Quaternary International xxx (2014) 1–9

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

A survey of temperature and precipitation based aridity indices in Iran

Hossein Tabari [a,*], P. Hosseinzadeh Talaee [b], S.S. Mousavi Nadoushani [c], Patrick Willems [a], Aldo Marchetto [d]

[a] Hydraulics Division, Department of Civil Engineering, KU Leuven, Kasteelpark Arenberg 40, BE-3001 Leuven, Belgium
[b] Young Researchers and Elite Club, Hamedan Branch, Islamic Azad University, Hamedan, Iran
[c] Department of Water Resources Engineering, Faculty of Water & Environmental Engineering, Power & Water University of Technology (PWUT), Tehran, Iran
[d] National Research Council, Institute for Ecosystem Study, Largo Tonolli 50, 28922 Verbania Pallanza, Italy

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Climatic index
Climate classification
Spatial distribution
Temporal trend
Statistical techniques

ABSTRACT

In arid and semi-arid lands with warm climates, aridity and associated water scarcity is more severe because of greater populations and associated water use. The goal of this study was to explore the spatial and temporal variations of the de Martonne and Pinna aridity indices over Iran based on temperature and precipitation data from 41 stations for 40 years (1966–2005). The spatially interpolated maps of the aridity indices were prepared using the Ordinary Kriging technique in a GIS environment. The arid and semi-arid regions cover about 88% of Iran according to the de Martonne index, while about 96% of the country's areas are classified as dry and semi-dry based on the Pinna index. A strong relationship was found between the values of the de Martonne and Pinna indices, confirming their similar spatial distribution. Around 63% of the two indices series had a decreasing tendency. The significant decreasing trends of the aridity indices were observed mainly in the western and northwestern regions of the country. The relative changes of the aridity indices at the stations with significant decreasing trends were in the range of 18%–54%.

1. Introduction

Aridity, as defined by the shortage of moisture, is essentially a climatic phenomenon that is based on average climatic conditions over a region (Agnew and Anderson, 1992). Increased aridity, dryness, and desertification have become a major environmental problem affecting the living conditions of the people in the affected region in many countries of the world. Once the aridity or dryness of an area increased beyond a certain level, it becomes difficult to recover (Adnan and Haider, 2012).

Climatic indices are diagnostic tools used to describe the state of a climate system and understand the various climate mechanisms (Deniz et al., 2011). The aridity index is a climatic index which can be used for monitoring and prediction of drought (Nastos et al., 2013), and change in the aridity index would inevitably have impacts on the hydrological cycle, water resources management, and ecosystem in the region (Liu et al., 2012).

Generally, climate indices are derived from temperature and precipitation measurements. Temperature and precipitation data are climate indicators, and the sense of changes expected to accompany climate warming are reasonably well defined. In addition, records of temperature and precipitation are often longer and probably have a better chance of revealing a detectable change than alternative climate variables such as cloud cover, winds, and humidity (Toros et al., 2008). Whereas temperature and precipitation are very useful individual parameters to study climatic change, the overall expression and significance of climatic change in bioclimatic terms is better expressed by the aridity or humidity index (Kafle and Bruins, 2009). Climate change alters local dry/wet conditions and affects the regional agriculture sector (Du et al., 2013).

Changes in the aridity index have been studied in the literature. Baltas (2007) studied the spatial distribution of climatic indices in northern Greece during the period 1965–1995. The climatic indices used were the Johansson Continentality Index, the Kerner Oceanity Index, the de Martonne (I_{DM}) Aridity Index, and the Pinna Combinative (I_P) Index. The results showed that the Johansson index is preferable to the Kerner index owing to

* Corresponding author.
E-mail address: tabari.ho@gmail.com (H. Tabari).

http://dx.doi.org/10.1016/j.quaint.2014.03.061
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the former's distinct limit values separating continental from oceanic climates. It was also found that the I_{DM} led to a more precise definition of each station's climate due to its more climate categories, in contrast to the few climate categories of the I_P. Paltineanu et al. (2007) investigated the range of the I_{DM} aridity index in Romania, and determined its relationship with irrigation water requirements of representative crops of Romania. They found an inverse and strong correlation between the I_{DM} aridity index and crop evapotranspiration and irrigation water requirements of crops. Deniz et al. (2011) explored the spatial variability of the continentality, oceanity, and aridity indices in Turkey. The climatic indices were same as those used by Baltas (2007). They found a significant correlation of 0.91 between the I_{DM} and I_P indices. The extreme locations which were found using the I_{DM} were also addressed by the I_P. Croitoru et al. (2013) analyzed the indices of I_{DM} and I_P in order to identify critical areas in the most important agricultural regions of the extra-Carpathian areas of Romania over the period 1961–2007. They found that the trends calculated for I_{DM} index were mostly negative, but they were not statistically significant in the great majority of cases. For I_P, the trends were mainly positive, but also statistically insignificant.

Recently, changes in the aridity index in Iran were analyzed in several studies. Tabari and Aghajanloo (2013) and Shifteh Some'e et al. (2013) analyzed the UNESCO index, utilizing ratio of precipitation (P) over reference evapotranspiration (ET_o), in Iran. In another study, Tabari and Hosseinzadeh Talaee (2013) investigated the moisture conditions of Iran using the revised Thornthwaite moisture index, a ratio of evapotranspiration to precipitation. The overall results showed that similar to the precipitation variations in Iran (Modarres and da Silva, 2007; Tabari and Hosseinzadeh Talaee, 2011; Soltani et al., 2012; Shifteh Some'e et al., 2012), the significant trends of the moisture index are not evident at the majority of the stations.

