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ORIGINAL PAPER

Sensitivity analysis of monthly reference crop evapotranspiration trends in Iran: a qualitative approach

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Abstract The main objective of this study was to analyze the sensitivity of the monthly reference crop evapotranspiration (ET_o) trends to key climatic factors (minimum and maximum air temperature (T_{max} and T_{min}), relative humidity (RH), sunshine hours (t_{sun}), and wind speed (U_2)) in Iran by applying a qualitative detrended method, rather than the historical mathematical approach. Meteorological data for the period of 1963–2007 from five synoptic stations with different climatic characteristics, including Mashhad (mountains), Tabriz (mountains), Tehran (semi-desert), Anzali (coastal wet), and Shiraz (semi-mountains) were used to address this objective. The Mann–Kendall test was employed to assess the trends of ET_o and the climatic variables. The results indicated a significant increasing trend of the monthly ET_o for Mashhad and Tabriz for most part of the year while the opposite conclusion was drawn for Tehran, Anzali, and Shiraz. Based on the detrended method, RH and U_2 were the two main variables enhancing the negative ET_o trends in Tehran and Anzali stations whereas U_2 and temperature were responsible for this observation in Shiraz. On the other hand, the main meteorological variables affecting the significant positive trend of ET_o were RH and t_{sun} in Tabriz and T_{min}, RH, and U_2 in Mashhad. Although a relative agreement was observed in terms of identifying one of the first two key climatic variables affecting the ET_o trend, the qualitative and the quantitative sensitivity analysis solutions did never coincide. Further research is needed to evaluate this interesting finding for other geographic locations, and also to search for the major causes of this discrepancy.

1 Introduction

Human emissions of greenhouse gases over the past half century have resulted in global warming across the globe (National Research Council 2010). Higher air temperatures tend to increase the availability of energy for evaporation and accelerate the pace of the hydrologic cycle (Huntington 2006). These changes of the hydrological processes have already caused major problems for water resources in some regions of the world (Li et al. 2007; McVicar et al. 2007; Bandyopadhyay et al. 2009), especially those located in the arid and semi-arid zones (Liang et al. 2010).

Reference crop evapotranspiration (ET_o) is an important variable of the hydrologic cycle and plays a vital role in estimating crop water requirements (Beyazgul et al. 2000), optimizing water management issues (Andreu et al. 1996), preparing input data to hydrological models of water balance study (Xu et al. 2006), as well as scheduling irrigation scenarios (Espadafor et al. 2011; Sadeghi et al. 2015). It essentially dominates the water balance (Bouwer et al. 2008) and accounts for over 90 % of the total water use in agroecosystems (Irmak et al. 2012). Consequently, it is highly important to identify the temporal variations of potential

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evapotranspiration and quantify its trend under changing climatic conditions (Burn and Hesch 2007; Zhang et al. 2009). In addition, it is essential to determine the dominant meteorological factors affecting ET_o trends in order to better understand the connection between climate change and ET_o variability as well as data availability and estimation accuracy of ET_o (Yin et al. 2010). Burn and Hesch (2007) reported that the mechanisms that are responsible for the observed trends in evaporation are not clearly understood, although it is widely accepted that global temperatures are increasing (IPCC 2007).

In general, climate change scenarios project an increase in ET_o in upcoming years as a result of substantiated increases in global precipitation and cloudiness as well as drier air near the surface of terrestrial ecosystems (Brutsaert and Parlange 1998; Roderick and Farquhar 2002; Yin et al. 2010). However, several studies have surprisingly reported significant decreasing trends in ET_o in several regions of the world over the past 60 years (Chattopadhyay and Hulme 1997; Thomas 2000; Moonen et al. 2002; Hobbins et al. 2004; Roderick and Farquhar 2004, 2005; Xu et al. 2006; Wang et al. 2007; Zhang et al. 2007; Limjirakan and Limsakul 2012). Moreover, a consensus has not been reached on the underlying causes for the ET_o reduction (Yin et al. 2010). For instance, the decreasing ET_o has been primarily attributed to decreased sunshine duration or solar radiation in Russia, the USA (Peterson et al. 1995), and China (Liu et al. 2004; Gao et al. 2006); to wind speed in Australia (Rayner 2007; Roderick et al. 2007), the Tibetan Plateau (Chen et al. 2005; Zhang et al. 2007), and Canadian Prairies (Burn and Hesch 2007); to relative humidity in India (Bandyopadhyay et al. 2009), and to maximum temperature in China (Cong and Yang 2009). Uncertainty regarding the aforementioned results is mostly due to the possible interaction between climatic parameters (Dinpashoh et al. 2011), the non-linear complex form of the functions representing ET_o (Yin et al. 2010) and also applying temperature or radiation-based empirical formulas, rather than the Penman–Monteith equation for calculating the reference evapotranspiration (Irmak et al. 2012).

Iran is dominated by the semi-arid Mediterranean climate and long dry summer and winter rainfalls (Bannayan et al. 2010) and is very vulnerable to the potential future climate changes (Eyshi Rezaie and Bannayan 2012). Recent GCM-based projections suggest significant changes in temperature and precipitation for the country (Sayari et al. 2013) which will definitely influence agricultural production and environmental sustainability (Dinpashoh et al. 2011, Bannayan et al. 2010). Several studies have investigated the annual, seasonal, and/or monthly trends of reference evapotranspiration and/or the contributions of the meteorological variables (i.e., relative humidity, temperature, wind speed, and solar radiation) to the changes of ET_o for Iran (Dinpashoh et al. 2011; Tabari et al. 2011, 2012; Shadmani et al. 2012; Nafarzadegan et al. 2013; Kousari et al. 2013). Very few approaches have also evaluated the sensitivity of the temporal ET_o trends to its key climatic variables over the country. Eslamian et al. (2011) reported that temperature and relative humidity are the two most important variables affecting the monthly trends of the ET_o in Iran. Bakhtiari and Liaghat (2011) showed that the computed seasonal ET_o was sensitive to vapor pressure deficit in all months, to wind speed during March to November, and to solar radiation during the summer months in the semi-arid climate of Kerman in southeast of Iran. Sharifi and Dinpashoh (2014) found that ET_o in Iran was most sensitive to average air temperature in annual time scale while it was least sensitive to vapor pressure. In all of these studies, the sensitivity of the ET_o trend was analyzed “quantitatively,” i.e., by changing the value of the climatic variables within a specific range (e.g., ±20 %, in 5 % steps). An alternative solution, however, is to perform a recovered stationary series method in which the trends of effective meteorological variables are detrended. Such a “qualitative” approach essentially assumes that the trend removal of any input variable reduces the significant level in comparison to the original ET_o trend and that the difference between the resultant and the original ET_o is the influence of that variable on the trend (Xu et al. 2006; Liu et al. 2010). To the best of our knowledge, the detrended method has never been applied to investigate the sensitivity of ET_o to its key climatic factors in Iran. The present study attempts to address this objective for five synoptic stations that well represent the different climatic regions of the country. The other important objective here was to compare the results of the detrended methodology with those of the historical non-dimensional quantitative approach.

2 Material and methods

2.1 Study area and data

The coefficient of variation of annual rainfall in Iran is about 70 % (Nazemosadat 2000), denoting the fact that climate is both temporally and spatially variable. As such, we picked five synoptic stations (Mashhad, Anzali, Tehran, Tabriz, and Shiraz) (Fig. 1) that could represent well the major climate regions of the country. The stations are very different in terms of geographical and climatological characteristics and their elevation varies from −26 to 1484 m above the MSL (Table 1). Mashhad is located in the northeast of Iran, and its overall climate is mountainous. Anzali spans across the southern Caspian Sea coastline and has a coastal wet climate throughout the year. Tehran (the capital of Iran) is surrounded by the Alborz Mountain Chain from the north and by the Salty Desert from the south and has a semi-desert climate. Tabriz is situated in the northwest of the country and experiences a cold and mountainous climate. Its precipitation is affected by the seasonal Siberian anticyclone (Moradi 2009) which

