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Assessment of short- and long-term memory in trends of major climatic variables over Iran: 1966-2015

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Abstract

In arid and semi-arid regions, water scarcity is the crucial issue for crop production. Identifying the spatial and temporal trends in aridity, especially during the crop growing season, is important for farmers to manage their agricultural practices. This will become especially relevant when considering climate change projections. To reliably determine the actual trends, the influence of short- and long-term memory should be removed from the trend analysis. The objective of this study is to investigate the effect of short- and long-term memory on estimates of trends in two aridity indicators – the inverted De Martonne (ϕ_{IDM}) and Budyko (ϕ_B) indices. The analysis is done using precipitation and temperature data over Iran for a 50-year period (1966-2015) at three temporal scales: annual, wheat growing season (Oct-Jun), and maize growing season (May-Nov). For this purpose, the original and the modified Mann-Kendall tests (i.e. modified by three methods of trend free pre-whitening (TFPT), effective sample size (ESS) and long-term persistence (LTP)) are used to investigate the temporal trends in aridity indices, precipitation and temperature by taking into account the effect of short- and long-term memory. Precipitation and temperature data were provided by the Islamic Republic of Iran Meteorological Organization (IRIMO). The temporal trend analysis showed that aridity increased from 1966 to 2015 at the annual and wheat growing season scales, which is due to a decreasing trend in precipitation and an increasing trend in mean temperature at these two time scales. The trend in aridity indices was decreasing in the maize growing season, since precipitation has an increasing trend for most parts of Iran in that season. The increasing trend in aridity indices is significant in Western Iran, which can be related to the significantly more negative trend in precipitation in the west. This increasing trend in aridity could result in an increasing crop water requirement and a significant reduction in the crop production and water use efficiency. Furthermore, the modified Mann-Kendall tests indicated that unlike temperature series, precipitation, ϕ_{IDM} and ϕ_B series are not affected by short- and long-term memory. Our results can help decision makers and water resources managers to adopt appropriate policy strategies for sustainable development in the field of irrigated agriculture and water resources management.

Keywords: Inverted De Martonne, Budyko, Mann-Kendall, serial correlation, Hurst exponent.

Introduction

Global warming has significant effects on the hydrology cycle, water resources and therefore the availability of water for crop growth. From 1880 to 2012, the average land and ocean surface temperature increased by 0.83°C (0.65-1.06 °C) globally (IPCC 2013). It was found that the rate of warming in some drylands of the world, including southwest Asia, is slightly higher than in other drylands (Hulme 1996). Arid and semi-arid regions, which are mostly located in developing countries, cover approximately 40% of the world (Aydin 1995; Bannayan et al. 2010). According to the UNFCCC (UNFCCC 2007), precipitation (for three projected periods of 2030, 2050 and 2100) will probably decrease under climate change in arid and semi-arid regions, leading to degradation of agricultural lands and affecting food security. As a consequence of this decreasing precipitation, the frequency and severity of droughts will increase in more arid areas (Heathcote 1983). Hence, adaptation and mitigation strategies for dryness and aridity are very important in different sectors, including agriculture, which seem to have received most severe damages due to drought. Therefore, the frequent occurrence of drought has become such a critical issue for researchers to be concerned about.

Although temperature and precipitation are common parameters for climate change studies, significance of climate change on bioclimatic or water supply fields can be better expressed by aridity or humidity indices (Kharel Kafle and Hendrik 2009). Aridity indices are calculated based on different climatic parameters. Some aridity indices use only precipitation (e.g., SPI: Mckee et al. 1993, 1995), others use temperature and precipitation (e.g., De Martonne aridity index: De Martonne 1925), whereas precipitation and evaporation are used in the UNEP index (UNEP 1992) and Budyko index (Budyko 1974).

In this study, we focus on arid and semi-arid regions, since those areas are especially vulnerable to climate change. Generally, arid and semi-arid conditions are formed as a result of dry and descending air and are found in regions with anticyclonic conditions such as Iran (Shifteh Some'e et al. 2012). Seventy five percent of Iran's area is located in arid and semi-arid regions (Ahmadi 2008) and it makes Iran one of the most arid countries in the world. The climate of Iran is highly variable in space and time (Bannayan and Sanjani 2011; Sanjani et al. 2011) as the coefficient of variation for annual rainfall is about 70% (Nazemosadat and Cordery 2000), meaning that annual rainfall (average 250 mm year^{-1} (Eyshi Rezaie and Bannayan 2012)) can vary between almost zero (southern and eastern parts and central desert) to 2000 mm year^{-1} (Caspian Sea coastal areas) (Ashraf et al. 2013). These conditions would result in high risk of droughts in Iran (Bannayan et al., 2010; Sayari et al., 2013). By analyzing trends in these spatial and temporal variabilities, water resources managers can gain knowledge for making appropriate decisions on sustainable development and water resources management.

A number of researchers (Croitoru et al. 2013; Moral et al. 2016; Muhire and Ahmed 2016; Rai et al. 2010; Shifteh Some'e et al. 2012; Tabari and Aghajanloo 2013; Türkes 2003; Zhang et al. 2009) have studied the trend in aridity indices all over the world. For example, Croitoru et al. (2013) found a mostly statistically insignificant negative trend in the De Martonne aridity index and statistically insignificant positive trend in the Pinna Combinative index. Furtheremore, Moral et al. (2016) found an apparently increase in aridity index (decrease in De Martonne aridity index) during the study period, mostly in the more humid regions.

Temporal trends in precipitation and temperature were also analyzed by several Iranian researchers. For example, Tabari and Hosseinzadeh Talaee (2011b) showed that there was a decreasing trend in annual precipitation in Iran during 1966–2005 with a significant negative trend in the northwest region. Ghahraman & Taghvaeian (2008) reported that among 30 stations, 7 and 6 stations showed a significant negative and positive trend in precipitation, respectively, for the entire record length of 1951-2000 (50 years). Furthermore, Tabari and Hosseinzadeh Talaee (2011a) found a significant positive trend in maximum and minimum temperature in some arid and semi-arid regions of Iran during the last decades. They showed that this positive trend was more pronounced in summer and winter than in autumn and spring. Shabani et al. (2013) used the SARIMA model and showed that maximum and minimum temperature for a future period of 2009-2018 would increase by 1 °C and 2 °C, respectively in comparison to base period (1987-2008). Ghahraman (2006) reported that at 50% of the synoptic stations in Iran, there are significant positive trends in annual temperature. He showed a higher mean temperature during the years 1999-2002 in comparison to that for the period 1968-1998.

In none of these studies on trend analysis carried out in Iran, the trend in precipitation, temperature and aridity index has been conducted simultaneously. Such a simultaneous analysis is important because, as the time duration of the series changes, the results of temporal trend may change (e.g., Ghahraman (2006)). Therefore, a thorough analysis needs a pre-definition of this time span which is constant for all variables under study.

Moreover, a trend analysis of the aridity indices in the growing seasons has not been investigated in the previous studies in Iran. As stated by Mekonnen and Hoekstra (2016), the current freshwater resources are enough to meet the water demand at the annual and global scale, but the large spatial and temporal variations of water demand and availability can lead to water scarcity in several parts of the world when look at smaller temporal scales. Therefore, it is important to investigate the aridity at different time scales, especially for the growing seasons. Furthermore, the effect of long term memory has not been investigated for precipitation, temperature and these aridity indices over Iran. Only the temporal trend in precipitation, temperature and runoff was investigated by Fathian et al. (2014) in Urmia Lake basin and the temporal trend in precipitation was investigated by Dinpashoh et al. (2014) in the northwest of Iran, using the original and the modified Mann-Kendall test.

The main objective of this study is to investigate the effect of short- and long-term memory on trend analysis of aridity indices over Iran using the inverted De Martonne aridity index and Budyko aridity index, as well as precipitation and mean temperature. Since both maize and wheat are the most important cereal crops in Iran, the aridity was analysed during the growing seasons of these two main crops, and during the annual time scale.

