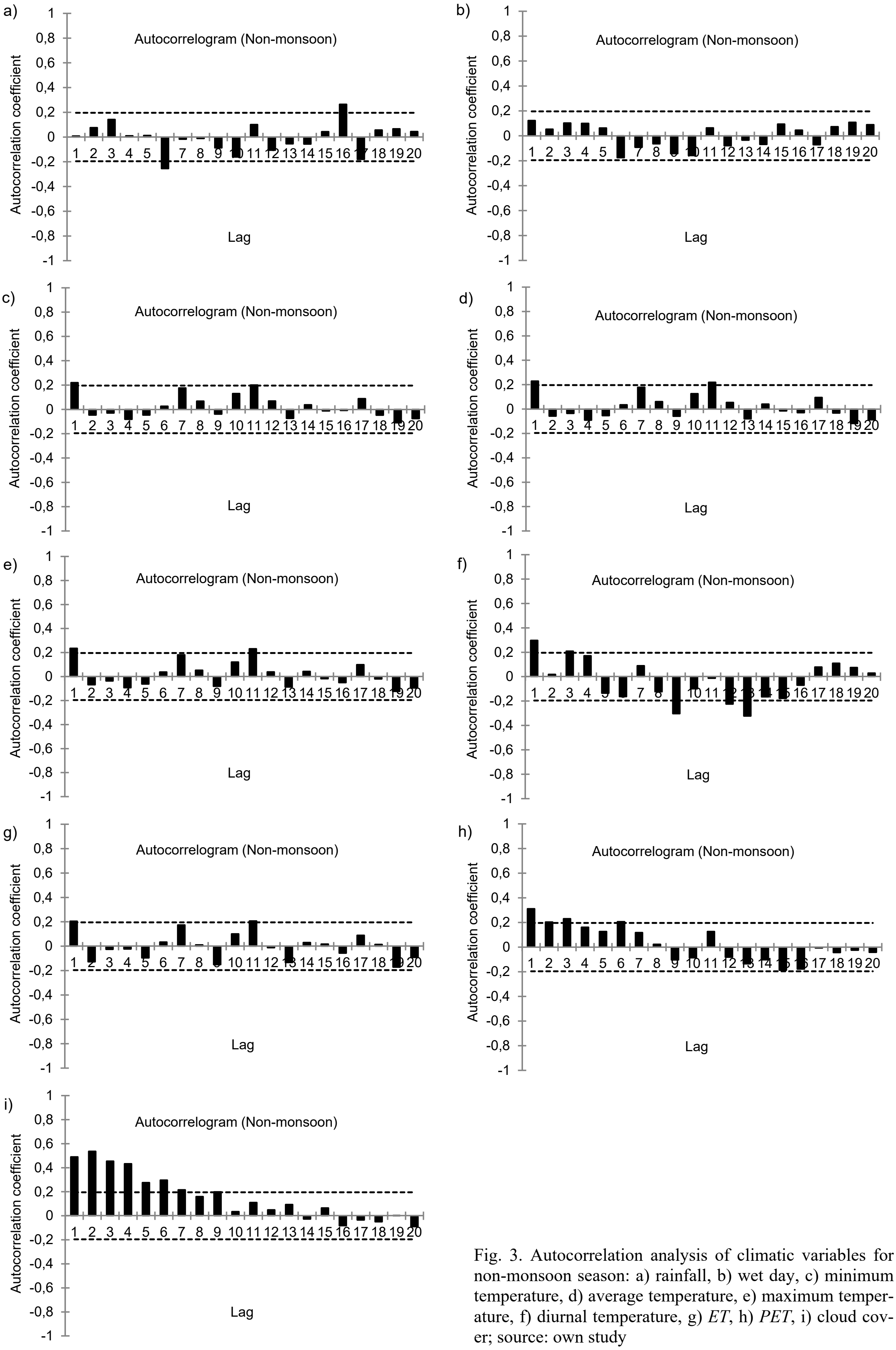

Fig. 3. Autocorrelation analysis of climatic variables for non-monsoon season: a) rainfall, b) wet day, c) minimum temperature, d) average temperature, e) maximum temperature, f) diurnal temperature, g) *ET*, h) *PET*, i) cloud cover; source: own study

