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SEARCHING EVIDENCE FOR THE EXISTENCE OF EVAPORATION PARADOX IN ARID ENVIRONMENTS OF NORTHWEST INDIA

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ABSTRACT

Trends in pan evaporation (E_{pan}) and temperature were identified through the Mann-Kendall test over Jaisalmer to probe the existence of evaporation paradox in arid environments of Thar Desert, northwest India. We also analyzed trends in rainfall, relative humidity, wind speed, and sunshine duration in the context of climate change. Decreasing trends in E_{pan} were witnessed over Jaisalmer in the months of January, June, October and November in the range of -2.04 to -4.1 mm year^{-1}. Significant rainfall decreases were witnessed in the three crucial months of monsoon season, i.e., July, August and September, in range of -0.23 to -1.25 mm year^{-1}. Increasing trends in mean temperature were witnessed corresponding to annual and monthly (January, April, September, October and November) time scales in the range of 0.03 to 0.07 °C year^{-1}. The simultaneous E_{pan} decrease and temperature rise at Jaisalmer confirmed the existence of evaporation paradox in the months of winter and post-monsoon seasons, which may be due to decreases in wind speed and bright sunshine hours. The increase in temperature along with decreases in E_{pan}, rainfall, sunshine duration, and wind speed over Jaisalmer may have far reaching consequences for the fragile ecosystem of the Thar Desert.

Keywords: Trend; Evaporation Paradox; Mann-Kendall; arid; Thar; India.

1. Introduction

Water provides important controls for the world's weather and climate. Weather refers to short-term changes in atmospheric conditions, while climate deals with events happening over a much longer period (Jhajharia *et al.*, 2007). Water management practices may be less effective due to global warming and climate change and due to increasing scarcity proper planning and management of water resource is crucial.

Linking land surface hydrology and atmosphere, evaporation is one of the most important components of the hydrologic cycle and its accurate estimation is needed for various water resources projects. Irrigation of crops depends on rainfall and evaporation and evapotranspiration. Kumar *et al.* (2012) highlighted the importance of evapotranspiration for the determination of water requirements of crops and irrigation scheduling.

In recent years, global warming, arising from anthropogenic-driven emissions of greenhouse gases, has become an important issue all over the globe. The well-acknowledged global warming and climate change may also have far reaching consequences for the common people who depend on natural resources, including water for their livelihood (Jhajharia *et al.*, 2013). The temperature rise may have harmful effects on human health as well (Jhajharia and Singh, 2011). Jhajharia *et al.* (2013) reported increasing trends in *plasmodium falciparum* malaria incidences in arid environments of Rajasthan, India, along with concomitant increases in temperature.

Most of the observed increase in temperature since the mid-20th century is very likely due to the observed increase in greenhouse gas concentrations. One would expect an increase in evaporation in view of the rise in temperature. In recent decades, it has been observed that evaporation has been decreasing in various parts of the world.This contrasting situation, i.e., decrease in evaporation under rising temperature, is called as the evaporation paradox. Choudhary *et al.*, (2009) reported a rise in the mean temperature at the rate of 0.30 °C per decade over Bikaner located in the Thar Desert under arid climatic conditions of Rajasthan, India. The reported temperature rise in the arid region of Thar Desert by Choudhary *et al.* (2009) encouraged us to search for an evidence for the existence of evaporation paradox at Jaisalmer, India, using the pan evaporation (E_{pan}) data. Little information is available on trends in temperature and E_{pan} at the Jaisalmer site in the Thar Desert.

Thus, the present study was carried out with the main objective of investigating the trends in E_{pan} and temperature under arid climate over Jaisalmer site located in the Thar Desert, northwest India. Trends were analyzed through the Mann-Kendall test at the 5% level of significance to probe the existence of evaporation paradox in the arid environment for different durations: annual; and monthly: January to December. Trends in rainfall, relative humidity, wind speed, and sunshine duration were analyzed in the context of the climate change. Using linear regression, the magnitudes of observed trends in all the climatic parameters were obtained. We also tried to compare the changes in E_{pan} with the trends in the above meteorological parameters in order to find the causal mechanism of observed trends in E_{pan}, if any, under the arid climatic conditions.

