
Volume 118, Issue 2, 8 August 2010
ISSN 0378-4290
118(2) 105–198 (2010)
ELSEVIER
Field Crops Research
AN INTERNATIONAL JOURNAL

Field Crops Research 118 (2010) 105–114

Contents lists available at ScienceDirect

Field Crops Research

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

Association between climate indices, aridity index, and rainfed crop yield in northeast of Iran

Mohammad Bannayan[a,*], Sarah Sanjani[a], Amin Alizadeh[a], S. Sadeghi Lotfabadi[a], Azadeh Mohamadian[b]

[a] Ferdowsi University of Mashhad, Faculty of Agriculture, P.O. Box 91775-1163, Mashhad, Iran
[b] Climatological Research Institute, Climatology of Atmospheric Disasters Group, P.O. Box 91735-676, Mashhad, Iran

ARTICLE INFO

Article history:
Received 7 November 2009
Received in revised form 21 April 2010
Accepted 21 April 2010

Keywords:
Crop yield variability
Climate indices
Weather variability and agriculture
Rainfed crop production

ABSTRACT

Agricultural drought occurs when there is a deficit in soil water supply to crops. Severe drought limits crop water availability and reduces yield. Rainfed crop production is very vulnerable to drought conditions and farmers in northeast of Iran who heavily depend on their rainfed cereals production usually suffer from drought occurrence. Based on history, any severe drought resulted in severe financial problems and forced the affected farmers to move to cities in search of alternative jobs. Any possibility to enable the farmers to mitigate or adapt to drought is highly required. In this study, the relationship between aridity index (AI) and detrended crop yield (1985–2005) of selected crops (wheat and barley) and the influence of three climate indices (AO, NAO and NINO-3.4) were assessed for Khorasan province in northeast of Iran. All associations were assessed at annual, seasonal (wet and dry seasons) and monthly scale considering both concurrent and lag correlations (1-year and 2-year lag). Our results indicated a significant correlation ($P<0.05$) between the AI and crops yield mostly in central Khorasan province. Our study also showed that correlation coefficient between AI and barley yield was stronger than AI and wheat yield across all study locations. Seasonal (wet) AI showed significant correlation with crops yield. These results demonstrated that, in some areas of Khorasan, drought is one of the key causes of interannual yield variability. We also observed a significant association between NAO and NINO-3.4 with AI. Precipitation is one of the components of AI, so AI response to NAO and NINO-3.4 can be related to the observed association between this index and precipitation. It seems that these indices could be useful tools to monitor drought patterns and subsequent yield variability in some regions of Khorasan province.

1. Introduction

Drought with varying frequency, intensity, and duration affect most land areas of the world. In addition, drought is one of the most expensive types of natural disasters in developed societies where a large part of the economy is based on industrial agriculture (FEMA, 1995), and is very costly in terms of human life in societies that are dependent on subsistence agriculture (FAO, 2004). Complex nature and varying effects of drought on many aspects of biosystems have made it difficult to understand and project any possible mitigation of its adverse impacts (Wilhite, 2000). Drought is the result of insufficient or lack of rainfall for an extended period, that causes a considerable hydrological (water) imbalance. Drought reduces the productions of crops (Bates et al., 2008; Giunta et al., 1993), horticulture and rangeland forest (Guarín and Taylor, 2005), water level and quality (Van Vliet and Zwolsman, 2008), and increases livestock and wildlife mortality (Díaz-Solís et al., 2009; Oba, 2001). Water deficit during drought spells is one of the most significant stress factors on crop production worldwide (e.g., Narasimhan and Srinivasan, 2005; Lobell and Field, 2007; Bannayan et al., 2008). Crop production is highly vulnerable to climate variability, particularly recurrent droughts (Chimeli et al., 2002). Hlavinka et al. (2009) found a statistically significant correlation ($P<0.05$) between the palmer's relative Z-index for the main growing period of crops and the yield departures of spring barley within 81% (winter wheat in 57%, maize in 48%, potato in 89%, oats in 79%, winter rye in 52%, rape in 39%) at their study districts in Czech Republic.

The country of Iran covers an area of 1,648,000 km^2 and due to its geographical location and topographical features has arid and semiarid climates. Its climate, both temporally and spatially, is highly variable with coefficient of variation of annual rainfall as high as 70% (Nazemosadat, 2000). The average annual precipitation in Iran is approximately 250 mm (Moradi, 2004). Most parts of Iran

* Corresponding author. Tel.: +98 511 8795616; fax: +98 511 8787430.
E-mail addresses: mobannayan@yahoo.com, bannayan@uga.edu (M. Bannayan).

0378-4290/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2010.04.011

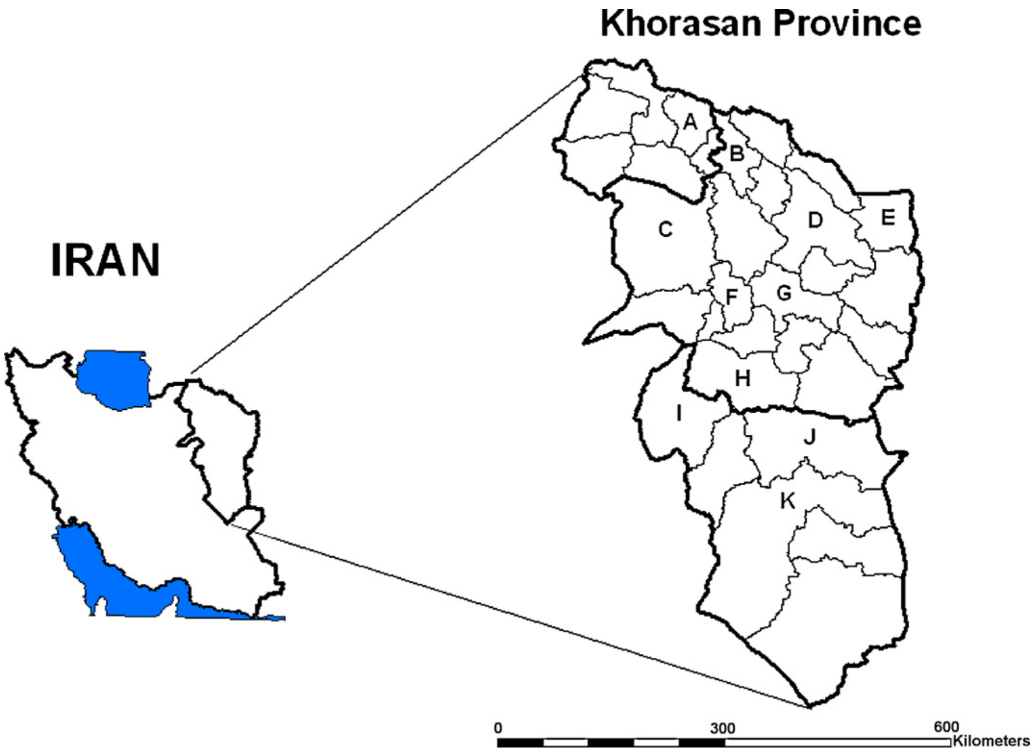


Fig. 1. Geographical study locations and synoptic weather stations (A: Boujnord, B: Ghoochan, C: Sabzevar, D: Mashhad, E: Sarakhs, F: Kashmar, G: Torbat heydarieh, H: Gonabad, I: Ferdows, J: Ghaen, K: Birjand).

experienced an exceptional drought that lasted more than 2 years (1998–2000) (Nazemosadat, 2000). In some areas, drought has also extended into the winter 2001. The 1998–2000 droughts inflicted \$3.5 billion loss, killing 800,000 head of livestock and drying up major reservoirs and internal lakes (Nazemosadat, 2000). The crops from a rainfed area of 4 million ha as well as those from an irrigated area of 2.7 million ha were completely destroyed (Shahabfar and Eitzinger, 2008). The rural population in central parts of the country has started migrating from their villages to other areas in search of water. Losses in agricultural and livestock production and the environmental damage of the drought have also been far greater.

