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Assessing long-term spatio-temporal variability in humidity and drought in Iran using Pedj Drought Index (PDI)

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A R T I C L E I N F O

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A B S T R A C T

Although drought is a normal feature of climate, there is confusion about its characteristics in both arid and semi-arid regions. This study investigated the effects of changes in precipitation and temperature on spatio-temporal drought and humidity variations throughout the diverse (principally arid- and semi-arid) climates of Iran during recent decades using the Pedj Drought Index (PDI). The standardized anomaly index (SAI) for annual precipitation (SAI_{Pr}) and mean temperature (SAI_{Tm}) was calculated using their monthly records at sixteen meteorological stations scattered throughout Iran during 1951–2010. The results showed: (1) statistically significant ($p < 0.05$) drying trends in annual PDI values at most of the stations, primarily accompanied by substantial increases in annual SAI_{Tm}; (2) considerable positive and negative relationships of annual PDI with annual SAI_{Tm} and SAI_{Pr}, respectively; (3) the 1970s/2000s as the predominant humid/dry decade; (4) More frequent drought than humidity events at ~81% of stations; (5) the longest drought was 13 years (1998–2010) seen at the Kermanshah station, with the semi-dry climate in the west of Iran; and (6) the 2010 drought spatially extended over all the stations studied throughout the country. In conclusion, the PDI acceptably succeeded to characterize annual droughts in Iran previously captured by other prominent recommended drought indices.

1. Introduction

Since the last decade of the twentieth century, drought has been known as the most detrimental natural hazardous phenomenon mainly because of its disruptive impacts on the environment, economy, and society (Dai, 2011; Obasi, 1994; Wehner et al., 2011). The term 'drought' is differently defined in the literature (Mishra and Singh, 2010). According to European Commission (2007), a drought event is characterized by a significant shortage of natural freshwater availability for an extended period (months-years), principally due to the changes in precipitation and temperature patterns (Kundzewicz, 2009). Hence, the periods covering below-average precipitation could typically lead to temporary droughts, particularly in arid and semi-arid regions with relatively high temperatures. In general, the drought events around the world are classified into four groups of meteorological/climatological, soil moisture (agricultural), hydrological, and socio-economic (Mishra and Singh, 2010).

A large number of indices have already been developed based on hydroclimatic variables (e.g. precipitation, temperature, runoff, and soil moisture) (Dracup et al., 1980) to quantify different drought characteristics, in terms of severity, frequency, duration, and extension (Richard R Heim, 2002; Vicente-Serrano et al., 2012). Mishra and Singh (2010) and Mu et al. (2013) comprehensively reviewed such drought indices. The most common drought indices are Palmer Drought Severity Index (PDSI), Moisture Anomaly Index (Z-index) (Palmer, 1965), Precipitation Anomaly Index (RAI) (Van Rooy, 1965), Crop Moisture Index (CMI) (Palmer, 1968), Bhalme and Mooly Drought Index (BMDI) (Bhalme and Mooley, 1980), Surface Water Supply Index (SWSI) (Shafer and Dezman, 1982), National Precipitation Index (NRI) (Gommes and Petrassi, 1994), Standardized Precipitation Index (SPI) (McKee et al., 1993), Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), Reclamation Drought Index (RDI)

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(Weghorst, 1996), and Standardized Anomaly Index (SAI) (Katz and Glantz, 1986). Besides, Jiao et al. (2019) introduced an integrative drought index “Geographically Independent Integrated Drought Index (GIIDI)” based on a combination of different remote sensing indices. For most of these drought indices, precipitation is the only and/or key input hydrometeorological variable. However, drought analysis based on a single variable might not thoroughly describe this phenomenon, which is naturally related to different components of the water cycle (Quiring, 2009).

Keyantash and Dracup (2002) evaluated the ability of different drought indices to assess drought severity using a weighted set of criteria, including robustness, tractability, transparency, sophistication, extendibility, and dimensionality. They concluded that the most important criteria are robustness and tractability. The robustness refers to the ability of any given drought index to be spatially and temporally comparable, and the tractability to the practical aspects of the drought index. On the other hand, a drought index should simply be calculated using readily available data. To assess different drought characteristics, hence, Keyantash and Dracup (2002) recommended the use of SPI particularly due to its acceptable ability for detecting the onset of drought. On short timescales (1–3 months), the SPI is closely related to soil moisture, while at longer timescales (12–24 months), the SPI can be related to groundwater and reservoir storage. In spite of the popularity, the interpretation of SPI may be problematic in arid and semi-arid environments, where relatively high temperatures can affect climatic water balance (Mishra and Singh, 2010). In fact, a drought index based only on precipitation, particularly the SPI, can generally under-estimate the severity of dryness in the regions with very low or even zero precipitation (Naresh Kumar et al., 2009; Stagge et al., 2015). In other words, it does not deal with changes in evapotranspiration. Alternative indices that are suited for studies of the effect of global warming on drought severity have also been proposed (e.g. SPEI, RDI, etc.). These indices principally consider the effect of reference or potential evapotranspiration on drought severity. Elagib and Elhag (2011) used the Pedj drought index (PDI) devised by Pedj (1975) for detecting spatio-temporal variations in drought throughout the arid environment of Sudan in Northeast Africa. This index (PDI) is sensitive to both precipitation and temperature, with high performance for estimating the onset of drought on a long-term scale (12 months or annual). Elagib and Elhag (2011) also emphasized that the PDI determines the drought episodes as similar to the well-known United Nations Environment Program (UNEP, 1997) aridity index (AI). Another bright feature of PDI is related to its ability to monitor drought events in regions with sparse meteorological stations and poorly recorded data (Elagib and Elhag, 2011).

In case of Iran, Morid et al. (2006) compared some drought indices, including declines index (DI), percent of normal (PN), standardized precipitation index (SPI), China-Z index (CZI), modified CZI (MCZI), Z-Score and effective drought index (EDI). They concluded that SPI and EDI were able to consistently detect the onset of drought events and their spatial and temporal variations. The DI was the most responsive index to precipitation events of a particular year, while the DI showed inconsistent spatio-temporal variability (Morid et al., 2006). Employing the PDSI, Zoljoodi and Didevarasl (2013) reported that drought severity in Iran, particularly in the northwestern and northeastern parts, intensified during 1951–2005. They also concluded that the PDSI was strongly correlated with soil moisture, while poorly with both temperature and precipitation. Besides, Bazrafshan (2017) suggested applying SPEI (rather than SPI) for accounting the effects of both temperature and precipitation (rather than only precipitation) in monitoring historical drought variability in Iran. Mohseni Saravi et al. (2009) analysed drought characteristics in the Karoon river basin in Iran using SPI. Kazemzadeh and Malekian (2016) investigated spatio-temporal trends in historical droughts throughout the northwest of Iran applying SPI and SDI. Based on SPI, Nasrollahi et al. (2018) provided a drought hazard index map for the Semnan province of Iran. Choubin et al. (2014) used a neuro-fuzzy modelling approach for drought forecasting in the west of Iran applying SPI as a proxy for drought conditions. However, no study has yet examined the role of temperature and precipitation changes in spatio-temporal drought variability throughout Iran in recent decades using PDI (Pedj drought index).

This paper aimed at investigating spatiotemporal variability of drought and humidity characteristics across Iran during 1951–2010 using the PDI. The specific objectives were to (1) detect statistically ($p < 0.05$) significant trends in historical drought and humidity severities in Iran; (2) examine the effects of temperature and precipitation changes on such significant trends; (3) determine the frequency of dry and humid years; (4) identify the longest historical drought and humidity events; and (5) analyze the spatial extent of both drought and humidity events over the country.

