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Reference evapotranspiration under changing climate over the Thar Desert in India

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ABSTRACT: Reference evapotranspiration (RET) plays a critical role in irrigation planning and is needed for the determination of water demands of crops. Thus, in the present study, trends in RET were identified over Bikaner located in the Thar Desert (Rajasthan) in India using the non-parametric Mann–Kendall (MK) test. First, RET values were estimated through the Penman–Monteith method for different time scales using meteorological data for 39 years from 1967 to 2005. Second, the effect of significant lag-1 serial correlation was removed from the time series of RET by pre-whitening. Third, trends were investigated using the MK test. RET was found to decrease significantly at Bikaner during annual, pre-monsoon, monsoon and post-monsoon time scales. On probing the causal meteorological parameters responsible for the observed RET trends in the Thar Desert, it was witnessed that wind speed dynamically influenced the observed RET changes at the annual time scale and all the four seasons over the Thar Desert. The maximum temperature, followed by relative humidity, influenced the RET trends at annual and seasonal (winter, pre-monsoon and monsoon) time scales. The calm atmosphere witnessed over this arid site substantiates RET decreases over this Thar Desert site. The results of this study support that the evapotranspiration decreases over Bikaner are controlled mainly by trends in the aerodynamic component, i.e. by the effects of significant wind speed decreases on RET, than the changes in the radiative component over the arid site located in the Thar Desert.

KEY WORDS evapotranspiration; trend; causal meteorological parameters; Thar Desert

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1. Introduction

Water resource has become a prime concern for development and planning, including food production and flood control. The impact of climate change may be relatively severe with the reduction in the water availability over different parts of the globe. Kothawale and Rupa Kumar (2002) have reported that the all India mean annual temperature has risen at a rate of 0.05 °C decade^{-1} during the last century, which is mostly due to the rise in maximum temperature (0.07 °C decade^{-1}) rather than because of the rise in minimum temperature (0.02 °C decade^{-1}). It is generally believed that a rise in temperature may frequently lead to a rise in evapotranspiration. Recognizing that evapotranspiration is one of the basic components of the hydrologic cycle, the Food and Agriculture Organization (FAO) adopted the concept of reference evapotranspiration (RET) in the FAO guidelines for crop water requirements based on studies by Doorenbos and Pruitt (1975, 1977), which are widely accepted for calculating evapotranspiration. RET is the phase change of water requiring a large amount of energy. Information on the amount of water required by different crops under a given set of region-specific climatic conditions will help greatly in irrigation planning and scheduling. RET is based primarily on measurements of radiation, vapour pressure, air temperature, relative humidity, and wind velocity over the evaporating surface.

A number of researchers (Dinpashoh *et al.*, 2011; Jhajharia *et al.*, 2012a; McVicar *et al.*, 2012) have analysed trends in evapotranspiration under warmer climates around the globe using data of different durations at different locations under different types of climate. Peterson *et al.* (1995), Chattopadhyay and Hulme (1997), Lawrimore and Peterson (2000), Golubev *et al.* (2001) and Roderick and Farquhar (2004) reported significant decreases in either (both) pan evaporation (E_{pan}) or (and) potential evapotranspiration (PET) over various parts of Russia and the United States, over India, over various parts of the United States, over a few sites in the United States and the former Soviet Union and over Australia, respectively. Similarly, several researchers from China reported decreasing trends in evapotranspiration (Chen *et al.*, 2006; Gao *et al.*, 2006, 2007; Xu *et al.*, 2006; Wang *et al.*, 2007; Zhang *et al.*, 2007, 2009; Liu *et al.*, 2010). Recently, Zhang *et al.* (2011b) reported the occurrences of decreasing annual and seasonal evapotranspiration in east, south and northwest China. Similarly, Tebakari *et al.* (2005), Jhajharia *et al.* (2009b) and Zhang *et al.* (2014) reported decreasing trends in E_{pan} in the Chao Phraya River basin (Thailand), in northeast India and over the entire territory of China, respectively. For other studies from the Indian subcontinent, Jhajharia *et al.* (2012a)

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reported significant decreasing trends in evapotranspiration over different parts of northeast India.

The RET trends may have a direct influence on the production of crops, and thus identifying trends in RET under climate change is important for understanding the effect of changing RET on agriculture. Bikaner, one of the well-known sites in the Thar Desert, has witnessed various changes due to urbanization and the extensive spread of irrigation canal networks of the Indira Gandhi Canal, carrying waters of the Satluj and Vayas Rivers through the states of Himachal Pradesh, Haryana and Punjab into the vast dry lands of the Thar Desert in the western part of Rajasthan, during the last few decades. Bikaner has witnessed significant increasing trends in minimum, maximum and mean temperatures at the annual time scale in the range of 0.1–0.4 °C decade^{-1} during the last 58 years from 1951 to 2008 (Choudhary *et al.*, 2009). The reported increases in temperature in the Bikaner area during this period provided the encouragement to determine if there would be any evapotranspiration increases under global warming scenarios in the arid climatic conditions of Bikaner in the Thar Desert. As no information is available about trends in RET over Bikaner, the present study was carried out with the following objectives: (1) to estimate RET using the Penman–Monteith (PM) method at annual and seasonal time scales over Bikaner under arid climatic conditions; (2) to investigate trends in RET using the Mann–Kendall (MK) non-parametric test; (3) to obtain the magnitudes of trends through the Theil–Sen test; (4) to perform trend analysis for the contributing meteorological parameters, i.e. wind speed, sunshine duration, relative humidity and temperature over the arid site located in the Thar Desert, and, (5) to identify the most dominating meteorological variables affecting RET using stepwise linear regression analysis.