Study area

Iran (Fig. 1) has an arid and semi-arid climate, and covers an area of 1,648,000 km^2 and is located in southwest of Asia (between 25° 3′ and 39° 47′ N and 44° 5′ and 63° 18′ E). Because of location of the Caspian Sea, Persian Gulf and Oman Sea as well as the mountain regions Albors and Zagros, the temporal and spatial characteristics of climate in Iran is highly variable with intense temperature gradients (Sanjani et al. 2011). Mean annual precipitation ranges from zero in the southern and eastern parts of Iran, to 2000 mm year^{-1} in the Caspian Sea coastal areas. Mean annual precipitation averaged over the entire country is about 250 mm year^{-1} and mean annual temperature ranges from 10°C (in the west) to 35°C (in the center). There is no general prevailing climatic season in Iran. Koppen climate classification shows that the south, east and center of Iran experience desert climate and semi-arid climate. The west and northwest of Iran have a hot or warm dry-summer continental climate and the coastal regions in the north of Iran have a Mediterranean climate.

Data and methods

Meteorological data

In this study, quality-controlled daily Meteorological data (precipitation and minimum and maximum temperature) of 37 synoptic stations in Iran for a 50-year period from 1966 to 2015 were used. The location of the selected stations is shown in Fig. 1.

Fig. 1 about here

Aridity indices

The degree of dryness in a given region can be described by some numerical indicators named aridity indices, which can classify the climate according to water availability and demand. In this study, inverted De Martonne (hereafter ϕ_{IDM}) and Budyko (hereafter ϕ_B) aridity indices are chosen to analyze the spatial and temporal distribution of aridity over Iran. Since crop production and yields are very sensitive to changes in climatic parameters such as temperature, precipitation and evaporation, the two mentioned aridity indices which only use these climatic parameters were chosen.

Inverted De Martonne aridity index (ϕ_{IDM})

de Martonne (1925) developed an aridity index as follows:

$$\phi_{DMa} = \frac{P}{T+10} \quad (1)$$

in which ϕ_{DMa} is the De Martonne aridity index at the annual time scale, P is the mean annual precipitation (mm/year) and T is the mean annual air temperature (°C). Since the aridity index distribution is a crucial factor for agricultural management, the spatiotemporal variations of the aridity indices for the growing seasons of winter wheat (Oct-Jun) and maize (May-Nov) were analyzed. Although the growing periods for winter wheat and maize are different in different parts of Iran, but to have a homogeneous results, a similar period for each crop was chosen, as conducted by Croitoru et al. (2013) in Romania. Based on the growing season length, Croitoru et al. (2013) developed the equations (2) and (3) for maize and winter wheat, which are the main cereal crops in Romania, respectively.

$$\phi_{DMgsMaize} = \frac{1.714P_{gsMaize}}{T_{gsMaize} + 10} \quad (2)$$

$$\phi_{DMgsWinterWheat} = \frac{1.333P_{gsWinterWheat}}{T_{gsWinterWheat} + 10} \quad (3)$$

in which, $P_{gsMaize}$ and $P_{gsWinterWHeat}$ are the total amount of precipitation (mm per unit of time) of the growing season of maize and winter wheat, respectively. $T_{gsMaize}$ and $T_{gsWinterWheat}$ are the mean air temperature (°C) of the maize (7 months) and winter wheat (9 months) growing season, respectively.

In this study, these three equations were used to calculate the aridity index for the annual scales and growing season of Maize and wheat in Iran. Furthermore, The De Martonne aridity index was inverted to make our results on the trend more logical: an increase in the index (a positive trend) indicates an increase in aridity. A 9-month period (Oct-Jun) for winter wheat and a 7-month period (May-Nov) for maize were considered. These periods are chosen based on average length of growing season for wheat and maize in Iran. The climate type of a given region based on ϕ_{IDM} has been shown in Table 1.

Table 1 about here

Budyko aridity index (ϕ_B)

Budyko (1974) defined the aridity index as the ratio of mean annual potential evaporation (E_P) to mean annual precipitation (P), both in millimeter per unit of time:

$$\emptyset_B = \frac{E_P}{P} \quad (4)$$

Since UNEP aridity index is defined as the ratio of mean annual precipitation (P) to mean annual potential evaporation (E_P) and it is an inversion of ϕ_B, so in this study, the classification criteria of UNEP aridity index was inversed to show the classification criteria of Budyko aridity index (Table 2).

Afterwards, reference evaporation is calculated by Hargreaves equation (equation 5) (Hargreaves and Samani 1985).

$$E_P = 0.0135\,(K_T)(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a \quad (5)$$

where E_P is reference evapotranspiration (mm day^{-1}), T_{mean}, T_{max} and T_{min} are mean, maximum and minimum temperature (°C), R_a is extraterrestrial radiation (mm day^{-1}) (Allen et al. 1998) and K_T is calculated as follows (Knapp et al. 1980):

$$K_T = 0.00185(T_{max} - T_{min})^2 - 0.0433(T_{max} - T_{min}) + 0.4023 \quad (6)$$

Table 2 about here

Trend analysis

The non-parametric Mann‑Kendall test (Mann 1945; Kendall 1975) is one of the most common methods for detecting trends in hydroclimatic variables. Mann-Kendall is a distribution-free test, frequently used for trend analysis of the hydroclimatological variables with non-normal distribution. In this study, the Mann-Kendall test was used to detect the temporal trends in precipitation, mean temperature, ϕ_{IDM} and ϕ_B.

While the original Mann-Kendall test assumes that the series are independent with no serial correlation between the observations (Zhao et al. 2010), sometimes the series are autocorrelated and therefore, the null hypothesis of no trend may be rejected, while it is actually true. In these cases, the serial correlation must be removed. Analogously, the long term persistence might influence the trends in the series. Therefore, the significance of the trends can be reduced (Hamed 2008) by considering the Hurst exponent (Hurst 1951).

Original Mann-Kendall test

The original Mann-Kendall test (hearafter MK_O) is defined as follows:

$$z_{MK_O} = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{var}(S)}} & if\ S < 0 \end{cases} \quad (7)$$

where

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sign}(x_j - x_k) \quad (8)$$

$$\mathrm{var}(S) = \frac{[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)]}{18} \quad (9)$$

in which n is the number of data points, t_i is the number of ties for the i-th value, m is the number of tied groups and x_j and x_k are the sequential data values. The positive value of z_{MK} shows an increasing trend and a negative value shows a decreasing trend.

Modified Mann-Kendall test using trend free pre-whitening (TFPT) method

The MK_O test is applied for those time series which are serially independent. For time series with the serial correlation, the hypothesis of no trend will possibly rejected, while it is true (Yue and Hashino 2003). To relax the influence of lag-1 serial correlation, the method of pre-whitening approach of von Storch (1995) was used. At the first step, the data is detrended by using the Theil-Sen's estimator (Theil 1950; Sen 1968) as follows:

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

The detrended series is obtained by equation 11:

$$x_i' = x_i - \beta \times i \quad (11)$$

Then, the lag-1 serial correlation (ρ_1) is calculated by the formula presented by Salas (1980) as used by Kumar et al. (2009) and Yue et al. (2002). If ρ_1 is significant at 10% significace level (Hamed and Rao 1998), then the time series ($\acute{X} = \{\acute{x}_i, i = 1{:}n\}$) will be pre-whitened and will corrected to the new time series ($\acute{Y} = \{\acute{y}_i, i = 1{:}n\}$) as follows:

$$\acute{y}_i = \acute{x}_i - \rho_1 \acute{x}_{i-1} \qquad i = 1{:}n \quad (12)$$

Afterwatrd, the value of $\beta \times i$ will be added again to the series as follows:

$$y_i = \acute{y}_i + \beta \times i \qquad i = 1{:}n \quad (13)$$

After the correction, the MK test is applied for the new time series (hearafter MK_{TFPW}).