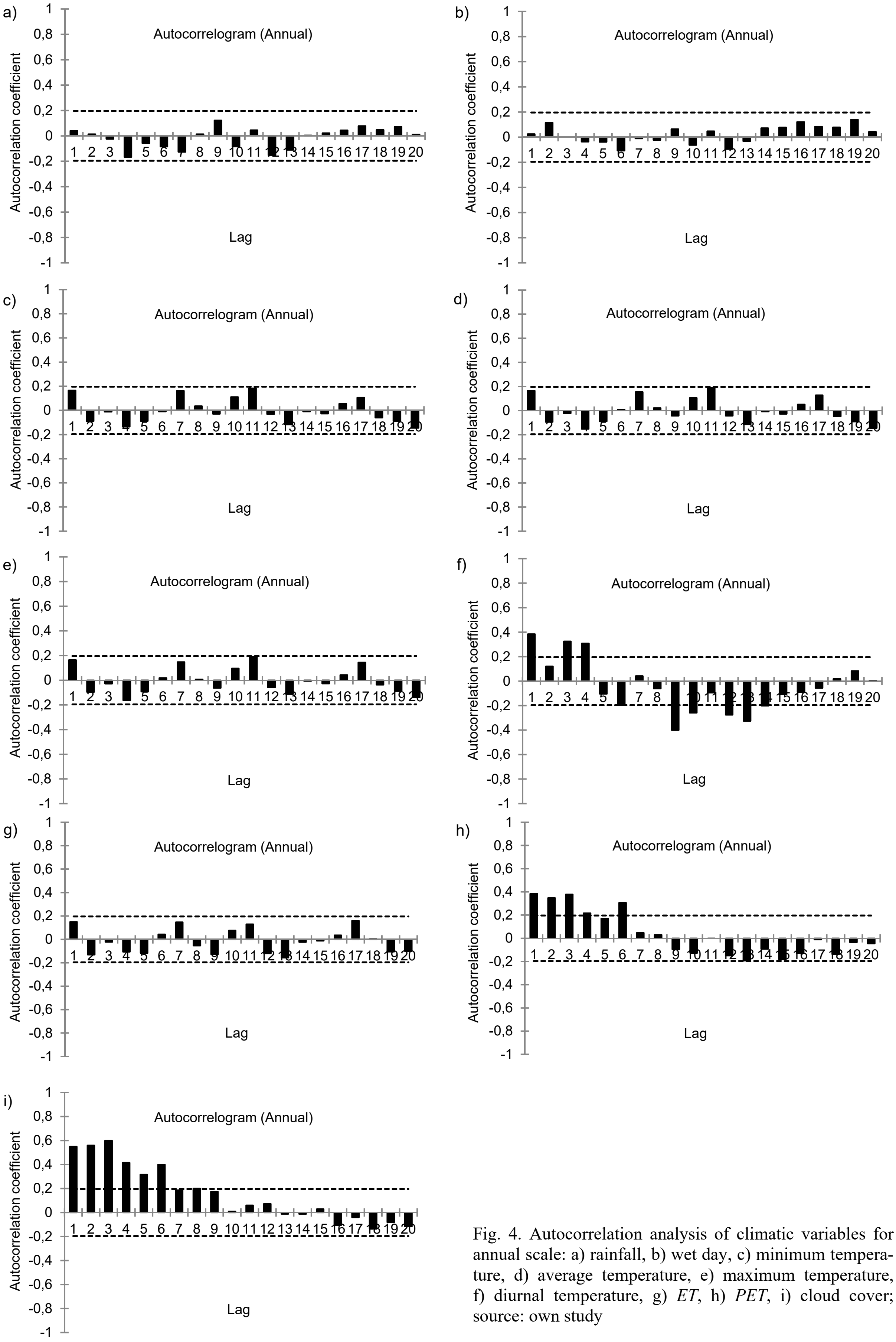

Fig. 4. Autocorrelation analysis of climatic variables for annual scale: a) rainfall, b) wet day, c) minimum temperature, d) average temperature, e) maximum temperature, f) diurnal temperature, g) *ET*, h) *PET*, i) cloud cover; source: own study