2. Materials and methods

2.1. Study area and data description

Iran is located in the Middle East (the southwestern part of Asia), between 25 and 40°N and 44–63°E, with the area of 1,648,000 km^2 and the elevation from −28 m (near the Caspian Sea) to about 5670 m (the Damavand peak) (Fig. 1). The country is bordered by the Caspian Sea from the north, while by the Persian Gulf and the Sea of Oman from the south. As Iran is located in the arid belt throughout the Northern Hemisphere (30–60°N), arid and semi-arid climate cover most parts of the country (Ganji, 1968). In more detail, however, the climate of Iran ranges from extra arid in central parts to per-humid along the Caspian coast in the north (Rahimi et al., 2013). This is mainly due to the existence of Elburz Chain in the north of the country, the Zagros Chain in the west, and two widespread deserts (The Kavir desert and the Lut desert) throughout the middle of the Iranian Plateau (Ganji, 1968).

This study selected sixteen meteorological stations, with long-term monthly precipitation as well as minimum and maximum temperature (Table 1), scattered throughout Iran (Fig. 1). As the central parts of Iran are mostly covered by deserts with flat topography, using a few stations from there unlikely influences the results. The monthly records at all these sixteen stations were obtained from the Islamic Republic of Iran Meteorological Organization (IRIMO). This study double checked the quality of such monthly time series for missing values and outliers, although IRIMO generally controls the data quality at all its weather measurement stations. A few discontinuities were found in monthly records at some stations, and thus, reconstructed using a multivariate regression model among surrounding high-correlated stations (Eischeid et al., 1995). At a 5% significance level, the homogeneity and randomness of data were also confirmed by applying the von Neumann ratio (Buishand, 1982) and the Runs (Bradley, 1968) tests, respectively. Long-term average values for annual precipitation ranged from 59 mm at the driest station (Yazd) in central Iran to 1337 mm at the wettest station (Rasht) along the Caspian coast in the north (Table 1 and Fig. 1). The coldest and warmest annual mean temperatures were 11.5 °C and 27.0 °C found at the Bandar Abbas and the Urmia stations located in the south and northwest of Iran, in turn (Table 1 and Fig. 1). Besides, the De Martonne aridity index (De Martonne, 1926; Pellicone et al., 2019) characterized four different climate classes of arid, semiarid, Mediterranean, and very humid at the meteorological stations selected for this study (Table 1).

2.2. Pedj drought index (PDI)

The PDI (Elagib and Elhag, 2011; Pedj, 1975) was used to determine the effects of changes in both precipitation and temperature on drought and humidity characteristics (in terms of severity, frequency, duration, and extension) at each of sixteen meteorological stations in Iran selected by this study. It is calculated as:

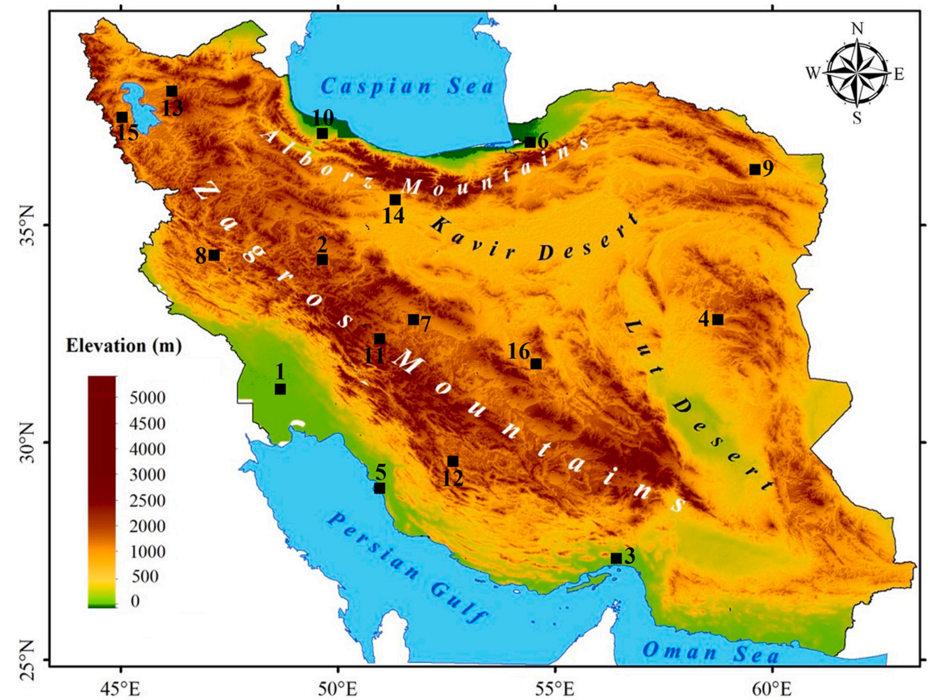

Fig. 1. Location of all sixteen meteorological stations selected by this study on the topographic map of Iran. Check Table 1 for the name of locations corresponding to the Nos. 1–16 on this map.

Table 1
Geographical information, record periods, and climatic characteristics for the meteorological stations in Iran selected by this paper.

No.	Station	Latitude (degrees)	Longitude (degrees)	Altitude (m)	Record Period	MAP[a] (mm)	Tmean[b] (°C)	Climate
1	Ahvaz	31.3	48.7	22.5	1956–2010	209	23.9	Dry
2	Arak	34.1	49.8	1708	1956–2010	337	13.9	Semi dry
3	Bandar Abbas	27.2	56.4	9.8	1956–2010	176	27	Dry
4	Birjand	32.9	59.2	1491	1956–2010	168	16.5	Dry
5	Bushehr	28.9	50.8	19.6	1951–2010	268	24.6	Dry
6	Gorgan	36.9	54.3	13.3	1955–2010	583	17.8	Mediterranean
7	Isfahan	32.7	51.9	1550.4	1951–2010	125	16.3	Dry
8	Kermanshah	34.4	47.2	1318.6	1951–2010	439	14.4	Semi dry
9	Mashhad	36.3	59.6	999.2	1951–2010	251	12.2	Semi dry
10	Rasht	37.2	49.7	36.7	1956–2010	1337	16	Very humid
11	Shahr-e Kord	32.3	50.9	2048.9	1956–2010	321	11.7	Semi dry
12	Shiraz	29.5	52.6	1484	1951–2010	334	17.8	Semi dry
13	Tabriz	38.1	46.3	1361	1951–2010	283	12.6	Semi dry
14	Tehran	35.7	51.3	1190.8	1951–2010	232	17.4	Dry
15	Urmia	37.5	45.1	1315.9	1951–2010	338	11.5	Semi dry
16	Yazd	31.9	54.3	1237.2	1951–2010	59	19.2	Dry

[a] MAP: long-term average value of annual precipitation.
[b] Tmean: long-term average value of annual mean temperature.

$$PDI = SAI_{Tm} - SAI_{Pr} \tag{1}$$

where SAI_{Tm} and SAI_{Pr} are the standardized anomaly indices (SAI) of mean temperature and precipitation, respectively, on the annual scale at the given meteorological station. The ranges of PDI corresponding to the different levels of drought and humidity are given in Table 2. Prior to estimating the PDI, however, this study needed to calculate the SAIs as follows:

$$SAI = \frac{(x - \bar{x})}{s} \tag{2}$$

where x is a particular year record, $\bar{x}$ is the mean of all year records, and s is the standard deviation. At each meteorological station selected by this study, annual precipitation and mean temperature time series were standardized with reference to the corresponding full record period given in Table 1.

Table 2
Ranges of PDI corresponding to the different levels of drought and humidity based on Potop and Soukup (2009).