This study attempts to analyze simple aridity indices based on only temperature and precipitation for the regions where full meteorological data may not be available for ET_o estimation. Thus, the aridity indices of de Martonne and Pinna were calculated by using monthly temperature and precipitation data from 41 meteorological stations in Iran. We focused on the spatial and temporal variations of aridity indices for the period 1966–2005. The temporal trend in the aridity indices was examined using the Mann–Kendall test modified by Hamed and Rao (1998). Additionally, the cumulative sum test was utilized for change point detection in aridity indices time series.

2. Materials and methods

2.1. Dataset

The data used in this study are monthly records of temperature and precipitation provided by the Islamic Republic of Iran Meteorological Organization (www.weather.ir/). In this study, 43 weather stations with a minimum record length of 40 years were considered. Only stations with less than 5% of missing values in relation to the total weather station data for the whole study period were selected. Therefore, two stations (Jask and Tabass) were excluded from the study and a total of 41 stations across the country were used to calculate the aridity indices over the period 1966–2005. A statistical summary of precipitation and air temperature at the considered stations is presented in Table 1 and the spatial distributions of the selected stations are shown in Fig. 1.

Table 1
A statistical summary of precipitation and air temperature at the considered stations.

Station	Precipitation		Air temperature	
	Mean (mm)	Standard deviation (mm)	Mean (°C)	Standard deviation (°C)
Abadan	167.9	58.9	25.5	0.73
Ahwaz	246.7	83.7	25.4	0.86
Arak	333.9	96.8	13.8	1.12
Babolsar	925.0	158.0	17.1	0.69
Bam	59.1	26.3	23.1	0.80
Bandar-Abbas	183.3	118.0	26.9	0.59
Bandar-Anzali	1775.3	341.6	16.2	0.67
Bandar-Lengeh	143.1	96.5	26.6	0.62
Birjand	169.7	52.3	16.4	0.77
Bushehr	268.2	113.1	24.7	0.66
Chahbahar	110.3	98.4	26.2	0.48
Dezful	416.5	127.7	24.0	0.60
Fassa	299.9	122.7	19.3	0.85
Ghazvin	324.3	87.3	13.9	1.06
Gorgan	595.9	106.4	17.7	0.71
Hamedan	328.7	82.7	10.8	0.92
Iranshahr	111.7	57.4	26.8	0.64
Isfahan	125.0	39.4	16.4	0.65
Kashan	137.1	52.3	19.1	0.85
Kerman	142.6	49.2	15.7	0.80
Kermanshah	464.3	125.6	14.4	0.90
Khorram-Abad	510.6	124.9	16.9	1.13
Khoy	298.2	85.1	11.9	1.19
Mashhad	261.1	74.1	14.3	1.17
Oroomieh	335.2	106.1	11.2	1.03
Ramsar	1208.7	286.8	16.0	0.70
Rasht	1379.4	252.1	16.0	0.83
Sabzevar	199.5	56.6	17.7	0.99
Saghez	503.9	131.8	11.1	1.18
Sanandaj	465.5	126.3	13.4	0.93
Semnan	142.6	54.4	18.1	0.71
Shahrekord	331.9	85.1	11.8	0.85
Shahroud	166.1	56.7	14.7	0.88
Shiraz	333.6	107.0	17.9	0.90
Tabriz	280.3	74.2	12.6	0.99
Tehran	241.5	69.7	17.5	0.92
Torbateheydarieh	281.2	77.2	14.2	0.75
Yazd	61.1	27.0	19.2	0.82
Zabol	60.9	31.1	22.1	0.76
Zahedan	79.6	40.6	18.5	0.73
Zanjan	305.6	74.6	10.9	0.92

2.2. Aridity indices

Aridity is the degree to which a climate lacks effective, life-promoting moisture; the opposite of humidity, in the climate sense of the term (American Meteorological Society, 2006). An aridity index is defined as the numerical indicator of the degree of dryness of the climate at a given location and it classifies the type of climate in relation to water availability. The higher the aridity indices of a region, the greater water resources variability. The increasing aridity represents a higher frequency of dry years over an area (Deniz et al., 2011). In this study, the de Martonne aridity index and the Pinna combinative index were calculated for Iran based on temperature and precipitation data for the period 1966–2005.

The I_{DM}, developed by de Martonne (1925), is calculated by the following equation:

$$I_{DM} = \frac{P}{T + 10} \tag{1}$$

where I_{DM} is the de Martonne aridity index, P is the annual mean precipitation in mm and T is the annual mean air temperature in °C. The climatic classification based on the I_{DM} values is shown in Table 2.

Table 2
Type of climate according to the de Martonne aridity index (Croitoru et al. 2013).

Climate type	I_{DM} values
Arid	$I_{DM} < 10$
Semi-arid	$10 \le I_{DM} < 20$
Mediterranean	$20 \le I_{DM} < 24$
Semi-humid	$24 \le I_{DM} < 28$
Humid	$28 \le I_{DM} < 35$
Very humid	$35 \le I_{DM} < 55$
Extremely humid	$I_{DM} > 55$

The Pinna combinative index, proposed by Pinna (Zambakas, 1992), was utilized for climate classification in northern Greece (Baltas, 2007), Turkey (Deniz et al., 2011) and the extra-Carpathian regions of Romania (Croitoru et al., 2013). This index describes in a better way the regions and seasons, where irrigation is necessary as it takes into account the precipitation and air temperature of the driest month (Deniz et al., 2011). The I_P is given by the following relationship:

$$I_P = \frac{1}{2}\left(\frac{P}{T+10} + \frac{12P_d}{T_d+10}\right) \quad (2)$$

where P and T are the annual mean values of precipitation and air temperature, respectively, and P_d and T_d are the mean values of precipitation and air temperature of the driest month, respectively. When the value of the I_P is less than 10 ($I_P < 10$), the climate is classified as dry and when the value of I_P varies between 10 and 20 ($10 \le I_P \le 20$) the climate is characterized as semi-dry Mediterranean, with formal Mediterranean vegetation (Baltas, 2007).