Understanding and developing tools to predict and monitor drought would help in planning to mitigate the impacts of drought (Bannayan and Hoogenboom, 2008). Circulation patterns especially in 500 hpa level as the mid-atmosphere help to understand and predict precipitation more precisely. A significant correlation has been found between precipitation in Iran and circulation patterns (Alijani, 2002). By recognizing such patterns climatologists can predict many environmental phenomena such as flood and drought. Under limited water conditions, it seems reasonable to relate crop yield to the occurrence and severity of drought, which is usually expressed in terms of one or few indices. The index concept is not intended to be rigorously predictive, but is expected to provide reliable assessment of risk and detection of risk change. Narasimhan and Srinivasan (2005) showed that wheat and sorghum crop yields were highly correlated ($r > 0.75$) with some drought indices during critical crop growth stages, indicating that the development of drought indices can be used for monitoring agricultural drought. However drought evaluation indices were different on the basis of classification methods and procedures and showed different results in estimating drought intensity (Borhani and Daliri, 2007). A number of aridity indices have been proposed. These indices serve to identify, and locate regions that suffer from a deficit of available water. Most drought indices are based on meteorological or hydrological variables. These include the Palmer Drought Severity Index (PDSI; Palmer, 1965), Rainfall Anomaly Index (RAI; Van Rooy, 1965), Rainfall deciles (Gibbs and Maher, 1967), Crop Moisture Index

Table 1
Latitude (Lat), longitude (Long), elevation (Elev), and annual average of weather variables for the study locations in Khorasan, Iran.

Station	Lat (N)	Long (E)	Elev (m a.s.l)	Average minimum temperature (°C)	Average maximum temperature (°C)	Total precipitation (mm)	Climate data period	Crop data period
Birjand	32°52′	59°12′	1491	8.2	24.3	165.4	1985–2005	1984–2004
Boujnord	37°28′	57°19′	1091	6.9	19.6	265	1985–2005	1984–2004
Ferdows	33°58′	58°02′	1293	10	24.4	147.7	1985–2005	1984–2004
Ghaen	33°43′	59°10′	1432	6.3	22.3	175.8	1987–2005	1986–2004
Ghoochan	37°4′	58°30′	1287	6.4	19.3	311.8	1985–2005	1984–2005
Gonabad	34°21′	58°41′	1056	10.7	28.3	143.6	1987–2005	1986–2001
Kashmar	35°12′	58°28′	1109	11.9	23.6	201.3	1986–2005	1984–2005
Mashhad	36°16′	59°38′	999	8.3	21.6	256.5	1985–2005	1984–2005
Sabzevar	36°12′	57°43′	977	11.8	24.7	197.8	1985–2005	1986–2005
Sarakhs	36°32′	61°10′	235	11.1	24.7	189.6	1985–2005	1991–2005
Torbat h	35°16′	59°13′	1450	7.5	20.4	276.6	1985–2005	1984–2005

(CMI; Palmer, 1968), Bhalme and Mooley Drought Index (BMDI; Bhalme and Mooley, 1980), Surface Water Supply Index (SWSI; Shafer and Dezman, 1982), National Rainfall Index (RI; Gommes and Petrassi, 1994), Standardized Precipitation Index (SPI; McKee et al., 1993, 1995), and Reclamation Drought Index (RDI; Weghorst, 1996).

Köppen and Geiger (1928) developed the concept of a climate classification where arid regions were defined as those locations where the annual rainfall accumulation (cm) is less than $R/2$, where $R = 2 \times T$, if rainfall occurs mainly in the cold season, while $R = 2 \times T + 14$, if rainfall is evenly distributed throughout the year, and $R = 2 \times T + 28$, if rainfall occurs mainly in the hot season, where T is the mean annual temperature (°C). This was one of the first attempts at defining an aridity index. In 1948, Thornthwaite proposed AI defined as: $AI_T = 100 \times d/n$, where the water deficiency (d) is calculated as the sum of the monthly differences between precipitation and potential evapotranspiration for those months when the normal precipitation is less than the normal evapotranspiration; and where (n) stands for the sum of monthly values of potential evapotranspiration for the deficient months. The United Nations Environment Programme (UNEP) issued a dryness map based on a different aridity index, proposed originally by Budyko (1958) and defined as, $AI_B = 100 \times R/LP$, where R is the mean annual net radiation, P is the mean annual precipitation, and L is the latent heat of vaporization for water.

More recently, the UNEP has proposed another index of aridity, defined as, $AI_U = P/PET$, where PET is the potential evapotranspiration and P is the average annual precipitation (UNEP, 1992). However, this index has not been used for description of crop yield variability since now. In this study we employed aridity index (AI) based on UNEP (1992) to quantify the drought occurrence at each study location. Further details are provided under Section 2.

Many studies showed that the interannual variations in tropical SST can affect similar variations in precipitation or drought indices in many areas of the world (Ropelewski and Halpert, 1986; Kiladis and Diaz, 1989; Dai and Wigley, 2000; Diaz and Markgraf, 2000; Romero et al., 2007). Nazemosadat and Cordery (2000), investigated the relationships between Iranian autumn rainfall and the El Niño-Southern Oscillation (ENSO) phenomenon for the period 1951–1990. They reported that the associations between SOI and rainfall and found that during El Niño episodes, the amount of rainfall over various parts of the country was several times more than during La Niña periods. They concluded that autumn rainfall could be predicted a season ahead for some parts of the country. Ghasemi and Khalili (2006) studied the impact of the AO on the winter surface air temperature over Iran, using 50 years (1951–2000) data considering both the negative and the positive AO phases. For the negative phase, westerly winds that originate from the warm Atlantic regions increase over Iran and consequently positive temperature anomalies are found across the country. The positive AO phase is accompanied by northerly winds that allow continental polar and arctic air masses to move into Iran, producing below normal temperatures. Baigorria et al. (2008) showed that specific atmospheric circulation patterns in favor of high humidity, temperature, and rainfall during summer months are associated with low cotton yields in the southeast United States. They indicated physical and biological relationships between cotton yield and regional atmospheric circulation patterns and surface temperatures and concluded that evaluation of the predictability of cotton yields require evaluation of the output of the global circulation model (GCM) forced by SSTs that are forecast at the same lead time (Baigorria et al., 2008). Diaz et al. (1998) found significant relations between sea surface temperatures (SSTs) and precipitations in Uruguay and south Brazil. Barros et al. (2000) evidenced the influence of the South Atlantic convergence zone and SSTSA

Table 2
Linear correlation between AI and yield for all four comparisons. Correlations reaching 5% significance level are in gray.

