

# Climate variability impacts on rainfed cereal yields in west and northwest Iran

Milad Nouri<sup>1</sup> · Mehdi Homaei<sup>2</sup> · Mohammad Bannayan<sup>3</sup>

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**Abstract** In order to assess the response of wheat and barley to climate variability, the correlation between variations of yields with local and global climate variables was investigated in west and northwest Iran over 1982–2013. The global climate variables were the El Niño–Southern Oscillation (ENSO), Arctic Oscillation (AO), and North Atlantic Oscillation (NAO) signals. Further, minimum ( $T_{\min}$ ), maximum ( $T_{\max}$ ), and mean ( $T_{\text{mean}}$ ) temperature, diurnal temperature range (DTR), precipitation, and reference evapotranspiration ( $ET_0$ ) was used as local weather factors. Pearson's correlation coefficient was applied to analyze the relationships between climatic variables and yields. Unlike  $T_{\min}$ ,  $T_{\text{mean}}$ ,  $ET_0$ , and  $T_{\max}$ , the yields were significantly associated with the entire growing season (EGS) DTR in most sites. Therefore, considering weather extreme variables such as DTR sheds light on the crop–temperature interactions. It is also found that the April–May–June (AMJ), October–November–December (OND), and EGS rainfall variations markedly influence the yields. Unlike the AO and NAO indices, the Niño-4 and SOI (the ENSO-related signals) were significantly correlated with the OND and EGS precipitation and DTR. Thus, the ENSO anomalies highly impact rainfed yields through influencing the OND and EGS rainfall and DTR in the studied sites. As the correlation coefficient of the OND and July–

August–September (JAS) Niño-4 with yields was significant ( $p < 0.05$ ) for almost all locations, the JAS and OND Niño-4 may be a good proxy for cereal yield forecasting. Further, an insignificant increment and a significant reduction in yields are expected in La Niña and El Niño years, respectively, relative to neutral years.

**Keywords** ENSO · Food security · Teleconnections · Water-limited regions · Yield forecasting

## Introduction

Agricultural outputs particularly under rainfed conditions are significantly influenced by climate variability (Ray et al. 2015). Although considerable investment on crop science, technical agricultural developments, and adopting appropriate policies have recently modified the crop–climate relationships and resulted in green revolution (Pingali 2012), crop production is still highly sensitive to climatic factors particularly in water-limited ecosystems (Homaei and Schmidhalter 2008). Changes of local weather, particularly during critical crop growth stages, may adversely or positively affect harvest and cause an economic loss or benefit (Alexandrov and Hoogenboom 2000; Bannayan et al. 2011). In addition to changes in local weather, global-scale climate oscillations such as El Niño–Southern Oscillation (ENSO), Arctic Oscillation (AO), and North Atlantic Oscillation (NAO) impact crop production and food security as they cause extreme weather events such as flood and drought (Bannayan et al. 2010; Cai et al. 2014; Stige et al. 2006). Hence, climatic variations and oscillations can still be considered as a potential threat to meeting growing food demands of the world population (Alexandrov and Hoogenboom 2000). Furthermore, as climate variability has been projected to be more frequent due

✉ Mehdi Homaei  
mhomaee@modares.ac.ir

<sup>1</sup> Department of Soil Science, Tarbiat Modares University, P.O. Box 14115-336, Tehran, Iran

<sup>2</sup> Department of Irrigation and Drainage, Tarbiat Modares University, P.O. Box 14115-336, Tehran, Iran

<sup>3</sup> Ferdowsi university of Mashhad, Faculty of Agriculture, P.O. Box 91775-1163, Mashhad, Iran

to climate change (Cai et al. 2014), climate variation-induced changes in harvests seem to be amplified in the future. Global food security is therefore anticipated to be more influenced by future climate variation.

Although there are a number of studies that addressed the impacts of local weather on crop yield (Brown 2013; Lobell et al. 2005, 2007; Shuai et al. 2013), some important weather factors such as diurnal temperature range ( $DTR = T_{\max} - T_{\min}$ ) and reference evapotranspiration ( $ET_0$ ) have been receiving negligible attention in such studies. DTR, an extreme temperature factor (Bonsal et al. 2001), seems to be of great importance in crop–climate interactions (Lobell 2007; Tao et al. 2008). In addition, since DTR plays a key role in estimating mean impacts of climate change and also the associated uncertainties, considering DTR in crop–climate impact assessments appears to be a necessity in changing climates (Lobell 2007).  $ET_0$ , as the evaporation power of atmosphere controlled by wind speed,  $T_{\min}$ ,  $T_{\max}$ , solar radiation, and relative humidity, influences crop yield through affecting crop water requirement (Allen et al. 1998). As a result, assessing the impacts of  $ET_0$  and DTR in addition to the commonly addressed climatic variables, e.g.,  $T_{\min}$ ,  $T_{\max}$ ,  $T_{\text{mean}}$ , and precipitation, may yield valuable insights into the crop–climate relationships. Although local weather directly conditions agricultural outputs, teleconnections of global climate, e.g., ENSO, NAO, and AO, may more properly explain agrohydrological processes (Stige et al. 2006). It is due to the fact that such climatic indices reduce the complexity of time and space into simple measures (packages of weather) (Hallett et al. 2004; Stenseth and Mysterud 2005; Stenseth et al. 2003). Moreover, the teleconnection indices can be forecasted for several future months (Barnston et al. 2012; Chen et al. 2004; Rodwell 2013) which helps decision makers and farmers predict crop response to near future climatic variations. Assessing the association between teleconnections and crop harvests therefore deepens our understanding of the plant–climate interactions (Brown 2013; Hallett et al. 2004; Stenseth and Mysterud 2005).

Climate variability is a prominent occurrence in arid and semi-arid regions and likely adversely affects biological productivity in these water-limited ecosystems (Bannayan et al. 2011; Hadley and Szarek 1981; Ribot et al. 2005; Weiss et al. 2004). Iran is located in the Middle East and its climate is predominantly semi-arid and arid (Bannayan et al. 2010). Above-average precipitation makes rainfed agriculture possible in semi-arid regions of Iran (Nouri et al. 2016). Wheat (*Triticum aestivum* L.) and barley (*Horedum vulgare* L.) are the two most abundant crops commonly grown under rainfed conditions in semi-arid areas of Iran. Around 75% of all rainfed wheat and barley produced in Iran is harvested from the fields located in the west and northwest of the country (Ministry of Agriculture 2015). However, there is a great year-to-year fluctuation in rainfed yield which has