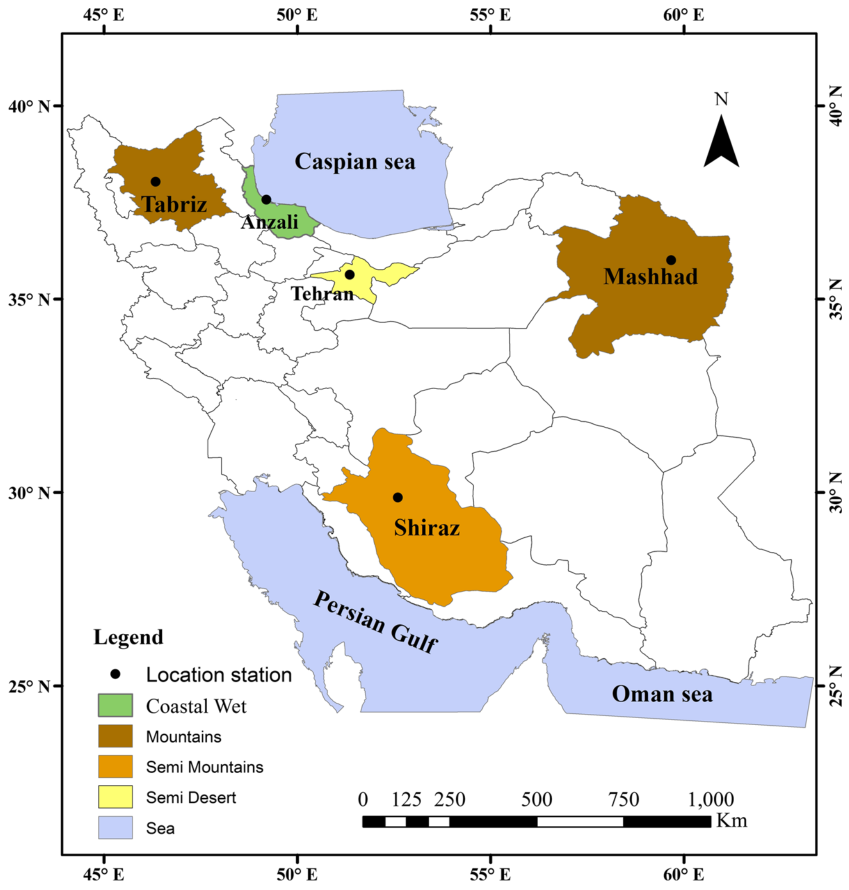


Fig. 1 Geographic location and climatological characteristics of the selected synoptic stations in Iran

dominates the region over the spring season. Finally, Shiraz embraces the southern semi-mountainous climate which is mainly affected by the Mediterranean and Sudanese atmospheric systems in fall and winter. In this study, the climate of each station was determined using the algorithm proposed by Alijani et al. (2008) who classified Iran's climate to six separate classes, namely desert, semi-desert, coastal wet, semi-mountainous, and mountainous. A detailed description of the selected synoptic stations and the mean weather data for the study period is given in Table 1.

2.2 ET_o calculation

The FAO56 Penman–Monteith (Eq. (1)) method was employed for ET_o estimation as it has been accepted as a standard method by many international organizations such

Table 1 Geographical characteristics of the five synoptic weather stations along with their mean annual meteorological variables for the period of 1963–2007

Stations	Coordinates			Climate type[a]	Meteorological variables					
	Latitude (N)	Longitude (E)	Height above MSL (m)		T_{min} (°C)	T_{max} (°C)	RH %	t_{sun} (h/day)	U_2 (m/s)	ET_o (mm/year)
Mashhad	36° 16′	59° 38′	999	Mountainous	7.4	21.3	54.3	7.9	3.0	1232.3
Anzali	37° 28′	49° 28′	−26	Coastal wet	13.4	19.1	84.1	4.9	2.9	849.9
Tehran	35° 41′	51° 19′	1190	Semi-desert	12.3	22.7	41.3	8.2	3.9	1513.1
Tabriz	38° 5′	46° 17′	1361	Mountainous	7.1	17.5	52.9	7.6	4.6	1346.1
Shiraz	29° 32′	52° 36′	1484	Semi-mountainous	9.9	25.8	40.5	9.2	3.4	1539.2

T_{min} minimum temperature, T_{max} maximum temperature, *RH* relative humidity, t_{sun} sunshine hours, U_2 *wind* speed at 2 m height, ET_o reference evapotranspiration)

[a] Climate type was based on Alijani et al. (2008)

as FAO (Allen et al. 1998) and the American Society of Civil Engineers (ASCE 2005).

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_\mathrm{n}-G)+\gamma\left(\frac{900}{(T+273)}\right)U_2(e_\mathrm{s}-e_\mathrm{a})}{\Delta+\gamma(1+0.34U_2)} \quad (1)$$

Where $\mathrm{ET_o}$ is the crop reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the daily soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature (°C), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the saturation vapor curve slope (kPa $°\mathrm{C}^{-1}$), and γ is the psychometric constant (kPa $°\mathrm{C}^{-1}$).

The meteorological datasets for the aforementioned stations were obtained from the Islamic Republic of Iran Meteorological Organization (IRIMO, www.irimo.ir) for the period of 1963–2007. Quality control and homogeneity of the data were checked prior to the analysis by (i) detecting missing data and the outliers and (ii) conducting a homogeneity test after data reconstruction.

The proportion of missing data with respect to the whole dataset for T_min, T_max, RH, and U_2 was low and never exceeded 1 %. For t_sun, however, the ratio could be as large as ~10 %. Thus, missing data were reconstructed by being replaced from nearby stations (i.e., Mashhad, Anzali, Tehran, Tabriz, and Shiraz by Sabzevar, Rasht, Doshan Tappeh, Maragheh, and Fassa stations, respectively) using the ratio method (Ter Braak et al. 1994). A considerable number of missing t_sun data, however, corresponded to the 1978–1981 period during which the revolution and the Iraq's invasion of Iran took place. As a consequence, nearby stations data were also incomplete for these years and an average monthly value was inevitably used to fill the gaps.

Outliers were detected using the van der Loo (2010) method which is implemented as "extreme values" package in R. The method uses a model cumulative distribution function to approximate the bulk of observed data by the regression of the observed values on their estimated QQ plot positions. The most appropriate model here was selected among one of the normal, Weibull, Pareto, log-normal, and exponential distribution functions following the Kolmogrov–Smirnov test. Only the normal distribution was considered for T_max and T_min as these variables could also take negative values. Results revealed very few outliers in the dataset which were reconstructed using the ratio method.

Data homogeneity was checked using the Algorithm Theoretical Basis Document (ATBD) test (Doerffer and Schiller 2008) that is available in the iki.dataclim package of R (Orlowsky 2014). The procedure involves conducting four different statistical tests, namely the standard normal homogeneity test (SNH), the Buishand range test (BHR), the PET test (PET), and the von Neumann ratio (VON). All four tests suppose under the null hypothesis that in the series of a testing variable, the values are independent with the same distribution. Under the alternative hypothesis, the SNH, BHR, and PET tests assume that a step-wise shift in the mean (a break) is present. The fourth test (VON) assumes under the alternative hypothesis that the series is not randomly distributed. Although the four tests imply different statistical approaches, they all define critical values of a test statistics (T_0) at the 1 and 5 % significance level and reject the null hypothesis if T_0 is above a certain level (see Klein Tank 2007a, b for more details). If no more than one of the four aforementioned tests indicates a break at the 1 % level, the variables are considered as "useful." If two tests indicate a break at the 1 % level, the variables are considered as "doubtful." Finally, with three or more breaks at the 1 % level, the respective observations are considered as "suspect." The results of the ATBD test revealed that none of the series belonged to the "suspect" class, indicating that the assumption of homogeneity was met and data reconstruction had no significant effect on the trend analysis.

The compiled data from IRIMO included average monthly values of minimum and maximum air temperature (T_max and T_min in °C), mean relative humidity (RH in %), sunshine hours (t_sun in h), and wind speed at 2 m height (U_2 in m s^{-1}). Using these data, average monthly estimates of $\mathrm{ET_o}$ were derived for each of the aforementioned synoptic stations following the procedure outlined in chapter 4 of the FAO 56 (Allen et al. 1998). The resultant $\mathrm{ET_o}$ (with the unit of mm day^{-1}) was then multiplied by the total number of days for the month under consideration in order to get monthly $\mathrm{ET_o}$ values with unit of millimeters per month.