Station	Crop	Lag	AI – yield	
			r	P-value
Birjand	Wheat	Lag 0	0.09	0.68
		Lag 1	−0.09	0.68
		Lag 2	−0.09	0.71
	Barley	Lag 0	0.01	0.95
		Lag 1	−0.14	0.59
		Lag 2	−0.01	0.96
Boujnord	Wheat	Lag 0	0.22	0.33
		Lag 1	0.21	0.37
		Lag 2	−0.003	0.99
	Barley	Lag 0	0.39	0.08
		Lag 1	0.16	0.5
		Lag 2	−0.41	0.08
Ferdows	Wheat	Lag 0	0.27	0.27
		Lag 1	0.17	0.5
		Lag 2	0.11	0.67
	Barley	Lag 0	NA	NA
		Lag 1	NA	NA
		Lag 2	NA	NA
Ghaen	Wheat	Lag 0	0.16	0.5
		Lag 1	0.25	0.33
		Lag 2	0.15	0.59
	Barley	Lag 0	0.24	0.34
		Lag 1	0.02	0.91
		Lag 2	0.36	0.19
Ghoochan	Wheat	Lag 0	0.72	0.0001
		Lag 1	0.35	0.12
		Lag 2	−0.08	0.72
	Barley	Lag 0	0.76	0.0005
		Lag 1	0.39	0.08
		Lag 2	−0.08	0.71
Gonabad	Wheat	Lag 0	0.42	0.18
		Lag 1	0.52	0.11
		Lag 2	0.1	0.78
	Barley	Lag 0	0.68	0.04
		Lag 1	0.8	0.1
		Lag 2	−0.15	0.84
Kashmar	Wheat	Lag 0	0.58	0.01
		Lag 1	−0.02	0.91
		Lag 2	−0.24	0.37
	Barley	Lag 0	0.5	0.03
		Lag 1	−0.02	0.93
		Lag 2	−0.18	0.5
Mashhad	Wheat	Lag 0	0.5	0.01
		Lag 1	0.3	0.19
		Lag 2	0.07	0.74
	Barley	Lag 0	0.27	0.25
		Lag 1	−0.07	0.77
		Lag 2	0.02	0.93
Sabzevar	Wheat	Lag 0	0.23	0.33
		Lag 1	−0.05	0.82
		Lag 2	−0.15	0.54
	Barley	Lag 0	0.36	0.13
		Lag 1	0.2	0.42
		Lag 2	−0.31	0.23
Sarakhs	Wheat	Lag 0	0.75	0.001
		Lag 1	0.38	0.19
		Lag 2	−0.41	0.18
	Barley	Lag 0	0.44	0.13
		Lag 1	0.2	0.52
		Lag 2	0.02	0.93
Torbat heydarieh	Wheat	Lag 0	0.54	0.01
		Lag 1	−0.08	0.7
		Lag 2	−0.13	0.18
	Barley	Lag 0	0.7	0.0005
		Lag 1	−0.006	0.97
		Lag 2	−0.36	0.13

on interannual summer rainfall variability in south-eastern South America (SESA). Mares et al. (2002) demonstrated that Palmer Drought Severity Index (PDSI) responses at the NAO signal in the cold half of the year with several lag months delay. Thus, it might be possible to find an association between climate indices (AO, NAO and NINO-3.4) and aridity index. In this way, it is expected to be able to predict the drought status and yield fluctuation of the following years. Research has indicated that the North Atlantic SSTs may have climatic predictability on the order of a decade or longer (Griffies and Bryan, 1997) which has important implications for climate forecasting. Various studies (Rao et al., 1997; Sun et al., 2006) indicated that corn yield in Ceará, Brazil are highly correlated with indices of SST (e.g., Niño-3.4 SST anomaly) and suggested that this can be used to predict crop yields in Ceará. The effects of climate indices are different at different locations and their effects may differ based on study crops. Gimeno et al. (2002) showed that the response to ENSO phases is weak, being only significant for lemon yields, whereas the response to NAO phases is stronger, being significant for lemon, wheat, rye and olive.

The goal of this work was to explore associations between aridity index and grain crop yield variability (wheat and barley) and precipitation in northeast of Iran known as Khorasan province (Fig. 1). Therefore the possible association between climate indices, aridity index and observed local crop yields in Khorasan province were investigated in order to find any potential predictability of aridity status and thus crop yields fluctuation, using climate indices.

2. Materials and method

2.1. Study site

The study area cover the northeast of Iran which includes the province Khorasan that lies between 38°S and 30°N latitude and 55°W and 61°E longitude, a semiarid location with area of 248,000 km^2 (Fig. 1). Cereals are the major crops in Khorasan province and this region (Table 1) is the top cereal producer among the other provinces. Cereals (wheat and barley in this study) are mainly produce under rainfed condition with cultivation area of 210,734 ha and 44,561 ha, respectively.

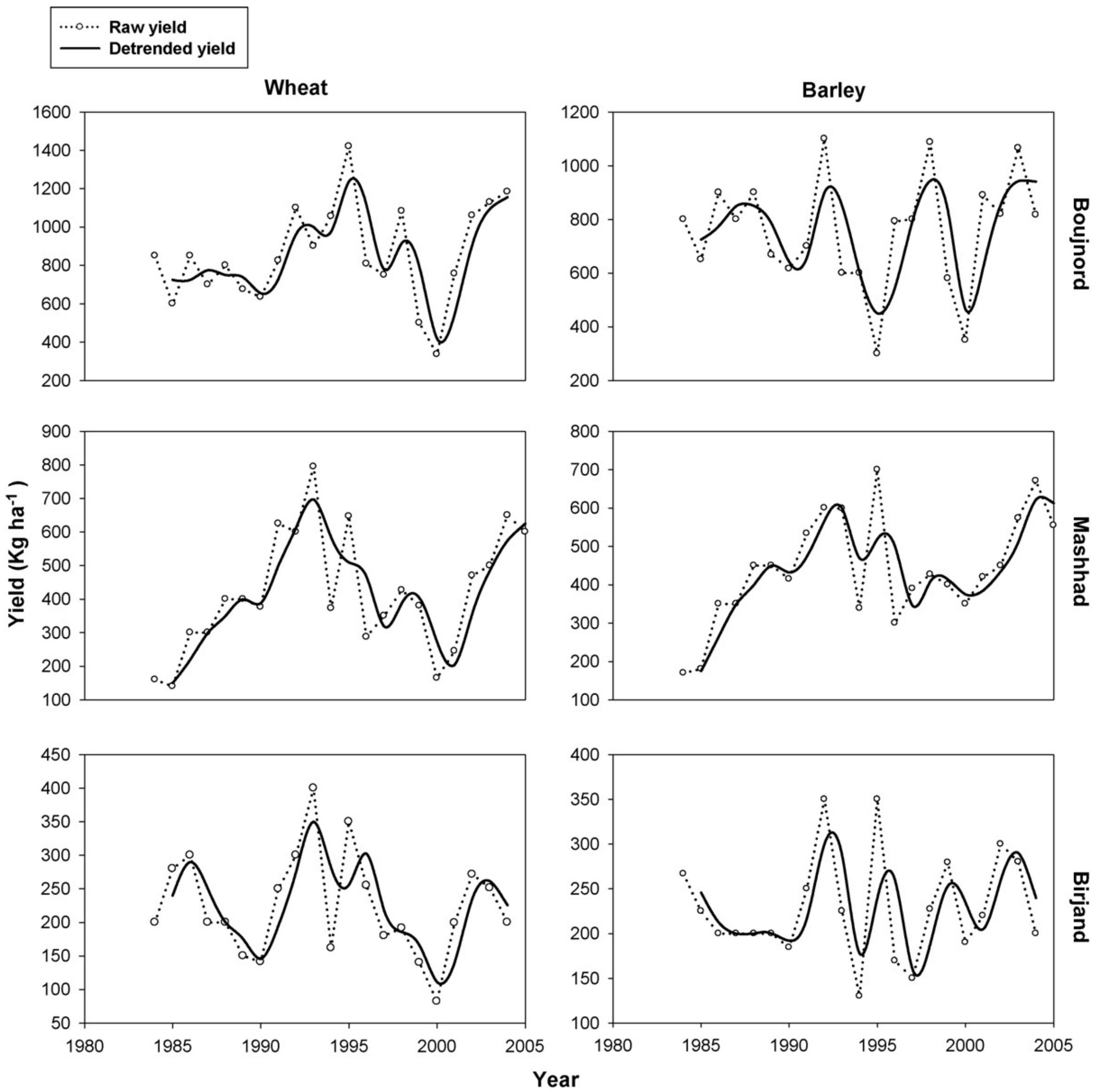


Fig. 2. Time series of wheat and barley (raw and detrended) yield, 1984–2005.