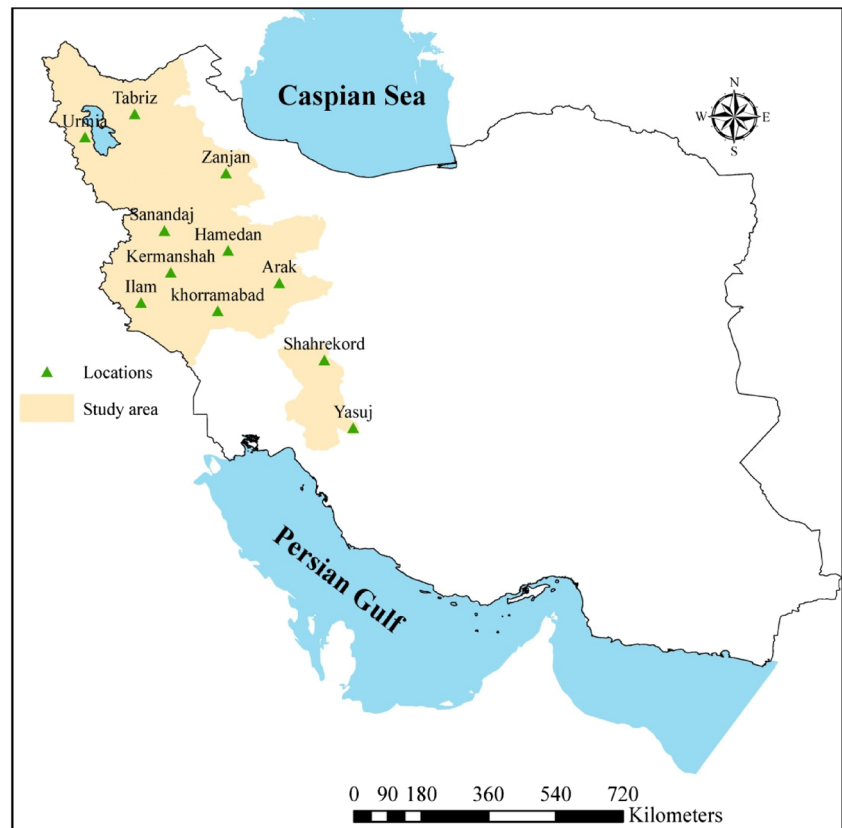
some negative eco-social consequences in the country (Bannayan et al. 2010, 2011). Bannayan et al. (2011) attributed 30–50% of rainfed cereal yield variation to precipitation anomalies in northeast Iran. Bannayan et al. (2010) also concluded that the correlations between wheat and barley harvests and aridity index (AI, the ratio of precipitation to  $ET_0$ ) were significant ( $p < 0.05$ ) in some regions located in northeast Iran. Furthermore, they pointed out that the cereal yields are not significantly associated with the ENSO, AO, and NAO indices as precipitation is poorly correlated with these global-scale signals in northeastern Iran. Unlike in eastern Iran, autumn precipitation (Nazemosadat 1999; Nazemosadat and Cordery 2000), winter precipitation (Nazemosadat 2001a, b), and autumn dry/wet spells (Modarres and Ouarda 2014; Nazemosadat and Ghasemi 2004) have been found to be greatly impacted by the ENSO interannual variability in the west and northwest of Iran. The correlations between wintertime  $ET_0$  and the NAO index (Tabari et al. 2014) as well as air temperature and the AO signal (Ghasemi and Khalili 2006) have been also reported to be statistically significant over the northwest and west regions of Iran. Despite large impacts of the large-scale fluctuations on local weather and importance of rainfed productions, to our knowledge, no comprehensive study has been carried out to date to assess the associations between the local weather, global climate, and crop yields in west and northwest Iran. Therefore, this study sought to find the associations between the local weather variable ( $T_{\min}$ ,  $T_{\max}$ ,  $T_{\text{mean}}$ , precipitation,  $ET_0$ , and DTR) and global climate signals (AO, NAO, Niño-4, and Southern Oscillation index (SOI)) with wheat and barley grain yields in the west and northwest of Iran.

## Materials and methods

### Study area

Iran has a wide range of climates mainly due to the existence of the Alborz and the Zagros mountain ranges. Rain-producing air masses predominantly enter from the west and northwest and cause above-average rainfall (around 300 to 500 mm annual precipitation) in the western half of the country owing to the Zagros mountain chain geographical location (Sadeghi et al. 2002). Consequently, semi-arid Mediterranean climate mostly dominates in west and northwest Iran. Semi-arid climatic conditions as well as fertile plains have made the west and northwest of Iran an appropriate region for rainfed agriculture. The study area and location of the studied sites are depicted in Fig. 1. The climate of all the studied sites is categorized as semi-arid according to UNEP (1997).

**Fig. 1** The local map of the study area



## Data

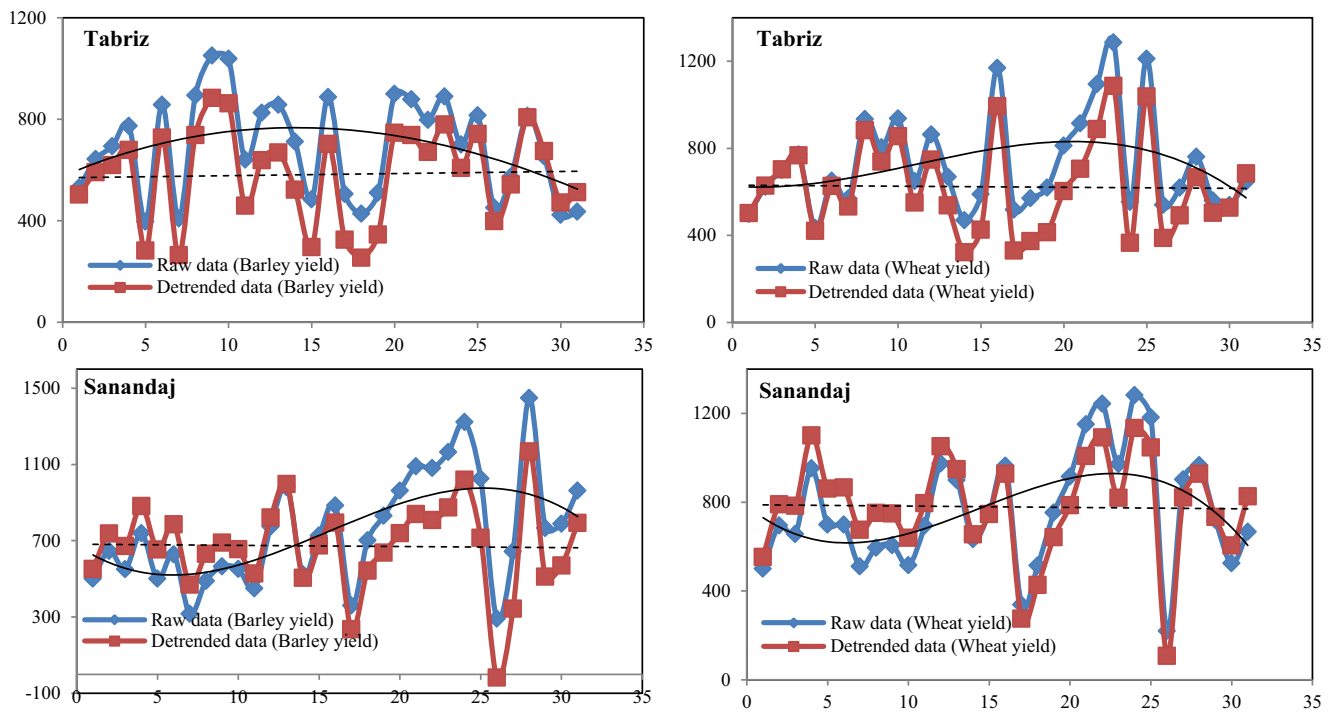
The required meteorological data including minimum and maximum temperature, precipitation, wind speed, and solar radiation of all sites were obtained from the Islamic Republic of Iran Meteorological Organization (IRIMO) for the period of 1982–2013. These data were also used to calculate DTR ( $=T_{\max} - T_{\min}$ ) and  $ET_0$  based on the Penman–Monteith FAO-56 (PMF-56) method. The crop yield data were obtained from the Ministry of Agriculture over 1982–2013. The monthly values of four climate indices (i.e., NAO, AO, Niño-4, and SOI) were also obtained from the NOAA website (<http://www.ncdc.noaa.gov/teleconnections>). The NAO is a recurrent and dominant climate variability pattern in the middle and high latitude of the northern hemisphere, most pronounced in the cold season (Hurrell et al. 2001, 2013). This phenomenon is quantified by the NAO index which is based on the normalized difference of sea level pressure (SLP) between Ponta Delgada, Azores, and Stykkisholmur, Iceland (Rogers 1984). Thompson and Wallace (1998) introduced the Arctic Oscillation pattern and its corresponding index, namely the AO index, to explain the leading Empirical Orthogonal Function (EOF) of wintertime SLP anomalies poleward of 20° N. The El Niño–Southern Oscillation (ENSO) is the most potent interannual climatic fluctuation which affects agrohydrological processes on the globe (McPhaden et al. 2006). In this study, two ENSO signals, i.e.,

Niño-4 and SOI, were used. The Niño-4 sea surface temperature (SST) index is defined as the mean monthly temperature anomaly in the area of the eastern tropical pacific, i.e., 5° S–5° N, 160° E–150° W (Trenberth 1997). The SOI index represents the difference between standardized Tahiti (17.58° S, 149.68° W) and Darwin (12.48° S, 130.98° E) SLP anomalies (Hanley et al. 2003).

## Analyses

Agricultural productions are affected not only by climatic variables but also by non-climate-related factors such as irrigation, fertilization, genomic manipulation, and machinery development (Homaei et al. 2002a, b; Lobell 2007; Podesta et al. 2002). As a result, trend evolved owing to anthropological effects must be removed for investigating crop response to climate variations (Gimeno et al. 2002; Tkadlec et al. 2006). In this investigation, the series were detrended using a third-order polynomial model. Figure 2 illustrates the raw and detrended series and their corresponding fitted trends for two studied sites with different trends.

