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Links between Arctic Oscillation (AO) and inter-annual variability of Iranian evapotranspiration

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ABSTRACT

Understanding the responding mechanism of reference evapotranspiration (ET_o) to large-scale atmospheric circulation patterns is of particular concern in arid and semi-arid environments, where water resources scarcity constrains agriculture. This study investigates the statistical relationships between the Arctic Oscillation (AO) and the annual and seasonal mean ET_o values of 41 weather stations in Iran for 1966–2005. The connections between the AO index and annual ET_o are also examined during the extreme phases of the AO (high and low phases). Significant correlations between annual ET_o and the corresponding AO index are quite rare, and the differences between the ET_o values during the extreme AO phases and the long-term average ET_o values were found to be significant only at three out of the 41 study stations. The lag correlations indicated that the greatest positive (0.506) and negative (−0.466) correlation coefficients were found for 2-season time lag. Furthermore, the mean time lag between the start of the AO events and the observed maximum effects on ET_o at the study stations was about 1.61 seasons or 5 months.

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1. Introduction

In recent years, the decrease of water availability in arid and semi-arid regions such as Iran has become a principal environmental problem which could severely restrict agricultural development. Low water availability happens where there are insufficient water resources to meet the demands for water. Under water scarcity conditions, proper irrigation scheduling is needed to maximize irrigation efficiency and prevent overapplication of water, while minimizing yield loss due to water shortage or drought stress. To schedule irrigation properly, knowledge of the environmental demand for surface water is required. The loss of surface water occurs primarily through evapotranspiration.

Evapotranspiration (ET) is an important component of the hydrological cycle and influence the availability of water, particularly for agriculture (Wang et al., 2012). The ET rate is essential for determining crop water demand and consequently for designing and managing irrigation systems, and any other hydrology related system (Lopez-Urrea et al., 2006).

A modification of the ET concept is reference evapotranspiration (ET_o) that provides a standard crop with an unlimited water supply so that a user can calculate maximum evaporative demand from that surface for a given day. This value, adjusted for a particular crop, is the amount of water that must be supplied through irrigation to meet the water demand of the crop (Fontenot, 2004). Analyzing the temporal variation of ET_o and identifying its probable reasons in arid and semi-arid environments, where water resources scarcity is much constraining for agriculture, offer valuable information for regional hydrology, agricultural water requirements and water resources management. The temporal trends and variability of ET_o in Iran have been addressed by several studies (Dinpashoh et al., 2011; Tabari et al., 2011, 2012a, b; Shadmani et al., 2012; Tabari, and Aghajanloo, 2013; Hosseinzadeh Talaee et al., 2013). Much of the variability and trends can be explained by large-scale atmospheric circulation. The relationship between the large-scale atmospheric circulation modes and evapotranspiration variability has rarely been reported in the literature. Sabziparvar et al. (2011) assessed the impacts of different phases of the El Niño Southern Oscillation (ENSO) on ET_o variability in some warm climates of Iran. The results of seasonal ET_o indicated that in 54% of the study sites, significant ($P < 0.05$) correlations between ENSO events and the ET_o variations exist. The mean time lag between the start of ENSO events and the observed ET_o changes was about 5 months. In

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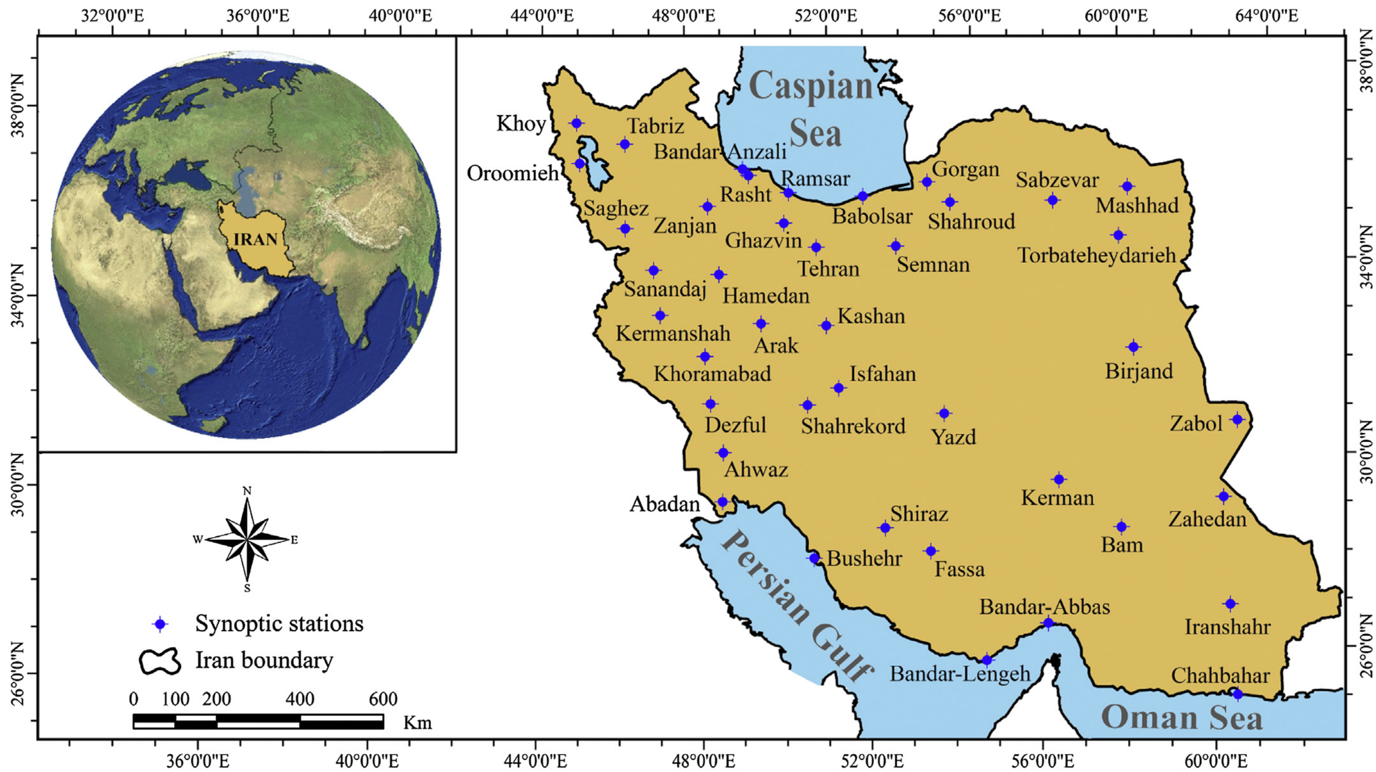

Fig. 1. Location of the weather stations in Iran map.

addition, the teleconnection impact of ENSO on ET_o in warm arid regions of Iran was more significant than that in warm humid regions.