Modified Mann-Kendall test using effective sample size (ESS) method

Using the ESS method, the effect of all significant autocorrelation coefficient is removed from the series (Hamed and Rao 1998). For this method, the modified variance of S ($V(S)^*$) is estimated as follows:

$$V(S)^* = V(S)\frac{n}{n^*} \quad (14)$$

where n^* is effective sample size. The ratio of $\frac{n}{n^*}$ is calculated from the following equation (Hamed and Rao 1998):

$$\frac{n}{n^*} = 1 + \frac{2}{n(n-1)(n-2)}\sum_{i=1}^{n-1}(n-i)(n-i-1)(n-i-2)r_i \quad (15)$$

in which n is the number of observations and r_i is lag-i significant autocorrelation coefficient of rank i of the series. Then the Mann-Kendall test is calculated by the $V(S)^*$ (hereafter MK_{ESS}).

Modified Mann-Kendall test for long-term persistence (LTP)

Long-term memory or long-term persistence proposed by Hurst (1951) who investigated the dependence properties of the phenomena such as levels of the Nile river. In this study, the effect of long term persistence was investigated by using Hurst exponent (H). Hurst exponent is between 0 and 1 and H>0.5 (if significant at a given confidence level) shows a relatively long-term dependency. If H<0.5, the series is anti-persistance and H=0.5 shows a random data set. The method of Hamed (2008) was used to estimate Hurst exponent as applied for precipitation (Fathian et al. 2014), temperature (Fathian et al. 2014), runoff (Li et al. 2008; Fathian et al. 2014), streamflow (Kumar et al. 2009; Ghahraman 2013) and aerosol (Nikkath and Selvaraj 2016). Firstly, the series is detrended by using equation 10. The equivalent normal variates (z_i) of the detrended series can then be obtained by equation 16:

$$Z_i = \emptyset^{-1}\left(\frac{R_i}{n+1}\right) \quad (16)$$

in which R_i is the rank of detrended data (x_i') and $\emptyset^{-1}(.)$is the invers standard normal distribution function. The correlation matrix for a given H ($C_n(H)$) is then calculated as follows:

$$C_n(H) = [\rho_{|j-i|}] \qquad i = 1{:}n, j = 1{:}n \quad (17)$$

where ρ_l, the autocorrelation function at lag l, is given by equation 18:

$$\rho_l = \frac{1}{2}(|l+1|^{2H} - 2|l|^{2H} + |l-1|^{2H}) \quad (18)$$

Afterward, H can be obtained by maximizing the log-liklihood function as follows:

$$\log L(H) = -\frac{1}{2}\log|C_n(H)| - \frac{Z^T[C_n(H)]^{-1}Z}{2\gamma_0} \tag{19}$$

with Z^T the transpose vector of Z (equation 16) and γ_0 is the variance of Z_i.

Then, if H is significant at a given confidence level, $\mathrm{var}(S)$ (equation 9) would be calculated as follows (Hamed 2008):

$$\mathrm{var}(S)^H = \sum_{i<j}\sum_{k<l}\frac{2}{\pi}\sin^{-1}\left(\frac{\rho_{jl} - \rho_{il} - \rho_{jk} + \rho_{ik}}{\sqrt{(2-2\rho_{ij})(2-2\rho_{kl})}}\right) \tag{20}$$

Since this estimate of $\mathrm{var}(S)^H$is biased, Hamed (2008) proposed a bias correction factor (B) which is multiplied by $\mathrm{var}(S)^H$ and then the Mann-Kendall test is calculated by the unbiased $\mathrm{var}(S)^H$ instead of $\mathrm{var}(S)$ in equation 9 (hearafter MK_{LTP}).

Results and discussion

Spatiotemporal trend

Figure 2 shows the spatial distribution of ϕ_{IDM}, ϕ_B, precipitation and mean temperature at annual time scale as well as growing season of maize and wheat over Iran (1966-2015). Moreover, this figure shows the trends inthe variables using MK_O.

The spatial distribution of ϕ_{IDM} and ϕ_B at the annual scale (Fig. 2a and 2d) indicates that the driest regions of Iran are located in the south, southeast and center of the country, which are classified as arid for ϕ_{IDM} and semi-arid to hyper-arid for ϕ_B. The regions in the north of Iran (coastal regions) are humid with ϕ_{IDM} values higher than 0.036. These regions have a humid or sub-humid climate based on ϕ_B classification. Except for the coastal region in the north, the other parts have arid conditions during maize growing season (Fig. 2b and 2e). During the wheat growing season the northwest part is mainly classified as humid to very humid (Fig. 2c). Furthermore, the spatial distribution of ϕ_B during wheat growing season (Fig. 2f) shows that most part of the country is under semi-arid to hyper-arid conditions. As shown in Fig. 2g-2i, most of the regions receive precipitation up to 500 mm year^{-1} and the coastal area in the north receive precipitation more than 1000 mm year^{-1}. In winter, as parts of the wheat growing season, because of moist air masses originating from the Mediterranean Sea and approaching from west, the northwest of Iran receive the higher amount of precipitation of the year and therefore these regions are located in the semi-humid to hyper humid climate.

The spatial distribution of mean temperature (Fig. 2j-2l) shows that most regions in Iran experience a mean temperature of higher than 10 °C, while some area in the center and in the south experience a mean temperature between 25 and 35 °C. A low rate of precipitation together with high temperature in most parts of Iran results in the high aridity in the country as shown by ϕ_{IDM} and ϕ_B. The prevailing climatic conditions (a high aridity) affect the crops production. During the warm months the crops encounter water stress and therefore, the farmers need to apply supplementary irrigation to avoid a reduction in crop yield.

Zambakas (1992) indicated that irrigation is needed during the months with ϕ_{DM} lower than 20 ($\phi_{IDM}>0.05$). Paltineanu et al. (2007) found inverse and strong regression relationships between the De Martonne aridity index and the water requirements of some representative crops in Romania. Therefore, more water as supplemental irrigation (mostly from groundwater withdrawal) is needed for the crops for the southeast of Iran during the wheat growing season and in all parts of the country during the maize growing season.

In general, the spatial distribution of ϕ_B is a little different from that of ϕ_{IDM}. This discrepancy is more pronounced for the wheat growing season in which the humid regions for ϕ_B are smaller than those for ϕ_{IDM}. Since ϕ_{IDM} includes more classification classes, it could distinguish the differences between classes better than ϕ_B especially in rainy seasons. Analogously, Baltas (2007) showed that in comparison to the Pinna Combinative index, de Martonne aridity index was more precise because of having more climate categories.

According to MK_O, the annual trends in ϕ_{IDM} were positive at the 90% confidence level at 14 out of 37 stations (38%). These stations were mostly located in the west of Iran. These results are in agreement with results reported by Tabari et al. (2014) for De Martonne aridity index. Significant positive trends in these stations may be associated with a significant decrease in precipitation (Fig. 2g) and significant increasing trends in air temperature (Fig. 2j). Tabari & Hosseinzadeh Talaee (2011b) showed that annual precipitation has significant negative trends in the northwest of Iran for the period of 1966-2005. Decreasing precipitation and increasing temperatures in the Lake Urmia basin in the northwest of Iran, resulted, for example, in high evaporation rates and dry conditions in this part of the country (Delju et al., 2013) and drying of Lake Urmia. At 23 out of 37 stations (62%), there are statistically insignificant trends (both negative and positive) at the annual scale (Fig. 2a). Increasing aridity intensifies the water deficiency, which has a significant impact on agricultural productions. As arid and semi-arid regions are very sensitive to water resources availability compared to humid regions (Zhang et al. 2010), the aridity would change the extent and severity of desertification (Tabari et al., 2014). The positive trends either significant or insignificant lead to reducing likelihood opportunities for agricultural, especially rainfed, productions. In this case, applying irrigation would be necessary.