PDI range	Drought/humidity category	Abbreviation
PDI ≥3	Extreme drouth	ExD
2 ≤ PDI <3	Severe drought	SeD
1 ≤ PDI <2	Moderately drought	MoD
0 < PDI <1	Mild drought	MiD
PDI = 0	Normal (Nor)	Nor
−1 ≤ PDI < 0	Excess of humidity (ExH)	ExH
−2 ≤ PDI < −1	Mean humidity (MeH)	MeH
−3 ≤ PDI < −2	Strong humidity (StH)	StH
PDI < −3	Very strong humidity (VStH)	VStH

2.3. Statistical methods

The non-parametric Mann-Kendall (MK) (Gilbert, 1988; Kendall, 1957; Mann, 1945) test was applied for detecting statistically significant ($p < 0.05$) trends in annual PDI, SAI_{Tm}, and SAI_{Pr} values. The magnitude of detected significant trends was computed by employing the Sen's slope estimator (Sen, 1968). The Spearman's rank correlation (rho) was used to measure statistically significant ($p < 0.05$) relationships among annual PDI, SAI_{Tm}, and SAI_{Pr} time series. The Spearman's rho was preferred to the Pearson correlation coefficient (r) because it assumes no specific distribution function for variables (Helsel, 2002; Kanji, 2006). However, in the existence of auto-correlation in any of the annual PDI, PDI, SAI_{Tm}, and SAI_{Pr} time series, this study used the trend-free pre--whitening (TFPW) method (Yue et al., 2002) and the residual bootstrap (RB) approach (Park and Lee, 2001) with 5000 independent replications to determine significant trends and estimate the standard deviations of rho values, respectively.

3. Results

Trend analysis only determined statistically significant ($p < 0.05$) increases in annual PDI values at about 69% of meteorological stations studied throughout Iran during 1951–2010 (Table 3). In general, these substantial drying trends were associated with significant ($p < 0.05$) increases in SAI_{Tm} (Table 3). Exceptionally, the significant drying trend in annual PDI values was accompanied by an increase in SAI_{Tm} and a decrease in SAI_{Pr} at the Tabriz station, while only by the later one (SAI_{Pr} reduction) at the Gorgan station (Table 3). This station (Gorgan), with the Mediterranean climate class in the north of Iran, showed the lowest rate (0.03/year) of significant drying trend in annual PDI values (Fig. 2). However, the highest rate was about 0.54 (/year) found at the Yazd station with the dry climate class located in the central part of the country (Fig. 2). Spatial distributions of such trends in annual PDI, SAI_{Tm}, and SAI_{Pr} at all meteorological stations studied over Iran are shown in Figs. 3 and 4, respectively.

Decadal variability of annual PDI values indicated that the 2000s was predominantly associated with drought events at all meteorological stations studied in Iran (Fig. 5), except at the Shahr-e Kord station that experienced more humidity events (Fig. 5k). The 2000s also showed the highest decadal PDI averages (Fig. 5) at the same meteorological stations with significant drying trends in annual PDI values given in Table 3. At the stations with no clear changes in annual PDI values, the highest decadal PDI averages were seen in the 1950s (the Urmia station), 1960s (the Bandar Abbas, Birjand, and Shahr-e Kord stations), and 1980s (the Isfahan station) (Fig. 5). On the other hand, except for the

Table 3
Trends in annual PDI, SAI_{Tm}, and SAI_{Pr} at the meteorological stations in Iran selected by this study during their record periods given in Table 1. In bold if statistically significant ($p < 0.05$).

No.	Station	PDI	SAI_{Tm}	SAI_{Pr}
1	Ahvaz	**0.05**	**0.05**	0.00
2	Arak	**0.04**	**0.02**	0.00
3	Bandar Abbas	−0.07	0.00	−0.01
4	Birjand	0.00	0.00	−0.01
5	Bushehr	**0.04**	**0.04**	0.00
6	Gorgan	**0.03**	0.01	**−0.02**
7	Isfahan	0.02	**0.03**	0.01
8	Kermanshah	**0.04**	**0.04**	0.00
9	Mashhad	**0.04**	**0.04**	0.00
10	Rasht	**0.04**	**0.03**	−0.01
11	Shahr-e Kord	−0.02	**−0.02**	0.01
12	Shiraz	**0.05**	**0.04**	−0.01
13	Tabriz	**0.06**	**0.04**	**−0.02**
14	Tehran	**0.03**	**0.04**	0.01
15	Urmia	0.01	−0.02	**−0.02**
16	Yazd	**0.54**	**0.04**	−0.01

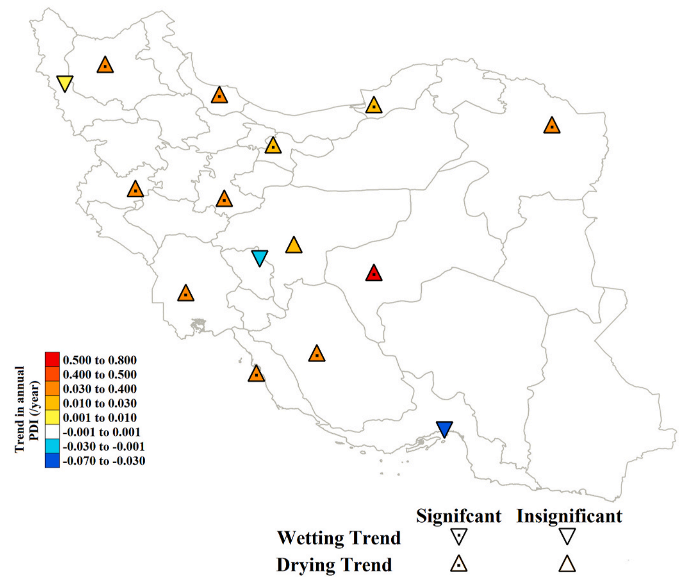

Fig. 2. Spatial distribution maps of trends (/year) in annual PDI at all sixteen meteorological stations in Iran selected by this study during their record periods given in Table 1.

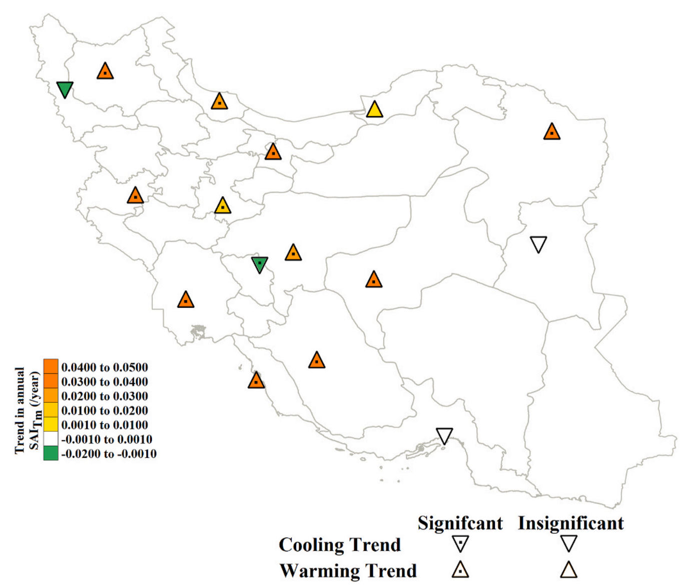

Fig. 3. Spatial distribution maps of trends (/year) in annual SAI_{Tm} at all sixteen meteorological stations in Iran selected by this study during their record periods given in Table 1.

Shahr-e Kord, all other stations generally experienced humidity during the 1970s (Fig. 5). At the second rank, the 1950s was associated with humidity events at 87.5% of meteorological stations studied (Fig. 5). The dry 2000s (humid 1970s) in Iran was typically accompanied by both warm (cold) SAI_{Tm} and dry (wet) SAI_{Pr} (Fig. 5). Similarly, annual PDIs showed statistically significant positive (rho = 0.70–0.87) and negative (with rho between −0.56 and −0.85) correlations with annual SAI_{Tm} and SAI_{Pr} values, respectively, at all stations (Table 4). There were also negative relationships between annual SAI_{Tm} and SAI_{Pr} throughout Iran, but significant ($p < 0.05$) only at about 56% (9 out of 16) of the stations (Table 4).