2.2. Crop yield data

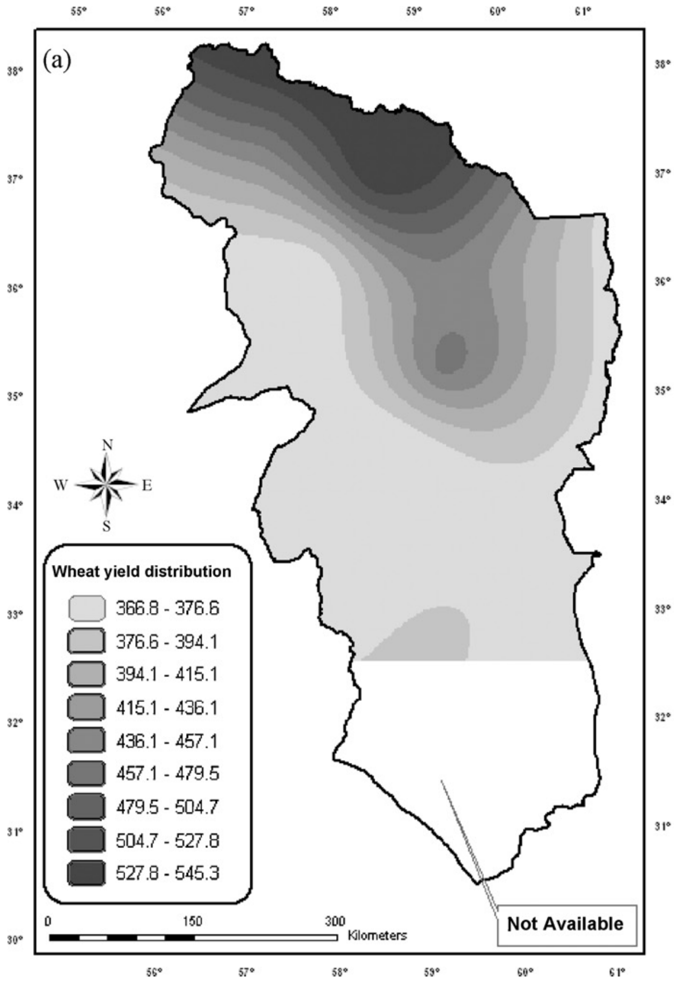
Wheat and barley are two main rainfed crops in Khorasan and the local farmers economy depends on the production of these two crops. The planting date of these two crops is not on a specific date but mainly depends on fall precipitation and their harvest also depends on late spring or the early summer temperature. Therefore both crops production under rainfed is totally depend on local climate. Historical crop yields at the county level for wheat and barley which are produced under rainfed conditions for 11 locations were obtained from the ministry of Agricultural Khorasan Research Station. For our study objectives, non-climatic influences such as improvement in crop genetics and technical factors were removed by detrending the time series in yield productions. To eliminate bias due to technological trend, yield was detrended (Fig. 2) by means of Double Exponential Smoothing (Joseph and LaViola, 2003) and yield anomalies were obtained as the difference between the yield in each year and average of observed long-term yield. Comparing to other approaches, exponential smoothing assigns exponentially decreasing weights as the observation get older. In other words, recent observations are given relatively more weight than the older observations. However, one should consider that it does not exactly remove the technology renovation trend across the years but is the best possible way to exclude the effect of other factors on historical yield change but the weather effects.

2.3. Climate indices and weather data

Daily weather data from 1985 to 2005 of 11 different locations (Table 1) across the study region were obtained from meteorological station at each location. These include minimum and maximum temperatures (°C), sunshine hours (h), relative humidity (%), wind speed (m h^{-1}), and precipitation (mm) to calculate ETo, using the FAO Penman-Monteith method (Jensen et al., 1990), and AI. These stations were selected in order to achieve a balanced, regional distribution as to represent the climatic conditions and availability of longer historical climate records (Fig. 1).

The three climate indices (monthly NAO, AO and NINO-3.4) were obtained from the NOAA website (http://www.cpc.ncep.noaa.gov/data/indices) which covers data from 1985 to 2005.

The North Atlantic Oscillation (NAO) is a dominant mode of multi-annual variability in the atmosphere, most pronounced in winter. It is characterized with the NAO index, which is defined as the pressure difference between Ponta Delgada, Azores (38°N, 26°W) and Akureyri, Iceland (66°N, 18°W) (Rogers, 1984; Jones et al., 1997). The Arctic Oscillation (AO) is the dominant pattern of non-seasonal sea-level pressure (SLP) variations north of 20N, and it is characterized by SLP anomalies of one sign in the Arctic and anomalies of opposite sign centered about 37–45N (Thompson and Wallace, 1998). The NINO-3.4 index defined as the mean monthly temperature anomaly in the area of the eastern tropical pacific: 5S–5N; 170–120W (Trenberth, 1997).



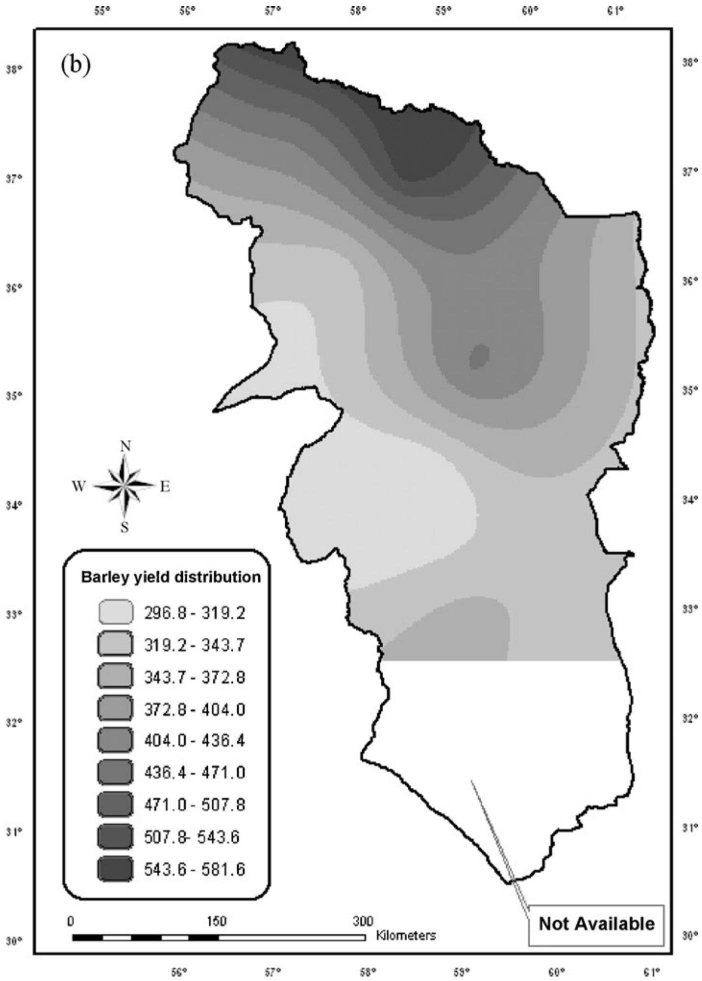


Fig. 3. Maps represent a spatial distribution of wheat (a) and barley (b) yield together with AI. Lower yields indicate higher AI.