In order to classify the ENSO events, the method proposed by the Center for Ocean–Atmospheric Prediction Studies (COAPS; available at [www.coaps.fsu.edu/](http://www.coaps.fsu.edu/)) was used. This method categorizes the ENSO into three episodes, i.e., El Niño (warm SST anomalies), El Viejo or La Niña (cold SST



**Fig. 2** The raw and detrended cereal yield series and corresponding trends (solid lines for raw data and dashed lines for detrended data) for Tabriz and Sanandaj in 1982–2013

anomalies), and neutral based on the JMA (Japan Meteorological Agency) index which is a 5-month running mean of spatially averaged SST anomalies over the tropical Pacific: 4° S–4° N, 150° W–90° W. If the JMA index is greater (lower) than +0.5 (–0.5) °C for six consecutive months (including October–November–December, OND), a year is categorized as El Niño (La Niña). Otherwise, a year is neutral in terms of SST anomalies. In the current study, 8 years (i.e., 1982, 1986, 1987, 1991, 1997, 2002, 2006, and 2009) and 5 years (i.e., 1988, 1998, 1999, 2007, and 2010) were, respectively, El Niño and La Niña years. The other investigated years were considered to be the ENSO neutral.

Analysis of variance (ANOVA) was used to identify the different ENSO episodes' influences on the cereal yields. The significance of the ENSO anomalies' effects upon yield was tested by the F-test (Fisher's test). Relationships between the yield data, climate variables, and the teleconnection signals were evaluated using two-tailed Pearson correlation coefficients. In addition, both concurrent and lag (1- and 2-year) correlations between the yields and the local weather factors and the teleconnection signals were determined.

In this study, we assessed the correlations between the yields and climate indices and local weather variables over the entire, pre-, early, mid-, and late growing season. Winter cereals are mainly sown in October and harvested in June under rainfed conditions in west and northwest Iran. October through June is hence referred to as the entire growing season (EGS). Furthermore, the July–August–September (JAS),

October–November–December (OND), January–February–March (JFM), and April–May–June (AMJ) correspond to the pre-, early, mid-, and late growing season, respectively.

In order to classify the dryness of growth season, the decile-based system initially proposed by Gibbs and Maher (1967) was used. In this method, the growing season precipitation is arranged from lowest to highest to establish the cumulative frequency distribution (CFD). Then, the developed CFD is divided to ten deciles. The first decile indicates the driest season in which the precipitation is lesser than 10% of all rainfall values. The seasons are categorized into seven groups, i.e., extremely wet (90% <), very wet (80–90%), moderately wet (70–80%), normal (30–70%), moderately dry (20–30%), severely dry (10–20%), and extremely dry (10% >) (Morid et al. 2006). In this study, first to third (10–30%), fourth to seventh (40–70%), and eighth to tenth (80–100%) deciles were considered as dry, normal, and wet seasons, respectively.

## Results and discussions

### Cereal yield and local weather associations

Except for the JFM season, there was an insignificant negative correlation between the crop yields and  $T_{\text{mean}}$  and  $T_{\text{max}}$  in majority of the sites (Fig. 3a, b, e, f). The highest negative correlation coefficient, average over all sites, was calculated



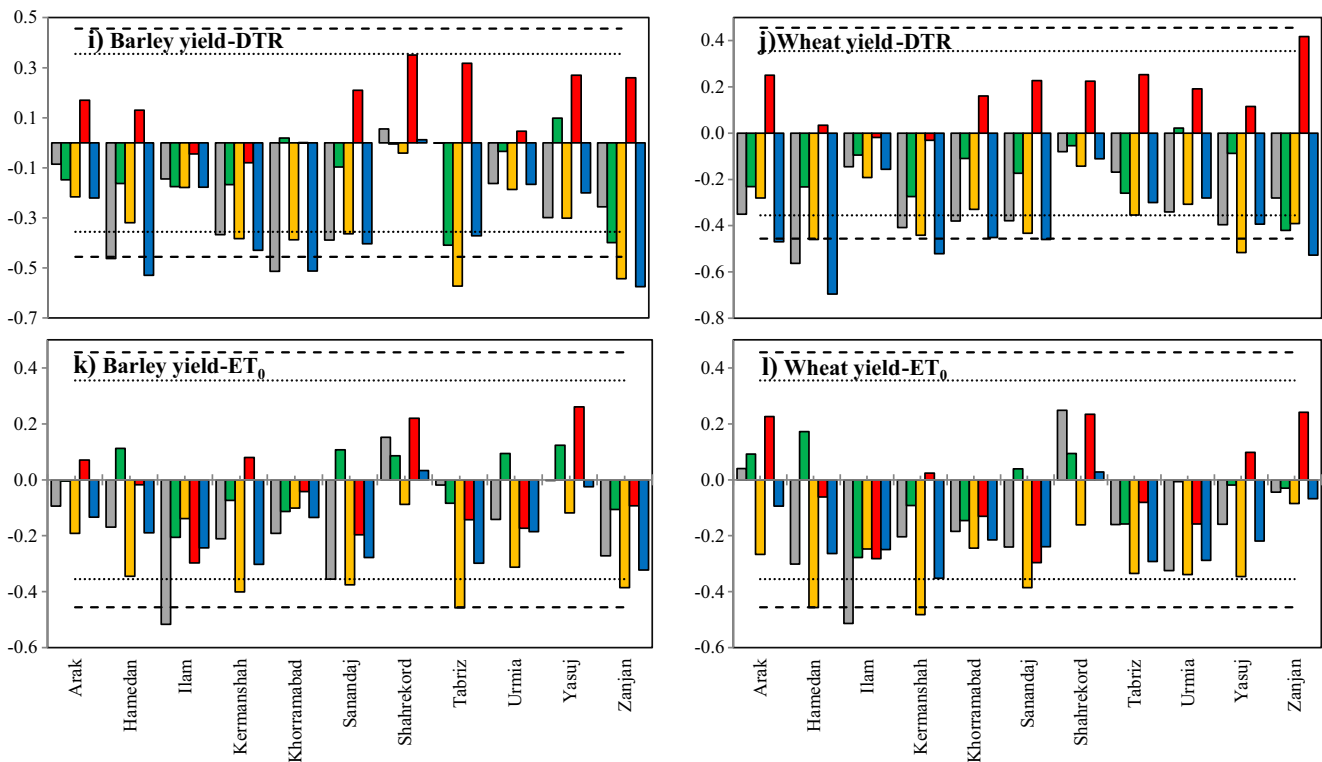
**Fig. 3** The correlation coefficients of the relationships between the yields and local weather factors during the OND, JFM, AMJ, JAS, and EGS (The dotted and dashed lines represent the significance levels of 95 and 99%, respectively). **a** Barley yield– $T_{mean}$ , **b** wheat yield– $T_{mean}$ , **c** barley

yield– $T_{min}$ , **d** wheat yield– $T_{min}$ , **e** barley yield– $T_{max}$ , **f** wheat yield– $T_{max}$ , **g** barley yield–precipitation, **h** wheat yield–precipitation, **i** barley yield–DTR, **j** wheat yield–DTR, **k** barley yield– $ET_0$ , **l** wheat yield– $ET_0$

between the cereal harvests and the late season  $T_{mean}$  ( $r = -0.29$ ) and  $T_{max}$  ( $r = -0.33$ ). High temperature during grain filling, which mainly occurs during the AMJ, adversely affects cereal yield (Asseng et al. 2011; Stone and Nicolas 1995). Therefore, a greater influence of  $T_{max}$  and  $T_{mean}$  variations on the yields was detected during the AMJ season. The

late season  $T_{max}$  and yield correlation was significant ( $p < 0.05$ ) in 45.5% of stations. In most cases, the correlation of  $T_{min}$  and yields was insignificantly positive during the OND, JFM, and EGS periods (Fig. 3c, d). Further, the yields were significantly positively correlated to the JFM  $T_{min}$  in three sites (Arak, Sanandaj, and Hamedan) and one site





**Fig. 3** (continued)

(Sanandaj) for wheat and barley, respectively. Winter cereal crops may fail to yield due to exposure to low temperature extremes during the JFM season particularly in those sites located in colder regions such as Hamedan and Sanandaj. Therefore, a higher winter  $T_{min}$  favors cereal growth and productivity. Moreover, the correlation of the EGS  $T_{min}$ ,  $T_{max}$ , and  $T_{mean}$  with yields was found to be insignificant except barley yield–EGS  $T_{max}$  relationship in Khorramabad.