2.3. Interpolation method

Interpolation is the process of using points with known values or sample points to estimate values at other unknown points. Kriging method is an exact interpolation estimator that is often refers to the best linear unbiased estimator (B.L.U.E). Ordinary kriging (OK) is the most frequently used form of kriging. It estimates at an unobserved location of variable z based on the weighted average of adjacent from that of regionalized variables and can be briefly indicated by considering an intrinsic random function $z(s_i)$, with (s_i) representing the locations of all samples ($i = 1,2,3,\ldots, n$). An estimation of weighted average given by the OK predictor at an unsampled size $Z(s_0)$ is defined by:

$$Z(s_0) = \sum_{i=1}^{n} \lambda_i z(s_i) \quad (3)$$

where λ denotes the weights allocated to each of the observed samples. To provide an unbiased estimation by the predictor, these weights sum to unity ($\sum_{i=1}^{n}\lambda_i = 1$). The weights are determined by the following matrix equation:

$$C = A^{-1}b, \quad (4)$$

where C is the resulting weights, A is a matrix of semivariogram between the data points, and b is a vector of estimated semivariances between the data points and the points at which the variable z is to be predicted.

The semivariogram is a statistical model that represents how the data vary spatially across the area of interest. The variation between points is measured using the semivariance. Pooling together pairs of data at a geographic distance h, the semivariance $\lambda(h)$ of the sample can be written as:

$$\lambda(h) = \frac{1}{2}N(h)\sum[z(x_i)\cdot z(x_i+h)]^2 \quad (5)$$

where z is the regionalized variables, $z(x_i)$ and $z(x_i + h)$ are measured sample values at x_i and $x_i + h$ points, and N is the number

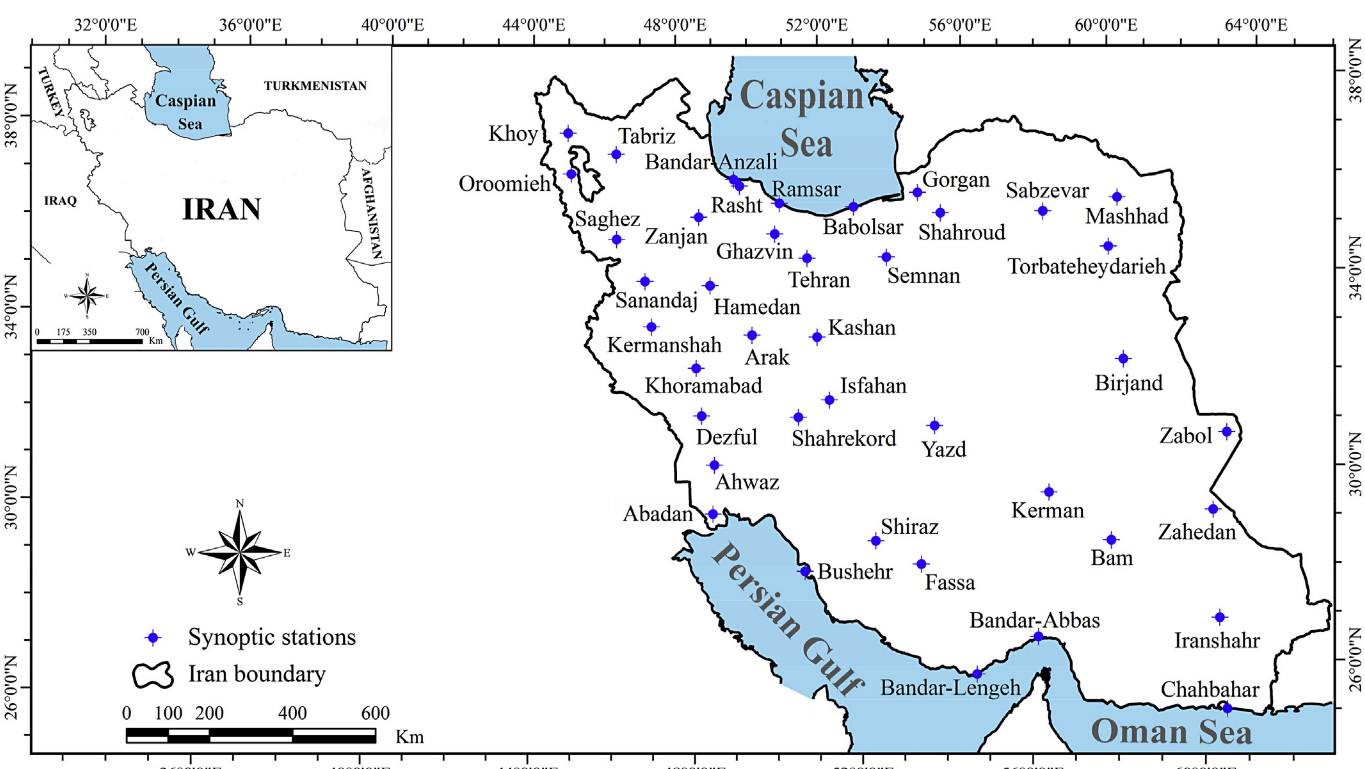

Fig. 1. Geographical positions of synoptic stations considered in this study.

of couple separated with distances h (lag space). The experimental semivariogram, $\lambda(h)$, is fitted to a theoretical model such as spherical, exponential, Gaussian or linear to define three parameters of nugget, sill and range (Alsamamra et al., 2009; Shifteh Somee et al., 2011). The detailed mathematical description of the theoretical models can be found in Shifteh Somee et al. (2011).