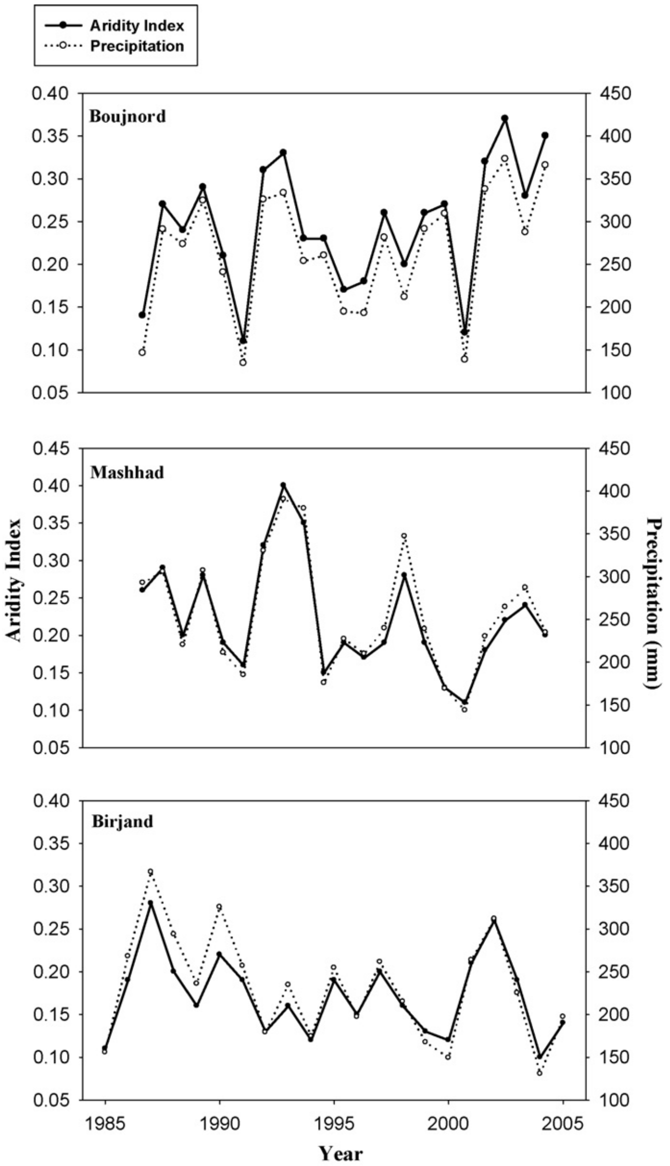


Fig. 4. Time series of annual AI and total precipitation for three representatives study locations (Boujnord, north; Mashhad, central; Birjand, south).

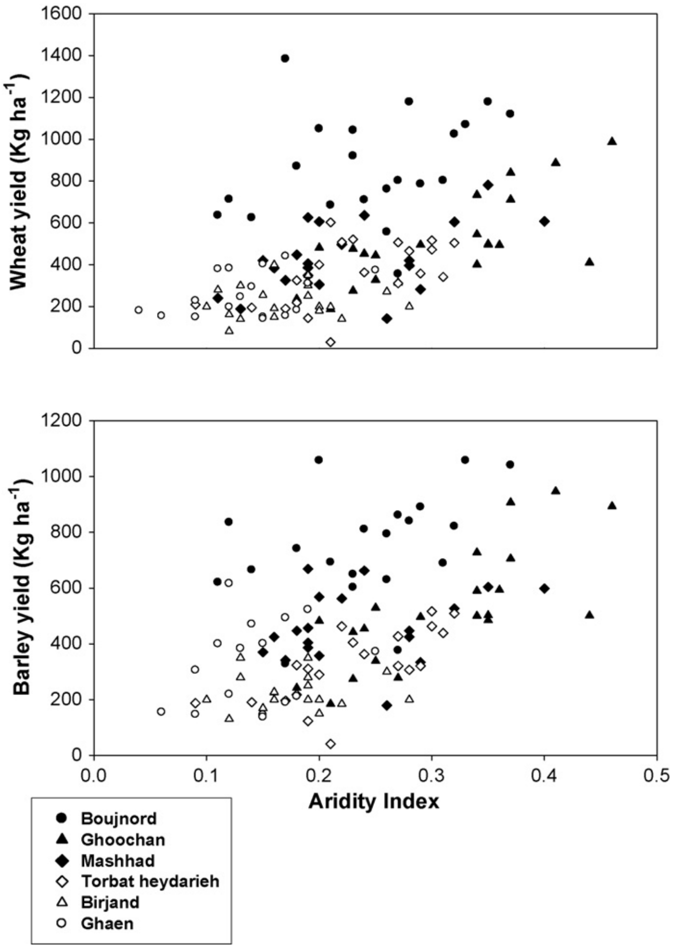


Fig. 5. Scattered plots of relationship between crop yield (wheat and barley) along with AI of six representatives locations which indicate high, medium and low crop yields.

2.4. Aridity index (AI)

In this study we employed Aridity index (UNEP, 1992) to quantify the drought occurrence as a numerical indicator of the degree of dryness of the climate at each study location. Aridity index (AI) was calculated as:

$$\mathrm{AI} = \frac{P}{\mathrm{PET}} \tag{1}$$

where PET is the either average monthly or annual potential evapotranspiration (mm) and P (mm) is the average monthly or annual precipitation (UNEP, 1992). To be consistent PET and P are expressed in the same units. In addition AI anomalies for each study location were also calculated as the difference between the AI in each year and long term AI average of the specific location. Such a definition corresponded to high values (above 0.6) for wet condition, which tend to have a positive effect on crop yield. Although the term of 'Aridity' becomes a misnomer. Potential ET (PET = ETo) was calculated using the FAO Penman-Monteith method (Jensen et al., 1990).

In this study, annual, seasonal and monthly time scale of AI were calculated. For seasonal calculation a year was considered as two season of wet and dry. Wet season included the Dec, Jan, Feb, Mar, Apr and May, months and dry season consisted of June, Jul, Aug, Sep, Oct and Nov months.

2.5. Analysis approach

Relation between grain yield (wheat and barley) and AI was assessed by means of linear correlation. Correlations were used as a measure of linear association between absolute yield/absolute AI, absolute yield/anomaly AI, anomaly yield/absolute AI and anomaly yield/anomaly AI at all study time scales. Correlation strength was measured in terms of its significance level (i.e. $P(|r| \neq 0)$) and only those with significance level lower than 0.05 are reported. Since our aim was also to give an insight into the potential for seasonal prediction, both concurrent and lag correlations (1-year and 2-year lag) were also computed.