2.3 Trend analysis

Trends are often calculated by using parametric or non-parametric methods (Fan 2003; Duhan and Pandey 2013). In parametric methods, the data has to be independent and normally distributed. However, for smaller departures from normality, non-parametric methods work sometimes better than parametric methods (Jhajharia et al. 2009). The non-parametric Mann–Kendall (M-K) test has been recommended by the World Meteorological Organization (WMO) in assessing trends for environmental data time series (Liang et al. 2010; Kousari et al. 2013). It has been widely used to test stationarity against trends in hydrological and meteorological variables such as evaporation, temperature, evapotranspiration, precipitation, stream flow, groundwater levels, and atmospheric deposition data (e.g., Modarres and da Silva 2007; Burn and Hesch 2007; Wang et al. 2008; Jhajharia et al. 2009; Liang et al. 2010; Mishra and Singh 2010; Zhou et al. 2013). The M-K test is not very sensitive to abrupt breaks in the time series and has the potential to examine the trends without requiring normality or linearity (Jaagus 2006 and Wang et al. 2008). The null hypothesis H_0 in the M-K test states that the depersonalized data ($x_1,\ldots, x_n$)

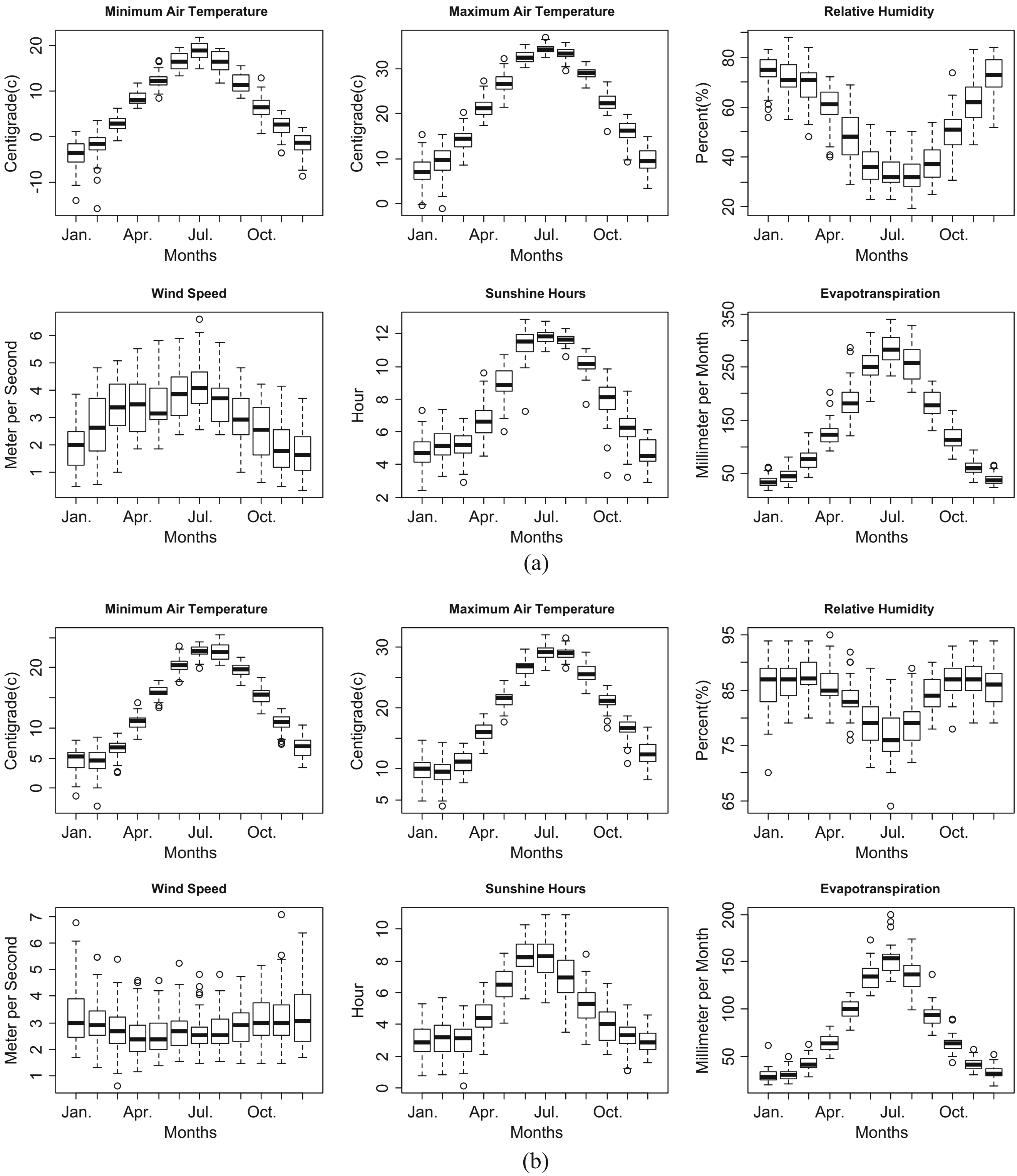
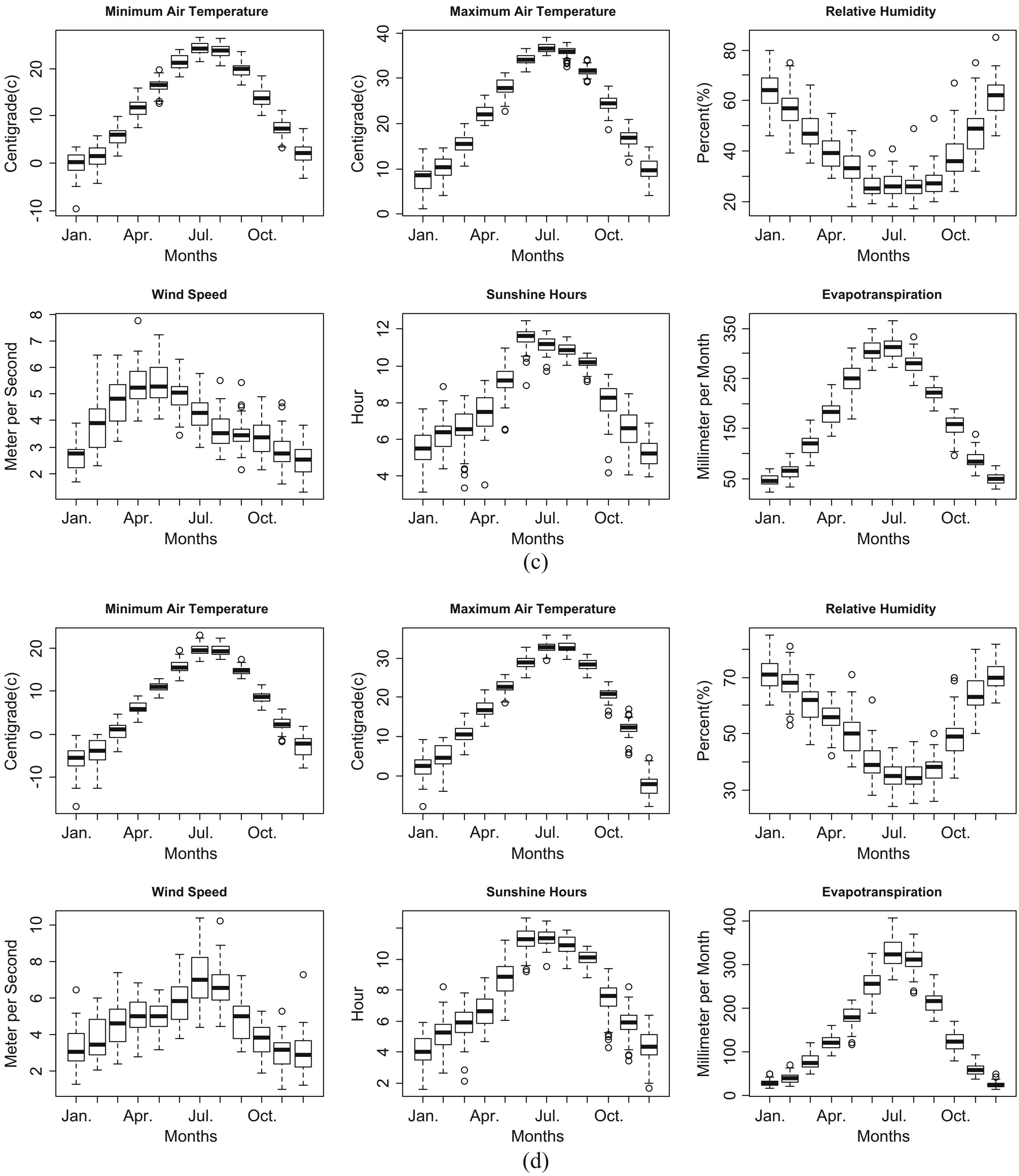


Fig. 2 Variation of monthly ET_o and its main meteorological variables for **a** Mashhad, **b** Anzali, **c** Tehran, **d** Tabriz, and **e** Shiraz stations. The *line inside the boxes* shows the median and the *upper and lower lines of the boxes* indicate the 75 and 25 % percentile, respectively. In addition, the *upper and lower parts of the whiskers* indicate the respective maximum and minimum values of climatic variables for each month