2. Materials and methods

2.1. Study area and meteorological data

Bikaner (71 ° 54 ′–74 ° 12 ′ E to 27 ° 11 ′–29 ° 3 ′ N with altitude 237.0 m above mean sea level), is one of the important sites of the Thar Desert, located in the northwestern part of Rajasthan. The Bikaner district of Rajasthan state (India) shares its boundary on the western side with Pakistan. The Thar region is characterized by hot summers, with maximum temperature around 48.3 °C, and cold winter nights with minimum temperature around 1.3 °C. The average rainfall in the area is about 250 mm, and the groundwater table is also very deep (Kumar *et al.*, 2009a). The climate of the arid regions in and around the Thar Desert has shown well-documented large-scale fluctuations and the recent regional modifications in climate are caused by the changing land-use pattern, with a large area progressively brought under irrigation. The Thar Desert consists of arid regions with not much forest cover and experiences a very high diurnal temperature range. The Thar Desert region is well-known for the high variability of annual rainfall and the highest extreme temperature range in India (Pant and Hingane, 1988).

The location map of the study area is shown in Figure 1. The different meteorological data required for the computation of RET are maximum temperature (°C), minimum temperature (°C), relative humidity (%), wind speed (km h^{-1}) and duration of actual bright sunshine (h). The monthly data of these climatic parameters were obtained from the India Meteorological Department (Pune), Maharashtra, for the station of Bikaner from 1951 to 2008 (Choudhary *et al.*, 2009). The present study uses the definitions of the four seasons for Bikaner in the Thar Desert as given by Jhajharia *et al.* (2013) to compute the seasonal and annual time series from the monthly datasets. The four seasons were defined as: winter (January–February), pre-monsoon (March–June), monsoon (July–September) and post-monsoon (October–December).

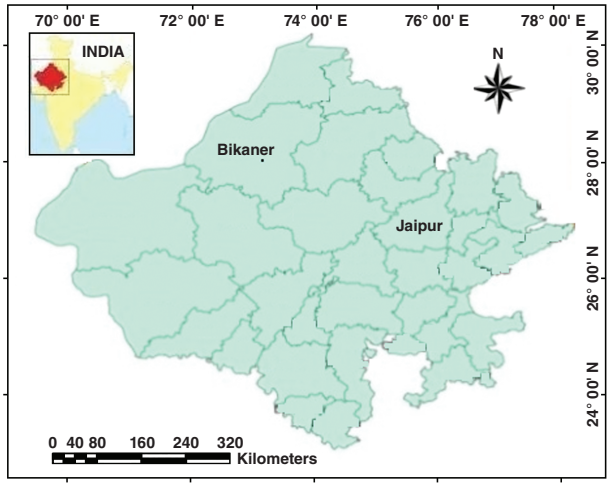


Figure 1. Location map of Bikaner situated in Rajasthan in northwest India.

2.2. Penman–Monteith FAO-56 method

Many investigators have developed equations to estimate evapotranspiration. The most commonly used RET method, i.e. the Penman–Monteith FAO-56, was selected for the present study, because it is physically based and explicitly incorporates both physiological and aerodynamic parameters (Xu *et al.*, 2006), and is the most reliable and universally accepted method to estimate evapotranspiration under various types of climate. The PM FAO-56 model for computing the RET is given as (Allen *et al.*, 1998):

$$\mathrm{RET} = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{900}{\overline{T}+273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \quad (1)$$

where RET is the reference evapotranspiration (mm day^{-1}); R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^{-2} day^{-1}); $\overline{T}$ is the mean daily air temperature (°C); u_2 is the wind speed at a 2 m height above the ground (m s^{-1}); e_s is the saturation vapour pressure (kPa); e_a is the actual vapour pressure (kPa); $e_s - e_a$ is the saturation vapour pressure deficit (kPa); Δ is the slope of vapour pressure *versus* temperature curve at temperature T (kPa °C^{-1}); and γ is the psychrometric constant (kPa °C^{-1}).

Allen *et al.* (1998) proposed a complete set of equations according to the available weather data and time step computation, which is known as the PM method. Additional details of the PM method are available in the works of Jhajharia *et al.* (2004a, 2004b) and Nandagiri and Kovoor (2005).

2.3. Mann–Kendall methods for trend analysis

In the present study, the non-parametric MK method was used for identifying trends in evapotranspiration and other climatic parameters, because this method is more suitable for non-normally distributed and censored data, and is less

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influenced by the presence of outliers in the data (Mann, 1945; Kendall, 1975). Most recently, Partal and Kahya (2006), Singh *et al.* (2008), Kumar and Jain (2010), Chattopadhyay *et al.* (2011a, 2011b), Jhajharia and Singh (2011), Dinpashoh *et al.* (2011, 2014), Jhajharia *et al.* (2012a, 2012b, 2013, 2014), Vousoughi *et al.* (2013) and Zhang *et al.* (2006, 2012) used this test for detecting trends in various climatic parameters under different types of environment. The MK test is carried out by computing an S statistic as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{2}$$

where n is the number of observations and x_j is the j^{th} observation and sgn(·) is the sign function which can be defined as follows:

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if} \quad \theta > 0 \\ 0 & \text{if} \quad \theta = 0 \\ -1 & \text{if} \quad \theta < 0 \end{cases} \tag{3}$$

Under the assumption that the data are independent and identically distributed, the mean and variance of the S statistic are given by (Kendall, 1975):

$$E(S) = 0 \tag{4}$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i \left(t_i - 1\right)\left(2t_i + 5\right)}{18} \tag{5}$$

where m is the number of groups of tied ranks, each with t_i tied observations. The Z-statistic can be computed as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}} & S < 0 \end{cases} \tag{6}$$

The null hypothesis of no trend can be accepted at a significance level of α, if $-Z_{1-\alpha/2} \le Z \le Z_{1-\alpha/2}$. Else the null hypothesis can be rejected and the alternative hypothesis can be accepted at the significance level of α.

The effect of serial dependence is one of the major problems faced during the identification of trends in various climatic parameters. First, the significance of lag-1 serial correlation (r_1) for all RET time series was tested to eliminate the effect of serial correlation. The RET time series was subjected to the original MK test if the absolute value of r_1 was less than the significance level value. Otherwise, the effect of serial correlation was removed from the time series by using the pre-whitening procedure prior to applying the MK test. Various researchers (Zhang *et al.*, 2001; Dinpashoh *et al.*, 2011, 2014; Jhajharia *et al.*, 2012a; Vousoughi *et al.*, 2013) have also used the pre-whitening procedure in the recent past.