2.4. Trend analysis methods

Mann-Kendall test:

The Mann–Kendall test is simple, robust and can cope with missing values and values below a detection limit. The Mann–Kendall test is highly recommended for general use by the World Meteorological Organization (Zhang et al., 2009) and has been widely used in water resources and environmental studies (e.g., da Silva, 2004; Pasquini et al., 2006; Celleri et al., 2007; Kumar and Jain, 2010; Mamtimin et al., 2011; Nyeko-Ogiramoi et al., 2013; Chen et al., 2014). In the present study, the Mann–Kendall test was used to detect temporal trends in the I_{DM} and I_P time series. The test statistic (Z_{MK}) is given as:

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if} \quad S < 0 \end{cases} \tag{6}$$

in which

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \mathrm{sgn}(x_k - x_i) \tag{7}$$

$$\mathrm{Var}(S) = \frac{\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5) \right]}{18} \tag{8}$$

where the x_k and x_i are the sequential data values, m is the number of tied groups (a tied group is a set of sample data having the same value), t_i is the number of data points in the ith group, n is the length of the data set, and $sgn(\theta)$ is equal to 1, 0, −1 if θ is greater than, equal to, or less than zero, respectively. (Tabari and Marofi, 2011). The positive (negative) values of Z indicate increasing (decreasing) trends and the value $Z_{1-\alpha/2}$ denotes a quantile of the standard normal cumulative distribution. The null hypothesis H_0 is accepted if $-Z_{1-\alpha/2} \le Z_{MK} \le Z_{1-\alpha/2}$.

The Mann–Kendall test can be misleading, if the data are serially correlated (Gilbert, 1987). The estimate of the variance of S is biased when there is a significant serial correlation in a time series (Hamed and Rao, 1998). To remove the serial correlation effect, Hamed and Rao (1998) recommend to subtract a non-parametric trend estimator from the initial time series X and to evaluate the autocorrelation between the ranks of the new time series. Serial correlation coefficients ($\rho_s(i)$ at lag(i)) that are significantly different from zero at the 5% level are then used to evaluate the modified variance of S, $V^*(S)$ as:

$$\mathrm{Var}^*(S) = \mathrm{Var}(S) \cdot Cor \tag{9}$$

where Cor represents a correction due to autocorrelation in the data, and

$$Cor = 1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-1)(n-i-1)(n-i-2)\rho_s(i) \tag{10}$$

In this study, the significance of trends is evaluated at the 5% significance level.

Cumulative sum test:

The cumulative sum (Cumsum) technique was used to identify the change point in the I_{DM} and I_P time series. The objective is to determine in which year (or years) an abrupt change occurred in a single time series. The 'Cumsum' is computed as follows (Kiely, 1999):

$$S_k^* = \sum_{t=1}^{k} (x_t - \bar{x}), \quad k = 1, 2, \ldots, n \tag{11}$$

where $\bar{x}$ is the average value of the time series. The possible change has occurred when S_k is a maximum. In the current study, the Cumulative sum test was applied for the time series with significant trends.

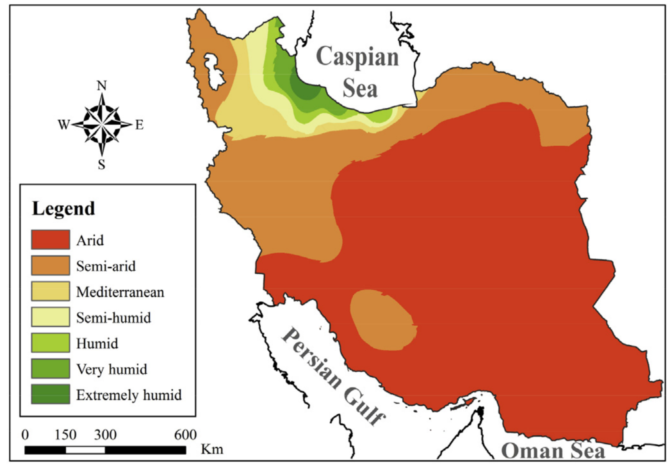

Fig. 2. De Martonne climate type map of Iran (1966–2005).

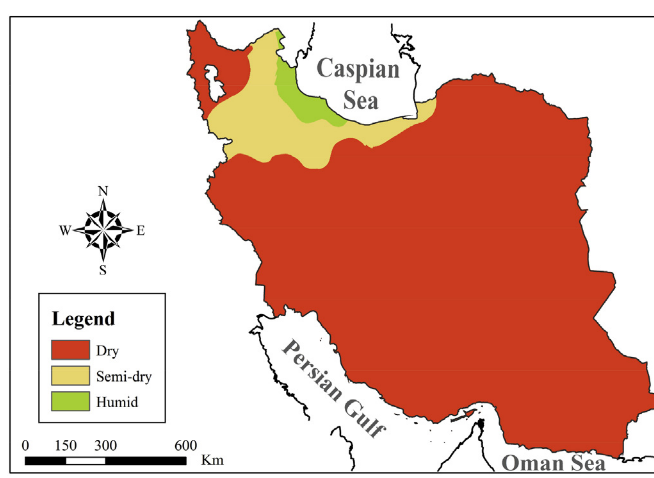

Fig. 3. Pinna climate type map of Iran (1966–2005).