The Arctic Oscillation (AO) is a large scale mode of climate variability, also referred to as the Northern Hemisphere annular mode. It is the result of the coupling between the stratospheric polar vortex and tropospheric circulation (deCastro et al., 2006). Fluctuation in the AO creates a seesaw pattern in which atmospheric pressure at the northern polar and middle latitudes alternates between positive and negative phases (Daoyi and Shaowu, 2003). The positive phase brings drier conditions to California, Spain, and the Middle East, and wetter weather to Alaska, Scotland, and Scandinavia (Cutlip, 2000). A study by Thompson and Wallace (1998) showed that the AO resembles the North Atlantic Oscillation (NAO) in many respects. However, its primary center of action covers more of the Arctic, giving it a more zonal symmetric appearance. While the AO effect is strong in boreal winter (Hu and Feng, 2010), it was found by Thompson and Wallace (2000) that the AO also explains 16% of the total variance of the warm season atmospheric circulation in the mid-latitude and high-latitude regions.

In Iran, about 14–46% and 25–32% of the winter air temperature variance can be explained with the winter and summer AO, respectively. In addition, the positive (negative) air temperature anomaly was found to be associated with the onset of the negative (positive) phase of the AO (Ghasemi and Khalili, 2006). However, a poor correlation between temperature anomalies and the AO was reported for northeast Iran (Bannayan et al., 2011). In spite of the importance of evapotranspiration or crop water requirement for irrigation scheduling and water resources management in arid and semi-arid regions including Iran, there was no study yet on the relationship between the AO and evapotranspiration. Therefore, this study was performed in the context of an on-going project to investigate the relationship between ET_o and the AO index at the annual and seasonal time scales, to analyze the ET_o changes corresponding to the various phases of the AO.

2. Materials and methods

2.1. Data used and study region

Iran is the eighteenth largest country in the world in terms of area. It is located in southwestern Asia (approximately between 25°00′ N and 38°39′ N; 44°00′ E and 63°25′ E) and covers more than 1,648,000 km^2. It is one of the world's most mountainous countries, its landscape dominated by rugged mountain ranges that separate various basins or plateaus from one another. The two highest mountain systems, the Alborz and the Zagros and two great deserts, Dasht-e Lut and Dasht-e Kavir strikingly affect the climate of Iran. The Alborz and north Zagros Mountains make up the major northern highlands of the country. The Mediterranean-type climate is dominant over the foothills of these ranges, but most of the country is classified as arid or semi-arid according to various climate classifications.

The meteorological parameters for calculating ET_o by the Penman–Monteith method including mean, maximum and minimum air temperatures, relative humidity, dew point temperature, water vapour pressure, wind speed, atmospheric pressure, solar radiation and sunshine hours were obtained from 41 stations covering the whole Iranian region for the period 1966–2005. The meteorological data were provided by the Islamic Republic of Iran Meteorological Organization (IRIMO). Seasonal ET_o values were calculated as the mean of monthly ET_o. The locations of the selected stations are shown in Fig. 1.

The meteorological data were missing for some stations for certain months and/or years. The stations with more than 5% of missing data were omitted from the study to minimize errors or biases in our analysis. The missing weather data were estimated

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using other available data according to Allen et al. (1998). In the absence of local direct solar radiation measurements, they were estimated from the observed duration of sunshine hours using the Angstrom formula. Where sunshine data were lacking, the difference between the maximum and minimum temperature was used to estimate solar radiation. Procedure for estimating missing wind speed data consists of using local long-term average wind speed value at each location.

The AO index (AOI) values were obtained from the Climate Prediction Center (CPC) at the National Center of Environmental Prediction (NCEP; www.cpc.noaa.gov). This index is constructed by projecting the daily 1000 mb height anomalies poleward of 20°N onto the leading the empirical orthogonal function (EOF) of the monthly mean 1000 mb height during 1979–2000 base period. Daily data of this index from 1965 to 2005 were obtained from CPC web site.

2.2. ET_o calculation

In the current study, the Penman–Monteith method was used to calculate ET_o at the study stations. The Penman–Monteith method was recommended by the Food and Agriculture Organization (FAO) as a standard to estimate ET_o (Allen et al., 1998) and has been used worldwide (e.g., Landeras et al., 2008; Trajkovic and Kolakovic, 2009; Sentelhas et al., 2010; Traore et al., 2010; Tabari et al., 2013b). The method assumes the ET_o as that from a uniform, well-watered grass surface, 0.12 m tall, a fixed canopy resistance (70 sm^{-1}) and with an albedo value of 0.23. With meteorological measurements done at a height of 2 m, the PMF-56 ET_o equation (Allen et al., 1998) is:

$$ET_o = \frac{0.408\Delta(R_{net} - G) + \gamma \frac{900}{T_{avg}+273} U_2(VPD)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where ET_o = reference crop evapotranspiration (mm day^{-1}), Δ = slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$), R_{net} = net radiation (MJ m^{-2} day^{-1}), G = soil heat flux (MJ m^{-2} day^{-1}), γ = psychrometric constant (kPa $°C^{-1}$), VPD = mean daily vapor pressure deficit (kPa), T_{avg} = average daily air temperature (°C), U_2 = mean daily wind speed at 2 m (m s^{-1}).