About 81% of stations studied in Iran experienced more drought than humidity events during 1951–2010 (Fig. 6). Most of the stations showed about 2% frequency of extreme drought (ExD) events, except at all four

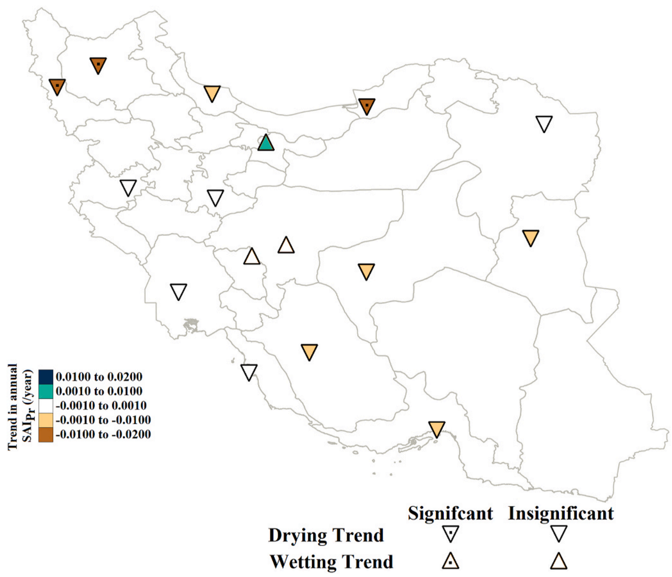

Fig. 4. Spatial distribution maps of trends (/year) in annual SAI_{Pr} at all sixteen meteorological stations in Iran selected by this study during their record periods given in Table 1.

stations of Gorgan, Isfahan, Tehran, and Urmia with no historical ExD experience (Fig. 6). Besides, the highest number of such ExD was 3.3% seen at the Mashhad station in the northeast of Iran (Fig. 6). For severe drought (SeD) events, however, the highest frequency was 14% occurred at the Isfahan meteorological stations in the central part of Iran (Fig. 6). On the other hand, the very strong humidity (VStH) event was experienced at all stations studied, with a range from 2% at the Bushehr station to 7.5% at the Rasht station (Fig. 6). The lowest frequency of strong humidity (StH) events were about 1.8% at the Gogran station, while the highest was attentively 12.5% at the Yazd station (Fig. 6), which showed the highest rate drying trend in annual PDI values (Table 3).

The longest humidity (drought) periods based on the consecutive annual PDI values permanently ≤ -1 (≥ 1) at all meteorological stations studied in Iran during 1951–2010 are given in Table 5. The longest humidity duration was 4 years observed at four stations of Gorgan (1956–1959), Shahr-e Kord (2004–2007), Tabriz (1971–1974), and Tehran (1951–1954) (Table 5). However, the longest drought duration

Table 4

Spearman's rank correlations (rho) of PDIs with SAI_{Tm} and SAI_{Pr} at the meteorological stations in Iran selected by this study during their record periods given in Table 1. In bold if statistically significant ($p < 0.05$).

No.	Station	PDI versus		SAI_{Pr} versus SAI_{Tm}
		SAI_{Tm}	SAI_{Pr}	
1	Ahvaz	**0.79**	**−0.74**	**−0.28**
2	Arak	**0.77**	**−0.81**	**−0.32**
3	Bandar Abbas	**0.87**	**−0.79**	**−0.45**
4	Birjand	**0.87**	**−0.78**	**−0.43**
5	Bushehr	**0.81**	**−0.56**	−0.05
6	Gorgan	**0.85**	**−0.63**	−0.21
7	Isfahan	**0.78**	**−0.81**	**−0.33**
8	Kermanshah	**0.76**	**−0.76**	−0.23
9	Mashhad	**0.78**	**−0.79**	**−0.33**
10	Rasht	**0.81**	**−0.81**	**−0.39**
11	Shahr-e Kord	**0.77**	**−0.80**	**−0.49**
12	Shiraz	**0.76**	**−0.72**	−0.18
13	Tabriz	**0.85**	**−0.85**	**−0.49**
14	Tehran	**0.73**	**−0.75**	−0.15
15	Urmia	**0.70**	**−0.70**	−0.08
16	Yazd	**0.77**	**−0.77**	−0.25

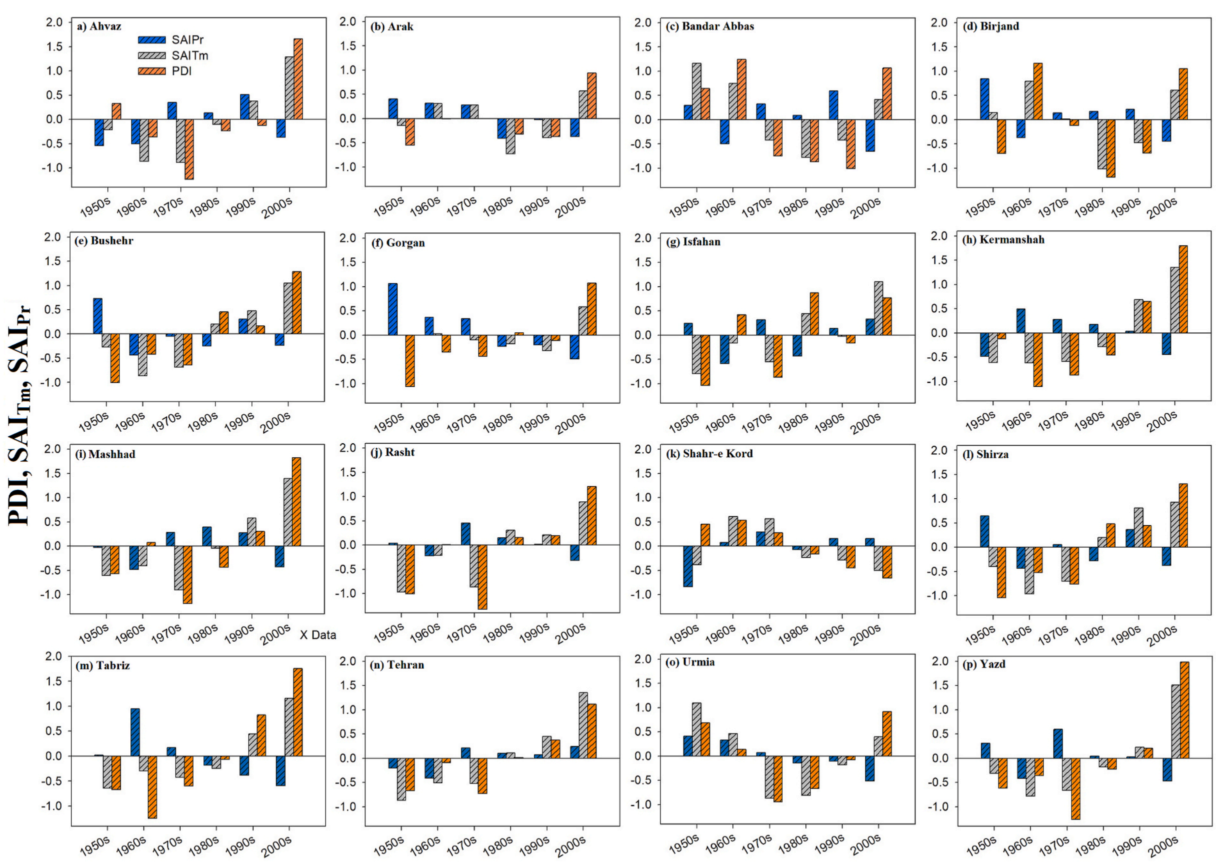

Fig. 5. Decadal variability in annual PDI, SAI_{Tm}, and SAI_{Pr} at all meteorological stations in Iran selected by this study during their record periods given in Table 1.