Table 2. Trend analysis of climatic variables for monsoon season at Ajmer District

Parameters	MK test		MK test with prewhitening		MMK test	
	S	Z_{mk}	S	Z_{mk}	S	Z_{mk}
Rainfall	250	0.74	245	0.73	250	0.74
Wet day frequency	406	1.21	409	1.22	406	**3.00**
Minimum temperature	–501	–1.49	–498	–1.48	–501	**–2.04**
Average temperature	–505	–1.50	–505	–1.50	–505	**–2.58**
Maximum temperature	–501	–1.49	–502	–1.49	–501	**–2.04**
Diurnal temperature	–247	–0.80	–302	–0.97	–247	–0.25
Cloud cover	–8	–0.02	–4	–0.01	–8	–0.01
Reference *ET*	–613	**–1.82**	–613	**–1.82**	–613	**–2.63**
PET	–284	–0.84	–284	–0.84	–284	–0.83

Explanations: S = Kendall test statistic, Z_{mk} = standardized MK test statistics, *ET*, *PET* as in Table 1; trends are highlighted in bold at the 10% level of significance.
Source: own study.

Table 3. Trend analysis of climatic variables for non-monsoon season at Ajmer District

Parameters	MK test		MK test with prewhitening		MMK test	
	S	Z_{mk}	S	Z_{mk}	S	Z_{mk}
Rainfall	323	0.96	315	0.94	323	1.14
Wet day frequency	669	**1.99**	671	**2.00**	669	**1.99**
Minimum temperature	1050	**3.12**	1046	**3.11**	1050	**3.82**
Average temperature	1053	**3.13**	1053	**3.15**	1053	**3.13**
Maximum temperature	1055	**3.14**	–1053	**–3.13**	1055	**3.39**
Diurnal temperature	27	0.08	36	0.11	27	0.03
Cloud cover	501	1.49	497	1.48	501	0.85
Reference *ET*	998	**2.97**	998	**2.97**	998	**2.97**
PET	550	1.64	550	1.64	550	1.40

Explanations as in Table 2.
Source: own study.

Table 4. Trend analysis of climatic variables for annual level at Ajmer District

Parameters	MK test		MK test with prewhitening		MMK test	
	S	Z_{mk}	S	Z_{mk}	S	Z_{mk}
Rainfall	344	1.02	343	1.02	344	1.02
Wet day frequency	667	**1.98**	674	**2.00**	667	**2.52**
Minimum temperature	558	**1.66**	557	**1.66**	558	**2.26**
Average temperature	525	1.56	534	1.59	525	1.22
Maximum temperature	517	1.54	515	1.53	517	**1.66**
Diurnal temperature	–333	–1.04	–377	–1.15	–333	–0.50
Cloud cover	425	1.26	430	1.28	425	0.76
Reference *ET*	443	1.32	443	1.32	443	1.37
PET	247	0.73	247	0.73	247	1.23

Explanations as in Table 2.
Source: own study.

Table 5. Sen's slope and percentage change over 100 years of climatic variables

Parameter	Monsoon season		Non-monsoon season		Annual	
	Sen's slope	% change	Sen's slope	% change	Sen's slope	% change
Rainfall	0.397	8.03	0.079	17.15	0.675	12.46
Wet day frequency	0.020	8.09	**0.011**	**17.83**	**0.033**	**10.77**
Minimum temperature	–0.004	–1.48	**0.007**	**4.25**	0.003	1.53
Average temperature	–0.004	–1.24	**0.007**	**2.86**	0.003	1.07
Maximum temperature	–0.004	–1.09	**0.007**	**2.20**	0.003	0.89
Diurnal temperature	0.000	0.00	0.000	0.00	0.000	0.00
Cloud cover	0.000	0.00	0.004	2.57	0.003	1.22
Reference *ET*	**–0.002**	**–0.94**	**0.006**	1.64	0.003	0.53
PET	–0.001	–0.29	0.003	0.51	0.001	0.18

Explanations: *ET*, *PET* as in Table 1; bold shows statistically significant Sen's slope at the 10% level of significance.
Source: own study.

climatic variables are given in Table 6. These represent the changes and variation in all the climatic variables over the 100 year period for the above mentioned time scales in the Ajmer District.