Correlations between each climate index (AO, NAO, NINO-3.4) and aridity index were calculated for each location. In this study we used two scenarios to assess relation between AI and climate indices:

1. Correlation between monthly AI and monthly NAO, AO and NINO-3.4 across the whole year.
2. Correlation between average AI from November to June (the main growing season of barley and wheat in the study

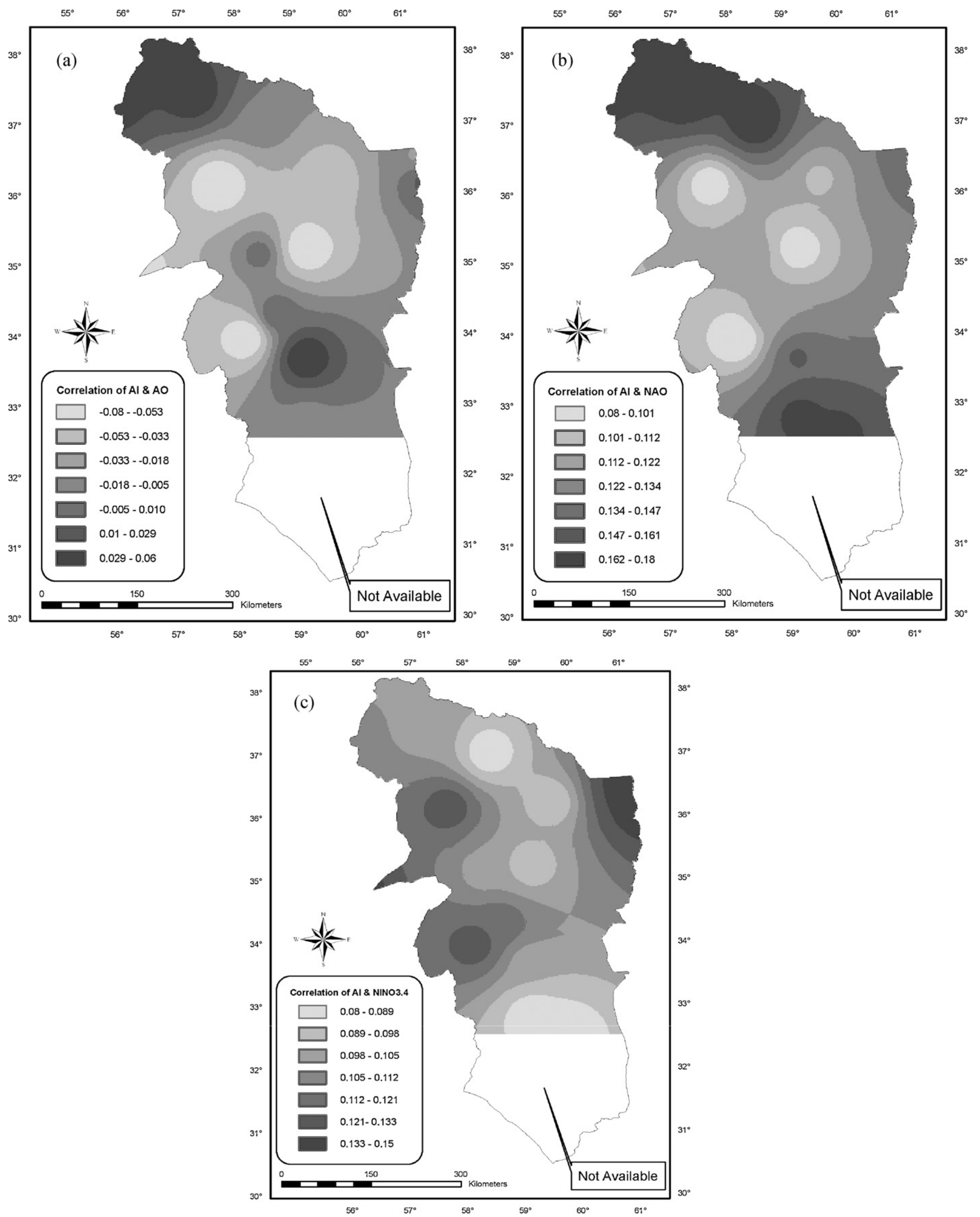


Fig. 6. Maps represent a spatial distribution of the correlation coefficient between the AI and climate indices including AO (a), NAO (b) and NINO-3.4 (c).

region) and three indices for each month of the growing season.

3. Results and discussion

3.1. Annual AI and crop yields

Correlations between annual AI and crop yield (wheat and barley) using four comparisons at the three lag period are shown in Table 2. Both the direction and extend of the correlation coefficients between absolute/anomalies of AI and absolute/anomalies of crop yield (all four possible comparisons) were similar for all study locations. Therefore reported correlations in here, were the relations between the absolute values of AI and crop yield. The range of correlation coefficient between AI and crop yield was −0.003 (Boujnord) and 0.75 (Sarakhs) for wheat and −0.01 (Birjand) and 0.76 (Ghoochan) for barley.

In some locations (Ghoochan, Gonabad, Kashmar, Sarakhs, Torbat heydarieh and Mashhad) a significant correlation ($P > 0.05$) between AI and both crop yields was obtained. The strongest correlation between AI and crop yield was found at Sarakhs ($r = +0.75$) for wheat and Ghoochan ($r = +0.76$) for barley. At other locations there was a high positive correlation but they were not significant. In Gonabad correlation coefficient was significant only for barley and in Sarakhs and Mashhad only for wheat. It can be concluded that the AI was able to describe the temporal variability of crop yield across different locations even when a severe drought spell emerge within the particular district. Mavromatis (2007) also showed that Palmer's drought severity index (PDSI) successfully described yield departures of durum wheat for severely dry years (R^2 was 0.83 within the Thessaloniki district, Greece), and during all their study years (high and low risk), PDSI explained 43.8% of the observed variability.

Significant correlation coefficient between AI and crop yield (wheat and barley) was found only at concurrent lag (Table 2). It may be due to the low soil storage capacity for water or rapid loss of water at hot summer months. High temperature during summer and even late spring together with almost no rain condition along with high evapotranspiration are typical characteristics of the study locations which are located within semiarid and arid environment. Nezami et al. (2005) in comparison of wheat-fallow with wheat-legume rotation, showed that due to soil water shortage under rainfed conditions, legumes almost did not produce any yield. At all study locations, significant correlation between AI and barley yield was stronger than wheat yield. The spatial distribution of the between crop yield (wheat (a) and barley (b)) and the AI is presented in Fig. 3. However it worth mention that any solid forecasting system should not only be based on a simple quantitative relation between variables alone and forecast skill and reliable method of climate indices calculations among other factors should be considered for further applications.

When wheat and barley are cultivated under rainfed conditions, they are strongly dependent to rainfall occurring during the growing season. Yield response to AI was linked through the association between this index and precipitation (Fig. 4). AI, quite closely followed the temporal and spatial variability of precipitation (Fig. 4) and grain yield of both crops have been raised as the AI decreased (Fig. 5).