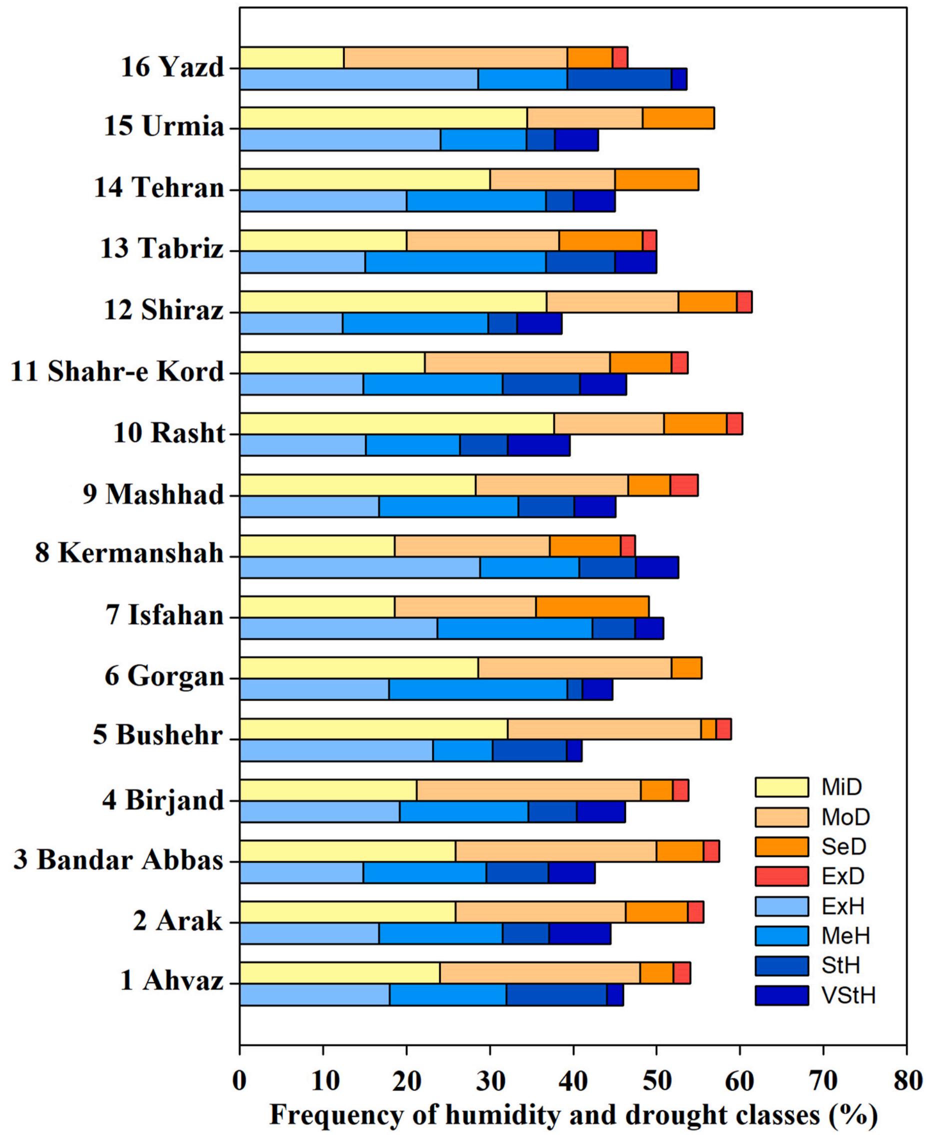

Fig. 6. Frequency (%) of different humidity and drought classes at all sixteen meteorological stations in Iran selected by this study during their record periods given in Table 1.

was 13 years (1998–2010) found at the Kermanshah station (Table 5)(. In general, the longest humidity events were seen before 1997 at all stations (except the Shahr-e Kord), while the longest droughts at most of the stations afterward (Table 5). Such longest drought (humidity) durations were simultaneously accompanied by warmer (colder) and drier (wetter) climatic conditions at the meteorological stations studied over Iran. Accordingly, the longest humidity and drought durations at three meteorological stations (Tabriz, Gorgan, and Kermanshah) with statistically significant trends in annual PDIs associated with substantial changes in SAI_{Tm} and/or SAI_{Pr} values are illustrated in Fig. 7.

Fig. 8 represents the spatial extent of humidity (annual PDI ≤ -1) and drought (annual PDI ≥ 1) events as the percentage of meteorological stations with annual PDI ≤ -1 and ≥ 1, respectively, throughout Iran during each year of the study period (1951–2010). More than 45% of stations studied in Iran (or 45% of the country) experienced drought conditions during both periods of 1998–2003 and 2007–2010 (Fig. 8). All stations (100%) throughout the country showed drought in 2010, while humidity in both 1957 and 1972 (Fig. 8). Besides, the humidity (drought) generally extended throughout most parts of Iran during the 1950s (after 1997) (Fig. 8).

4. Discussion

4.1. PDI for humidity/drought assessment

To assess humidity and drought, different indices have been developed, each with its strengths and weaknesses (e.g. Richard R. Heim, 2002; Mishra and Singh, 2010). Experts have already agreed that all National Meteorological and Hydrological Services should use the SPI for characterizing wetness and dryness in different parts of the world (Hayes et al., 2011; WHO, 2009). However, this index (SPI) is only dependent on precipitation and does not take into account the effects of other climatological variables, especially increases in evapotranspiration rate under global warming (Vicente-Serrano et al., 2012, 2010). Hence, applying drought indices including evapotranspiration is predominantly preferred to the only precipitation-based indices such as the SPI for identifying wetness/dryness variability (e.g. Tsakiris et al., 2007; Vicente-Serrano et al., 2010; Wells et al., 2004).

Vicente-Serrano et al. (2010) proposed the SPEI as the suitable drought index for studying the effects of climate warming on both humidity and drought. This index (SPEI) is dependent on climatic water balance (CWB) computed as the difference between precipitation (P)

Table 5
The longest humidity (PDI ≤ -1) and drought (PDI ≥ 1) events at all sixteen meteorological stations in Iran selected by this study.

No.	Station	Longest Humidity Event			Longest Drought Event		
		Number of Event	Period	Duration (Years)	Number of Event	Period	Duration (Years)
1	Ahvaz	1	1974–1976	3	1	2007–2010	4
2	Arak	2	1982–1984 1992–1994	3	1	1997–1999	3
3	Bandar Abbas	2	1991–1993 1995–1997	3	1	2001–2004	4
4	Birjand	2	1982–1984	3	2	1961–1963 1969–1971	3
5	Bushehr	1	1956–1957	2	1	2006–2010	5
6	Gorgan	1	1956–1959	4	1	1960–1962	3
7	Isfahan	1	1974–1976	3	1	1958–1960	3
8	Kermanshah	2	1967–1969 1992–1994	3	1	1998–2010	13
9	Mashhad	2	1952–1954 1974–1976	3	1	1958–1960	3
10	Rasht	4	1956–1957 1969–1970 1976–1977 1992–1993	2	3	1995–1996 1998–1999 2009–2010	2
11	Shahr-e Kord	1	2004–2007	4	1	1962–1963 1978–1979 1998–1999	2
12	Shiraz	1	1967–1969	3	1	1998–2003	6
13	Tabriz	1	1971–1974	4	1	1995–2001	7
14	Tehran	1	1951–1954	4	1	1997–2001	5
15	Urmia	1	1992–1994	3	1	1958–1962	5
16	Yazd	3	1956–1957 1967–1968 1978–1979	2	1	2005–2010	6