An ET_o calculator known as REF-ET and developed by Allen (2000) was used to determine the estimated ET_o values for the PMF-56 model. The REF-ET software which has the ability to read a

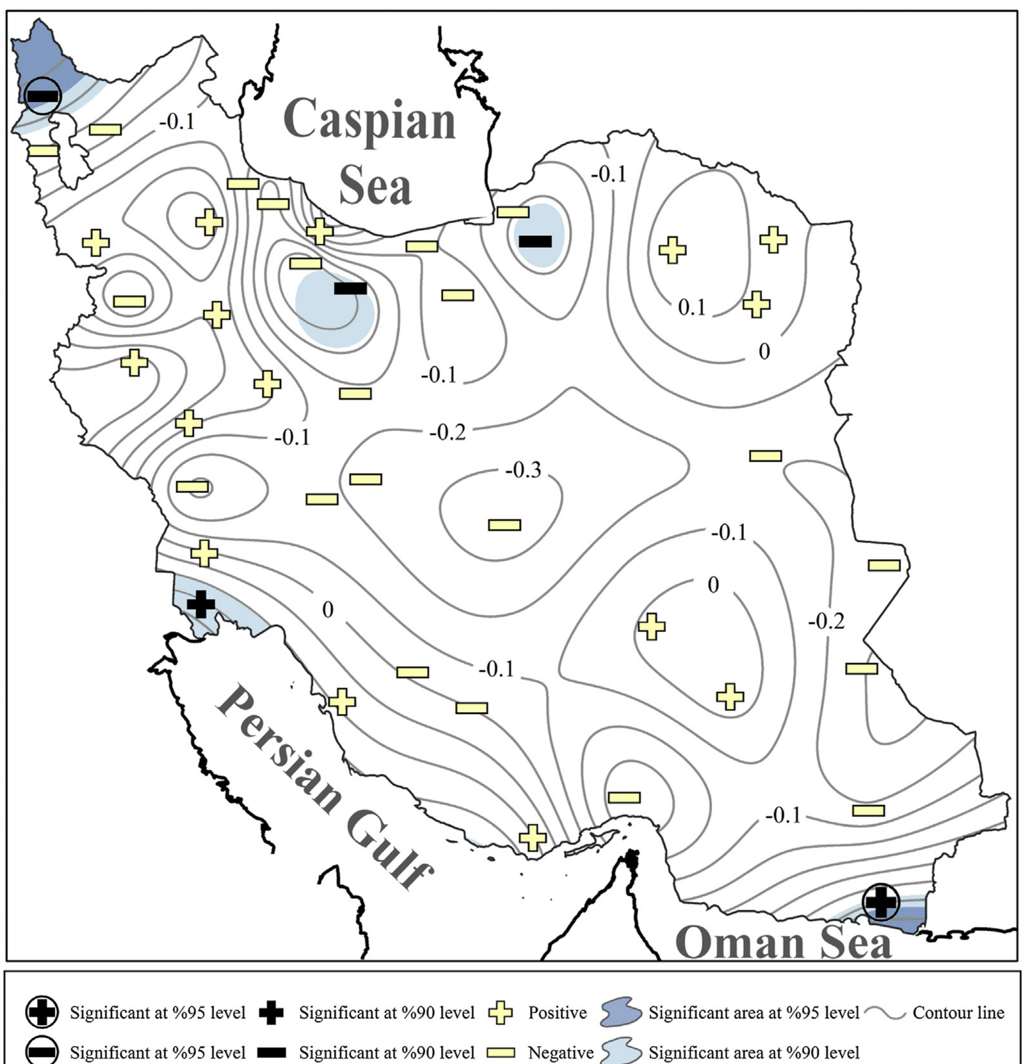

Fig. 2. Geographical distributions of correlation coefficients between the AO index and the annual ET_o of 41 stations in Iran.

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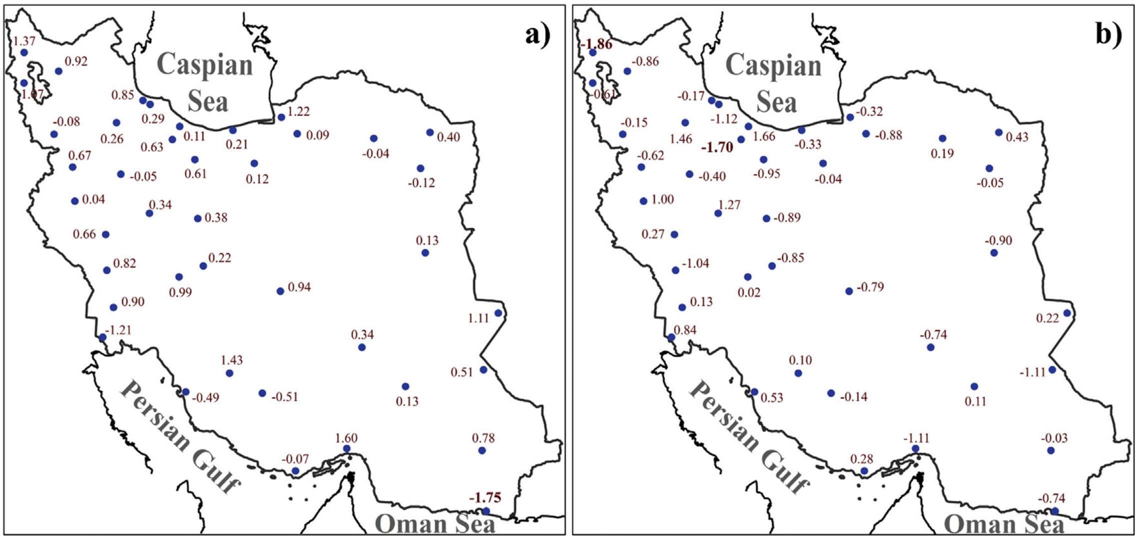

Fig. 3. The results of two-tailed Student's *t* test for investigating relative differences between long-term mean annual ET_o and the ET_o values during **a)** high and **b)** low AO phases (bold values indicate significant differences at the 0.10 level).

variety of data formats and site specifications (Itenfisu et al., 2003; Yoder et al., 2004) was specifically written to compute ET_o for a variety of commonly used equations. According to Allen et al. (1998), the parameters Δ and γ can be calculated using the following equations:

$$\Delta = \frac{4098 e_s}{(237.3 + T_{min})^2} \tag{2}$$

$$\gamma = 0.0016286 \frac{P}{\lambda} \tag{3}$$

$$\lambda = 2.501 - 0.0002631.T_{avg} \tag{4}$$

$$e_s = 0.6108 \exp\left(\frac{17.27 T_{dew}}{237.3 + T_{dew}}\right) \tag{5}$$

where T_{min} = minimum air temperature (°C), e_s = saturation vapor pressure (kPa), P = atmospheric pressure (kPa), λ = latent heat of vaporization (MJ kg^{-1}), T_{dew} = dew point temperature (°C).