The residual series after pre-whitening may be checked for trends through the MK test, and for this purpose the new time series is obtained as (Kumar *et al.*, 2009b):

$$x_i' = x_i - (\beta \times i) \tag{7}$$

where β is the Theil–Sen estimator (Theil, 1950; Sen, 1968).

The value of r_1 of the new time series is first computed and later used to determine the residual series as follows:

$$y_i' = x_i' - r_1 \times x_{i-1}' \tag{8}$$

The value of $\beta \times i$ was added again to the residual data set as follows:

$$y_i = y_i' + (\beta \times i) \tag{9}$$

The y_i series was subjected to trend analysis.

2.3.1. *Theil–Sen estimator*

The slope of n pairs of data points was estimated using the Theil–Sen estimator which is given as (Yue *et al.*, 2002):

$$\beta = \text{Median}\left(\frac{x_j - x_l}{j - l}\right) \quad \forall \quad 1 < l < j \tag{10}$$

The slope computed by this estimator is a robust estimate of the magnitude of a trend and is used extensively in identifying the slope of a trend line in a time series.

3. Results and discussion

RET, an important parameter for irrigation planning, needs to be determined for estimation of the water demands of various crops and also for water resource development and use (Jhajharia and Dhiman, 2006; Jhajharia *et al.*, 2009a). The RET values estimated by the PM method at annual and seasonal time scales along with different time series of total sunshine duration, relative humidity and wind speed are shown in Figures 2–4.

3.1. Estimation of RET by the PM method

The highest and the lowest values of total RET for the annual duration were found to be 2242.4 and 1520.42 mm in 1969 and 1983, respectively. At the annual time scale, the RET values were comparatively on the higher side starting from the late 1960s to the early 1970s over Bikaner. During the last four decades, the mean decadal RET was also found to be the highest from 1961 to 1970, i.e. a total of 1930.6 mm (the lowest during the decade from 1981 to 1990, i.e. a total of 1696.5 mm) over Bikaner. The statistical properties of various parameters of RET were also obtained for annual and seasonal time scales (see Table 1). These statistical properties of RET from 1960 to 2005 are useful in describing the characteristics of evapotranspiration over Bikaner. The mean of the total RET was found to be 1863.82 mm at the annual time scale. The standard deviation and the co-efficient of variation of the RET were found to be 182.2 mm and 9.77%, respectively, at the annual time scale.

It is worthwhile mentioning that the total annual RET values over Bikaner remained very high, i.e. above 2130 mm for 6 years, i.e. 1965, 1969–1970, 1999–2000 and 2002, with the occurrence of the highest RET (2242.4 mm) in 1969. These 6 years witnessed comparatively very high values of wind speed in the range of 198.0–228.2 km day^{-1}, with the occurrence of the highest (228.2 km day^{-1}) and the second highest (225.6 km day^{-1}) wind speed in 1965 and 1969, respectively. On the other hand, the total annual RET values remained very low, i.e. varying from 1520.42 to 1681.1 mm for 5 years, i.e. 1983, 1986, 1987, 1996 and 1997. The above-mentioned results related to the annual RET values, both the highest and the lowest values, witnessed over Bikaner can easily be explained through the time series of annual wind speed and annual RET as shown in Figure 2. The time series reveals that the lowest (highest) RET values are mainly due to the occurrence of the lowest (highest) wind speed at the annual time scale over the Thar Desert site, for example, the simultaneous occurrence of the lowest wind speed (76.6 km day^{-1}) and RET (1520.42 mm) in the year 1983 over Bikaner.

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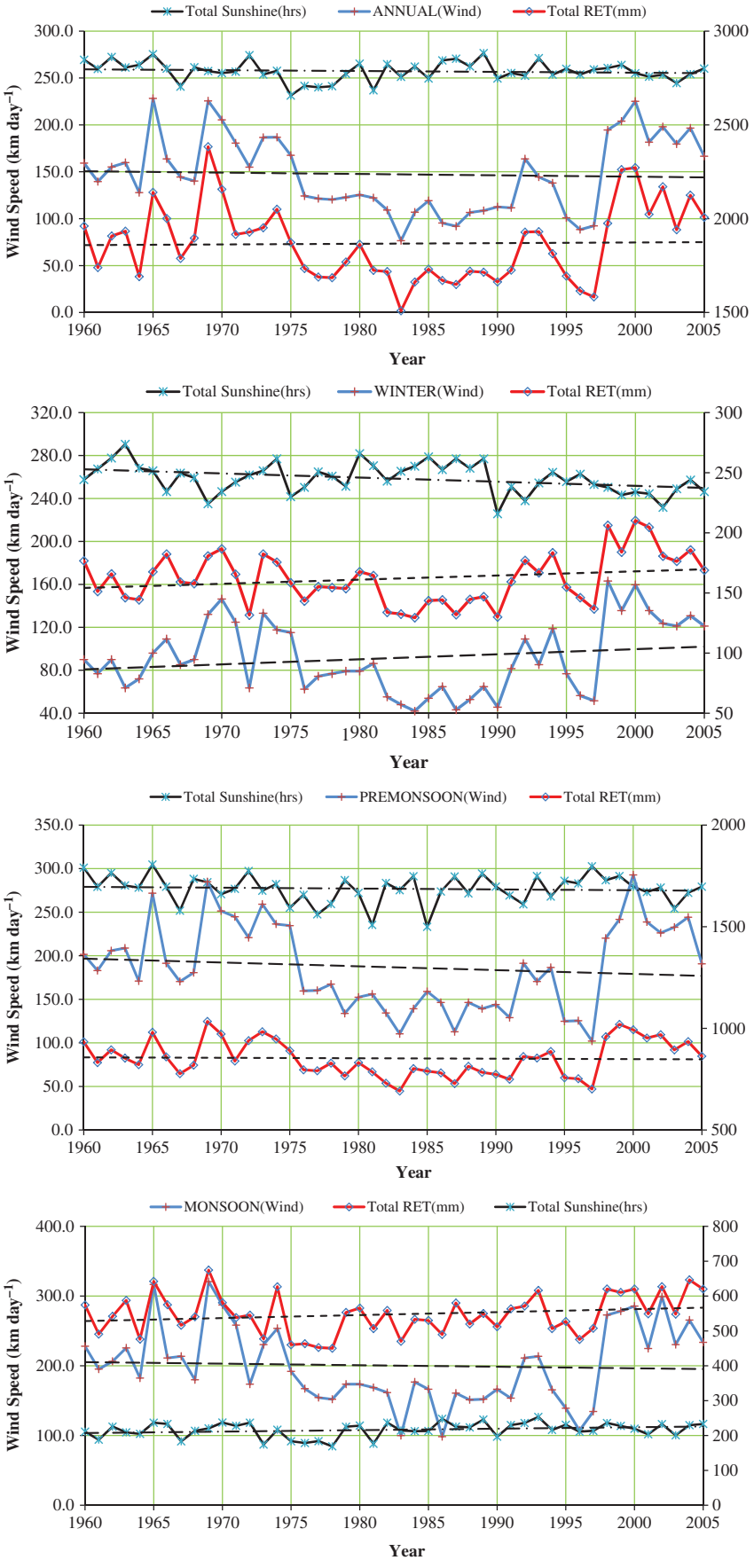