3.2. Seasonal AI and crop yields

Correlations between seasonal (wet and dry) AI and crop yield (wheat and barley) are shown in Table 3. There is no significant correlation between AI and crop yield at dry seasonal scale except in Sarakhs for wheat ($r = 0.56$) but correlation between AI and crop yield at wet seasonal scale was significant in Boujnord, Ghoochan, Gonabad, Kashmar, Sarakhs and Torbat heydarieh. The strongest correlation between AI and crop yield at wet seasonal scale (for wheat and barley, respectively) was obtained in Ghoochan ($r = +0.64$) and Torbat heydarieh ($r = +0.71$). As both crops are grown within the wet season, it seems that it is not possible to provide any projection at dry season for growth during the wet season. This is similar to annual scale results which indicated that concurrent year shows higher correlation provide more correlative relationship than 1 or 2 years lags. Correlation coefficient between the AI and both crops yield, calculated for wet season (Dec–May) was higher in comparison to dry season across all locations (Table 3). Local farmers experiences and their indigenous knowledge indicates that high rainfall within the wet season (early to the middle of growing season) has the major role on final grain yield than rainfall occurrence within dry season (towards the end of the growing season). This is consistent with the finding of Narasimhan and Srinivasan (2005) which showed that high correlations of drought indices with wheat yield were widely spread during the growing season. This indicates that a reasonable amount of soil moisture during most part of the growing season would be favorable for wheat production. Between the two crops, correlation between wet season AI and barley yield was stronger than wet season AI and wheat yield (except in Kashmar), there was no specific difference between the yield of two crops in dry season and AI (Table 3).

Table 3
Correlation between seasonal AI and yield, Correlations reaching 5% significance level are in gray.

Station	Crop	Wet AI – yield		Dry AI – yield	
		r	*P*-value	r	*P*-value
Birjand	Wheat	0.096	0.68	0.2	0.3
	Barley	−0.16	0.51	0.4	0.1
Boujnord	Wheat	0.43	0.05	−0.32	0.15
	Barley	0.59	0.005	−0.33	0.14
Ferdows	Wheat	0.32	0.19	−0.25	0.3
	Barley	NA	NA	NA	NA
Ghaen	Wheat	0.05	0.81	0.13	0.59
	Barley	0.37	0.15	−0.24	0.35
Ghoochan	Wheat	0.64	0.001	0.14	0.53
	Barley	0.66	0.001	0.2	0.37
Gonabad	Wheat	0.47	0.13	−0.36	0.26
	Barley	0.7	0.03	−0.42	0.25
Kashmar	Wheat	0.59	0.01	−0.18	0.48
	Barley	0.5	0.03	−0.04	0.87
Mashhad	Wheat	0.51	0.017	0.29	0.19
	Barley	0.25	0.29	0.42	0.07
Sabzevar	Wheat	0.31	0.18	−0.39	0.09
	Barley	0.34	0.16	0.08	0.73
Sarakhs	Wheat	0.59	0.02	0.56	0.03
	Barley	0.31	0.29	0.37	0.2
Torbat heydarieh	Wheat	0.56	0.007	−0.07	0.73
	Barley	0.71	0.0004	−0.02	0.9

3.3. AI and climate indices

As climate indices are available for future months then any robust correlation between those indices and AI could provide a potential basis for any possible projection and required adaptation before drought occurs. Calculated correlation coefficients between climate indices and AI for all study locations are shown in Fig. 6. AI showed significant positive correlation with NAO and NINO-3.4 index in some locations (Birjand, Boujnord, Ghaen, Ghoochan, Sarakhs, Ferdows and Sabzevar). The strongest correlation was obtained at Boujnord and Ghoochan ($r = 0.18$) for NAO index and in Sarakhs ($r = 0.15$) related to NINO-3.4. No significant relationship was found between the AI and AO at all locations. Although previous studies (Ghasemi and Khalili, 2006) showed and inverse relationship between AO and temperature anomalies over Iran but there was no study yet on the relationship between AO and precipitation, which plays a main role in rainfed crop production, in this area. The relationship between NAO and AI was stronger than NINO-3.4. AI response to NAO and NINO-3.4 can be certainly related to the observed association between this index and precipitation (Fig. 4). Moradi (2004) showed that NAO had influence on precipitation and temperature across the whole country of Iran and demonstrated that the correlation between NAO and precipitation in northeast of Iran was high, especially in Boujnord, Mashhad, Sabzevar and Birjand.

4. Conclusion

Our study showed a significant correlation ($P > 0.05$) between AI and crop yields in some locations (Ghoochan, Gonabad, Kashmar, Sarakhs, Torbat heydarieh and Mashhad) in northeast of Iran. It can be concluded that the AI was able to describe the temporal variability of crop yield across different locations. AI, quite closely followed the temporal and spatial variability of precipitation and grain yield of our study crops have been raised as the AI decreased. Among the three study climate indices, AI showed significant positive correlation with NAO and NINO-3.4 index in most of our study locations (Birjand, Boujnord, Ghaen, Ghoochan, Sarakhs, Ferdows and Sabzevar). As climate indices are available for future months then any robust correlation between those indices and AI could provide a potential basis for any possible projection and required adaptation before drought occurs.

Acknowledgements

This study has been supported by the grant approval of the Ferdowsi University of Mashhad, Iran and the authors would like to appreciate it.