2. Materials and methods

2.1 Details of study area and climatic data

Jaisalmer, located in the Thar Desert, Rajasthan, India, has an arid climate or Ed type of climate as per the climatic classification of India, based on Rao *et al.*, (1971). The maximum temperature is as high as 52 °C during summer, whereas the minimum temperature in winter sometimes goes below freezing. The average annual rainfall in the western parts of Rajasthan varies from 200 to 250 mm, with an average of 238 mm. About 90% of rainfall occurs during three months of the monsoon period, i.e., during July through September. Evapotranspiration and evaporation rates generally exceed precipitation in all but in the months of the monsoon season. The location map of the Jaisalmer site is shown in Fig. 1. There are two types of soils found in the Thar Desert, i.e., desert plain soils and dune soils (Kumar *et al.* 2009, 2012). The monthly data of E_{pan}, minimum temperature (T_{min}), maximum temperature (T_{max}), mean temperature (T_{mean}), rainfall, wind speed, relative humidity and sunshine duration of Jaisalmer were obtained from India Meteorological Department (Pune) from 1951 to 1997 (IMD code of the site: 42328). Rainfall values of only a few months were found to be missing, which were filled with the use of monthly rainfall values of the nearby sites located in the Thar Desert for the same time period.

Figure 1. Location map of Jaisalmer situated in Rajasthan (northwest India)

2.2 Methodology

For identifying trends, non-parametric methods are usually better than parametric methods. Non-parametric methods use ranks of observations rather than their actual values which relax the requirements concerning the distribution of data, and are less sensitive to outliers in data. In the present study, the non-parametric Mann-Kendall (MK) method (Mann, 1945; Kendall, 1975) was used for identifying trends in E_{pan}, temperature, rainfall and other meteorological parameters. Recently various researchers, for example, Chattopadhyay *et al.* (2011a; 2011b), Dinpashoh *et al.* (2011; 2014), McVicar *et al.* (2012), Jhajharia *et al.* (2012; 2013) and Vousoughi *et al.* (2013) used the MK test for detecting trends in various climatic parameters under different types of environments. The Mann-Kendall test was carried out by computing an S statistic defined as

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

Where n is the number of observations and x_j is the j^{th} observation and sgn($\cdot$) is the sign function which can be defined as

$$\operatorname{sgn}(\theta)=\begin{cases}1 & \text{if} \quad \theta>0\\ 0 & \text{if} \quad \theta=0\\ -1 & \text{if} \quad \theta<0\end{cases} \tag{2}$$

Then, the Z statistic was computed as

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{Var(S)}} & S>0\\ 0 & S=0\\ \dfrac{S+1}{\sqrt{Var(S)}} & S<0\end{cases} \tag{3}$$

The null hypothesis of no trend was accepted at a significance level of α, if $-Z_{1-\alpha/2} \leq Z \leq Z_{1-\alpha/2}$. Or else the null hypothesis was rejected and the alternative hypothesis was accepted at the significant level of α.

3. Results and discussion

In the present study, trends in E_{pan} and temperature were investigated to search for the evidence of existence of evaporation paradox. We also analyzed trends in rainfall, relative humidity, wind speed and sunshine duration in the context of climate change. Table 1 shows the values of test statistic (Z values) and magnitudes of trends corresponding to annual and monthly time scales for total E_{pan}, total rainfall, wind speed and sunshine duration. Table 2 provides the magnitudes of observed trends in maximum, minimum and mean temperatures, and diurnal temperature range. Trends in E_{pan}, temperature, rainfall and other climatic parameters are discussed in what follows.