Figure 2. Relationship between reference evapotranspiration (RET) and other climatic parameters in different time scales during 1960–2005. Dotted lines represent the linear trend lines for each individual climatic parameter.

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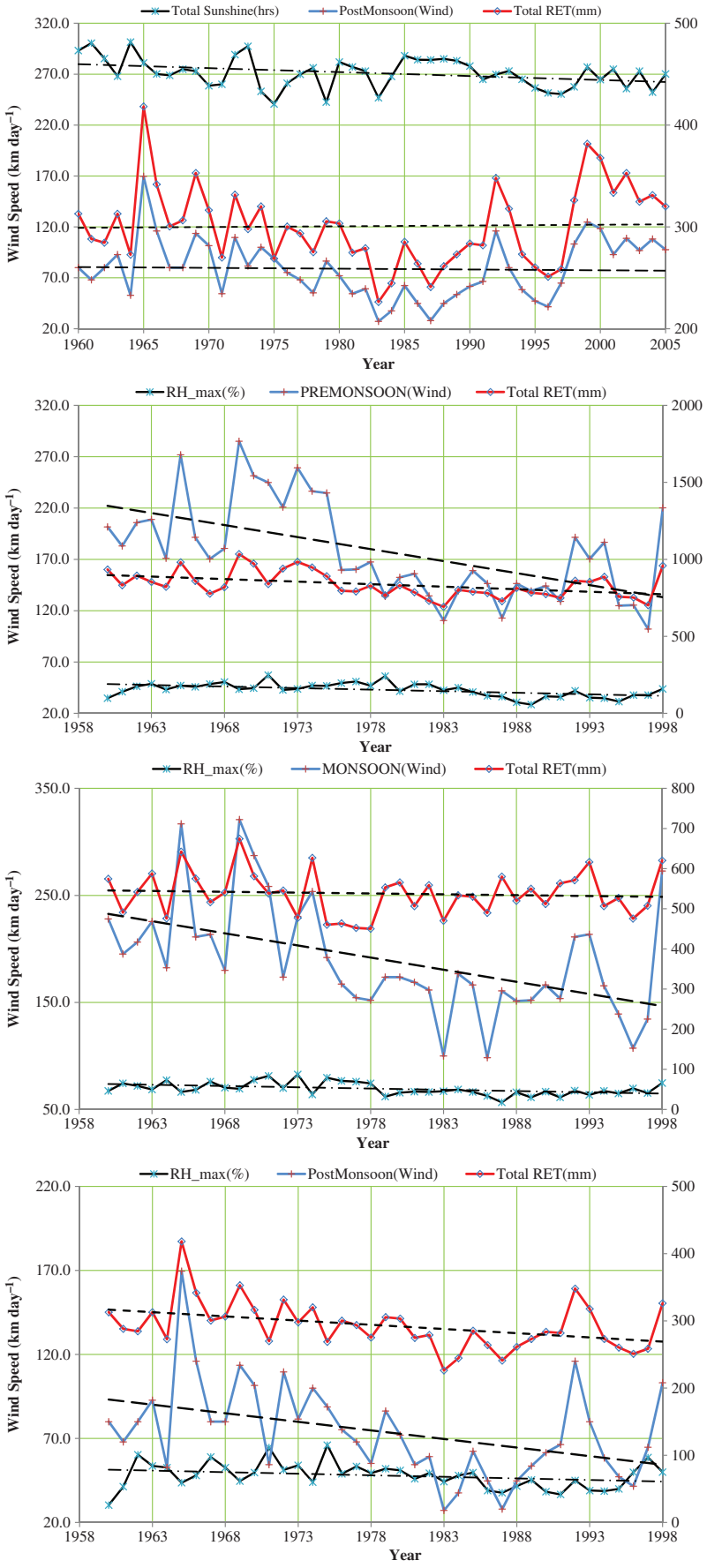


Figure 3. Relationship between reference evapotranspiration (RET) and other climatic parameters during two different durations in seasonal time scales. Dotted lines represent the linear trend lines for each individual climatic parameter.