The reference *ET* in the monsoon season showed a significant decreasing trend over the study period by the MK test, MK–PW test (Z_{mk} = –1.82) and MMK test (Z_{mk} = –2.63). However, these tests failed to detect a significant trend for the other climatic variables using the MK and MK–PW tests at a 10% level of significance. The MMK test failed only for rainfall, diurnal temperature and cloud cover in the monsoon season at the 10% significance level. The null hypothesis of no trend indicated that the evidence of trends was not sufficient on seasonal and annual time scales in some of the studied climatic variables at the 10% significance level. These results were in agreement with some studies in other regions of India that also found no trends in rainfall (e.g. Arora *et al.* [2005]; Dash *et al.* [2007]; Kumar *et al.* [2010]; Pingale *et al.* [2015]). However, increasing and decreasing trends in rainfall have been observed in other regions of the country (e.g. Basistha *et al.* [2007]; Rai *et al.* [2010]; Pingale *et al.* [2014]). It is clear from Table 2 that no significant increasing trend existed in wet day frequency and minimum temperature in the monsoon season based on the MMK test. However, Gowda *et al.* [2008] found decreasing trends in annual rainfall and expected high intensity rainfall or storm events for the Devangere district of Karnataka, India. Also, increasing trends in minimum temperature have been observed by other researchers in India (e.g. Jain *et al.* [2013]; Pingale *et al.* [2014]; Pingale *et al.* [2015]). Although significant decreasing trends were observed in average and maximum temperature using the MMK test (Tab. 2), previous studies have reported increasing trends in average and maximum temperature for other regions of India (e.g. Singh *et al.* [2008]).