Table 1. Trends in evaporation, wind speed, sunshine and rainfall at Jaisalmer

Site	Pan Evaporation		Wind Speed		Sunshine Duration		Rainfall	
Time	Z value	mm dec^{-1}	Z value	kmph dec^{-1}	Z value	Hrs dec^{-1}	Z value	mm dec^{-1}
JAN	**-2.46**	**-21.05**	**-3.04**	**-0.521**	**-2.00**	**-0.47**	*1.61*	*0.64*
FEB	*-1.04*	*-13.04*	*-0.54*	*-0.099*	*-0.85*	*-0.25*	**2.01**	**14.26**
MAR	*-0.59*	*-10.71*	**-3.51**	**-0.707**	*-1.19*	*-0.22*	**1.93**	**4.82***
APR	*-0.79*	*-10.52*	**-2.12**	**-0.688**	**-2.15**	**-0.51**	*1.64*	*2.18*
MAY	*-0.25*	*-7.45*	**-2.62**	**-1.137**	**-3.82**	**-0.90**	*-1.05*	*-3.51*
JUN	**-1.96**	**-25.07**	**-4.82**	**-3.167**	**-1.97**	**-0.93**	*-0.72*	*6.51*
JUL	*-0.54*	*-21.43*	**-2.88**	**-1.932**	**-1.91***	**-0.80***	**-2.55**	**-10.07**
AUG	*-1.11*	*-43.16*	**-3.43**	**-1.971**	**-3.19**	**-1.12**	**-2.46**	**-12.52**
SEP	**-1.73***	**-52.06***	**-2.94**	**-1.285**	**-2.49**	**-0.55**	**-2.47**	**-2.29**
OCT	**-3.36**	**-40.95**	**-2.65**	**-0.603**	*-1.10*	*-0.33*	*0.30*	*0.22*
NOV	**-2.41**	**-20.44**	*-1.17*	*-0.241*	*-1.56*	*-0.22*	*1.35*	*0.68*
DEC	**-1.79***	**-16.87***	**-2.37**	**-0.407**	**-2.13**	**-0.41**	**4.23**	**3.15**
ANU.	**-1.85***	**-282.74***	**-4.29**	**-1.063**	**-4.11**	**-0.56**	*-0.24*	*4.08*

Note: Italic values are statistically non-significant, even at 10% level of significance.

3.1 Probing the existence of evaporation paradox

Evaporation is routinely measured by various agencies in India (Jhajharia *et al.*, 2009). The annual E_{pan} over Jaisalmer was found to be 3188 mm. The highest and the lowest values of annual E_{pan} were found to be 4500 mm and 2588 mm in the years 1999 and 2007, respectively. The monthly total E_{pan} values stayed in the range of 110 mm to 155 mm during the months of January and February. The monthly total E_{pan} reached its peak value (434 mm) in the month of May, and afterwards the monthly E_{pan} values decreased gradually to reach the lowest values (111 mm) in the month of December.

It was observed that the test statistic values, i.e., Z values, obtained through the MK test denoting the trends in E_{pan} were negative ranging from -0.25 to -2.46 corresponding to all the time scales, indicating the occurrence of fall in pan evaporation over Jaisalmer. However, only four downward trends were found to be statistically significant at the 5% level of significance, i.e., mainly in the months of post-monsoon season (October and November), winter season (January) and pre-monsoon season (June). The magnitudes of statistically significant trends in E_{pan}, in mm/decade, varied in the range from –20.44 to –40.95. Significant decreasing trends in E_{pan} at the 10% level of significance corresponding to annual duration at the rate of –

282.74 mm/decade (in the months of September and December at the rate of –16.9 and –52.1 mm/decade) were witnessed.

The magnitudes of statistically significant trends in temperatures (in °C/decade), i.e., maximum, minimum and mean, for annual and monthly time scales are shown in Table 2.The rise in T_{min} (T_{max}) was witnessed in the range of 0.15 to 1.02 °C/decade (0.05 to 0.46 °C/decade), although all the time series were not convincing as they showed predominantly no significance. Statistically significant increasing trends in T_{mean} were witnessed in the range of 0.25 to 0.67 °C/decade corresponding to annual and monthly (January, March, April, September, October and November) scales. On the other hand, statistically significant decreasing trends in DTR were witnessed in the range of (-) 0.21 to (-) 0.92 °C/decade corresponding to annual and monthly (January to April, June, and October to December) time scales. Pant and Hingane (1988) analyzed temperature during the period 1901-1982 for the northwest region of India and reported decreasing trends in air temperature over most parts of the region.