In most sites, the correlation between DTR and yields was negative except for the period of JAS (Fig. 3i, j). In addition, there was a significant negative association between yield and the OND, AMJ, and EGS DTR in 45.4, 45.5, and 63.6% of studied sites for wheat and in 36.4, 45.5, and 54.5% of locations for barley, respectively. DTR increment adversely affects a wide range of crop physiological processes. Some vital processes such as photosynthesis, which exclusively occurs during the day, are negatively influenced by water stress and high temperature induced by increased  $T_{max}$  (Lobell 2007). At a given  $T_{mean}$ , reduction of  $T_{min}$  during nighttime may cause frost damage to crop productions (Tubiello et al. 2002). Furthermore, DTR is reported to be mostly negatively associated with cloudiness cover (Dai et al. 1999). This implies that increase in DTR is expected to coincide with rainfall shortage (Dai et al. 1999) and worsen the drought effects on crop growth and yield. In our study, the average correlation coefficient of the EGS precipitation–DTR was equal to  $-0.69$ . It seems that increased DTR over the OND (when the crop may not be well-developed and

resilient to freezing conditions and drought) and AMJ (when the crop is highly sensitive to high temperature and soil water stress) periods more adversely impacts the crop yield (Fig. 3i, j). Changes in DTR can be as a result of changes in  $T_{min}$  or  $T_{max}$  or both. Since  $T_{min}$  and  $T_{max}$  during the EGS showed no significant association with the harvests (except for Khorramabad), significant correlation of DTR and yields over the EGS in some locations seems most likely to link to simultaneous opposite variations of  $T_{min}$  and  $T_{max}$ . It is worth mentioning that considering sole  $T_{min}$  or  $T_{max}$  may not well explain the crop–temperature interactions. By including simultaneous variation of  $T_{max}$  and  $T_{min}$ , DTR (an extreme temperature variable) can account for the temperature–harvest association better.

Approximately 49 and 51% of wheat and barley yield variation, averaged over all sites, can be explained by the EGS rainfall variability, respectively. Further, the EGS rainfall–yield correlation was significant ( $p < 0.05$ ) in all sites except for Shahrekord (Fig. 3g, h). The relationship of the yields and precipitation was stronger over the OND and AMJ seasons compared to the JAS and JFM seasons. Averaged over all sites, the correlation coefficients of yield with the OND and AMJ rainfall were 0.39 and 0.45, respectively, for wheat and 0.38 and 0.42, respectively, for barley. Crop germination can be severely influenced by the OND rainfall shortage leading to germination kill and crop failure in the early growth period (Mearns et al. 1997). In addition, soil water deficit triggered by the AMJ drought can negatively affect anthesis and grain

filling processes (two phenological stages highly sensitive to water stress) and cause harvest failure (Mearns et al. 1997). The OND and AMJ rainfall deficit mostly coinciding with increased DTR can therefore result in a substantial harvest loss in drylands of western Iran. From these results, one can infer that in addition to total amount of precipitation, the rainfall temporal distribution plays a key role in rainfed cereal production. Thus, any measure to avoid rainfed harvest loss ought to be dealt with overcoming the early and late season drought.

The average correlation coefficients between the yields and precipitation,  $T_{min}$ ,  $T_{max}$ , and  $T_{mean}$  over wet, normal, and dry seasons are given in Table 1. The average correlation between the yields and precipitation was significant ( $p < 0.05$ ) in dry seasons. However, the association between the yields and rainfall was not strong during wet and normal seasons. It can be thus concluded that yield variation is significantly caused by rainfall anomalies in drier conditions. The relationships between the harvests and  $T_{min}$ ,  $T_{max}$ , and  $T_{mean}$  were statistically insignificant under normal and wet conditions. However, a negative significant correlation between the yields and  $T_{max}$  was obtained for dry seasons (Table 1). This can be attributed to the fact that the high temperature stress often occurs in combination with drought (Prasad et al. 2011). Therefore, the harvest loss or failure in drier seasons is mainly due to the simultaneous occurrence of high temperature and water stress.

In most cases, the crop yields were negatively associated with  $ET_0$  except for the period of JFM. The yield– $ET_0$  correlation coefficient was more negative (–0.27 for both crops) over the AMJ season with respect to that in other periods. Further, a significant correlation between the AMJ  $ET_0$  and cereal yields was found in 3 out of 11 sites (Fig. 3k, l). However, the yields were not significantly associated with the  $ET_0$  of EGS.

**Teleconnections and crop yield relationships**

The cereal yields were not significantly correlated (at all time lags) with the AO and NAO signals in almost all locations and periods (Fig. 4). The NAO signal exhibited a significant ( $p < 0.05$ ) negative association with the JFM  $T_{min}$ ,  $T_{max}$ ,  $T_{mean}$ , and  $ET_0$  in 9, 11, 11, and 8 out of 11 sites, respectively

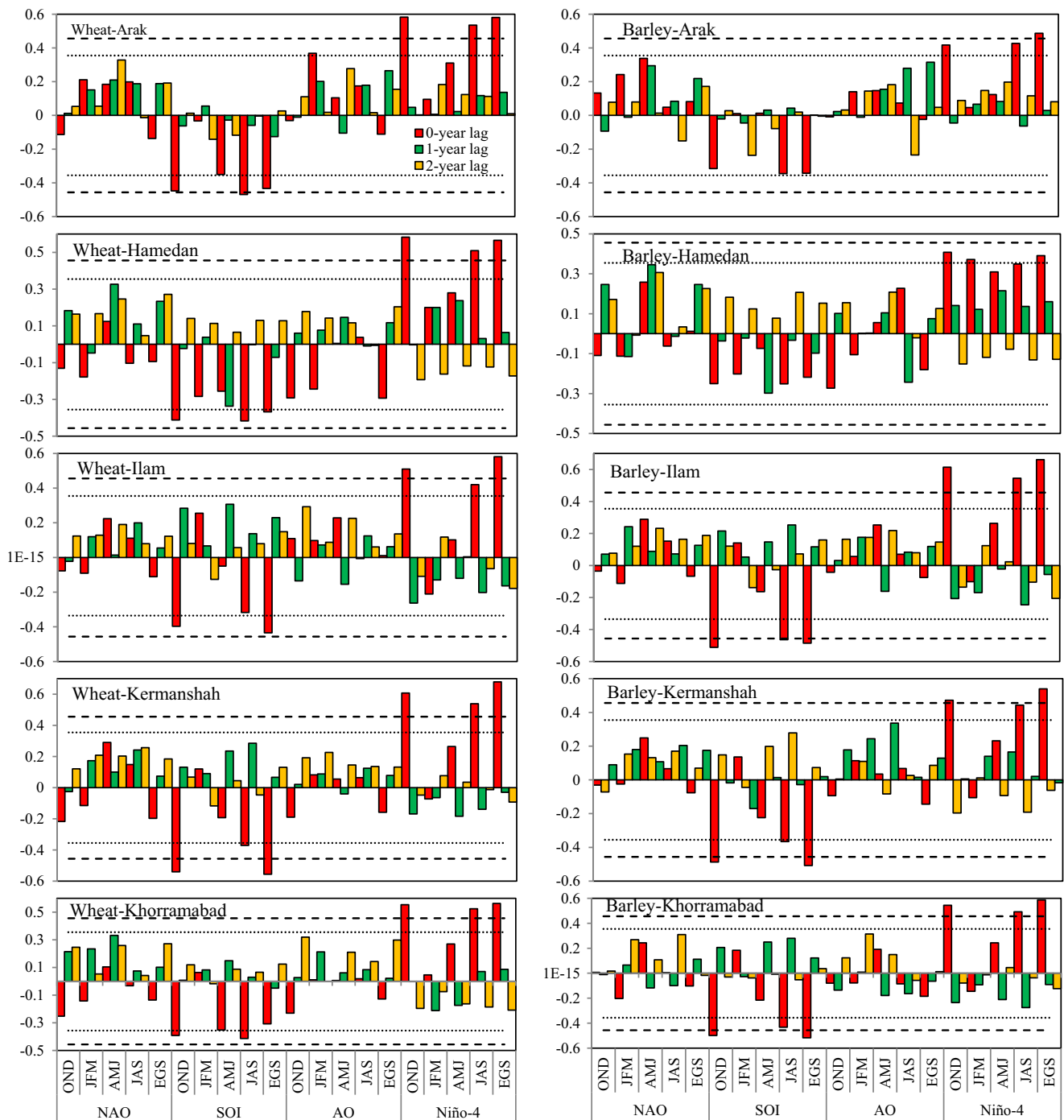
(Fig. 5c, d, e). There was also a significant negative correlation between the AO index and the JFM  $T_{min}$ ,  $T_{max}$ , and  $T_{mean}$  in all locations and the JFM  $ET_0$  in 54.5% of the investigated sites. Thus, the NAO and AO anomalies affect the wintertime temperature and  $ET_0$  over the studied area. Ghasemi and Khalili (2006) pointed out that the AO signal is negatively significantly correlated with winter temperature in the western half of Iran. Tabari et al. (2014) also reported a significant strong correlation between winter  $ET_0$  and the NAO teleconnection at northwest Iran. Weak correlation between the NAO and AO indices and cereal yields is attributed to poor associations obtained between these signals and DTR and rainfall (two climatic variables highly influence the yields (Fig. 3g, h, i, j)). Bannayan et al. (2010, 2011) also reported a low correlation between the NAO and AO indices and rainfall and cereal yields at northeastern Iran. As a result, rainfed cereal production is not profoundly affected by the NAO and AO phases over Iran.