For the maize growing season (Fig. 2b), all stations except Gorgan, experience no significant trend in ϕ_{IDM}. Since temperature shows an upward trend (Fig. 2k), the downward trend of ϕ_{IDM} is mostly related to the upward trend in precipitation in the maize growing season (Fig. 2h). During the winter wheat growing season, 17 stations (46%), which are mostly located in the west, have a significant upward trend (Fig. 2c). During the wheat growing season, the trends of precipitation and mean temperature in the west are negative (Fig. 2i) and positive (Fig. 2l), respectively. In spite of significant increasing trends in temperature, the majority of the stations have insignificant decreasing trends in precipitation and increasing trends in ϕ_{IDM}.

The trend analysis of annual ϕ_B shows that 11 stations (30%) experience significant upward trends, which means that the aridity increased (Fig. 2d). In general, at the annual scale, ϕ_B has a positive trend in the west, which may be associated to the negative trends in precipitation.

During the maize growing season there is a significant positive trend at the 90% confidence level at Gorgan station and a significant negative trend at Mashhad and Torbat-e Heydarieh (Fig. 2e). This significant positive trend in the aridity index at Gorgan is associated to the significant negative trend in precipitation and the significant positive trend in mean temperature. The wheat growing season ϕ_B series demonstrate that there are significant increasing trends at the 90% confidence level at the stations located in the west (Fig. 2f). The discrepancy of precipitation and aridity trends between maize and wheat growing season could be due to the low rate of precipitation (mostly zero) in summer in comparison to winter and spring.

Overall, it can be stated that for all time scales the aridity increased significantly in the northwest of Iran. Tabari & Aghajanloo (2013) showed that the north and northwest of Iran have become more arid during 1966-2005. They found that the increased aridity in this area was a result of the downward trends in precipitation and the upward trends in evapotranspiration. Our results for the period of 1966-2015 showed that the increased aridity was due to the downward trends in precipitation together with the upward trends in temperature. An increase in aridity has severe consequences for water scarcity and could make the crops –

especially rainfed crops- vulnerable and exposed to risk, especially during the growing season. The upward trends in the aridity indices in these regions may increase the water demand of crops, influence food production, and agricultural economy of the country (Tabari et al., 2011a). In the maize growing season, increasing precipitation and decreasing aridity at most stations would decrease the water demand of maize.

The other important point which should be noticed is the significant negative trend in temperature at Shahr-e Kord station, while the other stations, especially Isfahan which is its adjacent station, show significant upward trends at the 90% confidence level. Turkes & Sumer (2004) mentioned that this inverse trend for adjacent stations can be a result of some factors and spatial conditions. Tabari & Hosseinzadeh Talaee (2011a) showed that the inverse trend in T_{max} between Mashhad and Torbat-e Heydarieh during 1966-2005 (which is not the case during 1966-2015) can be explained by different microclimate, air quality, and urbanization characteristics. Generally, they showed that external factors rather than local factors may be the reason for the changes in temperature.

Hence our results are generally in agreement with other studies (Tabari et al. (2014), Tabari & Hosseinzadeh Talaee (2011b) and Tabari et al. (2011b)), but sometimes slightly differ (Table 3). One reason may be the different length of the series, as this study was focused on a period of 50 years from 1966 to 2015, while the others used shorter time scales. The results of Ghahraman and Taghvaeian (2008) in Iran, showed that the record length of the series could have some effects on the trend in mean annual precipitation. Tabari and Hosseinzadeh Talaee (2011b) mentioned that some large scale phenomena such as ENSO have significant effect on the precipitation variability in Iran and sea surface temperature affect precipitation variability in the costal regions, significantly. As they suggested, their results can be a part of a climate cycle which may have a frequency shorter than 40 years. Therefore, it is important to know that if the trend is related to a long term procces or related to a multidecadal natural oscillation. For this reason, Tabari and Hosseinzadeh Talaee (2011b) suggested that their results would be interesting to be compared to other tests of the trend analysis by future studies.

Table 3 about here

Figure 2 about here

Short term and long term memory

As mentioned in the introduction section, the series may be under influence of serial correlation or long term persistence which can lead to a rejected null hypothesis (e.g., no trend), while it is actually true. In these cases, the serial correlation and long term persistence must be removed from the data. Figures 3 and 4 demonstrate the magnitude and the significancy of the lag-1 serial correlation (ρ_1) and Hurst exponent (*H*) at 95% confidence level for the aridity indices as well as the precipitation and mean temperature. Figures 3a-3f show that lag-1 serial correlation of the aridity indices is only significant for Iranshahr at the annual scale. Furthermore, Figures 4a-4c show that the Hurst exponent is significant for Iranshahr, Zahedan and Sanandaj stations at the annual scale of ϕ_{IDM}. The Hurst exponent of ϕ_B series (Fig. 4d-4f) is significant for Iranshahr and Sanandaj at the annual scale and for Sanandaj in the maize growing season.

Figures 3g-3i show that lag-1 serial correlation of precipitation is only significant at the annual scale for Iranshahr station. The Hurst exponent is only significant at the annual scale for Iranshahr station as well as for Zahedan, Gorgan and Sanandaj. Figures 3j-3l indicate that 16 stations (43%) at the annual scale, 14 stations (38%) in the maize growing season and 9 stations (24%) in the wheat growing season show a significant lag-1 serial correlation. These stations are mostly located in the west. Figures 4j-4l indicate that 19 (51%), 17 (46%) and 16 (43) stations show a significant Hurst exponent at the annual scale, maize growing season and wheat growing season, respectively.

Table 4 summarizes the results of the MK_O, MK_{TFPW}, MK_{ESS} and MK_{MTP}. It shows the number (and percentage) of stations with significant positive or negative trends at the 90% confidence level by using MK_O, MK_{TFPW}, MK_{ESS} and MK_{MTP}. As shown in Table 4, according to MK_O, the trend in ϕ_{IDM} is increasing at 14 (38%), 1 (3%) and 17 (46%) station(s) for the annual, maize and wheat series, respectively. The ϕ_B series show a significant positive trend at 11 (30%), 1 (3%) and 12 (32%) station(s) for the annual, maize and wheat series, respectively. The negative trend was only observed at 2 (5%) stations (Mashhad and Torbat-e Heydarieh) for the maize growing season series.

Table 4 indicates that 11 out of 37 stations (30%) show negative trends in annual precipitation series and no station shows a positive trend. Precipitation series for the growing season of maize and wheat show a negative trend for one (3%) and 12 (32%) station(s), respectively. Both series do not show any positive trend. Our results for the period of 1966-2015 show that the precipitation series at the annual and both growing seasons is not autocorrelated except for Iranshahr (see Fig. 3g-3i) and do not have any long term persistence except for Gorgan, Sanandaj, Zahedan and Iranshahr (see Fig. 4g-4i). Therefore, the results of MK_O, MK_{TFPW}, MK_{ESS} and MK_{LTP} are the same for precipitation. Considering the influence of lag-1 serial correlation on MK test, Tabari et al. (2011b) showed that the variations of precipitation series were not the same at 13 stations in the west, south, and southwest of Iran for the period of 1966-2005. Like precipitation, the results of MK_O, MK_{TFPW}, MK_{ESS} and MK_{LTP} are the same for both aridity indices, except for the wheat growing season series of ϕ_{IDM} at Zahedan. The Autocorrelation Function (ACF) graph of ϕ_{IDM} at Zahedan (Fig. 5) shows that the lag-1 serial correlation was not significant, while lag-2 serial correlation was significant. At this station the trend in ϕ_{IDM} was significant for MK_O, MK_{TFPW} and MK_{LTP}, but insignificant for MK_{ESS}. Fathian et al. (2014) concluded that the consideration of only lag-1 serial correlation may be not sufficient for removing the effect of all significant serial correlation of the series. Moreover, they suggested that the data might be periodic or pseudo-periodic, which need more especial analysis, which is not in the scope of the current study.