References

Alijani, B., 2002. Variations of 500 hPa flow patterns over Iran and surrounding areas and their relationship with the climate of Iran. Theor. Appl. Climatol. 72, 41–54.
Baigorria, G.A., Hansen, J.W., Ward, N., Jones, J.W., O'Brien, J.J., 2008. Assessing predictability of cotton yields in the Southeastern United States based on regional atmospheric circulation and surface temperatures. J. Appl. Meteorol. Clim. 47 (1), 76–91.
Bannayan, M., Nadjafi, F., Azizi, M., Tabrizi, L., Rastgoo, M., 2008. Yield and seed quality of *Plantago ovata* and *Nigella sativa* under different irrigation treatments. Ind. Crops Prod. 27, 11–16.
Bannayan, M., Hoogenboom, G., 2008. Weather analogue: a tool for real-time prediction of daily weather data realizations based on a modified k-Nearest Neighbor approach. Environ. Model. Softw. 3, 703–713.
Barros, V., Gonzĭalez, M., Liebmann, B., Camilloni, I., 2000. Influence of the South Atlantic convergence zone and South Atlantic sea surface temperature on interannual summer rainfall variability in southeastern South America. Theor. Appl. Clim. 67, 123–133.
Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. (Eds.), 2008. Climate Change and Water. Technical Paper. International Panel on Climate Change (IPCC) Secretariat, Geneva.
Bhalme, H.N., Mooley, D.A., 1980. Large-scale drought/floods and monsoon circulation. Mon. Weather Rev. 108, 1197–1211.
Borhani, T., Daliri, S., 2007. Evaluation of performance of drought models in southern Khorasan Province. In: 2nd International Conference on Integrated Natural Disaster Management.
Budyko, M.I., 1958. The Heat Balance of the Earth's Surface, trs. Nina A. Stepanova, US Department of Commerce, Washington, D.D., 259 pp.
Chimeli, A.B., Mutter, C.Z., Ropelewski, C., 2002. Climate fluctuations, demography and development: insights and opportunities for northeast Brazil. J. Int. Affairs 56, 213–234.
Dai, A., Wigley, T.M.L., 2000. Global patterns of ENSO-induced precipitation. Geophys. Res. Lett. 27, 1283–1286.
Diaz, H.F., Markgraf, V. (Eds.), 2000. El Niño and the Southern Oscillation. Cambridge University Press, United Kingdom, p. 496.
Díaz-Solís, H., Grant, W.E., Kothmann, M.M., Teague, W.R., Díaz-García, J.A., 2009. Adaptive management of stocking rates to reduce effects of drought on cow-calf production systems in semi-arid rangelands. Agric. Syst. 100, 43–50.
Diaz, A.F., Studzinski, C.D., Mechoso, C.R., 1998. Relationships between precipitation anomalies in Uruguay and Southern Brazil and sea surface temperature in the Pacific and Atlantic oceans. J. Clim. 11, 251–271.
FAO, 2004. The State of Food Insecurity in the World. Food and Agricultural Organization of the United Nations, Rome, Italy, 41 pp.
FEMA, 1995. National Mitigation Strategy; Partnerships for Building Safer Communities. Mitigation Directorate, Federal Emergency Management Agency, Washington, DC.
Gibbs, W.J., Maher, J.V., 1967. Rainfall deciles as drought indicators. Bureau of Meteorology Bull. 48, Commonwealth of Australia, Melbourne, Australia.
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, 165–172.
Giunta, F., Motzo, R., Deidda, M., 1993. Effect of drought on yield and yield components of durum wheat and triticale in Mediterranean environment. Field Crop Res. 33, 399–409.
Ghasemi, A.R., Khalili, D., 2006. The influence of the Arctic Oscillation on winter temperatures in Iran. Theor. Appl. Climatol. 85, 149–164.
Gommes, R., Petrassi, F., 1994. Rainfall variability and drought in Sub-Saharan Africa since 1960. Agro-meteorology series working paper 9, Food and Agriculture Organization, Rome, Italy.
Griffies, S.M., Bryan, K., 1997. Predictability of North Atlantic multidecadal climate variability. Science 275, 181–184.
Guarín, A., Taylor, A.H., 2005. Drought triggered tree mortality in mixed conifer forests in Yosemite National Park, California, USA. Forest Ecol. Manage 218, 229–244.
Hlavinka, P, Trnka, M., Semer adovaĭ, D., Dubrovskyĭ, M., Zalud, Z., Mozny, M., 2009. Effect of drought on yield variability of key crops in Czech Republic. Agric. For. Meteorol. 149, 431–442.
Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practice No. 70, Am. Soc. Civil Engr., New York, NY, 332 pp.
Jones, P.D., Jonsson, T., Wheeler, D., 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. Int. J. Climatol. 17, 1433–1450.
Joseph, J., LaViola Jr., 2003. An Experiment Comparing Double Exponential Smoothing and Kalman Filter-Based Predictive Tracking Algorithms. vr, pp.283, IEEE Virtual Reality Conference (VR 2003).
Kiladis, G.N., Diaz, H.F., 1989. Global climatic anomalies associated with extremes in the Southern Oscillation. J. Clim. 2, 1069–1090.
Köppen, W., Geiger, R., 1928. Klimakarte der Erde, Wall-map 150 cm × 200 cm. Verlag Justus Perthes, Gotha.
Lobell, D.B., Field, C.B., 2007. Global scale climate-crop yield relationship and the impact of recent warming. Environ. Res. Lett. 2, 1–7.
Mares, I., Mares, C., Mihailescu, M., 2002. NAO impact on the summer moisture variability across Europe. Phys. Chem. Earth. 27, 1013–1017.
Mavromatis, T., 2007. Drought index evaluation for assessing future wheat production in Greece. Int. J. Clim. 27, 911–924.
McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scale. In: Preprints, Eighth Conf. on Applied Climatology, Anaheim, CA, Amer. Meteor. Soc, pp. 187–190.
McKee, T.B., Doesken, N.J., Kleist, J., 1995. Drought monitoring with multiple time scales. In: Preprints, Ninth Conf. on Applied Climatology, Dallas, TX, Amer. Meteor. Soc, pp. 187–190.
Moradi, H.R., 2004. The effects of NAO index on climate of IRAN. Geog. Res. 48, 17–30.
Narasimhan, B., Srinivasan, R., 2005. Development and evaluation of soil moisture deficit index (SMDI) and evapotranspiration deficit index (ETDI) for agricultural drought monitor. Agric. For. Meteorol. 133, 69–88.
Nezami, A., Bagehri, A., Kafi, M., Mahmoodi, A., Abedi, K., 2005. Evaluation of legumes in rotation as an alternative to fallow in rainfed production in Khorasan. Agric. Sci. Technol. 19 (1), 191–204 (Abstract in English).
Nazemosadat, M.J., Cordery, I., 2000. On the relationships between ENSO and autumn rainfall in Iran. Int. J. Climatol. 20, 47–61.
Nazemosadat, M.J., 2000. Winter drought in Iran: association with ENSO. Drought Netw. News 13, 1.
Oba, G., 2001. The effect of multiple droughts on cattle in Obbu, Northern Kenya. J. Arid Environ. 49, 375–386.
Palmer, W.C., 1965. Meteorlogical drought. U.S. Weather Bureau Tech Paper 45, 1–58.
Palmer, W.C., 1968. Keeping track of crop moisture conditions, nationwide: the new crop moisture index. Weatherwise 21, 156–161.
Rao, V.B., Sa, L.D., Hfranchito, A.S., Hada, K., 1997. Interannual variations of rainfall and corn yields in northeast Brazil. Agric. For. Meteorol. 85, 63–74.
Rogers, J.C., 1984. The association between the North Atlantic Oscillation and the Southern Oscillation in the northern hemisphere. Mon. Weather Rev. 112, 1999–2015.
Romero, C.C., Baigorria, G.A., Stroosnijder, L., 2007. Changes of erosive rainfall for El Niño and La Niña years in the northern Andean Highlands of Peru: the case of La Encañada watershed. Clim. Change 85, 343–356.
Ropelewski, C.F., Halpert, M.S., 1986. North American precipitation and temperature patterns associated with El Niño/Southern Oscillation (ENSO). Mon. Weather Rev. 114, 2352–2362.

Shafer, B.A., Dezman, L.E., 1982. Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snow pack runoff areas. In: Proc. Western Snow Conf., pp. 164–175.
Shahabfar, A., Eitzinger, J., 2008. Spatial and temporal analysis of drought in Iran by using drought indices. In: European Conference on Applied Climatology (ECAC) (EMS 2008), Amsterdam, the Netherlands, Sep 29–Oct 3, 2008.
Sun, L., Huilan, L., Nell Ward, M., 2006. Climate variability and corn yields in semiarid Ceará, Brazil. J. Appl. Meteorol. Clim. 46, 226–240.
Thompson, D.W.J., Wallace, J.M., 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys. Res. Lett. 25 (9), 1297–1300.
Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94.
Trenberth, K.E., 1997. The definition of El Niño. Bull. Am. Meteorol. Soc. 78, 2771–2777.
United Nations Environment Programme (UNEP), 1992. World Atlas of Desertification.
Van Rooy, M.P., 1965. A rainfall anomaly index independent of time and space. Notos 14, 43.
Van Vliet, M.T.H., Zwolsman, J.J.G., 2008. Impact of summer droughts on the water quality of the Meuse river. J. Hydrol. 353, 1–17.
Weghorst, K.M., 1996. The reclamation drought index: Guidelines and practical applications. Bureau of Reclamation, Denver, CO, 6 pp [Available from Bureau of Reclamation, D-8530, Box 25007, Lakewood, CO 80226.].
Wilhite, D.A., 2000. Drought as a natural hazard: concepts and definitions. In: Donald, A., Wilhite (Eds.), Drought: A Global Assessment, vol. I. Routledge, New York, pp. 3–18 (Chapter 1).