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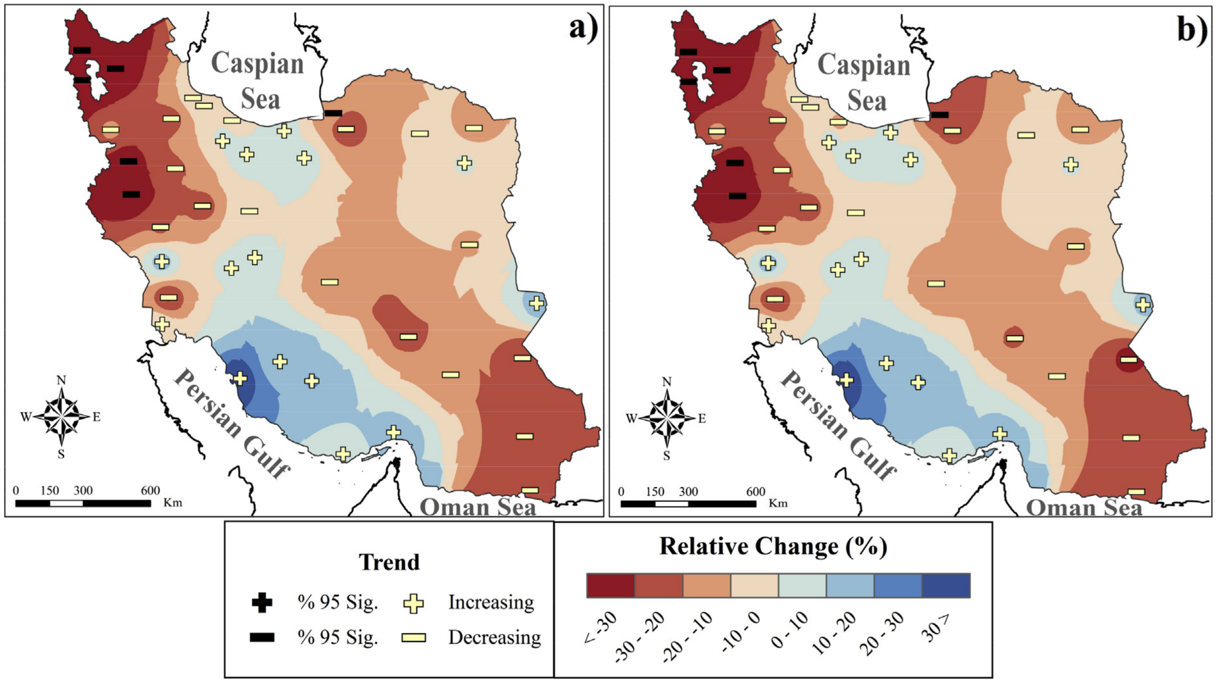

Fig. 4. Relative change (%) of the aridity indices over 1966–2005 (markers show the trends detected by the modified Mann–Kendall test): a) De Martonne index, b) Pinna index.

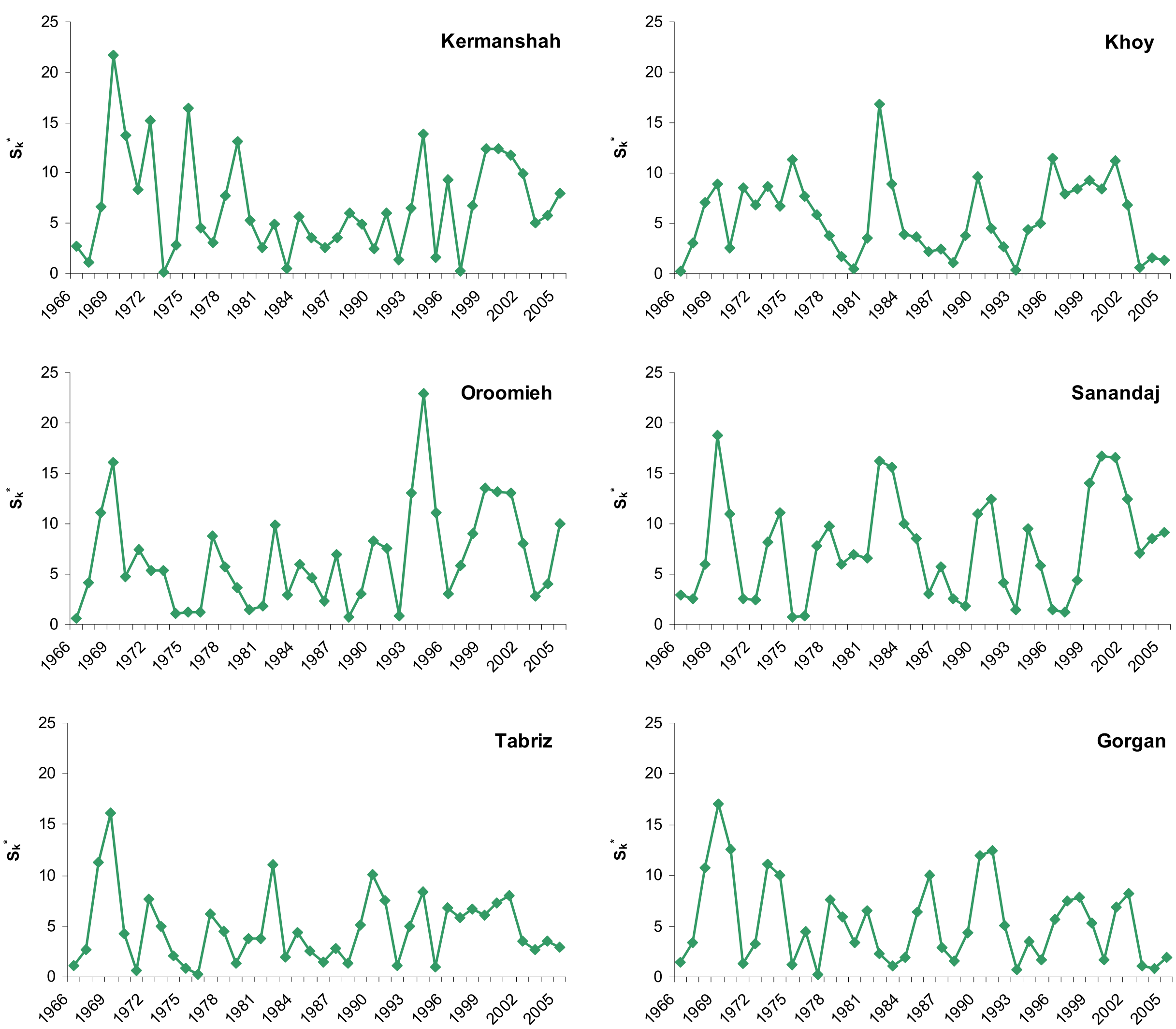

Fig. 5. Values of $|S_k^*|$ of the cumulative sum test for the I_{DM} series at the stations with significant trends.