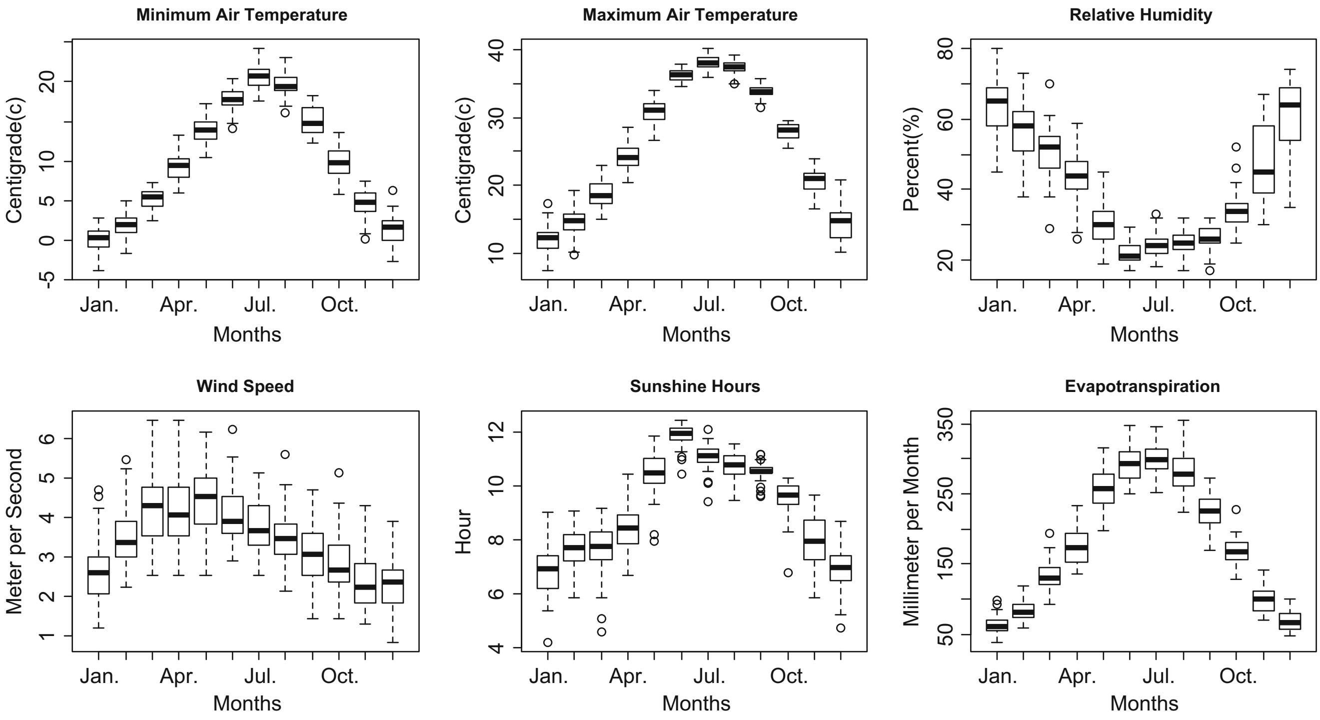


(c)

(d)

Fig. 2 continued.

is a sample of n independent and identically distributed random variables. On the other hand, H_1 denotes that the distributions of x_k and x_j are not identical for all k, $j \leq n$ with $k \neq j$ (Zelenakova et al. 2014).



(e)

Fig. 2 continued.

The test statistic S_t is asymptotically normal and has a mean of zero. It can be calculated by Eqs. (2) and (3), while its variance is given by Eq. (4) as follows:

$$S_\mathrm{t} = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n}\operatorname{sgn}\left(x_j - x_k\right) \tag{2}$$

$$\operatorname{sgn}\left(x_j - x_k\right) = \begin{cases} +1 & x_j > x_k \\ 0 & x_j = x_k \\ -1 & x_j < x_k \end{cases} \tag{3}$$

$$\operatorname{Var}(S_\mathrm{t}) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i-1)(2i+5)}{18} \tag{4}$$

Where n is the number of data points, m is the number of groups of tied ranks, and t_i is the number of ties of extent i.

Finally, for the sample size $n > 10$, the standard normal variable Z is computed as follows:

$$Z = \begin{cases} \dfrac{S_\mathrm{t}-1}{\sqrt{\operatorname{Var}(S_\mathrm{t})}}, & S_\mathrm{t} > 0 \\ 0, & S_\mathrm{t} = 0 \\ \dfrac{S_\mathrm{t}+1}{\sqrt{\operatorname{Var}(S_\mathrm{t})}} & S_\mathrm{t} < 0 \end{cases} \tag{5}$$

Positive and negative values of Z, respectively, indicates upward and downward trends. Thus, under a two-sided test for the trend, H_0 should be accepted if $|z| \le z_{\alpha/2}$ at the α level of significance (Partal and Kahya 2006). In this study, confidence levels of 99, 95, and 90 % were used as highly, strong, and relatively significant trend, respectively.

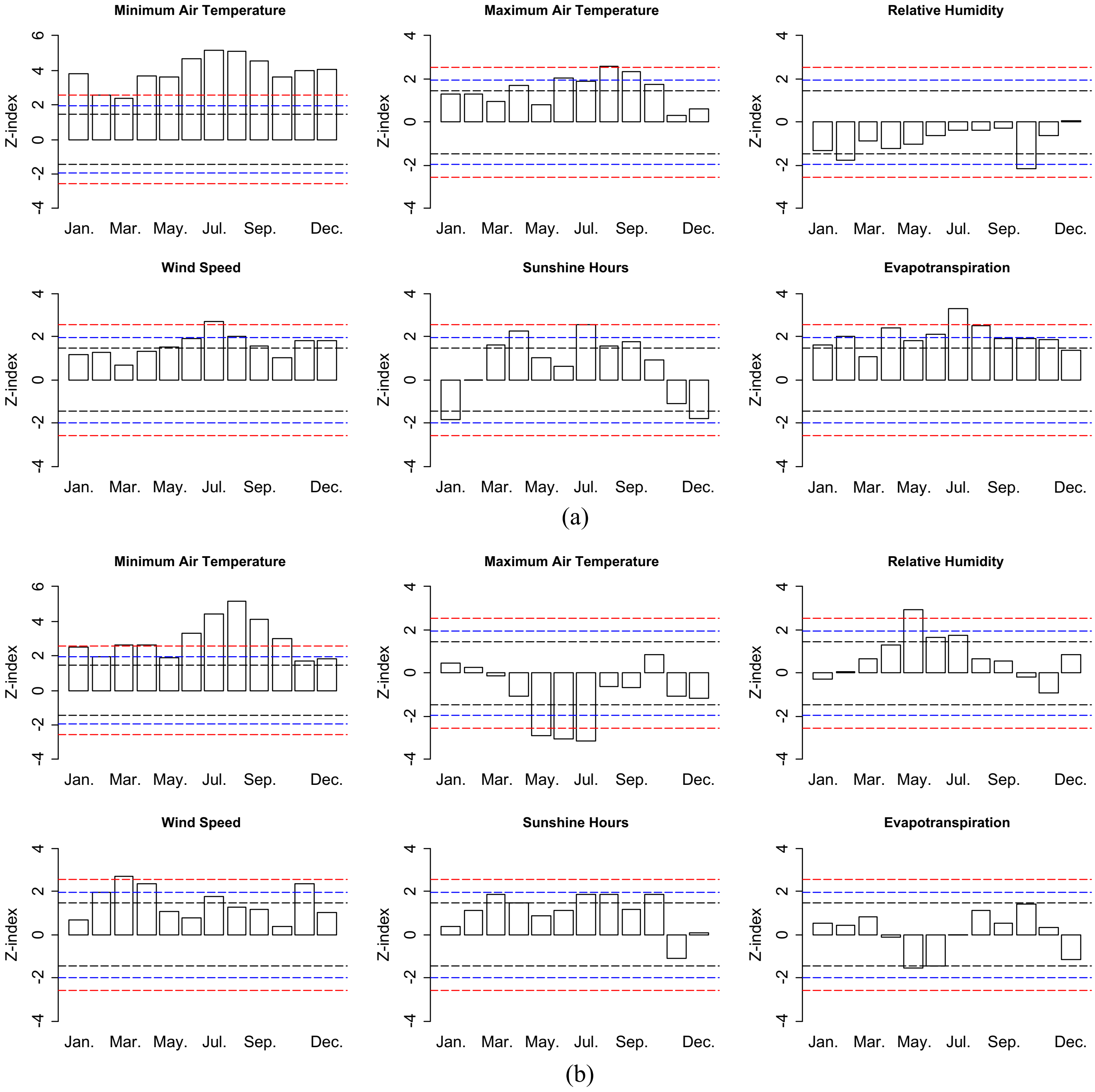
2.4 The qualitative sensitivity analysis method