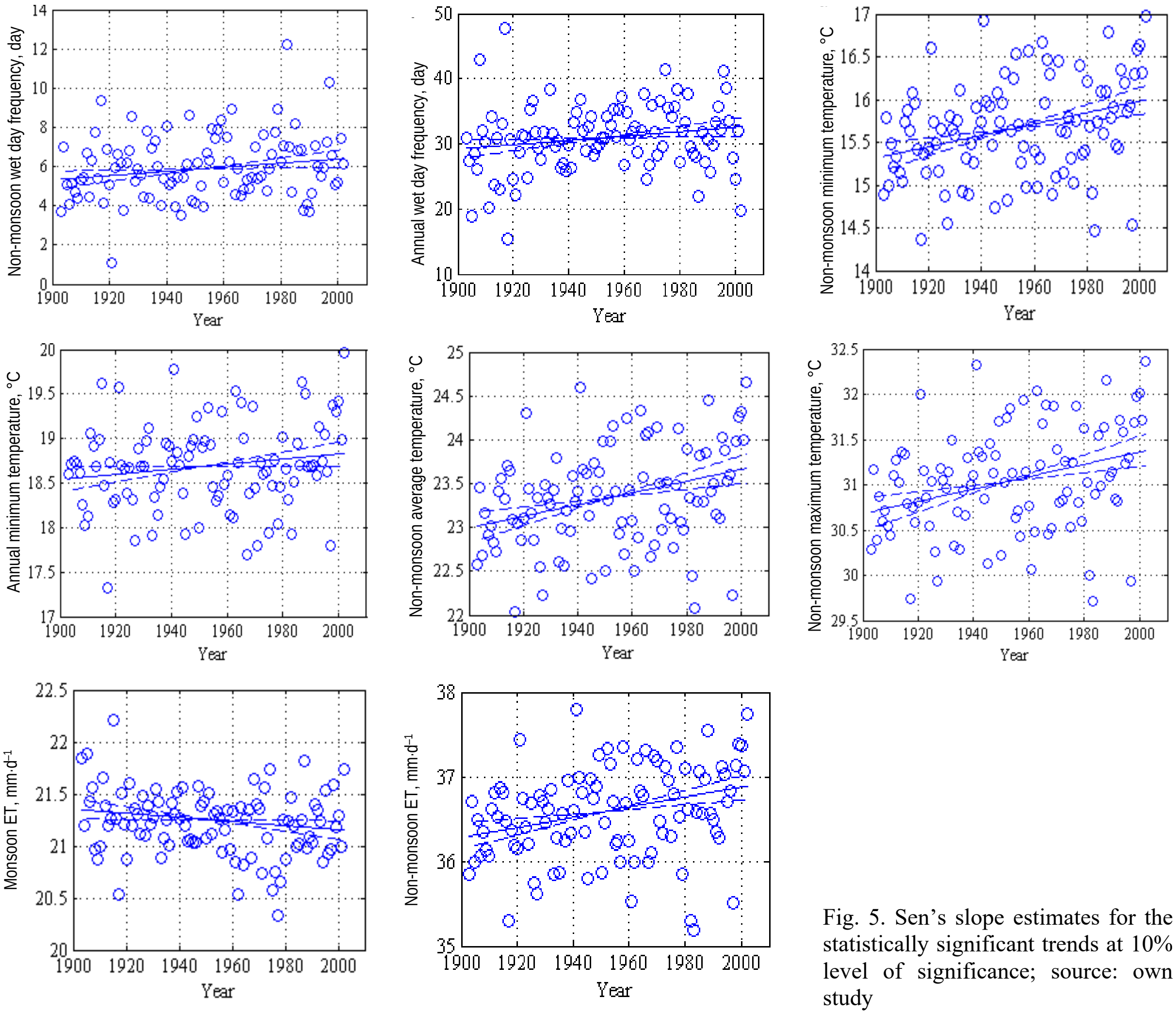

Fig. 5. Sen's slope estimates for the statistically significant trends at 10% level of significance; source: own study

Table 6. Summary of statistics of climatic variables at Ajmer District

Parameters	Monsoon season		Non-monsoon season		Annual	
	mean	*SD*	mean	*SD*	mean	*SD*
Rainfall, mm	495.07	177.11	46.29	28.71	541.35	183.78
Wet day frequency, days	24.87	4.81	5.99	1.65	30.86	5.18
Minimum temperature, °C	24.73	0.68	15.66	0.57	18.68	0.49
Average temperature, °C	29.33	0.68	23.34	0.58	25.33	0.49
Maximum temperature, °C	33.95	0.68	31.04	0.58	32.01	0.49
Diurnal temperature, °C	9.20	0.09	15.38	0.10	13.32	0.08
Cloud cover, %	49.93	2.54	16.70	1.98	27.78	1.79
Reference *ET*, mm	21.22	0.32	36.57	0.55	57.79	0.67
PET, mm	26.43	0.28	53.04	0.47	79.47	0.60

Explanations: *SD* = standard deviation; *ET*, *PET* as in Table 1.
Source: own study.

The significant increasing trends were observed in most of the climatic variables in the non-monsoon season by all three methods over the 100 year period with the exception of maximum temperature by the MK–PW test, which showed a significant decreasing trend in the non-monsoon season at the 10% significance level (Tab. 3). Significant increasing trends were observed in wet day frequency, minimum and average temperature and reference *ET* in the non-monsoon season from the three tests. However, these tests failed to detect significant trends for other climatic variables at the 10% level of significance (Tab. 3).

Significant increasing trends were observed in wet day frequency and minimum temperature on an annual scale using the three statistical methods over the study period. However, a significant increasing trend was only observed in annual maximum temperature using the MMK test (Tab. 4). These results are in good agreement with previous studies in India (e.g. KOTHYARI, SINGH [1996]; KOTHAWALE, KUMAR [2005]; JAIN *et al.* [2013]). A study conducted by PINGALE *et al.* [2015] similarly observed average temperature increases over time in the Ajmer District, which contrasted with findings of the IPCC that demonstrated both an average increase and decrease in temperature at the global level. All three trend tests failed to detect significant trends in the other remaining climatic variables at the 10% level of significance (Tab. 4). However, statistically significant upward slopes were observed in wet day frequency on an annual scale (Tab. 5), which indicated an increase in annual wet day frequency and a higher possibility of intense storms in the Ajmer District.