Trend analysis of mean temperature shows that 30 (82%), 27 (73%) and 28 (76%) out of 37 stations show a significant positive trend in annual, maize and wheat series, respectively. The significant negative trends are observed at 1 (3%), 2 (5%) and 1 (3%) station(s) for annual, maize growing season and wheat growing season series, respectively. Unlike precipitation, temperature has been influenced by both serial correlation and long term persistence as seen in Table 4. For example, at the annual scale, MK_O and MK_{TFPW} show that 30 (82%) stations have a siginificant positive trend, but MK_{ESS} and MK_{LTP}, 29 (78%) and 21 (57%) stations show significant positive trends (see Fig. 6). Using the MK_{TFPW}, the number of significant trends did not change at the annual time scale. Tabari et al. (2011a) showed that, for the period of 1966-2005, the number of significant trends did not change at the annual scale after pre-withening the data. The results of MK_{ESS} show that the trend in mean temperature at Bandar Abbas station at the annual scale was insignificant, while it has a significant trend by MK_O and MK_{TFPW}. During the maize growing season, Saqqez and Urmia showed insignificant mean temperature trends by MK_{ESS}, while they had significant negative and positive trends, respectively. Figure 6 shows the spatial distribution of the mean temperature trend using MK_{ESS} and MK_{LTP}. In comparison to Fig. 2e-2g (MK_O), the number of stations with significant trend in mean temperature reduces up to 25% for all temporal scales. Furthermore, the results show that the mean temperature series was more under influence of long term persistence than serial correlation. This figure shows that the negative significant trends in mean temperature were under influence of Hurst exponent, therefore, after removing the Hurst exponent effect, the trend changed to be insignificant. Koutsoyiannis and Montanari (2007) mentioned that natural variablilty factors such as solar forcing and volcanic activity could be reasons for long term persistence in the hydroclimatic series, but Fathian et al. (2014) suggested that in their study, for Urmia lake basin, human activities may affect the trend behavior. On the other hand, Ghahraman (2013) mentioned that since the majority of the synoptic stations in Iran are located on airports and suburbs, it is hard to relate increasing temperature to climate change and global warming.

Figure 3 about here

Figure 4 about here

Figure 5 about here

Figure 6 about here

Conclusion

In this study spatiotemporal variation of two aridity indices namely inverted De Martonne (ϕ_{IDM}) and Budyko (ϕ_B), as well as precipitation and mean temperature, were investigated at the annual time scale and the growing season of wheat and maize for the period 1966-2015. The results showed that, in general, the entire area of Iran is classified as arid and semi-arid with high temperatures and low precipitation rates except for the coastal area in the north, which has a humid climate. The trends in the ϕ_{IDM} series at the annual scale during 1966-2015 are positive for most stations. At this scale, 95% of the stations (35 out of 37 stations) have positive (both significant and insignificant) trends of increasing aridity. The significant positive trends (38%) are mostly observed in the west of Iran. The trend in the annual ϕ_B is significantly positive in the west. It means that the aridity increased significantly in the west of Iran more than other parts. The significant positive trend in aridity in the west might be accosiated to the significant downward trend in precipitation and significant upward trend in mean temperature in this region. The results demonstrated that precipitation would significantly decrease in the west where the highest rate of precipitation has occurred. On the other hand, mean temperature would increase siginificantly for most stations over the country. Generally, it can be concluded that the aridity indices in humid regions are more sensitive to decreasing precipitation than the arid and semi-arid regions. If this trend continues in these regions the irrigation requirement would increase. By taking short term and long term memory into account, it was found that aridity indices and precipitation are not autocorrelated and there are not any long term percistence in the series, except for ϕ_{IDM} at Zahedan station in the wheat growing season, which was serially correlated. Therefore, the results of MK_O are reliable for precipitation and aridity indices time series. On the other hand, the mean temperature series show a significant lag-1 serial correlation and Hurst exponent for some stations, which means the series are under the influence of the short term and long term memory.

Our results, as a base information, can help researchers for further exploration of the aridity and decision makers and water resources managers to adopt appropriate policy strategies in the case of sustainable development in the field of agriculture and water resources management. The aridity problem in Iran can be managed by redistributing water from wet parts to dry parts, which nowadays is one of the most important issues for the scientists and decision makers in Iran, but it should be evaluated accurately with environmental, economical, social and political considerations.

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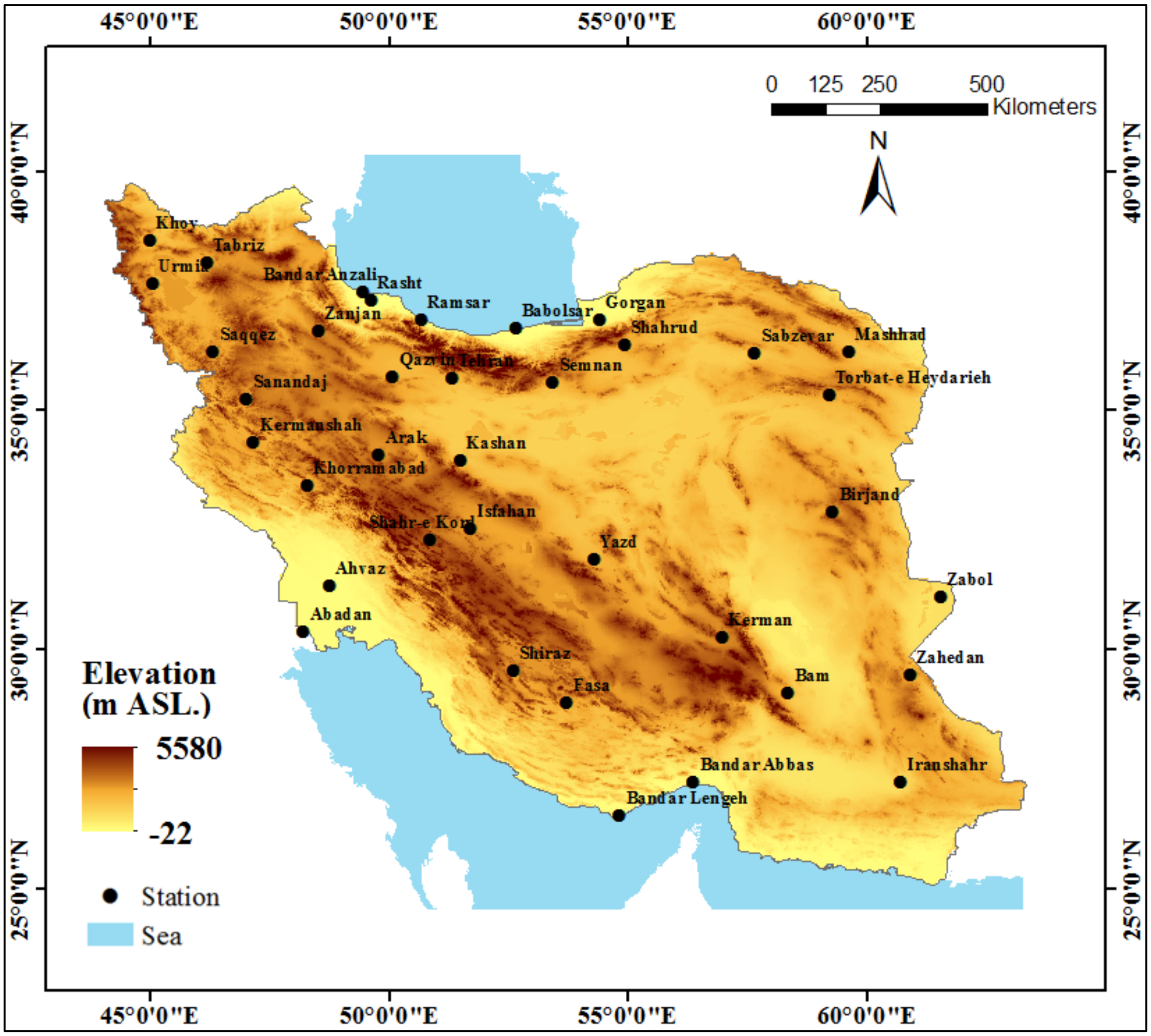

Figure 1- Geographical location of study area and synoptic stations considered.