2.3. Statistical procedures

In this study, the non-parametric Spearman's correlation coefficient (r_s) was used in order to measure the strength of the relationships between ET_o and the AOI. The correlations between the annual and seasonal ET_o and the corresponding AO index in two stages (with and without time-lag) were analyzed at the 5% and 10% levels. It is worthwhile to note that time lags from 1 to 3 seasons were used for seasonal correlations.

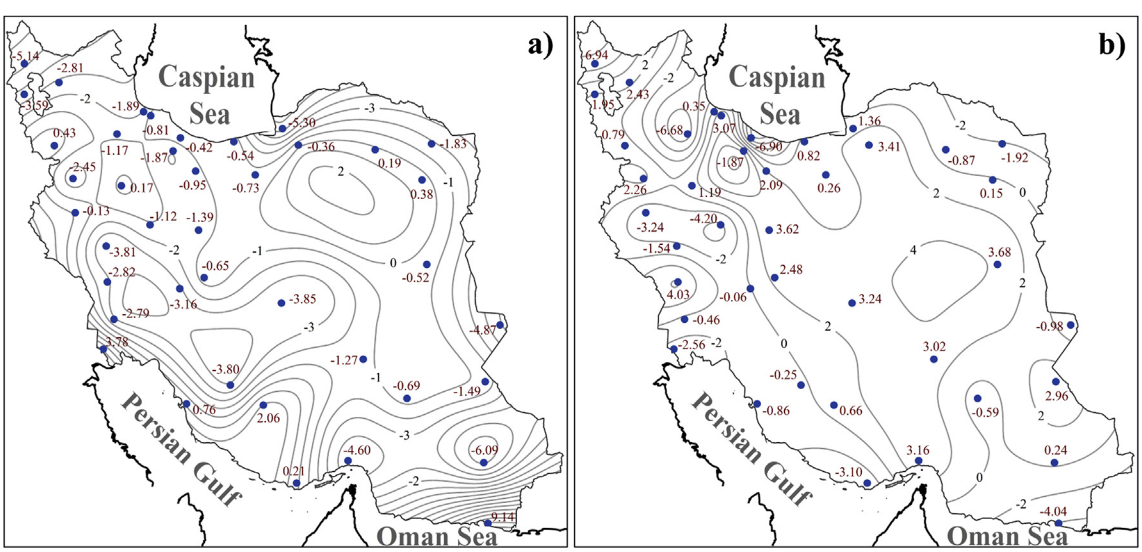

Fig. 4. Geographical distributions of **a)** the shift (ET_{o-h}_ET_{o-avg}) in the long-term annual ET_o during the high phase of the AO and **b)** the shift (ET_{o-l}_ET_{o-avg}) in the long-term winter ET_o during the low phase of the winter NAO (the shifts in percent are presented relative to the long-term annual ET_o).

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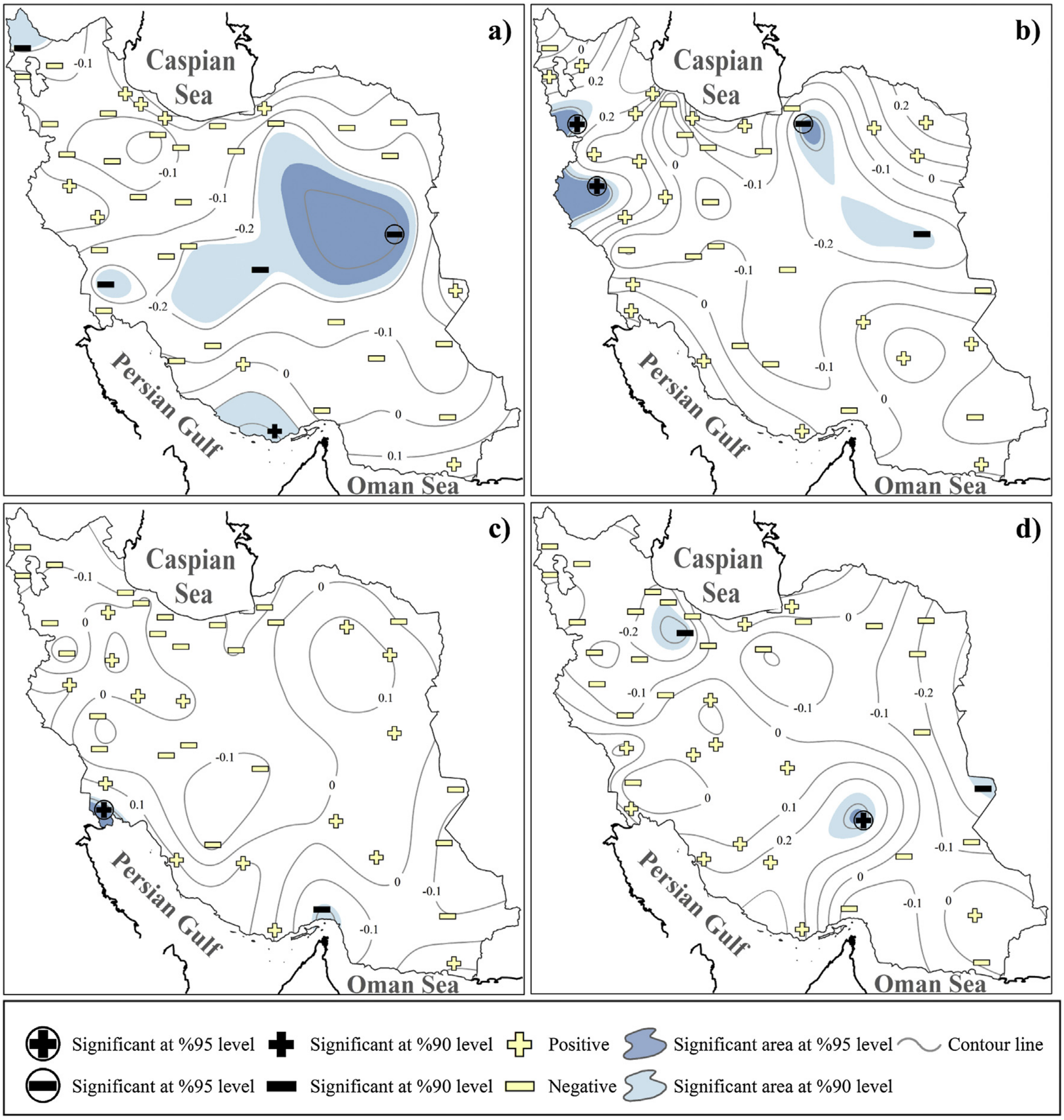