To qualitatively evaluate the contribution of each meteorological variable (i.e., T_max and T_min, RH, t_sun, and U_2) on the trend of $\mathrm{ET_o}$, a recovered stationary series method was applied as follows: (i) All months with a significant $\mathrm{ET_o}$ trend (levels of 99, 95, and 90 %) and also all the climatic variables that showed a significant trend for each of these months were determined. This was done by running the M-K test for all the five study locations. (ii) Assuming that a total of N meteorological variables showed statistically significant trends for a specific month (in which the $\mathrm{ET_o}$ trend was also significant), the detrended method was applied as follows: (a) the trend of a single (and arbitrary) meteorological variable is removed while the trends of the other variables is kept untouched. Detrending was performed by the cubic smoothing spline (CSS) method (Cook and Kairiukstis 1990). A detailed description of the CSS method for detrending the time series can be found in Xu et al. (2006) and Bosela et al. (2011). (b) The trend of the $\mathrm{ET_o}$ is re-calculated by the M-K test using Eqs. (2–5). (c) The detrended variable in step (a) is returned to its original value and another meteorological variable goes through the detrending process. Then, step (b) is repeated for this new combination. (d) The described procedure is separately replicated for all possible combinations of the meteorological variables. For instance, supposing that four meteorological variables induced a significant trend (upward or downward) for ET_o in a specific month, these processes must be repeated 15 times (i.e., $2^4 - 1$). All computations including ET_o calculations, the M-K test, as well as the detrending analysis were performed by the R software using the SPEI, dplR, and Kendall packages.

2.5 The non-dimensional quantitative sensitivity analysis solution

As previously indicated, the sensitivity coefficient approach was also carried out for comparative purposes. The equation used is as follows (Zhang et al. 2010):

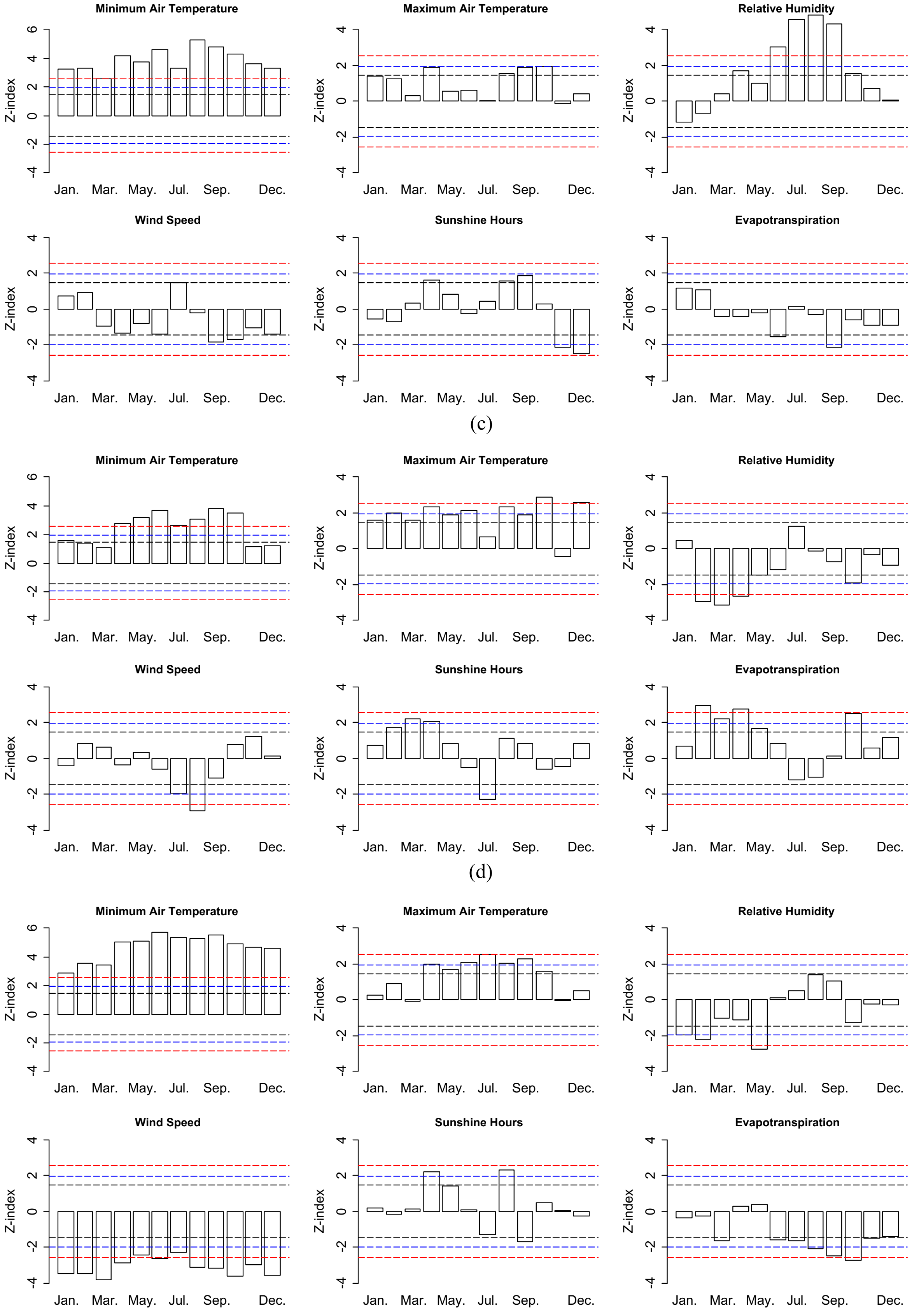
$$SC = \frac{\Delta ET_0}{\Delta CV} \cdot \frac{CV}{ET_0} \tag{6}$$



(a)

(b)

Fig. 3 The Z-index obtained by the M-K test for the ET_o and its meteorological variables for **a** Mashhad, **b** Anzali, **c** Tehran, **d** Tabriz, and **e** Shiraz stations. *Dotted lines* refer to the level of significance as follows: *red* (highly significant, 99 %), *blue* (significant, 95 %), and *black* (significant, 90 %)



(c)

(d)

(e)

Fig. 3 (continued)

Where SC is the dimensionless sensitivity coefficient, ΔCV is the unit change in the climatic variable, ΔET_o (mm month^{-1}) is the change in ET_o with respect to changes in climatic variables, and ET_o and CV are the base values before change. A positive (or negative) sensitivity coefficient for a variable implies that ET will increase (or decrease) as the variable increases. The larger the sensitivity coefficient, the larger the effect a given variable has on ET_o. For instance, the SC value of −0.15 would suggest that a 10 % increase in CV may be expected to decrease ET_o by 15 %.

In this study, the quantitative sensitivity analysis for monthly ET_o was conducted at the five stations from −30 % to +30 % at an interval of ±5 % (12 scenarios) to each of the five variables (i.e. T_{min} and T_{max}, U_2, t_{sun} and RH) while keeping all the other parameters constant. It is also important to note that in order to compare the results of the qualitative and the quantitative approach, the sensitivity analysis was only performed for the months with significant ET_o trends, notably those shown in Table 4.

Table 2 Evaluating the trend of monthly ET_o and the meteorological variables at study stations for the study period of 1963–2007

Stations	Variable	Time (month)											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mashhad	T_{min}	▲	△	△	▲	▲	▲	▲	▲	▲	▲	▲	▲
	T_{max}	+	+	+	↑	+	△	↑	△	△	↑	+	+
	RH	−	↓	−	−	−	−	−	−	−	▽	−	+
	t_{sun}	↓	+	+	△	+	+	△	+	↑	+	−	↓
	U_2	+	+	+	+	+	↑	▲	△	+	+	↑	↑
	ET_o	+	↑	+	△	↑	△	▲	△	↑	↑	↑	+
Anzali	T_{min}	△	↑	▲	▲	↑	▲	▲	▲	▲	▲	↑	↑
	T_{max}	+	+	−	−	▼	▼	▼	−	−	+	−	−
	RH	−	+	+	+	▲	+	↑	+	+	−	−	+
	t_{sun}	+	+	↑	+	↑	+	↑	↑	+	↑	−	+
	U_2	+	↑	▲	△	↑	+	↑	+	+	+	△	+
	ET_o	+	+	+	−	↓	−	+	+	+	+	+	−
Tehran	T_{min}	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
	T_{max}	+	+	+	↑	+	+	+	+	↑	↑	−	+
	RH	−	−	+	↑	+	▲	▲	▲	▲	+	+	+
	t_{sun}	−	−	+	+	+	−	+	+	↑	+	▽	▽
	U_2	+	+	−	−	−	−	+	−	↓	↓	−	−
	ET_o	+	+	−	−	−	−	+	−	▽	−	−	−
Tabriz	T_{min}	+	+	+	▲	▲	▲	▲	▲	▲	▲	+	+
	T_{max}	+	△	+	△	↑	△	+	△	↑	▲	−	▲
	RH	+	▼	▼	▼	−	−	+	−	−	↓	−	−
	t_{sun}	+	↑	△	△	+	−	▽	+	+	−	−	+
	U_2	−	+	+	−	+	−	−	▼	−	+	+	+
	ET_o	+	▲	△	▲	↑	+	−	−	+	△	+	+
Shiraz	T_{min}	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
	T_{max}	+	+	−	△	↑	△	△	△	△	+	−	+
	RH	↓	▽	−	−	▼	+	+	+	+	−	−	−
	t_{sun}	+	−	+	△	+	+	−	△	↓	+	+	−
	U_2	▼	▼	▼	▼	▽	▼	▽	▼	▼	▼	▼	▼
	ET_o	−	−	−	+	+	↓	↓	▽	▼	▼	↓	−