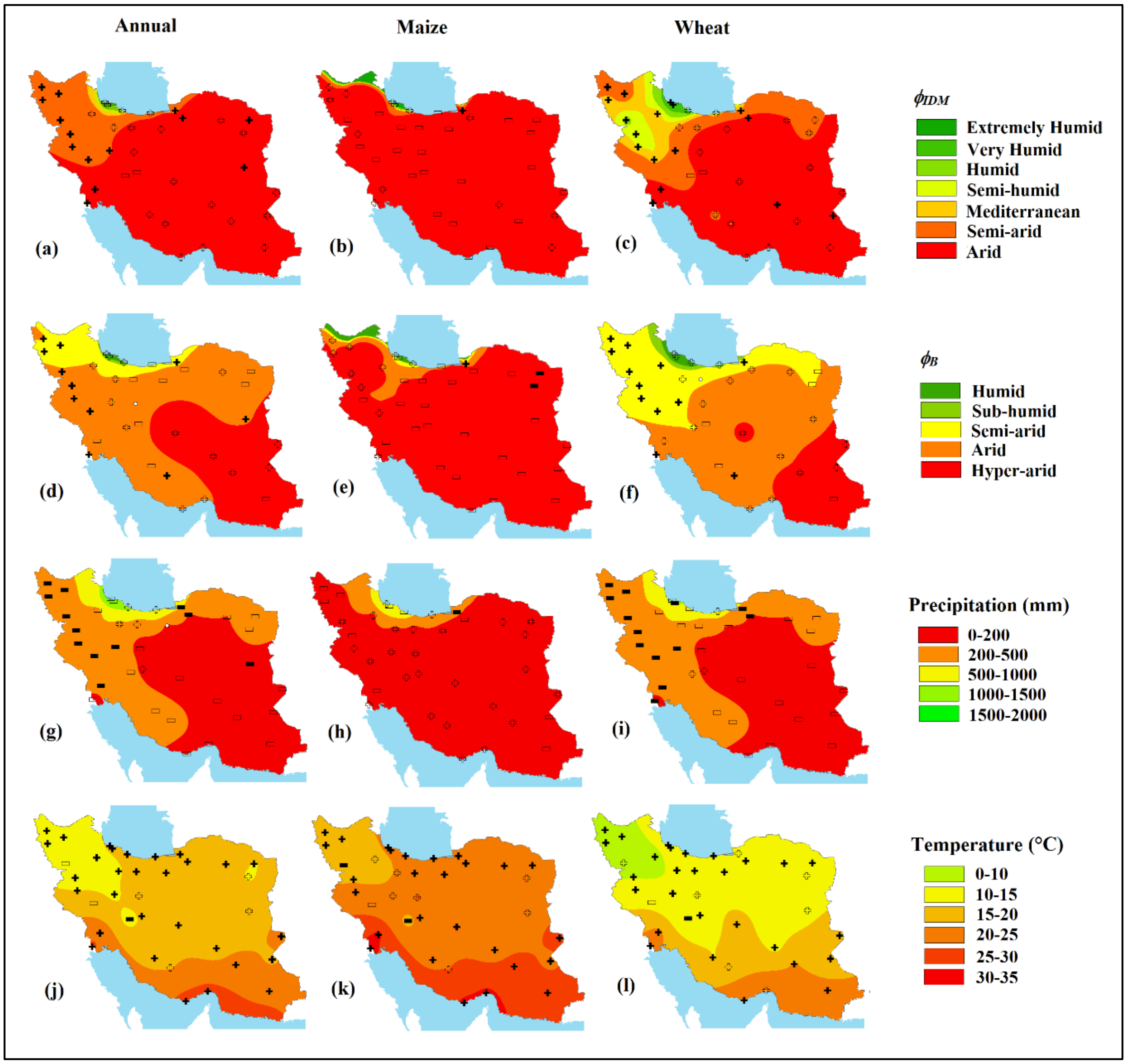

Figure 2- Spatial distribution of ϕ_{IDM}, ϕ_B, mean precipitation and mean temperature over Iran (1966-2015). Plus (+) and minus (-) show the positive and negative trends by MK_O at the 90% confidence level, respectively. Bold plus and minus show the significant trend.

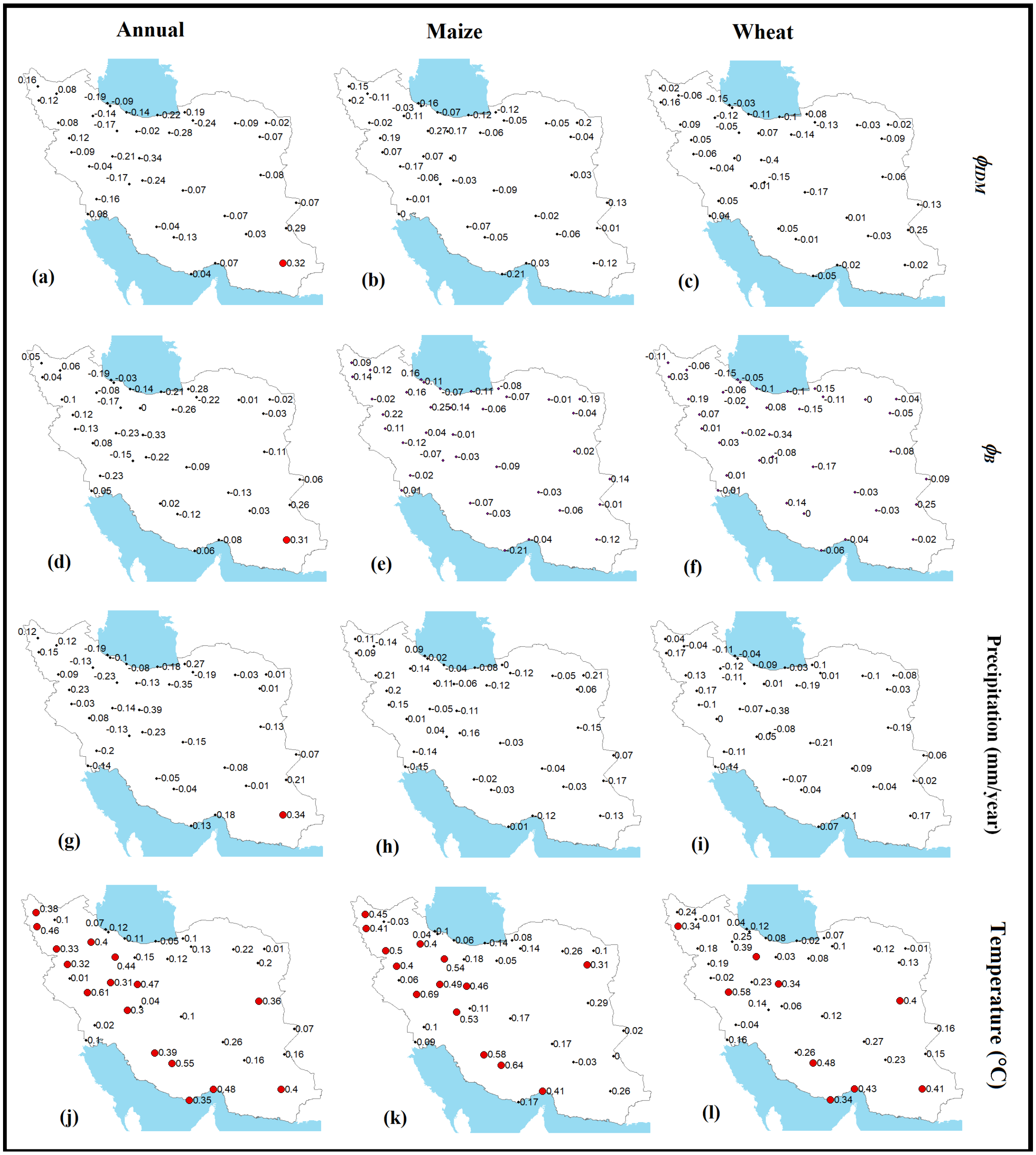

Figure 3- Spatial distribution of lag-1 serial correlation (ρ) of ϕ_{IDM}, ϕ_B, mean precipitation and mean temperature series over Iran (1966-2015). Red circles show the significant lag-1 serial correlation at the 95% confidence level.