Fig. 5. Geographical distributions of seasonal simultaneous correlation coefficients for the AO-ET_o relationships: **a)** winter AO index–winter ET_o; **b)** spring AO index–spring ET_o; **c)** summer AO index-summer ET_o; **d)** autumn AO index-autumn ET_o.

The relationships between annual ET_o and the AOI were analyzed during the extreme phases of the AO. Following Ghasemi and Khalili (2006), in this study, the upper 25 and lower 25% values of the AO series were selected as the high and low phases of the AO respectively, when data are ranked in ascending order. The AOI values between the values of high and low phases were considered as normal phase. Such procedure was used by several authors (e.g., Shabbar and Khandekar, 1996; Nazemosadat and Cordery, 2000; Nazemosadat and Ghasemi, 2004; Sabziparvar et al., 2011; Tabari et al., 2013a) for distinguishing the extreme phases of the Southern Oscillation Index (SOI) and the NAO index. After determining the high, low and normal phases of the AO, the ET_o values corresponding to these phases were classified and the average ET_o values of each phase were computed ($ET_{o\text{-}h}$, $ET_{o\text{-}l}$, $ET_{o\text{-}N}$, respectively). The amounts of $ET_{o\text{-}h}$ and $ET_{o\text{-}l}$ at each station were then compared statistically to long-term average ET_o of the station by a two-tailed Student's *t* test. Significance tests of the results are based on the null hypothesis of no significant difference between the ET_o values corresponding to the high and low phases of the AOI and the long-term average ET_o values for the entire period of the record. The significant differences were assessed at a significance level of 0.10.

3. Results and discussion

3.1. Annual analysis

The correlations between the AO index and annual ET_o were analyzed at each station from 1966 to 2005 (Fig. 2). As can be seen from Fig. 2, both positive and negative correlations were found between annual ET_o data and the corresponding AO index. About 59% of the stations had a negative correlation with the AO index. The negative corrections ranged from −0.001 to −0.327 with an average of −0.167, while the positive correlations varied from 0.007 to 0.351 with an average of 0.111. A significant positive correlation

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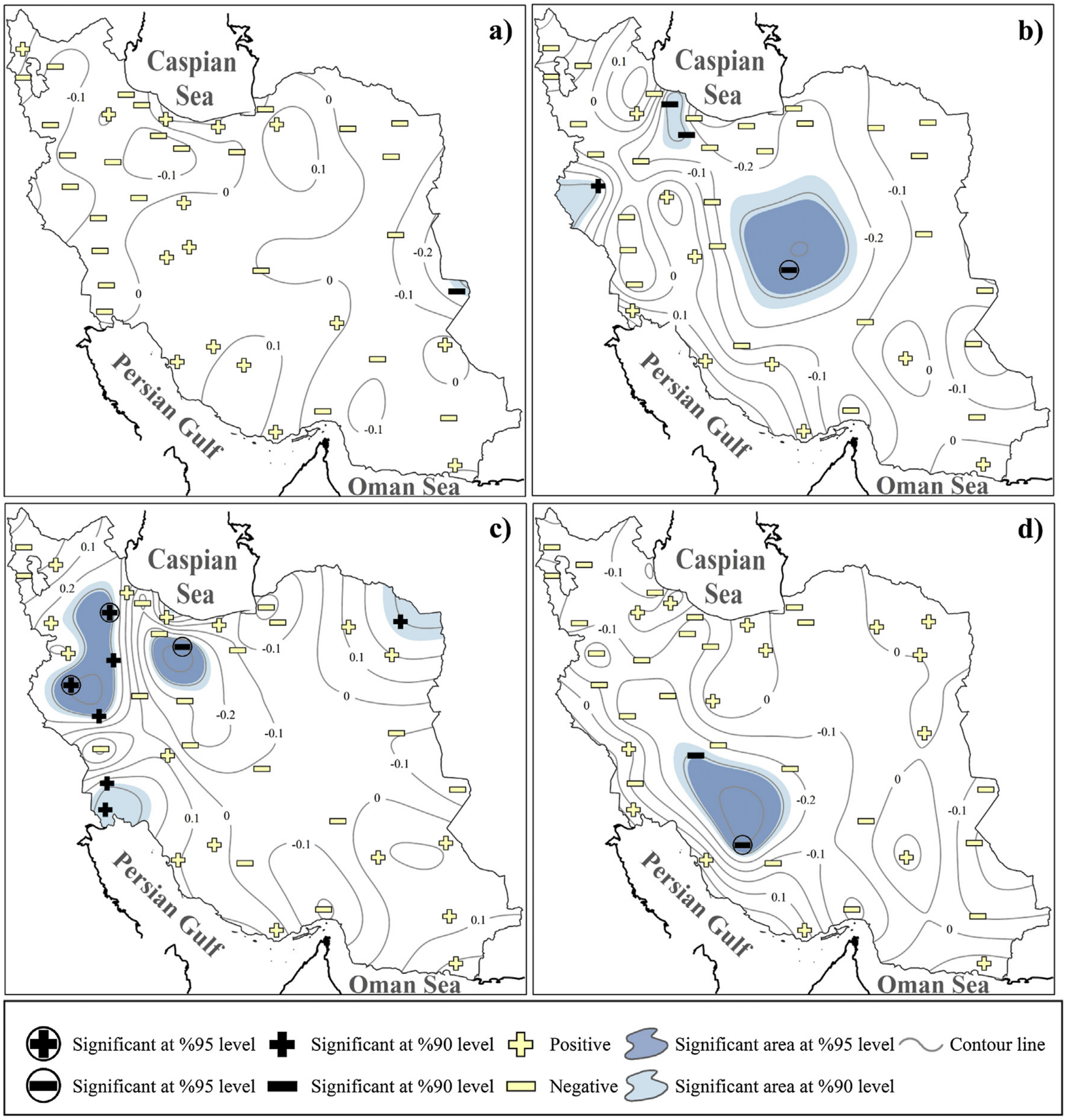