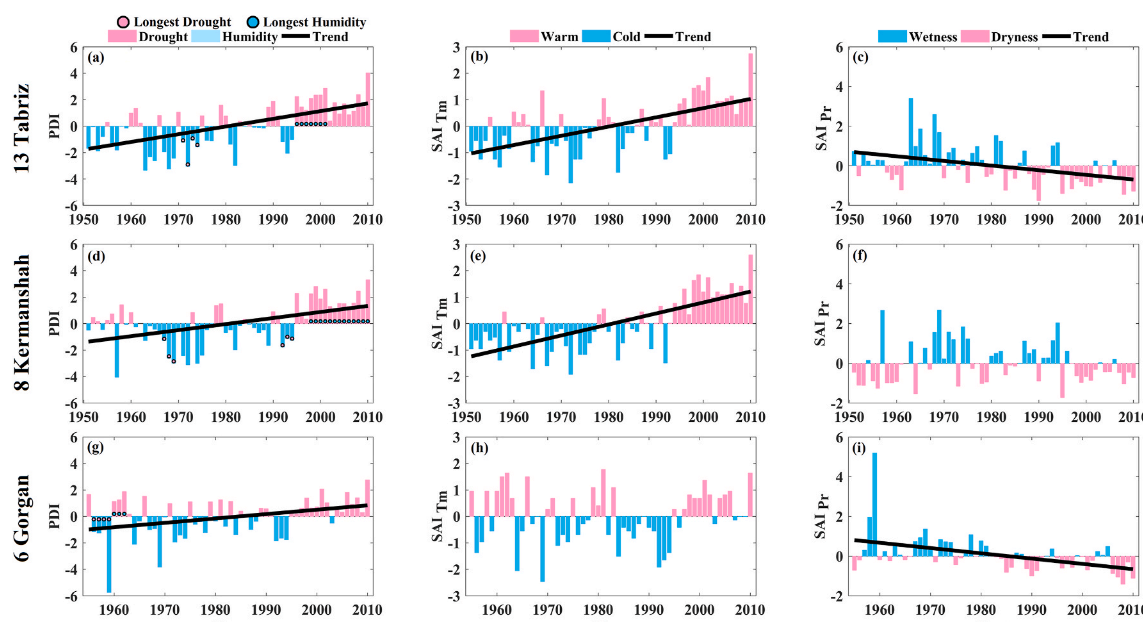

Fig. 7. Time series and statistically significant ($p < 0.05$) trends for annual PDI, SAI_{Tm}, and SAI_{Pr} at (a–c) Tabriz, (d–f) Kermanshah, and (g–i) Gorgan, meteorological stations in Iran. Based on the PDI values, the longest drought and humidity events are shown at (a) Tabriz, (d) Kermanshah, and (g) Gorgan, meteorological stations.

and the potential evapotranspiration (PET) (Vicente-Serrano et al., 2012, 2010). The original algorithm of SPEI estimates the PET using the Thornthwaite equation (Thornthwaite, 1948), which only needs the mean temperature and latitude of the given station. In response to climate change, however, modifications in other hydro-meteorological factors can also play important roles in estimating the PET (Chen et al., 2005). Thus, using the SPEI might not always be superior to the SPI.

As the most common climatological drought indices, SPI (McKee et al., 1993) and SPEI (Vicente-Serrano et al., 2010) measure normalized anomalies in P and CWB, respectively. Hence, using an appropriate parametric probability distribution function for transforming the highly skewed distribution of accumulated precipitation (SPI) and CWP (SPEI), generally seen in arid and semi-arid regions with zero precipitation months, to the standard normal distribution plays a crucial role in calculating SPI and SPEI values (Stagge et al., 2015). Accordingly, the two-parameter Gamma and the Log-logistic distributions are generally recommended for computing the SPI and the SPEI, respectively,

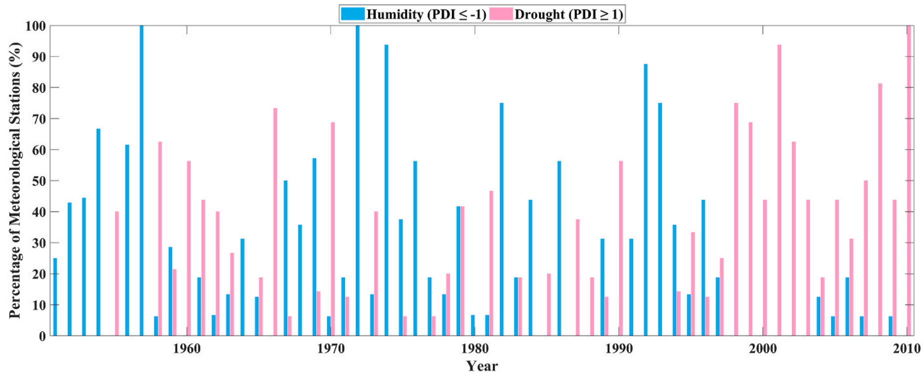

Fig. 8. Humidity (PDI ≤ -1) and drought (PDI ≥ 1) spatial extents throughout Iran.

particularly at annual scale (Stagge et al., 2015; Vicente-Serrano and Beguería, 2016).

Although SPI and SPEI are broadly recommended for characterizing meteorological/climatological wetness and dryness around the world, this study examined the suitability of PDI for identifying humidity and drought events over Iran, where is climatologically recognized as the semi-arid and arid environment. The PDI was preferred to SPI and SPEI because: (1) it is not only a precipitation-based drought index, unlike the SPI; (2) it considers effects of temperature warming on wetness and dryness, like SPEI; (3) it does not need to find a suitable parametric probability distribution function for normalizing accumulated precipitation (SPI) and CWB (SPEI); and (4) it has previously succeeded to capture humidity and drought episodes in the diverse climate of Sudan (Elagib and Elhag, 2011). To corroborate such preference, this study measured correlations of PDI with SPI and SPEI at all stations studied over Iran on the annual scale. The annual SPI values were calculated using the two-parameter Gamma distribution. This study also applied the Thornthwaite equation to estimate the PET, and then, the Log-logistic distribution to normalize the annual SPEI values. The results indicated statistically significant correlations of annual PDI with both annual SPI and SPEI values in Iran (Table 6). The stronger relationships of annual PDI with SPEI than that with SPI (Table 6) can mainly be referred to taking into account the temperature warming effects on humidity and drought events by both PDI and SPEI.

Table 6
Spearman's rank correlations (rho) of annual PDIs with both annual standardized precipitation index (SPI) standardized precipitation evapotranspiration index (SPEI) at all sixteen meteorological stations in Iran selected by this study during their record periods given in Table 1. In bold if statistically significant ($p < 0.05$).

No.	Station	PDI versus	
		SPI	SPEI
1	Ahvaz	**−0.73**	**−0.69**
2	Arak	**−0.81**	**−0.86**
3	Bandar Abbas	**−0.78**	**−0.76**
4	Birjand	**−0.79**	**−0.74**
5	Bushehr	**−0.56**	**−0.91**
6	Gorgan	**−0.63**	**−0.82**
7	Isfahan	**−0.82**	**−0.93**
8	Kermanshah	**−0.77**	**−0.93**
9	Mashhad	**−0.41**	**−0.48**
10	Rasht	**−0.82**	**−0.83**
11	Shahr-e Kord	**−0.81**	**−0.87**
12	Shiraz	**−0.72**	**−0.94**
13	Tabriz	**−0.85**	**−0.95**
14	Tehran	**−0.75**	**−0.96**
15	Urmia	**−0.71**	**−0.90**
16	Yazd	**−0.77**	**−0.78**

4.2. Historical drought variability in Iran

Drought is characterized by its severity, frequency, duration, and spatial extent (Ansari and Davari, 2010). Using the annual PDI, this study indicated that Iran has experienced significant increases in all these drought characteristics since 1951. Such results were consistent with the previous studies reporting severer, more frequent, longer, and larger in spatial coverage droughts throughout Iran in recent decades (e.g. Ansari and Davari, 2010; Bazrafshan, 2017; Nouri and Homaee, 2020; Raziei et al., 2009; Zehtabian et al., 2013). Interestingly, however, all these studies used other drought indices (SPI, SPEI, RDI, PDSI) than the PDI. Hence, this paper, as the first study up to our best knowledge, showed that the annual PDI, similar to other drought indices (e.g. SPI and SPEI) on the annual scale, satisfactorily succeeded to characterize historical year-to-year humidity and drought variations throughout Iran.