The negative correlations between the yields and the OND, JAS, and EGS SOI were, respectively, significant in 10, 8, and 9 sites for wheat and in 8, 7, and 7 sites for barley (Fig. 4). Furthermore, the yields showed a significant positive correlation with the OND, JAS, and EGS Niño-4 in all locations (except Shahrekord) at zero lag. Averaged across all sites, 37.4 and 51.4% of barley yield anomalies and 41.0 and 56.4% of wheat yield anomalies can be explained by the SOI and Niño-4 variations, respectively. Given greater correlation coefficient of the Niño-4 and yields (Fig. 4), one can conclude that the Niño-4 is more appropriate for yield forecasting and crop–climate impact assessment in the studied area. Furthermore, the higher correlation between wheat yield and the ENSO-related signals can be due to greater sensitivity of wheat to meteorological drought relative to barley. In all sites, there was a significant positive and negative association between the Niño-4 and precipitation and the Niño-4 and DTR over the OND and EGS periods at concurrent lag, respectively (Fig. 5b). Moreover, a statistically significant negative correlation between the SOI index and precipitation at zero lag was detected during the OND (with exception for Shahrekord) and EGS in all locations (Fig. 5a). Nazemosadat and Cordery (2000) and Nazemosadat (1999) found that autumnal

**Table 1** The average climate variables, crop yields, and correlation coefficients of the relationships between yields and precipitation ( $P$ ),  $T_{min}$ ,  $T_{max}$ , and  $T_{mean}$  in dry, normal, and wet seasons

Season	Barley				Wheat				Climatic variables and yields					
	$P$	$T_{mean}$	$T_{min}$	$T_{max}$	$P$	$T_{mean}$	$T_{min}$	$T_{max}$	Barley yield	Wheat yield	$P$	$T_{mean}$	$T_{min}$	$T_{max}$
Dry	0.55*	–0.23	–0.02	–0.37*	0.58*	–0.22	0.06	–0.39*	540.23	533.60	258.48	9.76	2.54	16.98
Normal	0.25	0.12	0.17	0.07	0.38*	0.15	0.25	0.05	683.21	668.00	328.80	9.50	2.73	16.28
Wet	0.17	0.24	0.25	0.18	0.10	0.27	0.28	0.22	777.95	764.71	408.97	9.29	2.65	15.94

\*Significant correlation coefficients at the 95% confidence level



**Fig. 4** Correlation coefficients of the cereal yields and the global teleconnection signals relationships in the OND, JFM, AMJ, JAS, and EGS at 0-, 1-, and 2-year lag (The dotted and dashed lines represent the significance levels of 95 and 99%, respectively)

precipitation in the northwest and west of Iran is remarkably affected by ENSO episodes. They also mentioned that autumn rainfall is several times more in the El Niño period (warm phase) with respect to that over La Niña years (cold phase) in the western half of Iran. Nazemosadat and Cordery (2000) also pointed out that in some central locations such as Shahrekord, autumn precipitation is poorly associated with

the SOI index. The correlations between the ENSO-related signals and DTR were also significant ( $p < 0.05$ ) during the OND and EGS for all locations. The strong correlation between the ENSO-related signals and yields is therefore explainable by the ENSO strong effects on the OND and EGS precipitation and DTR (Fig. 5a, b). The results also indicated that there is no delay in yield response to the ENSO anomalies