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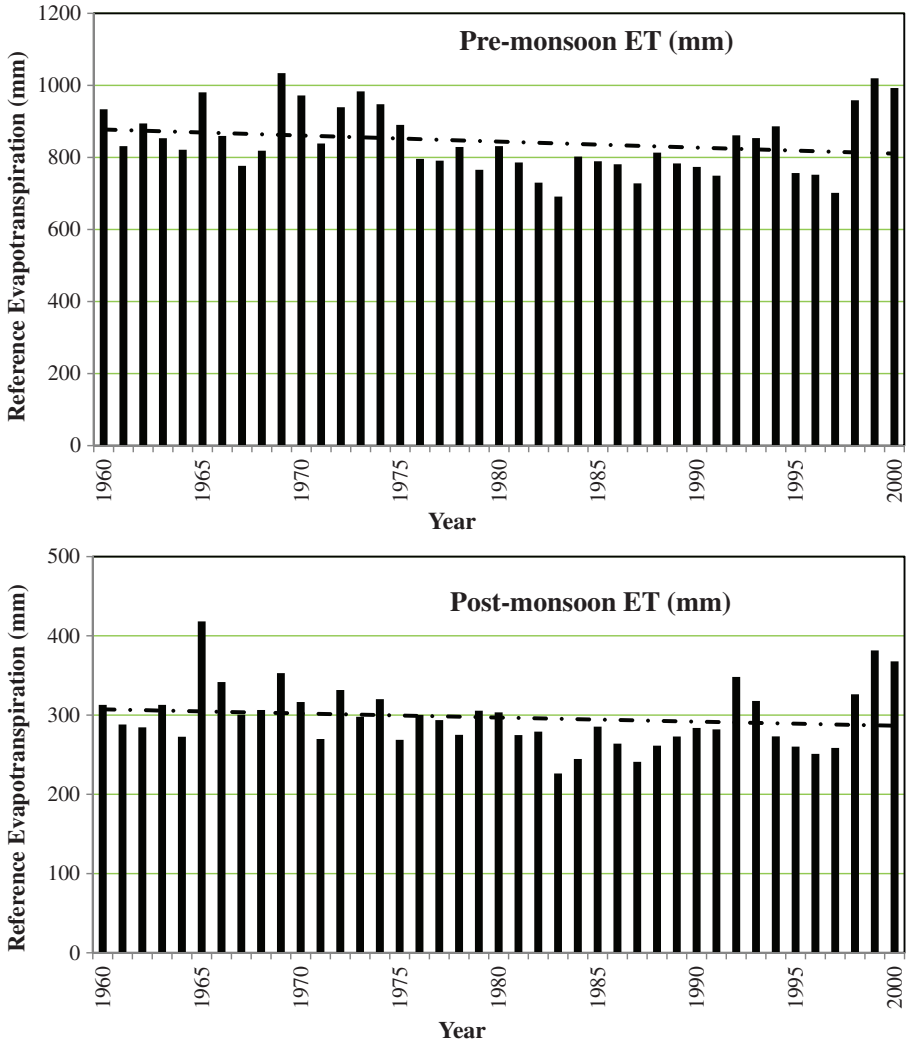


Figure 4. Sample seasonal time series of reference evapotranspiration (RET).

Table 1. Statistical properties of reference evapotranspiration (mm) over Bikaner site.

Time scale	Mean	Maximum	Minimum	SD	Skewness	Kurtosis	CV
Annual	1863.82	2242.41	1520.42	182.18	0.44	−0.76	9.77
Winter	161.93	210.24	129.41	20.93	0.36	−0.45	12.92
Pre-monsoon	852.54	1034.15	691.52	89.59	0.27	−0.89	10.51
Monsoon	548.25	674.56	450.11	58.37	0.21	−0.73	10.65
Post-monsoon	301.10	418.22	226.32	39.26	0.63	0.57	13.04

SD, standard deviation; CV, co-efficient of variation.

At the seasonal time scale, the mean of RET values estimated by the PM method for the four different seasons varied from 161.93 mm (winter) to 852.54 mm (pre-monsoon) over Bikaner. The maximum (minimum) of the RET varied from 210.2 (129.4) mm to 1034.2 (691.52) mm in the winter and pre-monsoon seasons, respectively. The standard deviations of RET were found to be 20.93 and 89.59 mm for the winter and pre-monsoon seasons, respectively. The values of the co-efficient of variation of RET varied from 10.51% to 13.04% in the pre-monsoon and post-monsoon seasons, respectively. A sample time series of total seasonal RET for pre-monsoon and post-monsoon seasons are given in Figure 4. Most of the total RET values in the winter (pre-monsoon) season hovered around 160 (800) mm. On the other hand, the total RET values in the monsoon season varied in the range of ∼500–600 mm. The pre-monsoon season witnessed the highest amounts of total RET value, whereas the winter season witnessed the lowest amounts of total RET value. The RET values of the pre-monsoon and monsoon seasons accounted for about 45.7 and 29.4% of the total annual RET, respectively. It is attention grabbing that the total RET values witnessed a sudden increase during 1998 in all the four seasons, which resulted in the total RET values of these recent 8 years (1998–2005) being at par with the seasonal RET values witnessed during the late 1960s over Bikaner. These sudden increases in the seasonal RET during 1998 can be explained as being similar to increases witnessed in annual RET based on near-simultaneous increases in the wind speed in these 8 years over Bikaner. Zhang *et al.* (2011a) report significant decreases in actual evapotranspiration

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Table 2. *Z*-values through MK test over Bikaner site located in Thar Desert, India.

Time scale	RET (mm)	RET* (mm)	T_{min} (°C)	T_{max} (°C)	Wind (km h^{-1})	Wind* (km h^{-1})	RH_{max} (%)	RH_{min} (%)	Sun (h)
Annual	*−0.42*	**−3.17**	**3.97**	**1.71***	*−1.09*	**−3.76**	**−2.40**	**−2.72**	*−1.16*
Winter	*0.53*	**−1.80***	**3.43**	*−0.31*	*0.62*	**−1.76***	*−0.42*	*−1.29*	**−2.52**
Pre-monsoon	*−0.93*	**−3.68**	**2.52**	*1.30*	*−1.38*	**−3.92**	**−2.61**	**−1.82***	*−0.77*
Monsoon	*0.53*	*−1.00*	*1.17*	**1.90***	*−1.14*	**−3.91**	*−1.25*	**−2.02**	**1.86***
Post-monsoon	*−0.32*	**−2.95**	**3.49**	**2.12**	*−0.28*	**−2.67**	**−2.56**	**−3.28**	**−2.36**

Bold and bold* values denote statistically significant trends obtained through MK test at 5 and 10% levels of significance, respectively, for 46 years from 1960 to 2005. Italic values are statistically non-significant even at 10% level of significance. Italic underlined values are statistically non-significant even at 10% level of significance for the time series of wind speed and RET from 1960–1998. RET* and WIND* (in third and seventh columns) denote the trend values for the data from 1960 to 1998. Bold and underlined trend values were obtained using the data for the duration of 39 years from 1960 to 1998.
MK, Mann–Kendall; RET, reference evapotranspiration; T_{min}, minimum temperature; T_{max}, maximum temperature; RH_{max}, maximum relative humidity; RH_{min}, minimum relative humidity.

in both 'energy-limited' Pearl River basin and 'water-limited' Yellow River basin of China. However, the middle and upper Yellow River basins witnessed RET increases and the Pearl River basin witnessed RET decreases. Jhajharia *et al.* (2009b) reported decreasing E_{pan} trends in humid environments of northeast India mainly in the pre-monsoon and monsoon seasons. Similarly, Zhang *et al.* (2014) identified significant decreases in E_{pan} in southern, central, southwestern, eastern and northwestern China. On the other hand, E_{pan} increases were found to be spread over a few sites intermittently across China.