Relative change:

Relative change (RC) of the aridity index was calculated using the following formula:

$$RC = \frac{n \times \beta}{|\overline{x}|} \times 100 \quad (12)$$

where n is the data set record length, β is the magnitude of trend in the time series and $|\overline{x}|$ is the absolute average value of the time series. The magnitude of the trends in the time series was estimated using the non-parametric Theil–Sen's estimator (Theil, 1950; Sen, 1968) as follows:

$$\beta = \text{Median}\left(\frac{X_i - X_j}{i - j}\right) \quad (13)$$

wherein $1 < j < i < n$.

3. Results and discussion

The spatial distribution of the I_{DM} index in Iran is plotted in Fig. 2. The values of the I_{DM} cover the entire range of the classification's climate categories. At 19 out of the 41 stations, the I_{DM} value was lower than 10, denoting arid climate. In contrast, the highest I_{DM} values, implying humid, very humid, and extremely humid climates, are distributed to the stations located on the southern coasts of the Caspian Sea. Generally, about 60% of the country was arid, 28% was semi-arid, 4% was Mediterranean, 1% was semi-humid, 2% was humid, 3% was very humid, and 2% was extremely humid. The I_{DM} values ranged from about 2 at Bam station in the southeast to about 68 at Bandar-Anzali station in the north.

According to the I_P values, about 96% of the entire area is classified as dry and semi-dry climates (Fig. 3). At 35 out of the 41 stations, the values of the I_P were less than 10, implying a dry climate. The semi-dry Mediterranean climate with formal Mediterranean vegetation is found only in the northwestern and northern regions of the country. Only the regions located on the southwestern coasts of the Caspian Sea had I_P values higher than 20.

The semi-dry area identified by the I_P is smaller than that found by the I_{DM}, but the arid area obtained by the I_P is bigger. Overall, the spatial distribution of the I_P is similar to that of I_{DM}. According to the results of the two indices, it can be concluded that the I_{DM} is more appropriate for climate classification since it with six climate categories defines more precisely the climate of each station. Such results were obtained for climate classification with the two indices in Romania (Croitoru et al., 2013), Greece (Baltas, 2007) and Turkey (Deniz et al., 2011).

The I_{DM} and I_P are highly correlated in the study stations. The coefficient of determination (R^2) equal to 1 was found for the arid