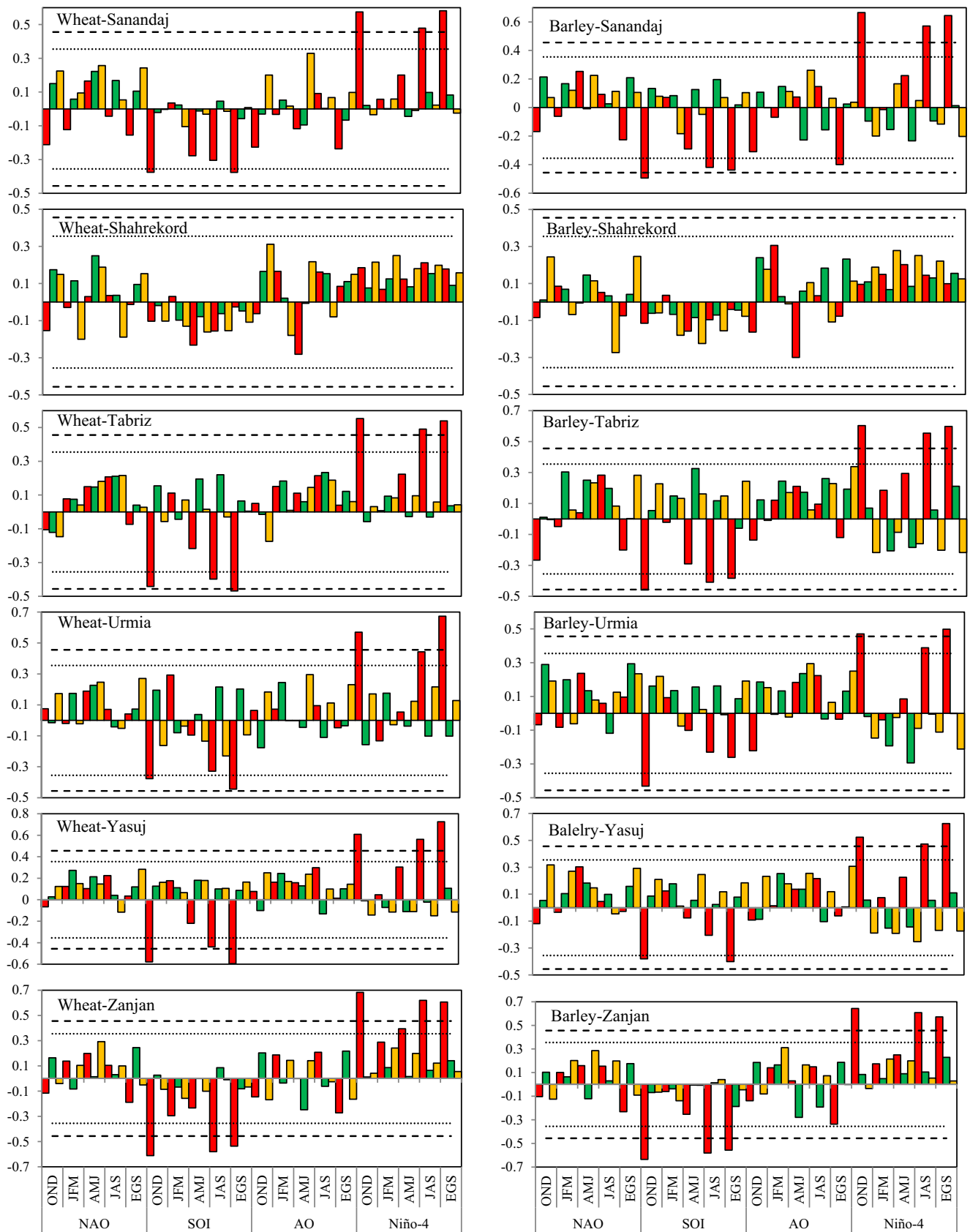
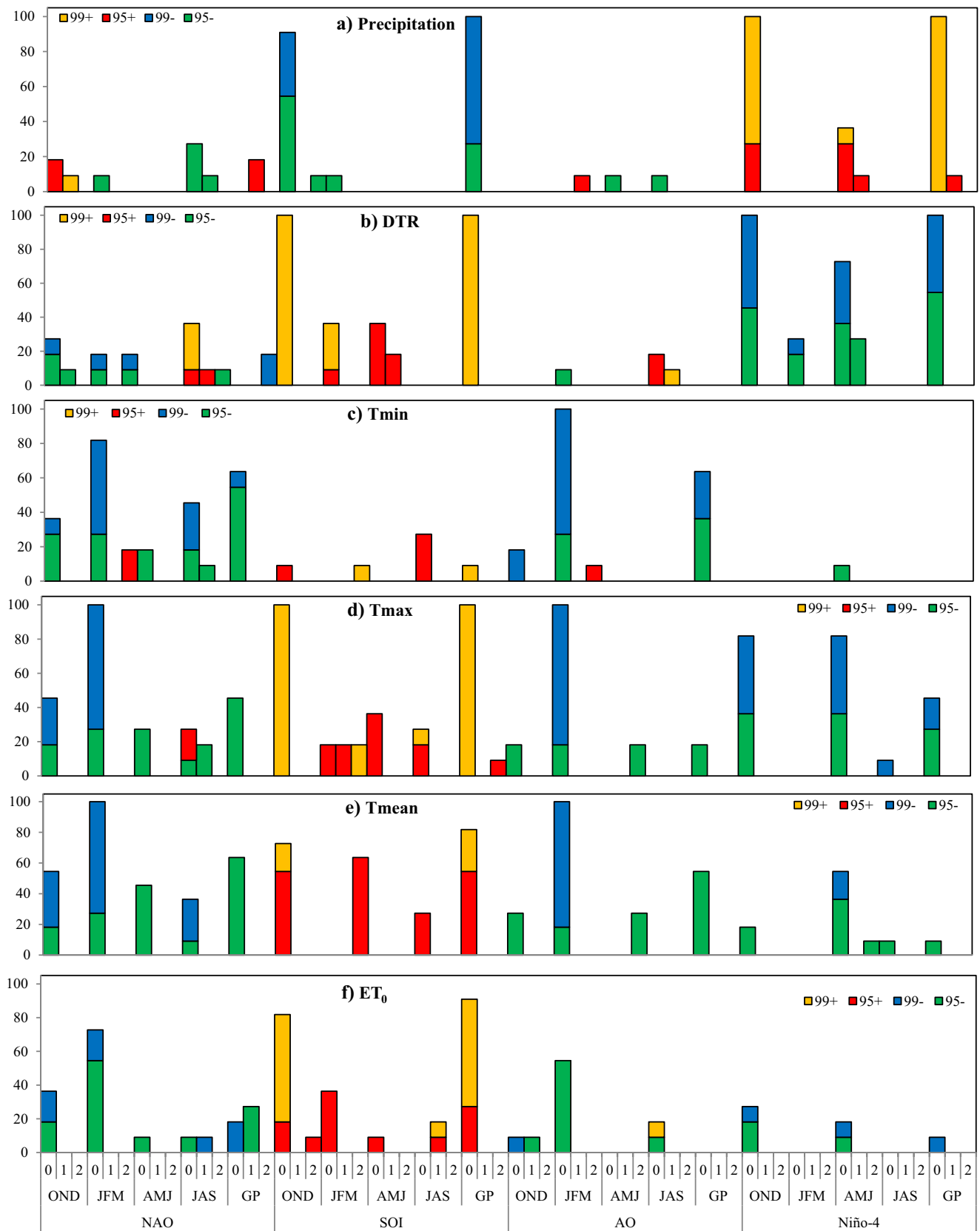


Fig. 4 (continued)



**Fig. 5** The percentage of the sites with significant association between the local weather factors and the global teleconnection indices over the OND, JFM, AMJ, JAS, and EGS at 0-, 1-, and 2-year lag (99+ and 95+

(99- and 95-) indicate significant positive (negative) associations at the levels of significance 0.05 and 0.01, respectively). **a** Precipitation, **b** DTR, **c**  $T_{min}$ , **d**  $T_{max}$ , **e**  $T_{mean}$ , **f**  $ET_0$

since the lag correlations were primarily found to be insignificant (Fig. 4). The average correlation coefficients of  $-0.52$  and  $0.47$  were, respectively, obtained for the JAS SOI and Niño-4 with the OND precipitation. Nazemosadat and Cordery (2000) also found that summer SOI can be used to predict autumn rainfall in northwest and west Iran. As a result, the pre-growing season (JAS) ENSO anomalies influence winter cereal yields through impacting the OND precipitation in the studied area. The OND and JAS ENSO-related signals can be therefore used as a reliable proxy for yield forecasting in the investigated regions. Unlike in northwest and west Iran, rainfed crop yield is not influenced by the ENSO phenomenon in northeast Iran (Bannayan et al. 2011).

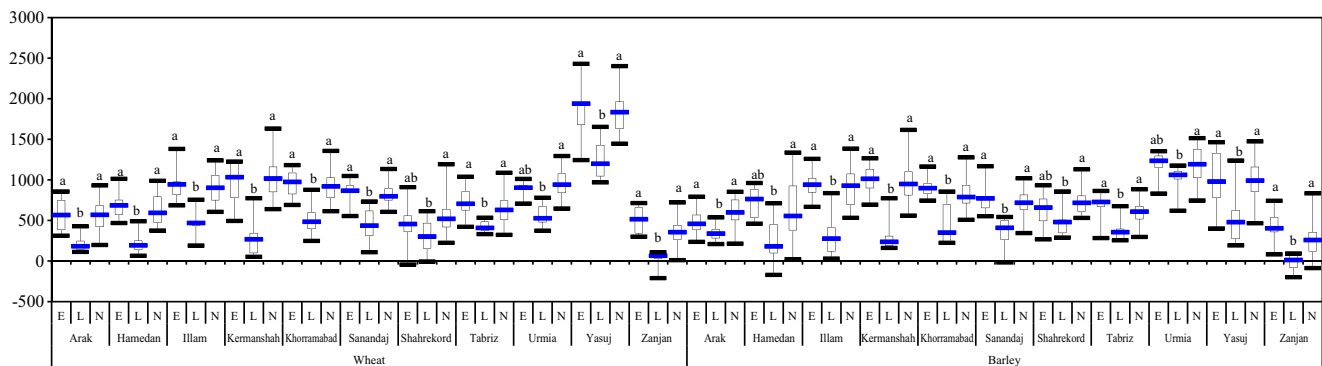
A strong correlation between  $T_{max}$  and the SOI ( $r = 0.58$ ) and Niño-4 ( $r = -0.35$ ) indices was identified in the study area (Fig. 5d). However, the correlation coefficients of the  $T_{min}$ -SOI and  $T_{min}$ -Niño-4 relationships were statistically insignificant for almost all locations at zero lag. Since  $T_{max}$ , but not  $T_{min}$ , is greatly affected by the ENSO oscillation (Fig. 5c, d), DTR is significantly correlated with the ENSO indices. The SOI signal has also a significant positive correlation with the OND and EGS  $ET_0$  in 72.7 and 81.8% and with the OND and EGS  $T_{mean}$  for 81.8 and 90.9% of sites, respectively. On the contrary, the relationship between the Niño-4 and  $T_{mean}$  and  $ET_0$  was statistically weak in most cases (Fig. 5e, f).