PETTITT–MANN–WHITNEY (PMW) TEST FOR SHIFT DETECTION

Shift detection is very important in identifying evidence of climate change and it provides valuable information for planning adaptation measures. Therefore, shift detection in the climatic time series was carried out using the PMW test on the seasonal and annual time scales for the climatic variables and a shift was observed in statistically significant climatic variables in the Ajmer District over the 100 year time period (Fig. 6 to 14). A shift in wet day frequency and average cloud cover variation (%) on an annual scale was observed during the years of 1941 and 1954, respectively (Fig. 6 and 14). However, a shift was not found in wet day frequency during the monsoon season and non-monsoon season and average cloud cover variation (%) during the monsoon season. No shift was observed in rainfall on either the seasonal or annual scale in the Ajmer District. However, this contrasted with Ajmer city where significant shifts have been observed in non-monsoon season rainfall in addition to an increasing trend in non-monsoon rainfall at the 10% significance level [PINGALE *et al.* 2015]. The surface temperature (minimum, average and maximum) in the non-monsoon season had a significant shift in 1937 (Fig. 6 to 9). There were no observable significant changes in surface temperature for the annual and monsoon season over the 100 year period. Significant shifts (increases) in both the reference evapotranspiration and *PET* were observed in the non-monsoon season in 1937 and 1930, respectively (Fig. 10 and 12). However, significant decreases in shift were observed for the *PET* during the monsoon season from 1952 onward (Fig. 11). There were no shifts in reference *ET* during the monsoon season and annual scale and no shifts in *PET* were observed at the annual time scale for the study period. The shifts in climatic variables were likely due to the global climate shift or factors such as the weakening global

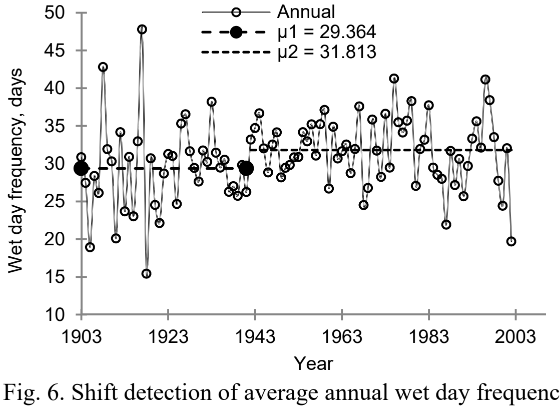

Fig. 6. Shift detection of average annual wet day frequency; source: own study

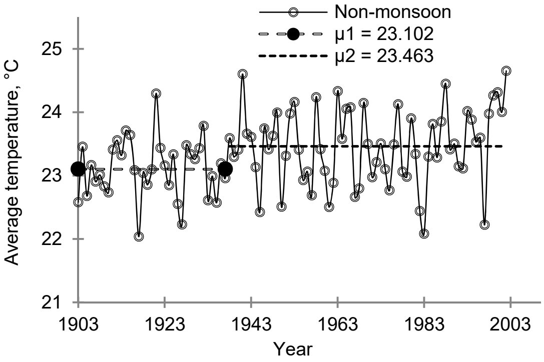

Fig. 7. Shift detection of non-monsoon season average temperature; source: own study

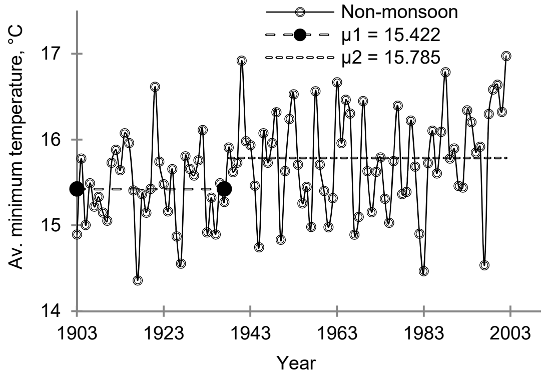

Fig. 8. Shift detection of non-monsoon season minimum temperature; source: own study

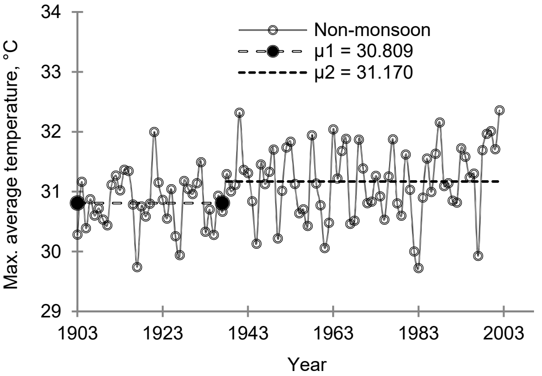

Fig. 9. Shift detection of non-monsoon season maximum temperature; source: own study