3.2. Identification of trends in RET and other climatic parameters

RET plays a critical role in irrigation planning and therefore identifying trends in RET is important for agriculture. In this study, trends in RET were investigated using the MK test after removing the effect of significant lag-1 serial correlation from the time series of RET by using the pre-whitening procedure. Table 2 shows the *Z*-statistic values obtained through the MK test for RET and other climatic parameters. The Theil–Sen estimator was used to obtain the magnitudes of trends in RET (see Table 3). Results revealed that RET was found to decrease significantly for different durations: annual and seasonal: winter, pre-monsoon and post-monsoon, during the 39 years from 1960 to 1998. The Thar Desert site witnessed statistically significant decreasing trends in RET in the annual time scale (winter, pre-monsoon and post-monsoon seasons) at a rate of 68.4 mm decade^{-1} (4.6, 40.8 and 14.9 mm decade^{-1}, respectively) from 1960 to 1998. However, no significant trend was witnessed in RET in the monsoon season over Bikaner, i.e. the values of RET remained stable in the monsoon season. Trends of the seasonal RET decreases indicate the presence of an element of a seasonal cycle in the evaporative demands, i.e. RET decreases more significantly in the pre-monsoon season and is completely non-significant in the monsoon season. Jhajharia *et al.* (2012a) also reported the existence of seasonality in the data of RET under the humid climatic conditions of northeast India. Statistically significant decreasing trends in wind speed were witnessed in the annual time scale and all the four seasons in the range of 0.258–0.064 m s^{-1} decade^{-1} during the 39 years from 1960 to 1998. It is interesting to note that both RET and wind speed became practically trendless in the annual and in all the four seasonal time scales during the last 46 years from 1960 to 2005 due to the occurrence of comparatively higher values of both the parameters from 1998 to 2005 in comparison with the previous years' values of RET and wind speed over Bikaner.

Bikaner witnessed statistically significant decreasing trends (increasing trend) in sunshine duration during the winter and post-monsoon (monsoon) seasons at the rate of 3.8 (4.16) h decade^{-1} during the last 46 years from 1960 to 2005. Significant decreases in sunshine during winter and post-monsoon seasons may have occurred due to smog (smoke and fog) formation in the Thar Desert. Formation of smog takes place due to the comparatively low air temperature over the Thar Desert in December, January and February. Zhang *et al.* (2011a) credited the decrease in sunshine hours to the increasing aerosol as an increase in cloud cover was witnessed over the Pearl River basin. Similarly, Zhang *et al.* (2011b) found that increased air pollution and aerosols were two main motivating factors for the dimming, i.e. decreases in net solar radiation, over the highly urbanized regions of east and south China.

Statistically significant decreasing trends were witnessed in the morning and afternoon relative humidity in different durations: annual and season: pre-monsoon and post-monsoon in the range of 1.31–2.48% decade^{-1}. On the other hand, statistically significant increasing trends were witnessed in night temperatures in annual and seasonal (all but monsoon) time scales in

Table 3. Magnitude of trends in various climatic parameters (decade^{-1}) over Bikaner.

Time scale	RET* (mm)	T_{min} (°C)	T_{max} (°C)	Wind* (km h^{-1})	RH_{max} (%)	RH_{min} (%)	Sun (h)
Annual	**−68.4**	**0.35**	**0.12***	**−0.71**	**−1.37**	**−1.79**	*−0.90*
Winter	**−4.6**	**0.55**	*−0.09*	**−0.23**	*−0.38*	*−1.53*	**−3.85**
Pre-monsoon	**−40.8**	**0.29**	*0.11*	**−0.98**	**−1.91**	**−1.31***	*−0.99*
Monsoon	*−8.1*	*0.08*	**0.22***	**−0.95**	*−0.93*	**−1.93**	**4.16***
Post-monsoon	**−14.9**	**0.35**	**0.17**	**−0.43**	**−1.78**	**−2.48**	**−3.89**

Bold and bold* values denote statistically significant trends obtained through MK test at 5 and 10% levels of significance, respectively, for 46 years from 1960 to 2005. Italic values are statistically non-significant even at 10% level of significance. Italic underlined values are statistically non-significant even at 10% level of significance for the time series of wind speed and RET from 1960–1998. RET* and WIND* denote the trend values for the data from 1960 to 1998. Bold and underlined trend values were obtained using the data for the duration of 39 years from 1960 to 1998.
RET, reference evapotranspiration; T_{min}, minimum temperature; T_{max}, maximum temperature; RH_{max}, maximum relative humidity; RH_{min}, minimum relative humidity.

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the range of 0.29–0.55 °C decade^{-1} during the last 46 years from 1960 to 2005. Similarly, statistically significant increasing trends were witnessed in day temperatures in annual and seasonal (monsoon and post-monsoon) time scales at the rate of 0.12–0.22 °C decade^{-1} from 1960 to 2005. The warming at night time was comparatively more strong than the warming at day time in this site, which might have led to decreases in the diurnal temperature range (difference between day and night temperatures) in annual and seasonal (all but monsoon) time scales. Increase in diurnal temperature range was witnessed due to significant increases in day temperature, with night temperature remaining trendless in the monsoon season over Bikaner.