The average wheat yields were 854.7, 427.3, and 835.9  $kg\ ha^{-1}$  and barley harvests were 792.2, 403.9, and 768.4  $kg\ ha^{-1}$  in El Niño, La Niña, and normal years, respectively. Moreover, the yields were mostly significantly lower in La Niña periods and insignificantly higher in El Niño episodes with respect to normal years (Fig. 6). West and northwest Iran mostly receive below-normal precipitation during autumn of La Niña years (Nazemosadat and Cordery 2000). The crop establishment and germination are likely therefore to be negatively impacted by autumnal drought in La Niña episode causing severe yield drop. As La Niña occurrence can be foreseen earlier, some measures such as changing planting date and/or supplemental irrigation can offset yield reduction

during La Niña phases in Iran’s western drylands. Iran imports a large portion of wheat from some countries such as Canada, Australia, France, and Turkey wherein wheat loss is anticipated during El Niño (Abdolrahimi 2016). Thus, increasing rainfed wheat production can reduce Iran’s need to import wheat and benefit the economy of the country. In addition to favorable climatic conditions, adopting some management practices such as pest and weed control can lead to a considerable increase in cereal harvests over western Iran in El Niño years.

### Conclusions

Our results indicate that rainfed cereal yields are not strongly impacted by temperature-related stresses at northwest and west Iran. However, the adverse influence of high temperature on crop yield was significant in dry crop seasons. The correlations of crop harvests with DTR and precipitation (particularly during the OND and AMJ) were significant for most cases. Increase in DTR mostly coinciding with precipitation shortage causes a yield loss. The NAO and AO indices showed no significant correlation with precipitation and DTR and consequently cereal yields. However, there is a strong correlation between the SOI and Niño-4 indices and precipitation and DTR over the OND and EGS. Unlike the AO and NAO anomalies, the ENSO teleconnection therefore considerably influences cereal yields through affecting the OND and EGS DTR and precipitation in the studied regions. Furthermore, the pre- and early season Niño-4 seems to be a good proxy for forecasting rainfed cereal yields in the study area. Compared with normal years, cereal yields were insignificantly higher in El Niño years and significantly lower during La Niña episodes. The harvest drop in the La Niña phase can be accounted for by autumnal drought. Some adaptive options such as supplemental irrigation and sowing date shift are thus needed to be adopted in La Niña years. Further,



**Fig. 6** The box plots of the crop yields ( $kg\ ha^{-1}$ ) in El Niño (E), La Niña (L), and normal (N) years (boxes’ boundaries indicate the 25th and 75th percentiles, the lines within the boxes mark the median, and the inner and

outer fences represent the lowest and highest values, respectively. Furthermore, different letters indicate the significant difference at 95% probability level)

rained production can be improved by implementing appropriate management practices over El Niño years.

## References

- Abdolrahimi M (2016) The effect of El Niño Southern Oscillation (ENSO) on world cereal production. The University of Sydney
- Alexandrov V, Hoogenboom G (2000) Vulnerability and adaptation assessments of agricultural crops under climate change in the south-eastern USA. *Theor Appl Climatol* 67:45–63. doi:10.1007/s007040070015
- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration—guidelines for computing crop water requirements—FAO irrigation and drainage paper 56. FAO, Rome 300:6541
- Asseng S, Foster I, Turner NC (2011) The impact of temperature variability on wheat yields. *Glob Chang Biol* 17:997–1012. doi:10.1111/j.1365-2486.2010.02262.x
- Bannayan M, Sanjani S, Alizadeh A, Lotfabadi SS, Mohamadian A (2010) Association between climate indices, aridity index, and rainfed crop yield in northeast of Iran. *Field Crop Res* 118:105–114. doi:10.1016/j.fcr.2010.04.011
- Bannayan M, Lotfabadi SS, Sanjani S, Mohamadian A, Aghaalikhani M (2011) Effects of precipitation and temperature on crop production variability in northeast Iran. *Int J Biometeorol* 55:387–401. doi:10.1007/s00484-010-0348-7
- Barnston AG, Tippett MK, L'Heureux ML, Li S, DeWitt DG (2012) Skill of real-time seasonal ENSO model predictions during 2002–11: is our capability increasing? *Bull Am Meteorol Soc* 93:631–651. doi:10.1175/BAMS-D-11-00111.1
- Bonsal BR, Zhang X, Vincent LA, Hogg WD (2001) Characteristics of daily and extreme temperatures over Canada. *J Clim* 14:1959–1976. doi:10.1175/1520-0442(2001)014<1959:CODAET>2.0.CO;2
- Brown I (2013) Influence of seasonal weather and climate variability on crop yields in Scotland. *Int J Biometeorol*. 57:605–614. doi:10.1007/s00484-012-0588-9
- Cai W, Borlace S, Lengaigne M, Van Rensch P, Collins M, Vecchi G, Timmermann A, Santos A, McPhaden MJ, Wu L (2014) Increasing frequency of extreme El Niño events due to greenhouse warming. *Nat Clim Chang* 4:111–116. doi:10.1038/nclimate2100
- Chen D, Cane MA, Kaplan A, Zebiak SE, Huang D (2004) Predictability of El Niño over the past 148 years. *Nature* 428:733–736. doi:10.1038/nature02439
- Dai A, Trenberth KE, Karl TR (1999) Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range. *J Clim* 12:2451–2473. doi:10.1175/1520-0442(1999)012<2451:EOCSMP>2.0.CO;2
- Ghasemi A, Khalili D (2006) The influence of the Arctic Oscillation on winter temperatures in Iran. *Theor Appl Climatol* 85:149–164. doi:10.1007/s00704-005-0186-4
- Gibbs WJ, Maher JV (1967) Rainfall deciles as drought indicators. Australian Bureau of Meteorology, Bull. 48, pp 37
- Gimeno L, Ribera P, Iglesias R, de la Torre L, García R, Hernández E (2002) Identification of empirical relationships between indices of ENSO and NAO and agricultural yields in Spain. *Clim Res* 21:165–173. doi:10.3354/cr021165
- Hadley NF, Szarek SR (1981) Productivity of desert ecosystems. *Bioscience* 31:747–753. doi:10.2307/1308782
- Hallett TB, Coulson T, Pilkington JG, Clutton-Brock TH, Pemberton JM, Grenfell BT (2004) Why large-scale climate indices seem to predict ecological processes better than local weather. *Nature* 430:71–75. doi:10.1038/nature02708
- Hanley DE, Bourassa MA, O'Brien JJ, Smith SR, Spade ER (2003) A quantitative evaluation of ENSO indices. *J Clim* 16:1249–1258. doi:10.1175/1520-0442(2003)16<1249:AQEOEL>2.0.CO;2
- Homae M, Schmidhalter U (2008) Water integration by plants root under non-uniform soil salinity. *Irrig Sci* 27:83–95. doi:10.1007/s00271-008-0123-2
- Homae M, Dirksen C, Feddes R (2002a) Simulation of root water uptake: I. Non-uniform transient salinity using different macroscopic reduction functions. *Agric Water Manag* 57:89–109. doi:10.1016/S0378-3774(02)00072-0
- Homae M, Feddes R, Dirksen C (2002b) Simulation of root water uptake: II. Non-uniform transient water stress using different reduction functions. *Agricultural water management* 57:111–126. doi:10.1016/S0378-3774(02)00071-9
- Hurrell JW, Kushnir Y, Visbeck M (2001) The North Atlantic Oscillation. *Science* 291:603–605. doi:10.1126/science.1058761
- Hurrell JW, Kushnir Y, Otttersen G, Visbeck M (2013) An overview of the North Atlantic Oscillation. In: the North Atlantic Oscillation: climatic significance and environmental impact. American Geophysical Union, pp 1–35. doi: 10.1029/134GM01
- Lobell DB (2007) Changes in diurnal temperature range and national cereal yields. *Agric For Meteorol* 145:229–238. doi:10.1016/j.agrformet.2007.05.002
- Lobell DB, Ortiz-Monasterio JI, Asner GP, Matson PA, Naylor RL, Falcon WP (2005) Analysis of wheat yield and climatic trends in Mexico. *Field Crop Res* 94:250–256. doi:10.1016/j.fcr.2005.01.007
- Lobell DB, Cahill KN, Field CB (2007) Historical effects of temperature and precipitation on California crop yields. *Clim Chang* 81:187–203. doi:10.1007/s10584-006-9141-3
- McPhaden MJ, Zebiak SE, Glantz MH (2006) ENSO as an integrating concept in earth science. *Science* 314:1740–1745. doi:10.1126/science.1132588
- Mearns LO, Rosenzweig C, Goldberg R (1997) Mean and variance change in climate scenarios: methods, agricultural applications, and measures of uncertainty. *Clim Chang* 35:367–396. doi:10.1023/A:1005358130291
- Ministry of Agriculture (2015) Statistics of agricultural products, crop production in 2013–2014. Office of Statistics and Information Technology. Ministry of Agriculture, Tehran
- Modarres R, Ouarda T (2014) Modeling the relationship between climate oscillations and drought by a multivariate GARCH model. *Water Resour Res* 50:601–618. doi:10.1002/2013WR013810
- Morid S, Smakhtin V, Moghaddasi M (2006) Comparison of seven meteorological indices for drought monitoring in Iran. *Int J Climatol* 26:971–985. doi:10.1002/joc.1264
- Nazemosadat M (1999) ENSO's impact on the occurrence of autumnal drought in Iran. *Drought Network News* (1994–2001) Paper 65
- Nazemosadat M (2001a) Winter drought in Iran: associations with ENSO. *Drought Network News* (1994–2001) Paper 63
- Nazemosadat M (2001b) Winter rainfall in Iran: ENSO and aloft wind interactions. *Iranian Journal of Science and Technology Transactions of Civil Engineering* 25:611–624
- Nazemosadat M, Cordery I (2000) On the relationships between ENSO and autumn rainfall in Iran. *Int J Climatol* 20:47–61. doi:10.1002/(SICI)1097-0088(200001)20:1<47::AID-JOC461>3.0.CO;2-P
- Nazemosadat M, Ghasemi A (2004) Quantifying the ENSO-related shifts in the intensity and probability of drought and wet periods in Iran. *J Clim* 17:4005–4018. doi:10.1175/1520-0442(2004)017<4005:QTESIT>2.0.CO;2
- Nouri M, Homae M, Bannayan M, Hoogenboom G (2016) Towards modeling soil texture-specific sensitivity of wheat yield and water balance to climatic changes. *Agric Water Manag* 177:248–263. doi:10.1016/j.agwat.2016.07.025
- Pingali PL (2012) Green Revolution: Impacts, limits, and the path ahead. *Proc Natl Acad Sci USA* 109:12302–12308. doi:10.1073/pnas.0912953109