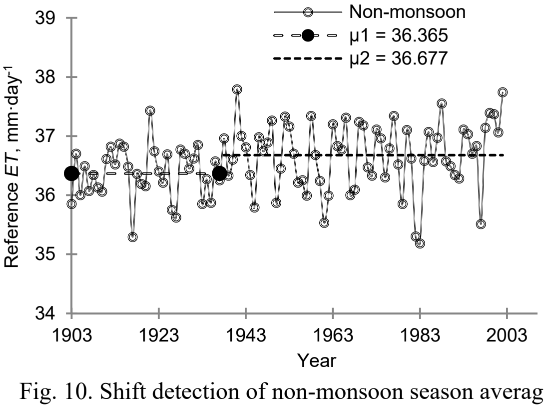

Fig. 10. Shift detection of non-monsoon season average reference evapotranspiration (*ET*); source: own study

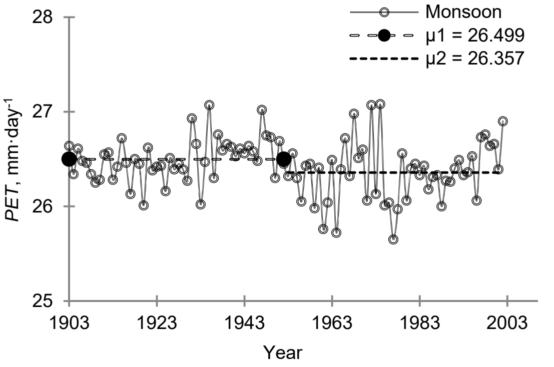

Fig. 11. Shift detection of monsoon season average potential evapotranspiration (*PET*); source: own study

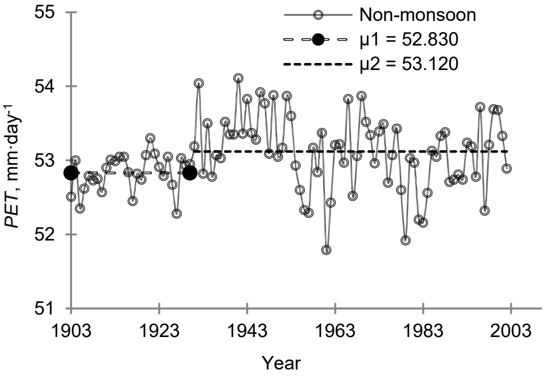

Fig. 12. Shift detection of non-monsoon season average potential evapotranspiration (*PET*); source: own study

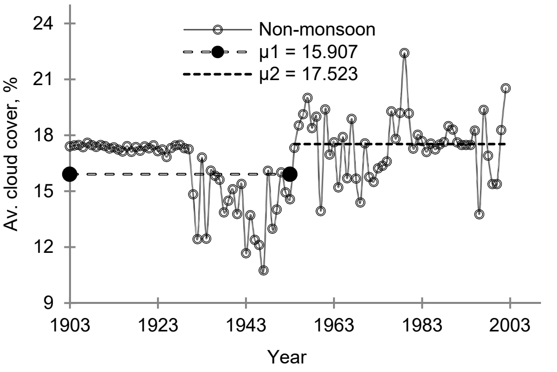

Fig. 13. Shift detection of non-monsoon season average cloud cover; source: own study

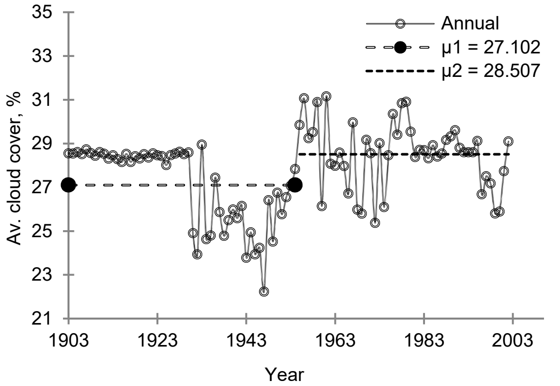

Fig. 14. Shift detection of annual average cloud cover; source: own study

monsoon circulation, the reduction in forest cover and increasing aerosol concentration in the atmosphere due to anthropogenic activities [BASISTHA *et al.* 2009].