Fig. 6. Geographical distributions of seasonal lag correlation coefficients for the AO-ET_o relationships: **a)** autumn AO index–winter ET_o; **b)** winter AO index–spring ET_o; **c)** spring AO index-summer ET_o; **d)** summer AO index-autumn ET_o.

of 0.351 at the 0.05 level was obtained between the AO index and annual ET_o at Chahbahar station. The stations indicating significant positive correlations with the AO index are located on the southern coasts of Iran. The negative correlation coefficients are detected to be significant at the 0.1 level at three stations of Khoy, Shahroud and Tehran.

The significant differences between the ET_o values corresponding to the high and low phases of the AOI and the long-term average ET_o values for the entire period of the record (1966–2005) were assessed at a significance level of 0.10 (Fig. 3). The differences between the ET_o values during the high AO phase and the long-term average ET_o values were found to be significant only at Chahbahar station located on the northern coast of the Oman Sea (Southeastern Iran). During the high phase of the AO, the annual ET_o at Chahbahar station increased at the average rate of 0.46 mm/day (9%) with respect to the long-term average (Fig. 4a). The alternation of the AO extreme phases would cause a strong change in Chahbahar's ET_o.

The analysis also revealed that the statistical significant differences between the ET_o values corresponding to the low AO phase and the long-term average ET_o values were only observed at Khoy and Ghazvin stations located in the northwest parts of the country (Fig. 3). During the low AO phase, the annual ET_o at Khoy and Ghazvin stations increased indicating that the occurrence of the low phase of the AO generally lead to a significant increase in the annual ET_o at the mentioned stations. The magnitudes of the increase were 0.19 (7%) and 0.20 (5%) mm/day at Khoy and Ghazvin stations, respectively (Fig. 4b).

3.2. Seasonal analysis

The correlation coefficients between seasonal ET_o and the simultaneous AO index are shown in Fig. 5. As shown in Fig. 5a, the winter ET_o values at 31 out of the considered 41 stations are negatively correlated with the simultaneous AO index. A significant positive correlation at the 0.10 level was observed between winter

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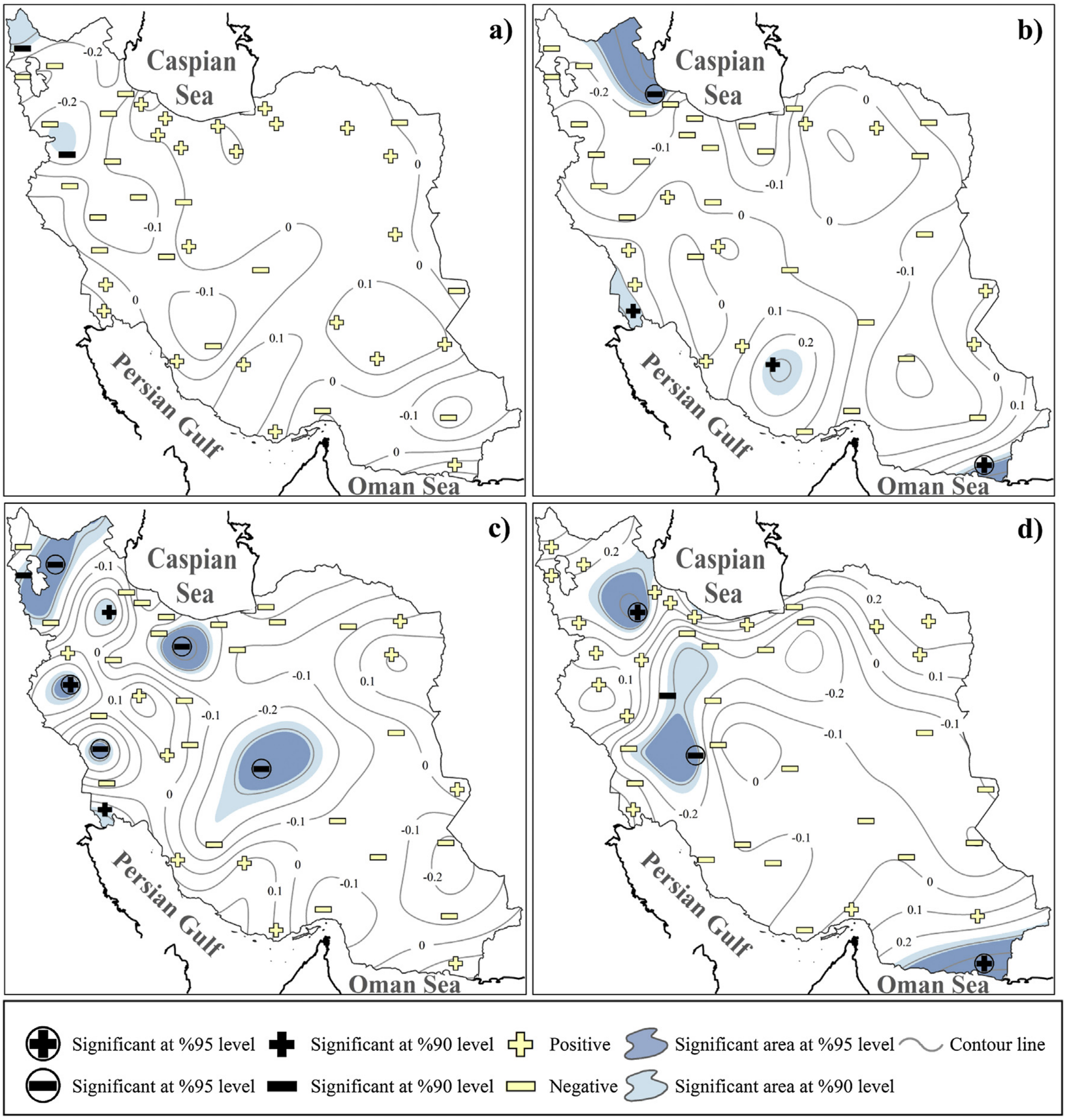

Fig. 7. Geographical distributions of seasonal lag correlation coefficients for the AO-ET_o relationships: **a)** summer AO index–winter ET_o; **b)** autumn AO index–spring ET_o; **c)** winter AO index-summer ET_o; **d)** spring AO index-autumn ET_o.