- Podesta G, Letson D, Messina C, Royce F, Ferreyra RA, Jones J, Hansen J, Llovet I, Grondona M, O'Brien JJ (2002) Use of ENSO-related climate information in agricultural decision making in Argentina: a pilot experience. *Agric Syst* 74:371–392. doi:[10.1016/S0308-521X\(02\)00046-X](https://doi.org/10.1016/S0308-521X(02)00046-X)
- Prasad PVV, Pispapati SR, Momčilović I, Ristic Z (2011) Independent and combined effects of high temperature and drought stress during grain filling on plant yield and chloroplast EF-Tu expression in spring wheat. *J Agron Crop Sci* 197:430–441. doi:[10.1111/j.1439-037X.2011.00477.x](https://doi.org/10.1111/j.1439-037X.2011.00477.x)
- Ray DK, Gerber JS, MacDonald GK, West PC (2015) Climate variation explains a third of global crop yield variability. *Nature Commun* 6 doi: [10.1038/ncomms6989](https://doi.org/10.1038/ncomms6989)
- Ribot JC, Najam A, Watson G (2005) Climate variation, vulnerability and sustainable development in the semi-arid tropics. In: Ribot JC, Magalhaes AR, Panagides S (eds) *Climate variability, climate change and social vulnerability in the semi-arid tropics*. Cambridge University Press, New York
- Rodwell MJ (2013) On the predictability of North Atlantic climate. In: Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (eds) *The North Atlantic Oscillation: climatic significance and environmental impact*. American Geophysical Union, pp 173–192. doi:[10.1029/134GM08](https://doi.org/10.1029/134GM08)
- Rogers JC (1984) The association between the North Atlantic Oscillation and the Southern Oscillation in the northern hemisphere. *Mon Weather Rev* 112:1999–2015. doi:[10.1175/1520-0493\(1984\)112<1999:TABTNA>2.0.CO;2](https://doi.org/10.1175/1520-0493(1984)112<1999:TABTNA>2.0.CO;2)
- Sadeghi A, Kamgar-Haghighi A, Sepaskhah A, Khalili D, Zand-Parsa S (2002) Regional classification for dryland agriculture in southern Iran. *J Arid Environ* 50:333–341. doi:[10.1006/jare.2001.0822](https://doi.org/10.1006/jare.2001.0822)
- Shuai J, Zhang Z, Sun D-Z, Tao F, Shi P (2013) ENSO, climate variability and crop yields in China. *Clim Res* 58:133–148. doi:[10.3354/cr01194](https://doi.org/10.3354/cr01194)
- Stenseth NC, Mysterud A (2005) Weather packages: finding the right scale and composition of climate in ecology. *J Anim Ecol* 74: 1195–1198. doi:[10.1111/j.1365-2656.2005.01005.x](https://doi.org/10.1111/j.1365-2656.2005.01005.x)
- Stenseth NC, Ottersen G, Hurrell JW, Mysterud A, Lima M, Chan KS, Yoccoz NG, Ådlandsvik B (2003) Review article. Studying climate effects on ecology through the use of climate indices: the North Atlantic Oscillation, El Niño Southern Oscillation and beyond. *Proc R Soc Lond Ser B Biol Sci* 270:2087–2096. doi:[10.1098/rspb.2003.2415](https://doi.org/10.1098/rspb.2003.2415)
- Stige LC, Stave J, Chan K-S, Ciannelli L, Pettorelli N, Glantz M, Herren HR, Stenseth NC (2006) The effect of climate variation on agropastoral production in Africa. *Proc Natl Acad Sci U S A* 103:3049–3053. doi:[10.1073/pnas.0600057103](https://doi.org/10.1073/pnas.0600057103)
- Stone P, Nicolas M (1995) Comparison of sudden heat stress with gradual exposure to high temperature during grain filling in two wheat varieties differing in heat tolerance. I. Grain growth. *Funct Plant Biol* 22:935–944. doi:[10.1071/PP9950935](https://doi.org/10.1071/PP9950935)
- Tabari H, Abghari H, Hosseinzadeh Talae P (2014) Impact of the North Atlantic Oscillation on streamflow in western Iran. *Hydrol Process* 28:4411–4418. doi:[10.1002/hyp.9960](https://doi.org/10.1002/hyp.9960)
- Tao F, Yokozawa M, Liu J, Zhang Z (2008) Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Clim Res* 38:83–94. doi:[10.3354/cr00771](https://doi.org/10.3354/cr00771)
- Thompson DW, Wallace JM (1998) The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys Res Lett* 25:1297–1300. doi:[10.1029/98GL00950](https://doi.org/10.1029/98GL00950)
- Tkadlec E, Zboril J, Losík J, Gregor P, Lisická L (2006) Winter climate and plant productivity predict abundances of small herbivores in central Europe. *Clim Res* 32:99–108. doi:[10.3354/cr0320999](https://doi.org/10.3354/cr0320999)
- Trenberth KE (1997) The definition of El Niño. *Bull Am Meteorol Soc* 78:2771–2777. doi:[10.1175/1520-0477\(1997\)078<2771:TDOENO>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<2771:TDOENO>2.0.CO;2)
- Tubiello F, Rosenzweig C, Goldberg R, Jagtap S, Jones J (2002) Effects of climate change on US crop production: simulation results using two different GCM scenarios. Part I: wheat, potato, maize, and citrus. *Clim Res* 20:259–270. doi:[10.3354/cr020259](https://doi.org/10.3354/cr020259)
- UNEP (1997) *World atlas of desertification*, Second edn. Arnold, United Nations Environment Programme, London
- Weiss JL, Gutzler DS, Coonrod JEA, Dahm CN (2004) Long-term vegetation monitoring with NDVI in a diverse semi-arid setting, central New Mexico, USA. *J Arid Environ* 58:249–272. doi:[10.1016/j.jaridenv.2003.07.001](https://doi.org/10.1016/j.jaridenv.2003.07.001)