It is interesting to note that the DTR decreases occurred due to comparatively higher rates of increase in night temperature than the day temperature over Jaisalmer for almost all time scales. The DTR increases, although non-significant, were witnessed during the months of August and September due to comparatively high magnitudes of T_{max} increases than T_{min} increases (see Table 2). The DTR changes indicated the presence of seasonality in the diurnaltemperature trends in day and night temperatures with comparatively higher rates of rise in T_{min} than T_{max} in the months of winter and post monsoon seasons.

Table 2. Trends (°C/decade) in temperature and diurnal temperature range

Time	T_{mean}	$T_{maximum}$	$T_{minimum}$	DTR
JAN	**0.35**	*0.05*	*0.51*	**-0.67**
FEB	*0.21*	*-0.22*	*0.64*	**-0.92**
MAR	**0.29***	*0.07*	*0.46*	**-0.46**
APR	**0.60**	*0.46*	*0.67*	**-0.21***
MAY	*0.14*	*0.04*	*0.21*	*-0.12*
JUN	*0.08*	*0.00*	*0.22*	**-0.23***
JUL	*0.14*	*0.10*	*0.17*	*-0.08*
AUG	*0.17*	*0.17*	*0.15*	*0.05*
SEP	**0.30**	*0.29*	*0.26*	*0.06*
OCT	**0.39**	*0.18*	*0.58*	**-0.51**
NOV	**0.67**	*0.13*	*1.02*	**-0.87**
DEC	*0.21*	*-0.11*	*0.56*	**-0.66**
ANU.	**0.25**	*0.08*	*0.46*	**-0.36**

Note: Italic values are statistically non-significant, even at 10% level of significance.

Trends in E_{pan} and temperature were analyzed together in order to search for the evidence of existence of evaporation paradox at Jaisalmer. Results shown in Tables 1 and 2 indicate the concomitant occurrences of rise in temperature and fall in E_{pan} values corresponding to the months of January, October and November. The contrasting situation of the E_{pan} decreases along with the rise in temperature indicate the presence of evaporation paradox mainly in the months of post-monsoon and winter seasons. Cong *et al.* (2009) reported the existence of E_{pan} paradox in China as a whole with decreases in E_{pan} and increases in air temperature, but not in northeast and southeast China. The rate of pan evaporation can be attributed to changes in the aerodynamic components, with some contribution from regional solar irradiance (BCAS, 2013). Observed near-surface wind speed might be the primary contributor to the decline of pan evaporation in China during the period from 1958 to 1993, while the combined effect from wind speed and vapor pressure deficit might have contributed to the increase of pan evaporation since 1993.

3.2 Trends in rainfall, wind speed and sunshine duration

In India, the south-west monsoon brings almost all of the rainfall over most parts of the country beginning from 1 June to the end of September when retrieval of monsoon starts. However in the arid regions of the Thar Desert in northwest India, the three months starting from July to September constitute the monsoon period. The average annual rainfall for Jaisalmer is found to be 232.5 mm for the considered period, which categorizes it as a very low rainfall place. The pre-monsoon rainfall and monsoon rainfall contribute about 26% and 70% to the total annual rainfall. Fig. 2 shows the annual time series of total rainfall since 1951 at Jaisalmer and trend lines in the total rainfall. Fig. 3 shows an annual anomaly in the annual rainfall based on averaged annual rainfall data of Jaisalmer, indicating a nearly constant trend. The annual rainfall anomaly for a given year was obtained by deducting the individual year's rainfall value from the average annual rainfall during the period 1951-1997. The nearly horizontal-broken line, denoting a trend in annual rainfall anomaly, confirms a nearly constant trend, i.e., the presence of no trend in annual rainfall anomaly. Results of trend analysis also reveal no trend corresponding to the annual time scale in total rainfall. A similar result was reported by Jhajharia *et al.*, (2014) for trend analysis of total rainfall at annual and monthly time scales for Barmer (Rajasthan) located in the northwest region of India. The average annual rainfall of Barmer is 267.3 mm and the total rainfall during months of June to October accounts for about 42% of average annual rainfall. They reported that no significant trend was obtained in total rainfall at Barmer at the 5% level of significance. Similarly, on analyzing rainfall from 1901-1982 for sites located in the northwest India, Pant and Hingane (1988) reported increasing trends in rainfall over most parts of the region. They reported that increasing trends in annual and monsoon season rainfall were significantly marked for the peripheral areas of the Rajasthan desert.