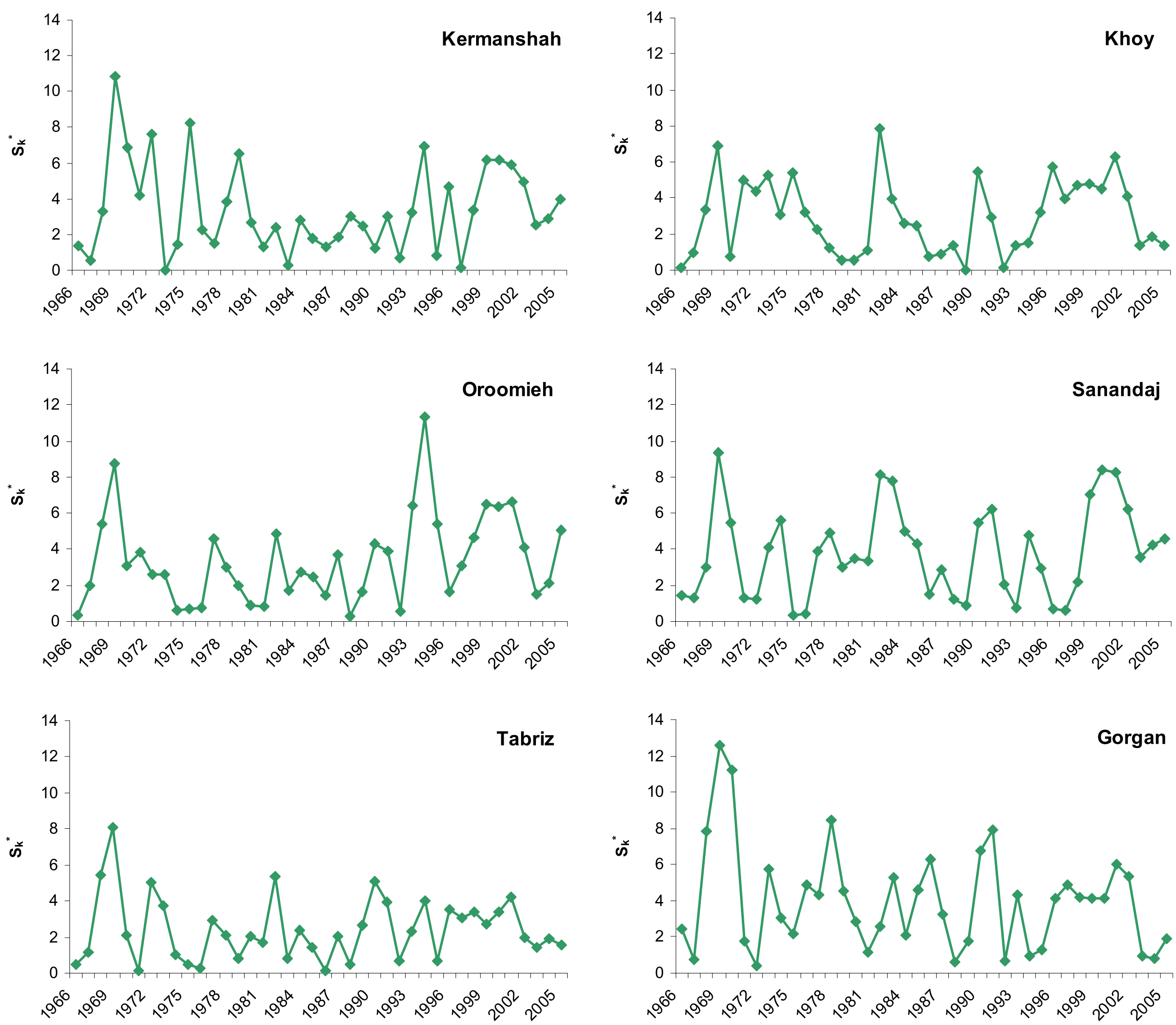

Fig. 6. Values of $|S_k^*|$ of the cumulative sum test for the I_P series at the stations with significant trends.

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and semi-arid regions. This is due to the zero value of precipitation in the driest month in the arid regions which causes the second term of Eq. (2) to be zero. In the extremely humid climate (Bandar-Anzali station), the R^2 value of 0.76 was obtained between the I_{DM} and I_P. At Rash station, which is located in the very humid region, the R^2 value of 0.84 was found between the I_{DM} and I_P. The R^2 values between the I_{DM} and I_P for the other stations were between 0.60 and 0.99. A high correlation coefficient between the two indices was also reported by Baltas (2007), Deniz et al. (2011) and Croitoru et al. (2013) in Europe.

The percent change of the I_{DM} and I_P is illustrated in Fig. 4. The markers in the maps show the temporal trends detected by the Mann–Kendall test in the I_{DM} and I_P series. It should be noted that the decreasing trend of the I_{DM} and I_P aridity indices means higher arid conditions. Around 63% of the I_{DM} series showed a decreasing tendency. The increased aridity generally results in reducing livelihood opportunities for human especially for the production of crops and livestock.

Significant decreasing trends in the I_{DM} series at the 5% level were found at Kermanshah, Sanandaj, Tabriz, Khoy, Oroomieh and Gorgan stations (Table 3). The relative changes of the I_{DM} at the above-mentioned stations were between 18% and 54%. A significant decreasing trend in the P/ET_o aridity indices (i.e., UNESCO and Thornthwaite indices) at Kermanshah, Sanandaj, Tabriz, Khoy and Gorgan stations was reported by Tabari and Aghajanloo (2013) and Tabari and Hosseinzadeh Talaee (2013). The significant decreasing trend of the I_{DM} series is related to the concurrent occurrences of significant increasing trends of air temperature (Tabari et al., 2011, 2012) and significant decreasing trends of precipitation (Tabari and Hosseinzadeh Talaee, 2011) at the stations.

Similar to the I_{DM} variations, around 63% of the I_P series showed a decreasing tendency. Significant decreasing trends in the I_P series at the 5% level were observed at Kermanshah, Sanandaj, Tabriz, Khoy, Oroomieh and Gorgan stations (Table 3). The relative changes of the I_P at the mentioned stations ranged between 28% and 51%. As seen in Fig. 4, the stations located in northwestern, western and

Table 3
Statistical summary of the indices examined in the study, the Z_{MK} statistic of the Mann–Kendall test and the magnitude of trends (β statistic) approximated by Theil-Sen's estimator (statistic of the modified Mann–Kendall test is presented in parenthesis).

Station	de Martonne index				Pinna index			
	Mean (mm/°C)	Standard deviation (mm/°C)	Z_{MK}	β (mm/°C)	Mean (mm/°C)	Standard deviation (mm/°C)	Z_{MK}	β (mm/°C)
Abadan	4.7	1.69	0.13 (0.02)	0.001	2.4	0.85	0.13 (0.02)	0.000
Ahwaz	7.0	2.44	−1.64	−0.054	3.5	1.22	−1.64	−0.027
Arak	14.1	4.41	−1.36	−0.091	7.1	2.20	−1.36	−0.045
Babolsar	34.1	5.82	0.41	0.047	18.7	3.53	0.15	0.010
Bam	1.8	0.80	−0.64	−0.007	0.9	0.40	−0.64	−0.004
Bandar-Abbas	5.0	3.26	0.64	0.020	2.5	1.63	0.64	0.010
Bandar-Anzali	67.8	13.91	−0.10	−0.022	37.7	8.30	−0.03	−0.009
Bandar-Lengeh	3.9	2.67	0.13	0.003	2.0	1.34	0.13	0.002
Birjand	6.5	2.09	−0.71	−0.017	3.2	1.04	−0.71	−0.009
Bushehr	7.7	3.27	1.46	0.070	3.9	1.63	1.46	0.035
Chahbahar	3.1	2.74	−0.85	−0.019	1.5	1.37	−0.85	−0.009
Dezful	12.3	3.82	0.64	0.050	6.1	1.91	0.64	0.025
Fassa	10.3	4.31	0.69	0.052	5.1	2.16	0.69	0.026
Ghazvin	13.6	3.94	0.27	0.016	6.8	1.98	0.29	0.008
Gorgan	21.5	4.05	**−2.47 (-1.97)**	−0.097	12.5	2.93	**−2.74 (-2.25)**	−0.087
Hamedan	15.9	4.32	−1.06	−0.084	7.9	2.16	−1.06	−0.042
Iranshahr	3.0	1.59	−0.78 (−0.87)	−0.018	1.5	0.79	−0.78 (−0.87)	−0.009
Isfahan	4.8	1.53	0.15	0.007	2.4	0.77	0.15	0.003
Kashan	4.7	1.86	−0.13 (−0.12)	−0.004	2.4	0.93	−0.13 (−0.12)	−0.002
Kerman	5.6	2.02	−1.01	−0.029	2.8	1.01	−1.01	−0.014
Kermanshah	19.1	5.49	**−2.50**	−0.217	9.6	2.75	**−2.50**	−0.109
Khorram-Abad	19.0	4.87	−1.39	−0.101	9.5	2.44	−1.39	−0.050
Khoy	13.7	4.30	**−2.90**	−0.185	7.2	2.41	**−2.64**	−0.092
Mashhad	10.8	3.30	−0.80	−0.038	5.4	1.65	−0.80	−0.020
Oroomieh	15.9	5.24	**−2.62**	−0.183	8.0	2.66	**−2.64**	−0.092
Ramsar	46.6	11.46	−0.73	−0.106	26.5	7.00	−0.94	−0.093
Rasht	53.3	10.99	−0.41	−0.072	30.5	7.09	−1.18	−0.084
Sabzevar	7.2	2.15	−0.38	−0.015	3.6	1.08	−0.38	−0.007
Saghez	24.1	6.85	−1.08	−0.104	12.0	3.42	−1.04	−0.053
Sanandaj	19.9	5.58	**−3.04 (-2.76)**	−0.181	10.0	2.79	**−3.04 (-2.76)**	−0.091
Semnan	5.1	2.02	0.38 (0.15)	0.007	2.5	1.01	0.38 (0.15)	0.003
Shahrekord	15.3	4.12	0.29	0.015	7.6	2.06	0.29	0.008
Shahroud	6.8	2.52	−1.36	−0.045	3.4	1.27	−1.20	−0.019
Shiraz	12.0	3.93	0.76	0.034	6.0	1.97	0.76	0.017
Tabriz	12.5	3.59	**−3.20 (-2.20)**	−0.115	6.3	1.86	**−3.18 (-2.15)**	−0.060
Tehran	8.8	2.69	0.55	0.019	4.4	1.37	0.57	0.010
Torbateheydarieh	11.7	3.34	0.01	0.004	5.8	1.67	0.01	0.002
Yazd	2.1	0.94	−0.62	−0.010	1.0	0.47	−0.62	−0.005
Zabol	1.9	0.98	0.52	0.007	1.0	0.49	0.52	0.003
Zahedan	2.8	1.46	−1.09	−0.021	1.4	0.73	−1.09	−0.011
Zanjan	14.7	3.86	−1.67 (−1.71)	−0.093	7.4	1.96	−1.67 (−1.57)	−0.043