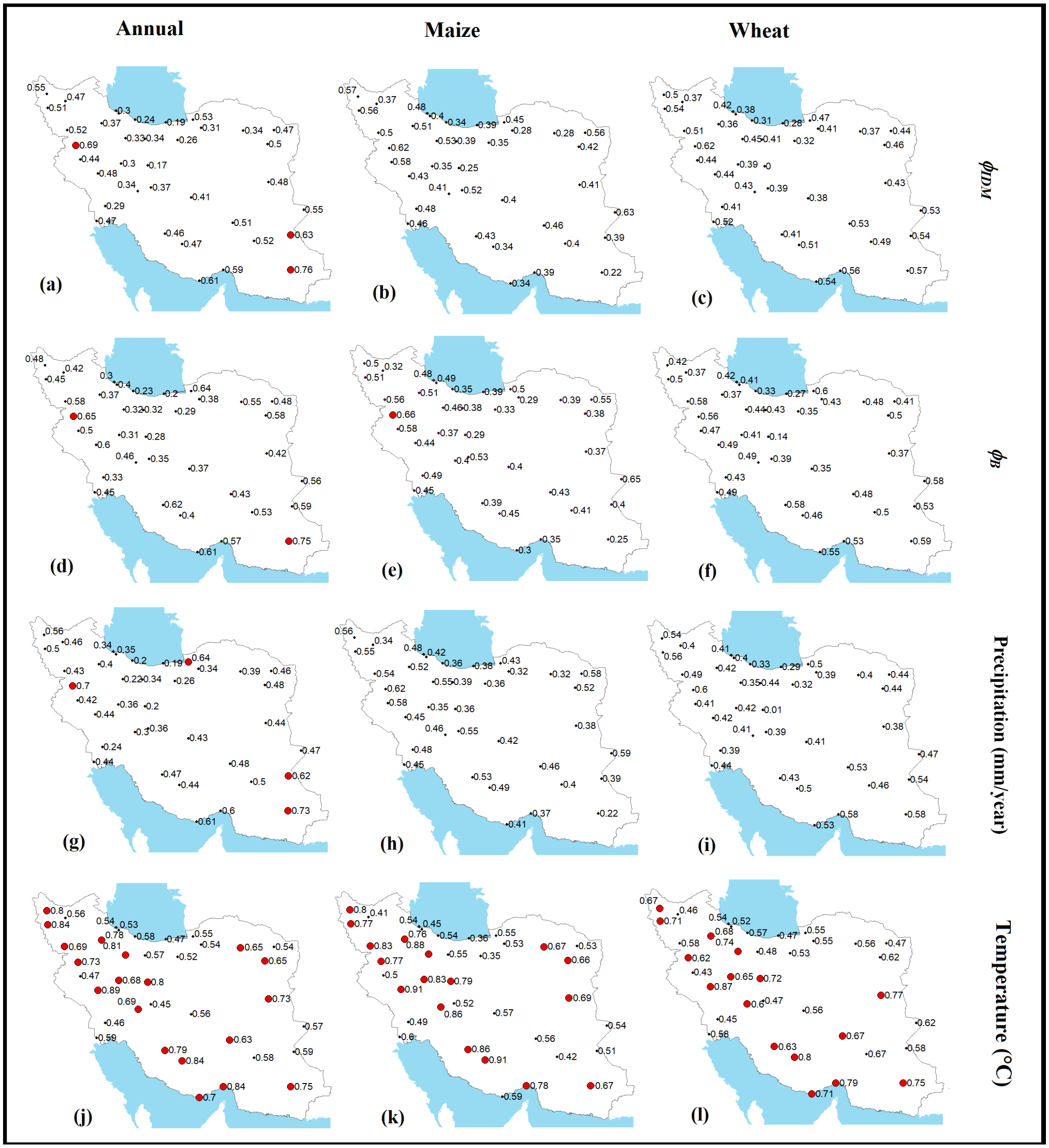

Figure 4- Spatial distribution of Hurst exponent (H) of ϕ_{IDM}, ϕ_B, mean precipitation and mean temperature series over Iran (1966-2015). Red circles show the significant Hurst exponent at the 95% confidence level.

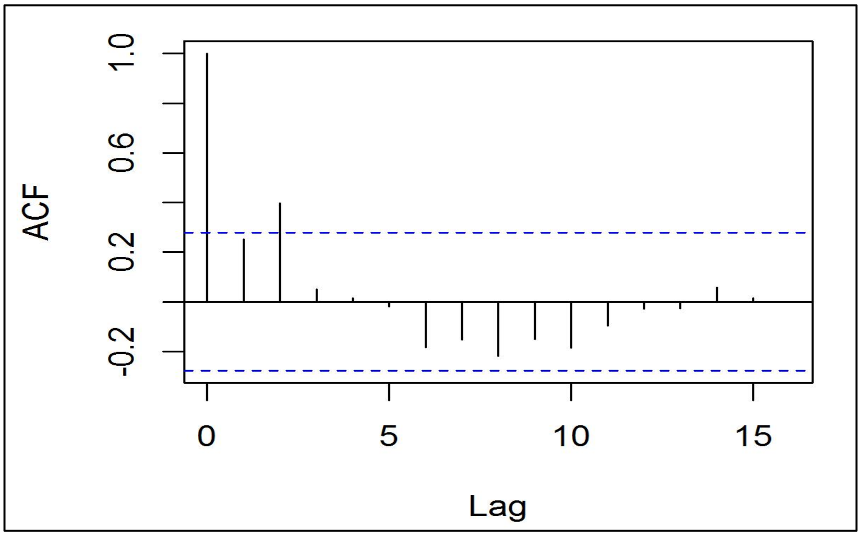

Figure 5- Autocorrelation function for ϕ_{IDM} at wheat growing season at Zahedan station, southeast of Iran.