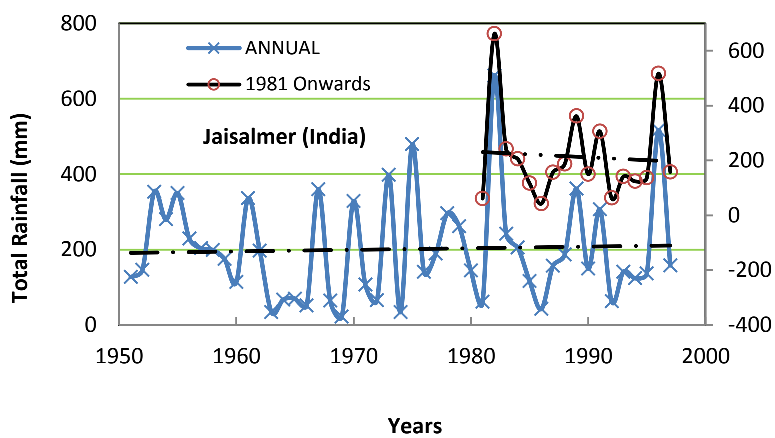

Figure 2. Annual time series of rainfall over arid site of Jaisalmer, northwest India
(Note: Truncated time series are black coloured with red markers, and are drawn on the secondary axis. The broken lines are the trend lines.)

On monthly time scales, statistically significant decreasing trends at the 5% level of significance were witnessed in total rainfall in the crucial months of July, August and September of the south-west monsoon season in the range of -2.3 to -12.5 mm/decade at Jaisalmer. However, significant increases in total rainfall in the months of February and December were witnessed (see Table 1). Decreasing trends in rainfall during all the three months of the monsoon period may put further pressure on the rainfed agriculture in arid environments of the Thar Desert. Similarly, Jhajharia *et al.* (2014) carried out trend analysis of total rainfall at monthly time scales for Barmer. However, they reported no significant trends in total rainfall during the four months of the monsoon season.

Trends in relative humidity, wind speed and sunshine duration were analyzed in the context of the climate change. Table 1 indicates the presence of downward trends for all the monthly and annual time scales, which supports the phenomenon of 'stilling' in the Thar Desert. On a monthly time scale, all but two (February and November) months witnessed very strong decreases in wind speed in the range of -0.04 to -0.317 kmph year^{-1}. Similarly, statistically significant decreasing trends at the 1% level of significance were observed in annual wind speed at the rate of -0.11 kmph year^{-1}. McVicar *et al.* (2012), in their global review work, reported that the stilling phenomena have severely affected the process of evaporation around the world. Strong significant decreases in wind speed have led to evaporation decreases in different regions of the globe under different types of environments.

Table 3 shows the values of test statistics and magnitudes of trends for morning relative humidity (RH), afternoon RH and mean RH. No trends were obtained in the morning RH corresponding to annual and monthly time scales. Similar results were obtained for trends in mean RH, i.e., no trends in mean RH were witnessed for annual time scale and corresponding to all but one (April) monthly time scales. Significantdecreases in mean RH were witnessed in April at the rate of -1.73% per decade. The test statistic values obtained through the MK test indicate the downward trends for all months and annual time scale, although most of the trends were statistically non-significant. Significant decreases in air moisture in the months of March and April at the rate of 2.2% per decade were observed. Similarly, air moisture had dried at the rate of 1.52% per decade at annual time scale. Results of trend analyses of relative humidity do not support the observed decreases in E_{pan} over Jaisalmer.