- Bold values indicate significant trends at the 95% confidence level.

southeastern Iran were seen to have the relative changes higher than 30%. Soltani et al. (2012) reported a significant negative trend of precipitation at Oroomieh station. Delju et al. (2013) showed that the combined effect of decreased precipitation and increased temperatures enhanced evaporation in the region and led to dry conditions in the Urmia Lake Basin in the northwest of Iran.

The significant increase of aridity was observed mainly in the semi-arid west and northwest regions of Iran. With increasing aridity in the regions, the water deficiency increases significantly which impacts on agriculture as the largest water user. Generally, arid and semi-arid regions are more sensitive to variability and availability of water resource when compared to humid regions (Zhang et al., 2010). Furthermore, the impacts of changes in aridity can alter the extent and seriousness of desertification.

Graphs of the cumulative sum test were used to determine the position of change points in the I_{DM} and I_P series with significant trends (Figs. 5 and 6). In this test, the position of the maximum $|S_k^*|$ can be taken as an estimate for the change point. Graphs of the cumulative sum test for the I_{DM} series at Kermanshah, Sanandaj, Tabriz and Gorgan stations show that $|S_k^*|$ reaches its maximum value in 1969 (Fig. 5). So, a change point in the I_{DM} series of the above four stations occurred in 1969. Khoy station shows a change point year in the I_{DM} series near 1982. Furthermore, there was a change point around 1994 in the I_{DM} series of Oroomieh station. According to the graphs of the cumulative sum test (Fig. 6), the I_P series of Kermanshah, Sanandaj, Tabriz and Gorgan stations experienced a change point year near 1969. The change point years in the I_P series of Khoy and Oroomieh stations were 1982 and 1994, respectively. The change point years obtained for the I_P series are consistent with those found for the I_{DM} series. Shifteh Some'e et al. (2012) found that the change points of annual precipitation at Khoy and Oroomieh stations were 1982 and 1994, respectively.

4. Conclusions

Annual de Martonne and Pinna aridity indices series of Iran were investigated with respect to spatial and temporal variations for the period 1966–2005. Around 96% of the country's areas are classified as dry or semi-dry based on the Pinna index, whereas the arid and semi-arid regions cover around 88% of Iran according to the de Martonne index. The trend analysis showed that around 63% of the stations were characterized by a decreasing aridity index trend. The significant decreasing trends of the aridity indices were observed mostly in the western and northwestern regions of Iran. The relative changes of the aridity indices at the stations with significant decreasing trends varied between 18% and 54% over the period 1966–2005. According to the results of the cumulative sum test, there was a change point around 1969 at the majority of the stations with significant jumps of the aridity indices.

Declining the quality and quantity of water resources represents a severely limiting factor for agriculture in Iran. These factors together with the increasing aridity can have adverse effaces on crop production in the country. Hence, the results of this study are of great importance for evaluating water deficit and water resources on local and regional scales in order to predict practical measures to control aridity in vulnerable areas.

Acknowledgments

The authors wish to express a gratitude to the Islamic Republic of Iran Meteorological Organization (IRIMO) for providing access to the weather station data. We greatly appreciate the constructive comments and thoughtful suggestions for improving the manuscript given by the reviewers and Professor Norm Catto (editor-in-chief).

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Please cite this article in press as: Tabari, H., et al., A survey of temperature and precipitation based aridity indices in Iran, Quaternary International (2014), http://dx.doi.org/10.1016/j.quaint.2014.03.061

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