Based on the results, substantial increases in temperature were the dominant driving force of drying trends experienced in Iran during 1951–2010. This was consistent with the global analysis of drought using SPEI (Naumann et al., 2018) as well as with the recent studies comparing the SPI with the SPEI throughout Iran (Bazrafshan, 2017; Nouri and Homaee, 2020; Raziei et al., 2009). On the other hand, the present study found changes in precipitation did not play a key role in drying trends in Iran. This may refer to the high radiation with warm-hot annual temperatures, but variable and infrequent precipitation in this country. Compared to the humid and Mediterranean regions, generally speaking, the arid and semi-arid regions (like Iran) have below-average precipitation. Thus, the severity level of drought would increase when such below-average precipitation is accompanied by high radiation/temperature. It seems that such a phenomenon has occurred in Iran, particularly since 1997. In fact, the simultaneous coincidence of highly warm temperature and naturally low precipitation (e.g. Barlow et al., 2016; Ghasemi, 2015; Tabari and Hosseinzadeh Talaee, 2011; Vaghefi et al., 2019) has cause dominance of drought conditions in Iran, specifically since the 2000s (Naumann et al., 2018).

For the period after 1997, this study showed that Iran has experienced mega-droughts, which can persist for several years or even decades (Stahle et al., 2007). Similarly, Raziei et al. (2009) reported the worst and prolonged drought event in Iran during 1998–2001. This mega-drought also influenced Iran's neighbor countries in the Middle East (e.g. Barlow et al., 2016; Hameed et al., 2018). In such region-wide mega-drought, large-scale climate teleconnections (e.g. Southern Oscillation Index, SOI) play an important role by influencing regional temperature and precipitation (Barlow et al., 2016, 2002) as the primary factors controlling moisture supply (Otkin et al., 2018). For example, Barlow et al. (2016) concluded that the 1998–2001 and 2007–2008 mega-droughts in the Middle East were significantly associated with the prolonged positive SOI events (La Niña). Similarly, the recent study by (Nouri and Homaee, 2020) reported 1998–2001, 2007–2009, and

2010–2012 positive SOI (La Niña) events have led to severe and long droughts in Iran since the late 1990s. Although previous studies have primarily focused on the effects of La Niña events on droughts in Iran, the role of other large-scale climate teleconnections (e.g. Arctic Oscillation (AO), North Sea-Caspian Pattern (NCP)) - that can influence both regional temperature and precipitation, and thereby the source and transport pathway of atmospheric water vapor (Liu et al., 2020; Trenberth et al., 2003) – has received less attention in recent years. Hence, further and deeper investigation of interrelationships among climate teleconnections and their combined effects on the characteristics of annual humidity and drought events identified by the PDI throughout Iran is well motivated for future study.

5. Conclusions

Employing the PDI, this study investigated the effects of changes in both precipitation and temperature on long-term humidity and drought events at sixteen meteorological stations scattered throughout different climate classes of Iran during 1951–2010. The following major conclusions were drawn:

- Significant drying trends throughout Iran during recent decades were primarily accompanied by substantial increases in temperature (along with global warming), especially in the absence of clear changes in historical precipitation across the country. This was also reflected by the stronger correlations of PDI with SAI_{Tm} than SAI_{Pr}. Besides, negative relationships between SAI_{Tm} and SAI_{Pr} indicated that warmer temperature is generally associated with drier climatic conditions over most parts of Iran. This country, moreover, generally experienced humid and dry decades in the 1970s and 2000s, respectively, reflecting drying tendencies over time.
- In Iran, drought occurrences were more frequent than humidity events during 1951–2010. However, the highest frequency rate for very strong humidity events (7.5%) was more than that for extreme droughts (3.3%). Such very strong humidity (extreme drought) events were attentively seen at all (most) of stations studied over the country, particularly before (after) the mid-1990s.
- In general, the longest humidity duration was about 3–4 years, while the longest drought continued for more than 5 years. The longest humidity durations were observed at different stations studied before 1997, while the longest droughts afterward. Accordingly, the humidity and drought showed the large spatial extents throughout Iran primarily during the 1950s and after the mid-1990s, respectively.
- On the annual scale, the PDI satisfactorily succeeded to characterize spatio-temporal variations in historical humidity and drought in Iran that formerly captured by both SPI and SPEI as the most prominent meteorological/climatological drought indices. The stronger correlations of PDI with SPEI than that with SPI showed the ability of PDI to account for the effects of changes in both precipitation and temperature on humidity and drought events in different climate classes of Iran.

CRediT authorship contribution statement

Azam Lashkari: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Supervision. **Masoud Irannezhad:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing, Visualization, Supervision. **Hossein Zare:** Conceptualization, Methodology, Software, Formal analysis, Resources, Writing - original draft. **Lev Labzovskii:** Validation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ansari, H., Davari, K., 2010. Spatial and temporal variations of drought by using palmer drought severity index (case study: ghareghom and part of atrak basins). J. water soil Conserv. 17, 125–140.

Barlow, M., Cullen, H., Lyon, B., 2002. Drought in central and southwest Asia: La Niña, the warm pool, and Indian ocean precipitation. J. Clim. https://doi.org/10.1175/1520-0442(2002)015<0697:DICASA>2.0.CO;2.

Barlow, M., Zaitchik, B., Paz, S., Black, E., Evans, J., Hoell, A., 2016. A review of drought in the Middle East and southwest Asia. J. Clim. https://doi.org/10.1175/JCLI-D-13-00692.1.

Bazrafshan, J., 2017. Effect of air temperature on historical trend of long-term droughts in different climates of Iran. Water Resour. Manag. 31, 4683–4698. https://doi.org/10.1007/s11269-017-1773-8.

Mooley, D.A., Bhalme, H.N., 1980. Large-scale droughts/floods and monsoon circulation. Mon. Weather Rev. 108, 1197–1211.

Bradley, J.V., 1968. Distribution-free Statistical Tests, Illustrate. Prentice-Hall, the University of Michigan.

Buishand, T.A., 1982. Some methods for testing the homogeneity of rainfall records. J. Hydrol. https://doi.org/10.1016/0022-1694(82)90066-X.

Chen, D., Gao, G., Xu, C.Y., Guo, J., Ren, G., 2005. Comparison of the Thornthwaite method and pan data with the standard Penman-Monteith estimates of reference evapotranspiration in China. Clim. Res. https://doi.org/10.3354/cr028123.

Choubin, B., Khalighi-Sigaroodi, S., Malekian, A., Ahmad, S., Attarod, P., 2014. Drought forecasting in a semi-arid watershed using climate signals: a neuro-fuzzy modeling approach. J. Mt. Sci. 11, 1593–1605. https://doi.org/10.1007/s11629-014-3020-6.

Dai, A., 2011. Drought under Global Warming: A Review. Wiley Interdiscip. Rev. Clim. Chang. https://doi.org/10.1002/wcc.81.

De Martonne, E., 1926. Aerisme, et índices d'aridite. Comptesrendus L'Academie des Sci. 182, 1395–1398.

Dracup, J.A., Lee, K.S., Paulson, E.G., 1980. On the definition of droughts. Water Resour. Res. https://doi.org/10.1029/WR016i002p00297.

Eischeid, J.K., Baker, C.B., Karl, T.R., Diaz, H.F., 1995. The quality control of long-term climatological data using objective data analysis. J. Appl. Meteorol. https://doi.org/10.1175/1520-0450(1995)034<2787:TQCOLT>2.0.CO;2.

Elagib, N.A., Elhag, M.M., 2011. Major climate indicators of ongoing drought in Sudan. J. Hydrol. https://doi.org/10.1016/j.jhydrol.2011.08.047.

European Commission, 2007. Communication from the commission to the european parliament and the council-Addressing the challenge of water scarcity and droughts in the European Union. Official Journal of the European Union. https://doi.org/10.1017/CBO9781107415324.004.

Ganji, M.H., 1968. Climate. In: The Cambridge History of Iran, the Land of Iran. Cambridge University Press. https://doi.org/10.1017/CHOL9780521069359.