Table 3. Trends and magnitude of trends in relative humidity over Jaisalmer

Time	Morning RH		Afternoon RH		Average RH	
	Z value	%/decade	Z value	%/decade	Z value	%/decade
JAN	*0.68*	*0.46*	*-1.33*	**-1.96**	*-0.45*	*-0.76*
FEB	*0.87*	*0.62*	*-0.82*	**-1.95**	*-0.44*	*-0.67*
MAR	*-0.51*	*-0.30*	**-1.66***	**-2.09***	*-1.17*	*-1.19*
APR	*-0.94*	*-1.08*	**-2.82**	**-2.38**	**-2.07**	**-1.73**
MAY	*0.94*	*0.74*	*-0.43*	**-1.09***	*0.81*	*-0.18*
JUN	*0.03*	*0.04*	*-0.39*	-0.33	*0.11*	*-0.14*
JUL	*0.02*	*0.05*	*-1.18*	-0.57	*-0.53*	*-0.26*
AUG	*0.76*	*0.17*	*-0.56*	-0.62	*0.65*	*-0.22*
SEP	*0.80*	*0.29*	*-1.38*	-1.63	*-0.27*	*-0.67*
OCT	*-0.71*	*-0.79*	*-1.02*	**-2.03**	*-1.21*	*-1.41*
NOV	*1.20*	*0.32*	*-0.20*	**-1.91***	*0.45*	*-0.79*
DEC	*0.82*	*0.43*	*-0.63*	**-1.69**	*0.22*	*-0.63*
ANU.	*1.33*	*0.08*	**-2.24**	**-1.52**	*-0.54*	*-0.72*

Note: Italic values are statistically non-significant, even at 10% level of significance.

Trends obtained for bright sunshine duration were similar to the trends obtained for wind speed, i.e., downward trends in sunshine duration corresponding to annual and monthly time scales. The trend results indicate the presence of 'dimming' phenomenon in the arid environments. Decreases in bright sunshine hours were witnessed in three crucial months of monsoon season, i.e., July, August and September in the range of -0.055 to -0.112 hours year^{-1} and at an average rate of -0.082 hours year^{-1} in three monsoon months possibly due to the blockage of solar radiation by monsoon clouds. Similarly, sunshine decreases in the range of -0.051 to -0.093 hours year^{-1} were witnessed in the months of April, May and June. It is interesting to note that the strongest decrease in bright sunshine hours in terms of the highest value of test statistics value was found in the month of May due to possible increases in strong dust-storm events in May bringing black-brown dust particles from the regions of Pakistan and Afghanistan in summer. However, sunshine decreases at an average rate of -0.044 hours year^{-1} were witnessed in the months of December and January due to occurrence of smog (fog and smoke).

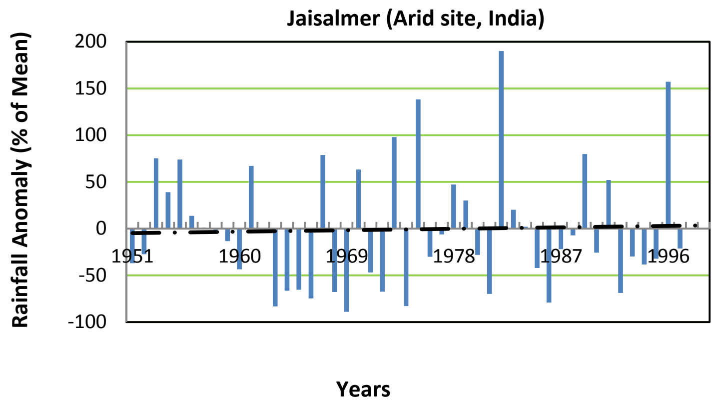

Figure 3. Rainfall anomaly of rainfall over arid site of Jaisalmer, northwest India

4. Conclusions

In the present paper, we analyzed trends in rainfall, E_{pan}, temperature, relative humidity, wind speed and sunshine duration in the context of climate change in arid environments of Jaisalmer, Thar Desert, India. Significant increases in mean temperature in the months of March, April, September, October and November are observed. However, decreasing trends in E_{pan} are observed at the rate of about 2.95 mm year^{-1}. Decreasing trends in south-west monsoon rainfall are also witnessed in July, August and September which may put considerable strain on the local economy, which is primarily agrarian. The concomitant decrease in E_{pan} and rise in mean temperature prove the existence of evaporation paradox mainly during the months of winter and post-monsoon seasons. This paradoxical situation of E_{pan} decreases in warming conditions at Jaisalmer may be due to the decreasing trends in wind speed and bright sunshine duration during winter and post-monsoon seasons.

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