The assessment of trends and shifts in different climatic variables on annual and seasonal scales is crucial for adaptation planning in arid and semi-arid regions of India at district scales. Similar studies like PINGALE *et al.* [2014] that assess trends on local and regional levels at annual and seasonal time scales are useful for adaptation planning measures.

SUMMARY AND CONCLUSIONS

In this study, trend analysis of nine climatic variables during the monsoon season, non-monsoon season and annual scale was performed for the period of 1903 to 2002 in the Ajmer District using three non-parametric statistical tests (i.e., MK test, MK–PW test and MMK test). The PMW test was applied to detect temporal shifts in the climatic series over the study period. The Sen's slope and percentage change in climatic variables were also estimated over the period of 100 years. The trend analysis revealed an overall upward precipitation trend even though no statistically significant trends were observed for the seasonal and annual scales. On the seasonal and annual scales, a noticeable increase was revealed in wet day frequency, surface temperature (i.e. minimum, average and maximum temperature) and reference *ET* during the non-monsoon season based on the results of the three non-parametric statistical tests at the 10% significance level, while maximum temperature experienced statistically significant decrease based on the MK–PW test). No change in average diurnal temperature was observed over the period of 100 years in the study area. This type of information should be helpful in facilitating a transition to more sustainable and adaptive water resources planning and management in the Ajmer District of India. Ultimately, this will help policy makers and scientists to focus on district scale planning measures for climate change adaptation and mitigation, by considering regional and local scale variability in trends compared to global climatic trends.

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Santosh M. PINGALE, Deepak KHARE, Mahesh K. JAT, Jan ADAMOWSKI

Analiza trendu czynników klimatycznych na suchych i półsuchych obszarach dystryktu Ajmer w Radżasthanie, Indie

STRESZCZENIE

Słowa kluczowe: *nachylenie Sena, test Manna–Kendalla (MK), test Pettitta–Manna–Whitneya (PMW), trendy, Rajasthan, zmodyfikowany test Manna–Kendalla (MMK)*

W pracy analizowano trendy i zmienność czynników klimatycznych (opad, częstotliwość dni wilgotnych, temperaturę powierzchni ziemi, temperaturę dobową, zachmurzenie oraz ewapotranspirację wskaźnikową i potencjalną) w skali sezonowej i rocznej w dystrykcie Ajmer, w Radżasthanie (Indie). Analizę przeprowadzono za pomocą nieparametrycznych technik statystycznych Manna–Kendalla (MK) i zmodyfikowanej techniki MK (MMK) dla 100-letniego okresu. Test MK z eliminacją korelacji serii klimatycznych (prewhitening – MK–PW) zastosowano także do zmiennych klimatycznych, a wyniki porównano z uzyskanymi z użyciem testów MK i MMK, co pozwoliło na ocenę wiarygodności wykrywania trendu zmian w czasie.

W celu wykrycia czasowych przesunięć serii klimatycznych zastosowano test Pettitta–Manna–Whitneya (PMW). Na podstawie analizy trendu stwierdzono, że opady roczne i sezonowe nie wykazywały statystycznie istotnego trendu na poziomie istotności 10%. Wykorzystując trzy testy nieparametryczne, stwierdzono rosnący trend w przypadku częstości występowania wilgotnych dni, temperatury powierzchni i ewapotranspiracji wskaźnikowej w okresie pozamonsunowym na poziomie istotności 10%. Statystycznie istotny spadek maksymalnej temperatury w tym okresie stwierdzono jedynie, gdy stosowano test MK–PW. Przedstawiona analiza kilku zmiennych klimatycznych w skali dystryktu może być pomocna w planowaniu i zarządzaniu zasobami wodnymi i w rozwoju strategii adaptacji do niekorzystnych warunków klimatycznych.