Trends in total rainfall for Bikaner were also obtained by applying pre-whitening procedures on annual and seasonal time series of rainfall. No significant trends in total rainfall were observed in annual duration and in all but one (winter) seasonal time scales under the arid environments of Bikaner. On the other hand, statistically significant increasing trends were witnessed in winter at Bikaner from 1960 to 2005. In order to verify the relationship between RET and rainfall over Bikaner, comparisons were drawn between these two parameters for the annual duration and all the four seasons. Negative relationships between total rainfall and total RET of Bikaner were witnessed in annual time scale, and in the pre-monsoon, monsoon and post-monsoon seasons, and are shown in Figure 5. Decreases in crop water requirements may be seen under conditions of significant decreases in total RET, steady rainfall and changing climates of Bikaner as part of the fragile ecosystems of the Thar Desert region of India.

3.3. Probing the causal parameters for the RET changes

Increases in night (day) air temperature are witnessed over Bikaner in almost all time scales (in monsoon and post-monsoon seasons). In spite of increase in temperature in annual time scale and in all the four seasons, RET has been found to decrease significantly over Bikaner in different durations: annual and seasonal: all but one, which establishes that besides air temperature, few other climatic parameters such as wind speed, relative humidity and radiation may be responsible for the observed RET decreases in the Thar Desert. Therefore, in order to identify the dominant variables associated with RET, the procedure recently used by Chattopadhyay and Hulme (1997), Thomas (2000) and Jhajharia *et al.* (2009b) was adopted in the present study. They used the stepwise regression method to search for and possibly explain the underlying mechanisms of observed RET changes under the arid climatic conditions over the Bikaner region. Stepwise regression analysis was performed between RET and all the meteorological parameters for annual and seasonal time scales by using SPSS (Norusis, 1988). While performing the stepwise regression analysis, RET was selected as a dependent variable and all the remaining climatic parameters as independent variables in order to look for the possible climatic parameters responsible for the RET changes in annual and seasonal time scales, and the results are shown in Table 4.

On probing the causal meteorological parameters responsible for the observed RET trends in the Thar Desert, it was found that wind speed dynamically influenced the observed RET changes at the annual time scale and all the four seasons, i.e. wind was found to be the most dominating meteorological variable which affected RET over the Thar Desert at all time scales. The process of air movement and vapour removal depends to a large extent on wind which is a major driving factor in transporting the water vapour transpired from the plants into the atmosphere (Darshana *et al.*, 2013). Therefore, the wind speed decreases may have the potential to offset the influence of temperature increases on the RET under the arid environments of Thar Desert region. Surface wind decreases may have occurred due to the intensive urbanization in the Thar Desert in the last 50 years. Steady decreases in wind speed witnessed over India may be related to the obstruction of wind flow caused by the ever-increasing construction works (Bandyopadhyay *et al.*, 2009). The global wind speed decreases may have occurred due to the possible role played by the increases in terrestrial surface roughness (McVicar and Roderick, 2010; Vautard *et al.*, 2010). Zhang *et al.* (2011a) report that urbanization may be one of the few causes behind the decreases in surface wind speed over the Pearl River and Yellow River basins of China.

The maximum temperature, followed by the relative humidity and bright sunshine hours, influenced the RET trends at annual and seasonal (winter, pre-monsoon and monsoon) time scales, and thus temperature and relative humidity were found to be the other two important contributing variables for the observed trends in RET. It is interesting to note that the sunshine duration did not have any influence on the observed trends in RET for the annual duration and for all but one season over the Thar Desert, or, it can be concluded that the evaporative demands are not affected by the changes in the radiative component over the arid environment of the Thar Desert. The calm atmosphere witnessed over this arid site substantiates the RET decrease witnessed in all the four seasons and the annual time scale over this site. Thus, the present study also proves that the declining rates of evaporative demand over the arid site are mainly controlled by trends in the aerodynamic component, i.e. deceases witnessed in wind speed, than the changes in the radiative component in annual and seasonal (all but post-monsoon) time scales. However, in the post-monsoon season, bright sunshine hours followed by the relative humidity and maximum temperature influenced the changes in RET. The results obtained for the arid environments over Bikaner are similar to the findings of Jhajharia *et al.* (2012a) under the humid climatic conditions of northeastern India. After wind speed, minimum relative humidity (RH_{min}) was the second most important influencing variable responsible for RET changes in winter, pre-monsoon and monsoon seasons over northeastern India (Jhajharia *et al.*, 2012a). Sunshine duration followed by wind speed strongly influenced changes in E_{pan} at various sites in the northeastern region of India in different seasons (Jhajharia *et al.*, 2009b). Similarly, Thomas (2000) and Xu *et al.* (2006) report that the wind speed over the evaporative surface is found to be the most dominating meteorological parameter influencing trends in evapotranspiration in China. Also, the RET changes were found to be influenced by the precipitation amount in the Yellow River basin, a 'water-limited' system and by the phenomena of stilling and dimming observed over the dry environments of the Yellow River basin (Zhang *et al.*, 2011a). Zhang *et al.* (2011b) report that evapotranspiration decreases are found to be influenced by net solar radiation and relative humidity over different parts of China as well.

4. Conclusions

An attempt has been made in the present study to estimate reference evapotranspiration (RET) by the Penman–Monteith (PM) method over the Thar Desert (Rajasthan, India) because of the importance of RET in water balance studies, irrigation planning, planning and operation of reservoirs. After estimating the RET through the PM method, the trends in RET in the arid environments of the Thar Desert were analysed under the