▲ or ▼ indicate highly significant increasing and/or decreasing trends (significant at <0.01 level), respectively. △ or ▽ indicate strong increasing and/or decreasing trends (significant at <0.05 level), respectively. ↑ or ↓ indicate relatively strong increasing and/or decreasing trends (significant at <0.10 level), respectively. + or − represent positive and/or negative trends (not significant at 0.10 level), respectively

3 Results and discussion

3.1 Variation of monthly ET_o and the climatic variables

The variation of average monthly ET_o and its affecting metrological variables for the five synoptic stations is illustrated in Fig. 2. As expected, the ET_o increased when the minimum and maximum air temperature and/or sunshine hours increased and RH decreased. Except for Anzali, wind speed had a positive impact on ET_o. This non-consistency in the Anzali station can be explained by recent findings of Eslamian et al. (2011) who reported that compared to wind speed, humidity had a more significant effect on evapotranspiration in Iran. Eslamian et al. (2011) also found that as relative humidity approaches 100 %, the sensitivity of the ET_o to wind speed decreases drastically. Apparent from Fig. 2, the variation of the RH throughout the year is much lower in Anzali compared to the other four locations (i.e., 75–95 % RH variation in Anzali compared to 20–80 % for other stations). In addition, the wind velocity variation in Anzali was low and did not follow the same pattern shown for the other stations (Fig. 2). These all indicate that in contrast to the other locations, wind speed has a minimal effect on the temporal trend of the ET_o in the humid region of Anzali.

3.2 Trend analysis of monthly ET_o and its meteorological variables

The results of the M-K test including the magnitude (i.e., Z-index) and the significance level of the trends for the monthly ET_o and the other meteorological variables are summarized in Fig. 3 and Table 2, respectively. Our analysis detected significant decreasing trends in monthly ET_o for all the stations except those having a cold climate (i.e., Mashhad and Tabriz; Fig. 3a, d, Table 2). A more detailed analysis revealed the following results:

At the Mashhad station, the tendency of monthly ET_o series was upward in February and also from April–November. The trend seemed to be positive for the rest of the year but did not show any level of significance. In addition, it was observed that three out of five variables, namely T_{min}, T_{max}, and U_2 had a significant increasing trend, while this was not true for RH and t_{sun}, which respectively showed a significant negative trend and no tendency over the study period. The monthly T_{min} in Mashhad showed a significant increasing trend over the entire year. However, the highly positive trend of the monthly T_{max} only took place from April to October (except May). Any specific tendency for the RH was not observed between March to September, but the results indicated a decrease in February and a significant decrement in October. As for the t_{sun}, the positive trend was significant in April and July, less significant in September but showed significant decreasing trend in January (Table 2). There was no obvious changing during the rest of the year. Finally, the trend for U_2 was positive in June, November, and December but showed a significant increase during July–August.

At Anzali station, a high significant decreasing ET_o trend was detected but only in May (Fig. 3b, Table 2). The highly significant increasing trend of T_{min}, RH, t_{sun}, and U_2 and decreasing trend of T_{max} were found to be responsible for this observation (Fig. 3b). Table 2 also shows that for the Anzali station, T_{min} had a significant increasing trend during the entire year whereas U_2 and t_{sun} only showed positive trends. The only exception was for t_{sun} in November when no positive or negative trend could be detected. At Tehran station, the ET_o trend was never significant except for September (Fig. 3c, Table 2). The negative trend in this month is the result of the significant upward trends in T_{min} (Z-index always >2.58; Fig. 3c), T_{max}, RH, and t_{sun} and also due to the significant downward trend of U_2.

In Tabriz, an increasing ET_o trend was observed in February–May and in October (Fig. 3d, Table 2). There was no significant (less than 90 % confidence) positive or negative trend for the rest of the year (Table 2). The T_{min} trend in Tabriz was always significantly positive except the first three and last two months of the year. Finally, it was observed that the monthly ET_o significantly decreased in June to November at Shiraz station during the investigated period. Other months, however, did not show any significant positive or negative trend. The monthly T_{min} had a highly significantly increasing trend over the year whereas the U_2 trend was always significantly negative at this station (Fig. 3f, Table 2).

Examining the tendency for the T_{min} and T_{max} at study stations also showed that the level of significance was higher for T_{min}. This agrees well with the results of Tabari et al. (2011) who reported a warming trend in annual T_{min} and T_{max} time series at the majority of the Iranian territory. It is also in agreement with the findings of Turkes and Sumer (2004) who demonstrated that the tendency of T_{min} was significant and greater than that of the T_{max} series in many regions of Turkey, the northwestern neighbor of Iran.

3.3 Trend sensitivity analysis

Results of the qualitative trend sensitivity analysis are illustrated in Table 3 for only three stations (i.e., Mashhad, Tabriz and Shiraz) and 3 months (which had a significant ET_o trend). It is an attempt to describe how detrending could contribute to detect the most sensitive meteorological variables. For instance, (i) Mashhad station has experienced a significant positive trend of T_{min} in May; however, by detrending the T_{min} in this month, the significant trend of ET_o did not change. Such result is most likely because the ET_o was also indirectly related to other meteorological variables not considered in this study, such as vapor pressure deficit. (ii) Three meteorological variables (T_{min}, T_{max}, and RH) with significant trends are

Table 3 Examples of the qualitative trend sensitivity for some of the synoptic stations and some months

Station	Time (month)	Significant level of original ET_o series	Affecting variables with significant trend				Detrended variables				Significant level of detrended ET_o series
Mashhad	May	↑	–				T_{min}				↑
Tabriz	October	△	T_{min}	–	–		T_{max}	RH	–		↑
			T_{max}	–	–		T_{min}	RH	–		+
			RH	–	–		T_{min}	T_{max}	–		△
			T_{min}	T_{max}	–		RH	–	–		+
			T_{min}	RH	–		T_{max}	–	–		▲
			T_{max}	RH	–		T_{min}	–	–		△
			–	–	–		T_{min}	T_{max}	RH		+
Shiraz	September	▲	T_{min}	–	–	–	T_{max}	t_{sun}	U_2	–	↑
			T_{max}	–	–	–	T_{min}	t_{sun}	U_2	–	+
			t_{sun}	–	–	–	T_{min}	T_{max}	U_2	–	–
			U_2	–	–	–	T_{min}	T_{max}	t_{sun}	–	▼
			T_{min}	T_{max}	–	–	t_{sun}	U_2	–	–	–
			T_{min}	t_{sun}	–	–	T_{max}	U_2	–	–	△
			T_{min}	U_2	–	–	T_{max}	t_{sun}	–	–	–
			T_{max}	t_{sun}	–	–	T_{min}	U_2	–	–	–
			T_{max}	U_2	–	–	T_{min}	t_{sun}	–	–	▼
			t_{sun}	U_2	–	–	T_{min}	T_{max}	–	–	▼
			T_{min}	T_{max}	t_{sun}	–	U_2	–	–	–	+
			T_{min}	T_{max}	U_2	–	t_{sun}	–	–	–	▼
			T_{min}	t_{sun}	U_2	–	T_{max}	–	–	–	+
			T_{max}	t_{sun}	U_2	–	T_{min}	–	–	–	▼
			–	–	–	–	T_{min}	T_{max}	t_{sun}	U_2	–