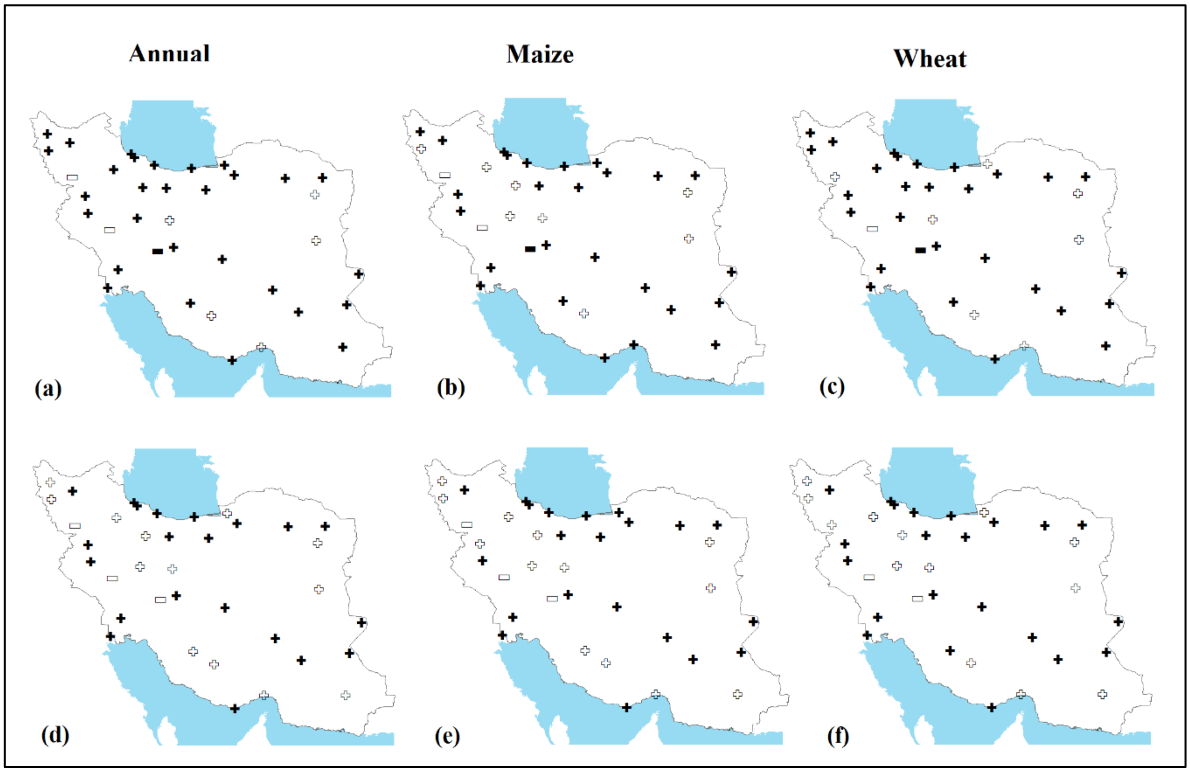

Figure 6- Spatial distribution of mean temperature Mann-Kendall trend modified by effective sample size method (MK_{ESS}) (the top row) and long term persistence method (MK_{LTP}) (the bottom row).

Table 1- Type of climate according to De Martonne (ϕ_{DM}) and inverted De Martonne (ϕ_{IDM}) aridity indices.

Climate type	ϕ_{DM} values [mm y^{-1} Celsius^{-1}]	ϕ_{IDM} values [Celsius mm^{-1} y]
Arid	ϕ_{DM}<10	$\phi_{IDM} \geq 0.1$
Semi-arid	10≤ϕ_{DM}<20	0.05≤ϕ_{IDM}<0.1
Mediterranean	20≤ϕ_{DM}<24	0.042≤ϕ_{IDM}<0.05
Semi-humid	24≤ϕ_{DM}<28	0.036≤ϕ_{IDM}<0.042
Humid	28≤ϕ_{DM}<35	0.028≤ϕ_{IDM}<0.036
Very Humid	35≤ϕ_{DM}≤55	0.018≤ϕ_{IDM}<0.028
Extremely humid	ϕ_{DM}>55	ϕ_{IDM}<0.018

Table 2- Type of climate according to the Budyko aridity index (ϕ_B).

Climate type	ϕ_B values
Hyper-arid	$\phi_B \geq 20$
Arid	$5 \leq \phi_B < 20$
Semi-arid	$2 \leq \phi_B < 5$
Sub-humid	$1.5 \leq \phi_B < 2$
Humid	$\phi_B \leq 1.5$

Table 3- Comparison of the resuts of the current study with the other studies. “D”, “I” and “NT” show the decreasing, increasing and no trend, respectively. Bold letters and the underlined letters indicate the significant trends and the different results among this study and the others, respectively.

Station	Precipitation		Temperature		Aridity	
	This study	Tabari & Hosseinzadeh Talaee (2011b)	This study	Tabari et al. (2011a)	This study	Tabari et al. (2014)
Khoy	**D**	**D**	**I**	**I**	**I**	**I**
Tabriz	**D**	**D**	**I**	**I**	**I**	**I**
Urmia	**D**	**D**	**I**	I	**I**	**I**
Bandar Anzali	D	D	**I**	**I**	I	I
Rasht	D	D	**I**	**I**	I	I
Saqqez	**D**	**D**	D	-	**I**	I
Zanjan	D	**D**	**I**	I	I	I
Qazvin	I	I	**I**	I	I	D
Ramsar	I	D	**I**	**I**	I	I
Babolsar	I	I	**I**	**I**	I	D
Gorgan	**D**	**D**	**I**	I	**I**	**I**
Shahrud	**D**	D	**I**	**I**	**I**	I
Sabzevar	D	D	**I**	**I**	I	I
Mashhad	D	NT	**I**	**I**	**I**	I
Sanandaj	**D**	**D**	**I**	-	**I**	**I**
Tehran	I	I	**I**	**I**	I	D
Semnan	NT	I	**I**	**I**	I	D
Torbat-e Heydarieh	D	I	I	D	I	D
Kermanshah	**D**	**D**	**I**	-	**I**	**I**
Arak	**D**	D	**I**	I	**I**	I
Khorramabad	**D**	**D**	D	-	**I**	I
Kashan	D	D	I	NT	I	I
Shahr-e Kord	D	I	**D**	-	D	D
Isfahan	I	I	**I**	**I**	D	D
Birjand	**D**	D	I	D	**I**	I
Ahvaz	**D**	D	**I**	-	**I**	I
Yazd	D	D	**I**	**I**	I	I
Zabol	D	I	**I**	**I**	I	D
Abadan	D	I	**I**	-	**I**	D
Kerman	D	D	**I**	**I**	I	I
Shiraz	D	I	**I**	-	I	D
Bam	D	D	**I**	**I**	I	I
Zahedan	D	**D**	**I**	**I**	I	I
Fasa	D	I	I	D	I	D
Bandar Abbas	D	I	**I**	-	I	D
Iranshahr	D	D	**I**	I	I	I
Bandar Lengeh	D	I	**I**	-	I	D

Table 4- Number (and percentage in parenthesis) of stations with significant positive and negative trend in ϕ_{IDM} and ϕ_B, precipitation and mean temperature for MK_O, MK_{TFPW}, MK_{ESS} and MK_{LTP}.

Time Scale	ϕ_{IDM}		ϕ_B		*Precipitation*		*Mean temperature*	
	Positive Trend	Negative Trend	Positive Trend	Negative Trend	Positive Trend	Negative Trend	Positive Trend	Negative Trend
MK_O								
Annual	14(38%)	0(0%)	11(30%)	0(0%)	0(0%)	11(30%)	30(82%)	1(3%)
Maize	1(3%)	0(0%)	1(3%)	2(5%)	0(0%)	1(3%)	27(73%)	2(5%)
Wheat	17(46%)	0(0%)	12(32%)	0(0%)	0(0%)	12(32%)	28(76%)	1(3%)
MK_{TFPW}								
Annual	14(38%)	0(0%)	11(30%)	0(0%)	0(0%)	11(30%)	30(82%)	1(3%)
Maize	1(3%)	0(0%)	1(3%)	2(5%)	0(0%)	1(3%)	27(73%)	2(5%)
Wheat	17(46%)	0(0%)	12(32%)	0(0%)	0(0%)	12(32%)	28(76%)	1(3%)
MK_{ESS}								
Annual	14(38%)	0(0%)	11(30%)	0(0%)	0(0%)	11(30%)	29(78%)	1(3%)
Maize	1(3%)	0(0%)	1(3%)	2(5%)	0(0%)	1(3%)	26(70%)	1(3%)
Wheat	16(43%)	0(0%)	12(32%)	0(0%)	0(0%)	12(32%)	28(76%)	1(3%)
MK_{LTP}								
Annual	14(38%)	0(0%)	11(30%)	0(0%)	0(0%)	11(30%)	21(57%)	0(0%)
Maize	1(3%)	0(0%)	1(3%)	2(5%)	0(0%)	1(3%)	21(57%)	0(0%)
Wheat	17(46%)	0(0%)	12(32%)	0(0%)	0(0%)	12(32%)	22(59%)	0(0%)