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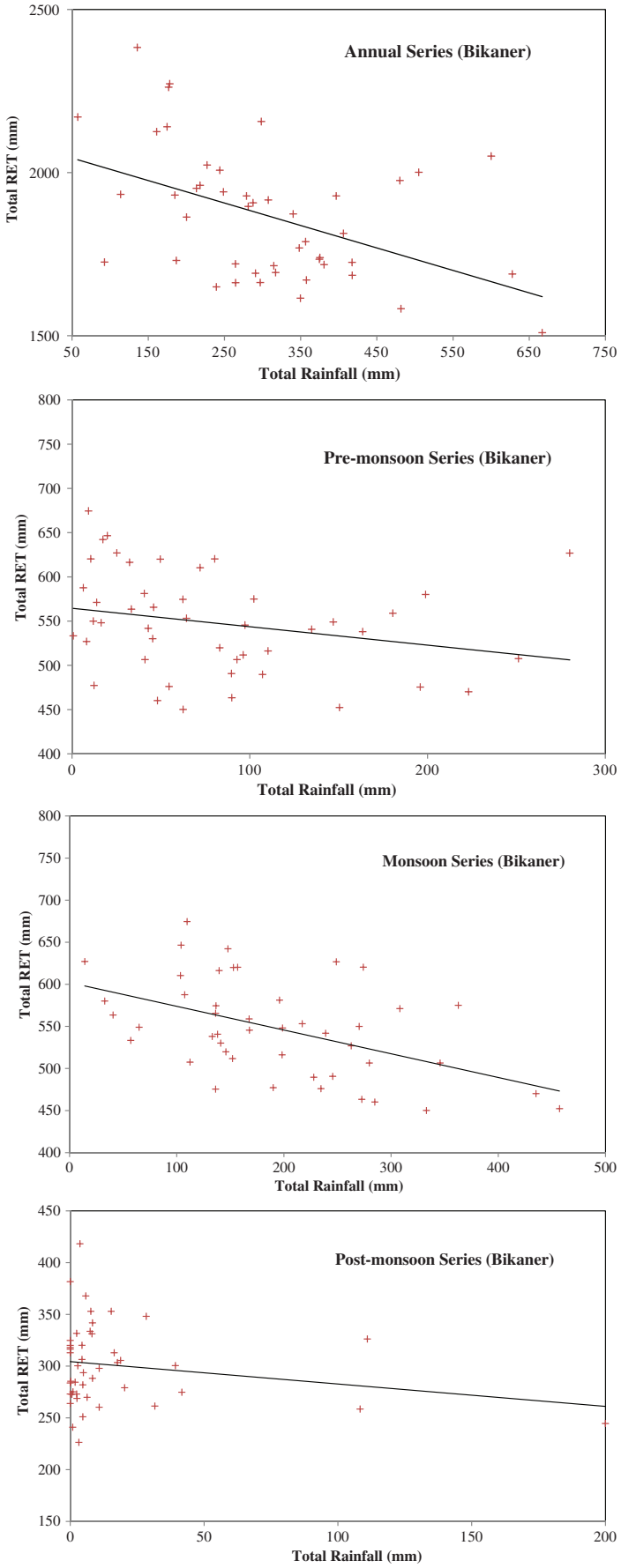


Figure 5. Relationship between rainfall and reference evapotranspiration (RET) in annual and seasonal time scales. Note that the time scale axis values are different for each figure part.

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Table 4. Results of stepwise regression analysis over Bikaner site.

Time scale	T_{max}	Wind	RH_{min}	Sunshine
Annual	II	I	III	–
Winter	II	I	III	–
Pre-monsoon	II	I	III	IV
Monsoon	II	I	III	–
Post-monsoon	IV	I	III	II

I, II, III and IV indicate the step at which the meteorological variable was selected in the stepwise regression method (I first, i.e. most dominant variable; IV fourth dominant variable). T_{max}, wind, RH_{min} and sunshine denote maximum temperature, wind speed, minimum relative humidity and sunshine duration, respectively.

changing climate. The trends in RET were investigated using the Mann–Kendall (MK) test after removing the effect of significant lag-1 serial correlation from the time series of RET by pre-whitening. Statistically significant decreasing trends in RET in annual and seasonal (winter, pre-monsoon and post-monsoon) time scales along with concurrent decreasing trends in wind speed in annual and seasonal time scales were witnessed over Bikaner. Decreasing (increasing) trends in maximum and minimum relative humidity (maximum and minimum temperature) were also witnessed in all the time scales, although significant during the annual duration and the pre-monsoon and post-monsoon seasons (during annual and post-monsoon). The RET increases were expected because of the decreasing trends witnessed in relative humidity along with increasing trends in temperature witnessed at Bikaner under the arid environments of Thar Desert. However, in spite of the favourable conditions for the expected increase in RET, significant decreasing trends in RET were witnessed at Bikaner. On examining the results of stepwise regression to determine the meteorological parameters responsible for the observed RET changes at the annual time scale, wind speed followed by maximum temperature (T_{max}) and minimum relative humidity (RH_{min}) were found to be the main climatic variables. At the seasonal time scale, wind speed was found to be the most dominating variable in all the four seasons. In all but one (post-monsoon) season, T_{max} followed by RH_{min} were the two other important causative variables for the observed RET changes. However, in the post-monsoon season, duration of bright sunshine followed by RH_{min} were the other two important causative variables for the observed RET changes.

McVicar *et al.* (2012) have reported that the evaporative demands are controlled principally by the aerodynamic component than secondarily by the radiative component more in the energy-rich environment than in the water-limited environments. In this study, it has been found that the change in the aerodynamic component namely, wind speed, is the main factor responsible for the observed RET changes than the radiative component under the arid environments of the Thar Desert at Bikaner. The trends also support the results of the stepwise regression analysis studying the causal parameters responsible for the observed decreases in RET, i.e. significant decreasing trends in wind speed in arid environments substantiates the RET decrease under the fragile desert ecosystem in annual and seasonal time scales. The steady decrease in wind speed over Bikaner may be due to the rise in urbanization as the buildings obstruct wind flow. Jhajharia *et al.* (2013) report that the land use pattern in Bikaner and surrounding areas in the Thar Desert has witnessed plenty of changes due to the execution of various irrigation projects and rapid urbanization in recent decades. The Thar Desert area was rainfed until 1957 when irrigation development activities gained momentum. In 1957, the Indira Gandhi Canal Project, approved by the Planning Commission of India, was taken up for implementation in two stages in Rajasthan for bringing water from the Harike barrage on the Satlaz and Vayas Rivers (Kumar *et al.*, 2009a, 2012). The Bhakra Nangal dam irrigates around two million hectares in the Punjab and Haryana, and half a million hectares in Rajasthan (Pant and Hingane, 1988). Thus, better irrigation facilities in the Thar Desert may have led to an increase in vegetation, which may possibly be an important factor responsible for the observed 'calming' phenomenon over Bikaner. The present study will be useful for estimating the principal crop water requirements accurately under changing climates in the arid region of the Thar Desert.

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