▲ or ▼ indicate high strong increase and/or decrease trends (significant at <0.01 level), respectively. △ or ▽ indicate strong increase and/or decrease trends (significant at <0.05 level), respectively. ↑ or ↓ indicate relatively strong increase and/or decrease trends (significant at <0.10 level), respectively.+ or − present increase and/or decrease trends (not significant at 0.10 level), respectively

responsible for the increasing positive trend of ET_o in October in Tabriz (Table 3). Our sensitivity analysis indicated that when T_{min} and T_{max} were detrended, RH held the tendency of ET_o on the 0.05 level of significance; when T_{max} and RH were detrended, T_{min} brought the tendency down to the 0.10 level of significance, and when T_{min} and RH were detrended, T_{max} did not cause any trend in ET_o. In addition, when T_{max} was detrended, T_{min} and RH raised the ET_o tendency up to 0.01 level of significance. However, if only T_{min} was detrended, the tendency of ET_o did not change while detrending RH removed the ET_o tendency (Table 3). Thus, the sensitivity analysis showed that in October, the ET_o of Tabriz is more sensitive to the RH than to T_{min} and/or T_{max} variables. (iii) Four meteorological variables (T_{min}, T_{max}, t_{sun}, and U_2) might have affected the ET_o trend in September of the Shiraz station. The highly significant increasing trend of T_{min} and T_{max} and decreasing trend of t_{sun} and U_2 (Table 2) can explain the decreasing trend of ET_o at this station. Detrending all the variables that might have induced a decreasing trend in ET_o would remove the tendency of the reference evapotranspiration (Table 3). This confirms that the considered influencing variables here are capable of explaining the trends of ET_o. Further evaluation indicated that when T_{min}, t_{sun}, and U_2 were detrended, T_{max} did not influence the ET_o trend in September. The same conclusion was found for t_{sun}. Finally, when T_{min}, T_{max}, and t_{sun} were detrended, the U_2 significantly decreased the trend in ET_o. Detrending of the T_{max}, t_{sun}, and U_2 resulted in signification of the T_{min} at the 0.1 level. Consequently, it can be found that U_2 is the most important variable affecting the trend of ET_o in September for Shiraz station. In addition, when T_{max} or t_{sun} were added to U_2 as the primary important variables, the significance level of ET_o did not show any change. If T_{min} was added to these variables, the significance level of ET_o would be removed. So T_{min} can be considered to be the secondary important variables. In the next stage, when T_{max}, U_2, and T_{min} were all considered together, the level of significance increased whereas adding t_{sun} to this combination removed the level of significance for ET_o. In summary, the sensitivity analysis for the Shiraz station indicated that the most important variable affecting the trend of ET_o in September was $U_{2,}$ followed by T_{min}, T_{max}, and t_{sun}, respectively (Table 3).

A similar approach to what was described above was carried out for all the five stations and for all the months showing significant ET_o trends. The results are summarized in Table 4. The observed negative trend of ET_o for Tehran that occurred in September was due to the significant upward trend in T_{min}, T_{max}, RH, and t_{sun} accompanied by a significant downward trend in U_2. The trend sensitivity analysis of effective meteorological parameters in this month, on the other hand, showed that ET_o was mostly sensitive to the RH, followed by U_2. The same interpretation can be presented to justify the negative ET_o trend at Anzali in May. It is, however, worth noting that the U_2 for Anzali has a significant upward trend in May while this is not true for Tehran in September. Considering the highly significant increasing trend of RH and its importance as a primary effective, this variable can explain the decreasing trend of the ET_o in May at Anzali station. Sharifi and Dinpashoh (2014) reported that the negative annual ET_o trend in Anzali was due to the downward trend of vapor pressure deficit, mean air temperature, and solar radiation. However, it should be noted that our conclusion here has a higher degree of accuracy since ET_o trends are analyzed on a monthly basis.

Table 4 Summary of dominant meteorological variables that caused a significant trend on ET_o at the selected stations

Stations	Time (month)	Order of importance for the variable				
		i	ii	iii	iv	v
Mashhad	February	RH	T_{min}	–	–	–
	April	T_{min}	T_{max}	t_{sun}	–	
	May	T_{min}	–	–	–	–
	June	T_{min}	U_2	T_{max}	–	–
	July	U_2	T_{min}	t_{sun}	T_{max}	–
	August	T_{min}	U_2	T_{max}	–	–
	September	T_{min}	T_{max}	t_{sun}	–	–
	October	RH	T_{min}	T_{max}	–	–
	November	U_2	T_{min}	–	–	–
Anzali	May	RH	U_2	T_{min}	T_{max}	t_{sun}
Tehran	September	RH	U_2	T_{min}	T_{max}	t_{sun}
Tabriz	February	RH	t_{sun}	T_{max}	–	–
	March	RH	t_{sun}	–	–	–
	April	RH	t_{sun}	T_{min}	T_{max}	–
	May	T_{min}	T_{max}	–	–	–
	October	RH	T_{min}	T_{max}	–	–
Shiraz	June	U_2	T_{min}	T_{max}	–	–
	July	U_2	T_{max}	T_{min}	–	–
	August	U_2	T_{min}	T_{max}	t_{sun}	–
	September	U_2	T_{min}	T_{max}	t_{sun}	–
	October	U_2	T_{min}	–	–	–
	November	U_2	T_{min}	–	–	–

A highly significant decreasing and increasing trends of RH and t_{sun} were observed for Tabriz during February to April (Table 2). The sensitivity trend analysis for this station indicated that the positive trend of ET_o over this period is mainly due to the effect of an increasing trend of RH, t_{sun}, and/or temperature. This is while only temperature variables were effective on the tendency of ET_o in May (Table 4).

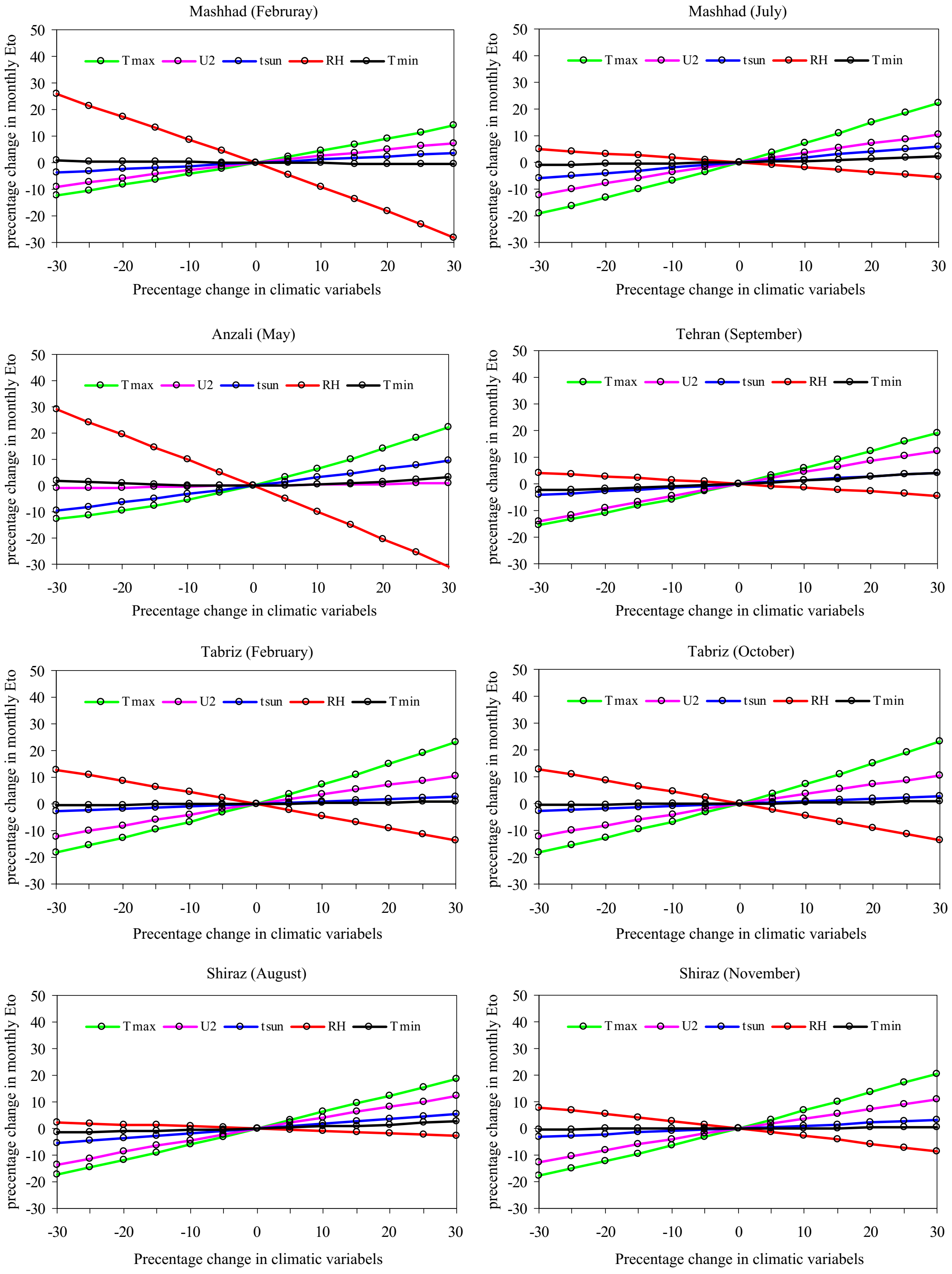
The U_2 and T_{min} were the two main meteorological variables responsible for the ET_o decline in March and October at Shiraz station. These two, followed by T_{max} and t_{sun} were the main four meteorological variables responsible for the ET_o decrease in August and September. The negative significant ET_o trend observed for Shiraz in June and July was due to the variation of U_2 which also showed to be the most effective variable (Table 4). On the other hand, T_{min} and T_{max} were the second and the third factors of interest. Thus, the most important factors affecting ET_o at Shiraz station were respectively U_2, T_{max}, and T_{min}. This was not completely in accordance with the results of Eslamian et al. (2011) who reported wind speed, relative humidity, and temperature as the most sensitive meteorological variables.