ET_o and the AO index at Bandar-Lengeh station. The significant negative correlation at the 0.10 level was found between the AO index and the winter ET_o values of Ahwaz ($r_s = 0.29$), Birjand ($r_s = 0.40$), Khoy ($r_s = 0.27$) and Yazd ($r_s = 0.28$) stations. The correlation coefficients between winter air temperature and the AO index at the above-mentioned stations were reported as 0.64, 0.52, 0.62 and 0.59, respectively (Ghasemi and Khalili, 2006).

Turkes and Erlat (2008) found an apparent negative relationship between year-to-year variability of winter temperature over Turkey and the AO winter index. Ghasemi and Khalili (2006) reported a significant negative correlation between winter air temperature and the AO index for about 53% of Iranian weather stations. However, we didn't find such strong relationships between evapotranspiration and the AO index. This is because of the dependency of evapotranspiration on several climatic variables such as solar radiation, humidity, wind speed, and air temperature explains only part of it.

In spring, there was a positive correlation between the AO index and ET_o at 56% of the stations (Fig. 5b). The significant positive correlations were observed at Kermanshah ($r_s = 0.355$) and Saghez ($r_s = 0.314$) stations which are suited in the west part of the country. The significant negative correlations were found at Shahroud ($r_s = 0.317$) and Birjand ($r_s = 0.279$) stations located in the east and northeast parts of the country.

In summer (Fig. 5c), the relationship was significant only on the southern coasts of the country. The significant positive correlation of 0.363 and the significant negative correlation of 0.298 were observed at Abadan and Bandar-Abbas stations, respectively. In autumn (Fig. 5d), the ET_o values at Ghazvin and Zabol stations had a significant negative correlation with the AO index, while a significant positive correlation was obtained between Kerman station's autumn ET_o and the AO index.

To check for the existence of lead/lag relationships between seasonal ET_o and the AO, the correlations for each season from lag-

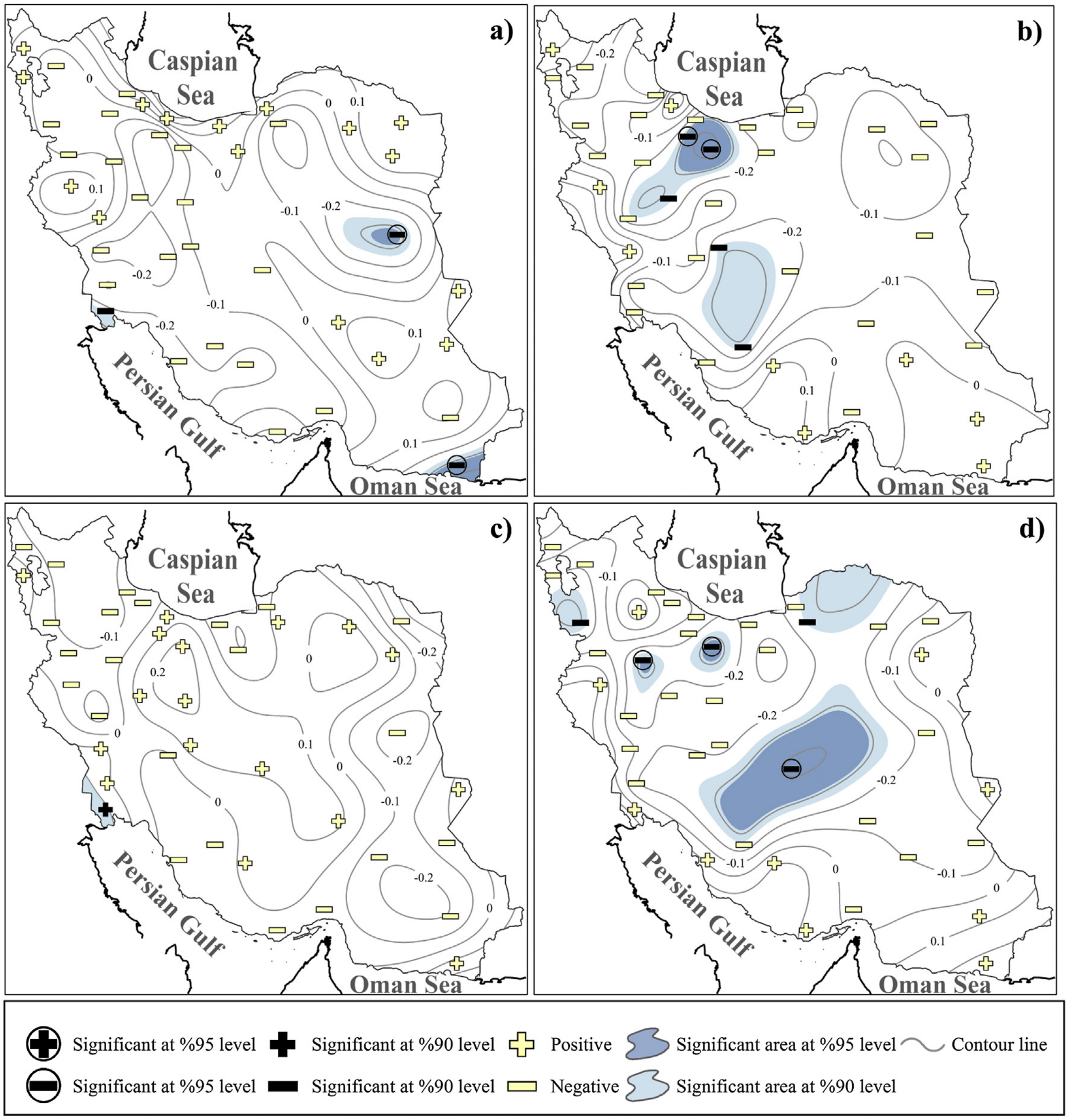

Fig. 8. Geographical distributions of seasonal lag correlation coefficients for the AO-ET_o relationships: **a)** spring AO index–winter ET_o; **b)** summer AO index–spring ET_o; **c)** autumn AO index-summer ET_o; **d)** winter AO index-autumn ET_o.