A significant positive ET_o trend was obtained in Mashhad for 9 months of the year (Table 2 and Fig. 3). The T_{min}, U_2, and RH were the most important parameters that could justify the significant trend of ET_o. Eslamian et al. (2011) reported that as temperature increase and relative humidity decrease, the sensitivity of ET_o trend to wind speed increases directly. These results are consistent with those reported in this study (Table 4), most likely because the ET_o trend had the similar trend for most of the year.

3.4 Comparative analysis

Examples of the sensitivity curves calculated by Eq. (6) for all the stations and the five climatic variables are depicted in Fig. 4. The most important climatic variables affecting ET_o trends were extracted visually by taking into account the magnitude of the slopes, and the final results are summarized in Table 5. The comparison showed that except in two cases (which occurred for Mashhad in May and October), the two methods always shared one (and only one) of their first two important key climatic variables. This reveals that there is generally a relative agreement between the two solutions in terms of the key climatic variables affecting ET_o trends. However, the second factor of interest (among these two) was almost never similar. One reason for this discrepancy might be due to the fact that the detrended method is capable of taking into account the interaction between the aerodynamic and the energy terms of the FAO-PM equation but the regular sensitivity analysis approach (Eq. (6)) is not. The qualitative method has also the advantage of only revealing the key climatic variables whose exclusion would remove the significant level of the ET$_o$ trends.

Results of this study may contribute to a better understanding of the factors affecting regional monthly ET$_o$ behavior in Iran. This will result in more suitable climate change strategies that could be adapted for agriculture. For example, if the trend



Mashhad (Februray)

Mashhad (July)

Anzali (May)

Tehran (September)

Tabriz (February)

Tabriz (October)

Shiraz (August)

Shiraz (November)

Fig. 4 Examples of the sensitivity coefficient (SC) curves plotted for different climatic variables and for the five synoptic stations. Only the months that indicated a significant ET$_o$ trend were considered of ET_o is positive in a specific region, crop water requirement will increase. Agricultural water in semi-arid regions is limited, so the crop production will be limited as well and may result in loss of yield quality. In addition, in arid and semi-arid regions such as Iran, dam construction is a common way to provide irrigation water during the drought season (Kousari et al. 2013). The agricultural sector in Iran consumes more than 80 % of the water resources collected in dam reservoirs. Thus, any increase in ET_o will increase the crop water demand and will impose considerable costs on the economy. Under these circumstances, it would be necessary to use alternative methods to reduce potential damages. In general, these could include the following: (i) optimizing agronomic water use efficiency through new irrigation management approaches (Sadeghi and Peters 2010, 2012; Sadeghi et al. 2010, 2015), (ii) planting tolerant crop varieties (Challinor et al. 2006), and (iii) optimizing deficit irrigation techniques (Gheysari et al. 2015).

4 Conclusion

Changes in the meteorological variables play an important role in the assessment of evapotranspiration with climate change and are of great importance for agricultural water use planning, hydrologic models database, and irrigation system design and management. In this paper, we analyzed the sensitivity of the monthly ET_o trends to its key climatic factors by applying a qualitative detrended method, rather than the historical mathematical approach (which builds upon changing the value of the climatic variables within a specific range).

Different sets of meteorological variables were found to affect the trend of the monthly reference evapotranspiration of each station, and at different months throughout the year. Results also indicated both the significant upward and downward trends of the monthly ET_o time series at all the selected stations. Other conclusions were as follows:

1. The main causes of the significant increasing ET_o trend in the mountainous region of Mashhad are the increasing trend in T_{min}, followed by a decreasing trend in RH and an increasing trend in U_2. The priority factor depended upon the month under consideration.
2. The main causes of the increasing trend in ET_o in the mountainous region of Tabriz were the decreasing trend of RH, followed by the increasing trend of the sunshine hours and/or temperature.

Table 5 Comparative analysis between the qualitative and the quantitative sensitivity analysis in terms of the dominant meteorological variables that caused a significant trend on ET_o at the selected stations

Station	Month with a significant ET_o trend	Key climatic variables per priority	
		Qualitative method	Quantitative method
Mashhad	February	RH, T_{min}	RH, T_{max}, U_2, t_{sun}
	April	T_{min}, T_{max}, t_{sun}	T_{max}, RH, U_2, t_{sun}
	May	T_{min}	T_{max}, RH, U_2, t_{sun}
	June	T_{min}, U_2, T_{max}	T_{max}, U_2, t_{sun}, RH
	July	U_2, T_{min}, t_{sun}, T_{max}	T_{max}, U_2, t_{sun}, RH
	August	T_{min}, U_2, T_{max}	T_{max}, U_2, t_{sun}, RH
	September	T_{min}, T_{max}, t_{sun}	T_{max}, U_2, t_{sun}, RH
	October	RH, T_{min}, T_{max}	T_{max}, U_2, RH, t_{sun}
	November	U_2, T_{min}	T_{max}, U_2, RH, t_{sun}
Anzali	May	RH, U_2, T_{min}, T_{max}, t_{sun}	RH, T_{max}, t_{sun}, U_2
Tehran	September	RH, U_2, T_{min}, T_{max}, t_{sun}	T_{max}, U_2, RH, t_{sun}
Tabriz	February	RH, t_{sun}, T_{max}	RH, U_2, T_{max}, t_{sun}
	March	RH, t_{sun}	RH, T_{max}, U_2, t_{sun}
	April	RH, t_{sun}, T_{min}, T_{max}	T_{max}, RH, U_2, t_{sun}
	May	T_{min}, T_{max}	T_{max}, RH, U_2, t_{sun}
	October	RH, T_{min}, T_{max}	T_{max}, RH, U_2, t_{sun}
Shiraz	June	U_2, T_{min}, T_{max}	T_{max}, U_2, t_{sun}, RH
	July	U_2, T_{max}, T_{min}	T_{max}, U_2, t_{sun}, RH
	August	U_2, T_{min}, T_{max}, t_{sun}	T_{max}, U_2, t_{sun}, RH
	September	U_2, T_{min}, T_{max}, t_{sun}	T_{max}, U_2, t_{sun}, RH
	October	U_2, T_{min}	T_{max}, U_2, t_{sun}, RH
	November	U_2, T_{min}	T_{max}, U_2, RH, t_{sun}

3. The significant increasing trend of RH followed by the decreasing trend in U_2 justified the observed decreasing $\mathrm{ET_o}$ trends in the semi-desert region of Tehran and the costal wet region of Anzali.
4. In general, the significant decreasing trend of $\mathrm{ET_o}$ in the Shiraz station was due to changes in U_2 followed by temperature variables (i.e., $T_{\max}$ and $T_{\min}$), respectively.
5. The results from the mathematical $\mathrm{ET_o}$ trend sensitivity analysis approach did not coincide with those of the detrended method. A comparative analysis indicated that there is a relative agreement between the two methods in terms of identifying one of the two most important climatic variables (that affect the $\mathrm{ET_o}$ trend). However, a perfect match between the two solutions was never achieved, most likely because the detrended solution has the advantage of considering the interaction between the energy and the aerodynamic terms of the FAO-PM formula. Further examination of these new findings on other datasets obtained from different geographical locations across the world is an active area of research.

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