one to lag-three at a station were determined. The lag-*k* correlation implies that the seasonal mean values of the AO index are correlated with the ET_o values in advance by *k* season(s). With respect to the relation at the lag-one between the seasonal AO index and ET_o series (Fig. 6), 15 statistically significant correlations were found, and eight significant correlations were observed between the spring AO index and the summer ET_o series. Almost all of the significant relationships between the spring AO index and the summer ET_o series were positive, while the other significant relationships at the 1-season lagged stage were mostly negative. At the 2-season lagged stage (Fig. 7), 18 significant correlation coefficients were observed. This number decreased for the 3-season lagged correlations where 14 significant correlations were obtained (Fig. 8). Generally, the correlation coefficient between seasonal ET_o and the AO index achieves its maximum value of 0.506 for a time lag of 2 seasons at Chahbahar station located on the northern coasts of the Oman Sea.

The maximum influence of the AO on the seasonal ET_o at each study station is given in Table 1. The time lag for the observed maximum influence of the AO on the seasonal ET_o was two seasons for 16 out of the 41 study stations. The greatest positive (0.506) and negative (−0.466) correlation coefficients were also obtained for two-season time lag. The observed maximum influence of the AO on the seasonal ET_o at nine, seven and nine stations were observed for zero-, one- and three-season time lags stages, respectively. The winter AO had the maximum impact on Iranian seasonal ET_o. The winter AO showed the maximum impact on the simultaneous or following seasons ET_o at 15 stations. Generally speaking, the mean time lags (time lags of the monthly correlations averaged over all the stations) between the AO occurrence and affected ET_o was about 1.61 seasons or 5 months. Ghasemi and Khalili (2006) found a significant link between the summer AO and the following winter air temperature in Iran for the period 1951–2000, indicating a 2-season time lag between the AO and Iranian air temperature.

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Table 1
The strongest correlation between the seasonal ET_o series and the AO index at each considered station (correlation values surpassing the 90% and 95% confidence levels are shown using bold and underlined bold italic, respectively).

Station	AO	ET_o	Correlation coefficient	Time lag (season)
Khoy	Summer	Winter	−**0.269**	2
Tabriz	Winter	Summer	−***0.373***	2
Oroomieh	Winter	Autumn	−0.200	3
Bandar-Anzali	Autumn	Spring	−***0.384***	2
Rasht	Winter	Spring	−**0.302**	1
Ramsar	Summer	Spring	−0.260	3
Gorgan	Winter	Summer	−0.239	2
Babolsar	Autumn	Spring	−0.249	2
Zanjan	Spring	Autumn	***0.419***	2
Shahroud	Spring	Spring	−***0.317***	0
Mashhad	Spring	Summer	**0.295**	1
Saghez	Spring	Spring	***0.314***	0
Ghazvin	Summer	Spring	−***0.315***	3
Sabzevar	Winter	Autumn	−0.217	3
Tehran	Winter	Summer	−***0.466***	2
Semnan	Autumn	Spring	−0.240	2
Sanandaj	Summer	Winter	−**0.266**	2
Torbateheydarieh	Winter	Summer	0.203	2
Hamedan	Winter	Autumn	−***0.312***	3
Kermanshah	Spring	Summer	***0.400***	1
Arak	Summer	Spring	−**0.280**	3
Kashan	Spring	Spring	−0.254	0
Khorram-Abad	Spring	Summer	**0.293**	1
Birjand	Winter	Winter	−***0.397***	0
Isfahan	Winter	Spring	−**0.266**	3
Dezful	Winter	Summer	−***0.348***	2
Shahrekord	Spring	Autumn	−***0.340***	2
Yazd	Winter	Autumn	−***0.410***	3
Ahwaz	Winter	Winter	−**0.290**	0
Abadan	Summer	Summer	***0.363***	0
Zabol	Summer	Winter	−**0.281**	1
Kerman	Autumn	Autumn	***0.313***	0
Shiraz	Summer	Autumn	−***0.392***	1
Zahedan	Winter	Spring	−0.246	1
Bam	Autumn	Spring	−0.207	2
Bushehr	Spring	Winter	−0.252	3
Fassa	Autumn	Spring	**0.305**	2
Bandar-Abbas	Summer	Summer	−**0.298**	0
Iranshahr	Summer	Winter	−0.246	2
Bandar-Lengeh	Winter	Winter	0.265	0
Chahbahar	Spring	Autumn	***0.506***	2

4. Conclusions

This work aimed to investigate the links between the AO fluctuations and the inter-annual variability of ET_o at the annual and seasonal time scales, to analyze the ET_o changes corresponding to the various phases of the AO. According to the obtained results, significant correlation between the annual ET_o values and the AO index was observed at few stations. The Student's *t* test indicated that the differences between the annual ET_o values corresponding to the high and low AO phases and the long-term average ET_o values were found to be significant only at three stations. The results also indicated that the time lag for the observed maximum influence of the AO on the seasonal ET_o was two seasons for 16 out of the 41 study stations. Moreover, the greatest positive (0.506) and negative (−0.466) correlation coefficients were obtained for two-season time lag.

Further study is needed to examine links to other climate phenomena that could potentially impact Iranian evapotranspiration (e.g., Indian monsoon). Also, analysis of direct correlations to SLP (or 500 hPa) fields could shed some light on the role of atmospheric dynamics. Finally, examination of links to other climate variables (e.g., precipitation) and presence of multidecadal oscillations and trends (as detected by e.g., Willems, 2013) would be very interesting and useful.

Acknowledgements

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