Ghasemi, A.R., 2015. Changes and trends in maximum, minimum and mean temperature series in Iran. Atmos. Sci. Lett. https://doi.org/10.1002/asl2.569.

Gilbert, R.O., 1988. Statistical Methods for Environmental Pollution Monitoring. Biometrics. https://doi.org/10.2307/2531935.

Gommes, R.A., Petrassi, F., 1994. Rainfall Variability and Drought in Sub-saharan Africa since 1960. FAO, Research and Technology Development Division, Agrometeorology Group, Rome, Italy.

Hameed, M., Ahmadalipour, A., Moradkhani, H., 2018. Apprehensive drought characteristics over Iraq: results of a multidecadal spatiotemporal assessment. Geosci. https://doi.org/10.3390/geosciences8020058.

Hayes, M., Svoboda, M., Wall, N., Widhalm, M., 2011. The Lincoln declaration on drought indices: universal meteorological drought index recommended. Bull. Am. Meteorol. Soc. 92, 485–488.

Heim, Richard R., 2002. A review of twentieth-century drought indices used in the United States. Bull. Am. Meteorol. Soc. https://doi.org/10.1175/1520-0477(2002)083<1149:AROTDI>2.3.CO;2.

Heim, Richard R., 2002. A review of twentieth-century drought indices used in the United States. Bull. Am. Meteorol. Soc. https://doi.org/10.1175/1520-0477(2002)083<1149:AROTDI>2.3.CO;2.

Helsel, D.R., R, M.H., 2002. Statistical Methods in Water Resources. Geological Survey. https://doi.org/10.3133/twri04A3.

Jiao, W., Tian, C., Chang, Q., Novick, K.A., Wang, L., 2019. A new multi-sensor integrated index for drought monitoring. Agric. For. Meteorol. 268, 74–85. https://doi.org/10.1016/j.agrformet.2019.01.008.

Kanji, G.K., 2006. 100 Statistical Tests, third ed. https://doi.org/10.4135/9781849208499

Katz, R.W., Glantz, M.H., 1986. Anatomy of a rainfall index. Mon. Weather Rev. https://doi.org/10.1175/1520-0493(1986)114<0764:AOARI>2.0.CO;2.

Kazemzadeh, M., Malekian, A., 2016. Spatial characteristics and temporal trends of meteorological and hydrological droughts in northwestern Iran. Nat. Hazards 80, 191–210. https://doi.org/10.1007/s11069-015-1964-7.

Kendall, M.G., 1957. Rank correlation methods. Biometrika. https://doi.org/10.2307/2333282.

Keyantash, J., Dracup, J.A., 2002. The quantification of drought: an evaluation of drought indices. Bull. Am. Meteorol. Soc. https://doi.org/10.1175/1520-0477(2002)083<1191:TQODAE>2.3.CO;2.

Kundzewicz, Z.W., 2009. Adaptation to floods and droughts in the Baltic Sea basin under climate change. Boreal Environ. Res.

Liu, B., Tan, X., Gan, T.Y., Chen, X., Lin, K., Lu, M., Liu, Z., 2020. Global atmospheric moisture transport associated with precipitation extremes: mechanisms and climate change impacts. WIREs Water 7, e1412. https://doi.org/10.1002/wat2.1412.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica. https://doi.org/10.2307/1907187.

McKee, T.B., Doesken, N.J., Kleist, J., others, 1993. The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology, pp. 179–183.

Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391, 202–216.

Mohseni Saravi, M., Safdari, A.A., Malekian, A., 2009. Intensity-Duration-Frequency and spatial analysis of droughts using the standardized precipitation index. Hydrol. Earth Syst. Sci. Discuss. 6, 1347–1383. https://doi.org/10.5194/hessd-6-1347-2009.

Morid, S., Smakhtin, V., Moghaddasi, M., 2006. Comparison of seven meteorological indices for drought monitoring in Iran. Int. J. Climatol. A J. R. Meteorol. Soc. 26, 971–985.

Mu, Q., Zhao, M., Kimball, J.S., McDowell, N.G., Running, S.W., 2013. A remotely sensed global terrestrial drought severity index. Bull. Am. Meteorol. Soc. https://doi.org/10.1175/BAMS-D-11-00213.1.

Naresh Kumar, M., Murthy, C.S., Sesha Sai, M.V.R., Roy, P.S., 2009. On the use of Standardized Precipitation Index (SPI) for drought intensity assessment. Meteorol. Appl. A J. Forecast. Pract. Appl. Train. Tech. Model. 16, 381–389.

Nasrollahi, M., Khosravi, H., Moghaddamnia, A., Malekian, A., Shahid, S., 2018. Assessment of drought risk index using drought hazard and vulnerability indices. Arab. J. Geosci. 11, 606. https://doi.org/10.1007/s12517-018-3971-y.

Naumann, G., Alfieri, L., Wyser, K., Mentaschi, L., Betts, R.A., Carrao, H., Spinoni, J., Vogt, J., Feyen, L., 2018. Global changes in drought conditions under different levels of warming. Geophys. Res. Lett. https://doi.org/10.1002/2017GL076521.

Nouri, M., Homaee, M., 2020. Drought trend, frequency and extremity across a wide range of climates over Iran. Meteorol. Appl. https://doi.org/10.1002/met.1899.

Obasi, G.O.P., 1994. WMO's role in the international decade for natural disaster reduction. Bull. Am. Meteorol. Soc. 2. https://doi.org/10.1175/1520-0477(1994)075<1655:writid>2.0.co.

Otkin, J.A., Svoboda, M., Hunt, E.D., Ford, T.W., Anderson, M.C., Hain, C., Basara, J.B., 2018. Flash droughts: a review and assessment of the challenges imposed by rapid-onset droughts in the United States. Bull. Am. Meteorol. Soc. https://doi.org/10.1175/BAMS-D-17-0149.1.

Palmer, W.C., 1968. Keeping track of Crop moisture conditions, nationwide: the new Crop moisture index. Weatherwise. https://doi.org/10.1080/00431672.1968.9932814.

Palmer, W.C., 1965. Meteorological drought. U.S. Weather Bur. Res. Pap 45.

Park, E., Lee, Y.J., 2001. Estimates of standard deviation of spearman's rank correlation coefficients with dependent observations. Commun. Stat. Part B Simul. Comput. https://doi.org/10.1081/SAC-100001863.

Pedj, D.A., 1975. On the indicator of drought and moisture surplus. In: Proceedings of HMC of USSR, pp. 19–38.

Pellicone, G., Caloiero, T., Guagliardi, I., 2019. The De Martonne aridity index in calabria (southern Italy). J. Maps. https://doi.org/10.1080/17445647.2019.1673840.

Potop, V., Soukup, J., 2009. Spatiotemporal characteristics of dryness and drought in the Republic of Moldova. Theor. Appl. Climatol. https://doi.org/10.1007/s00704-008-0041-5.

Quiring, S.M., 2009. Monitoring drought: an evaluation of meteorological drought indices. Geogr. Compass. https://doi.org/10.1111/j.1749-8198.2008.00207.x.

Rahimi, J., Ebrahimpour, M., Khalili, A., 2013. Spatial changes of Extended De Martonne climatic zones affected by climate change in Iran. Theor. Appl. Climatol. https://doi.org/10.1007/s00704-012-0741-8.

Raziei, T., Saghafian, B., Paulo, A.A., Pereira, L.S., Bordi, I., 2009. Spatial patterns and temporal variability of drought in Western Iran. Water Resour. Manag. https://doi.org/10.1007/s11269-008-9282-4.

Sen, P.K., 1968. Estimates of the regression coefficient based on kendall's tau. J. Am. Stat. Assoc. https://doi.org/10.1080/01621459.1968.10480934.

Shafer, B.A., Dezman, L.E., 1982. Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas (Colorado). Proc. East. Snow Conf. 39th Annu. Meet.

Stagge, J.H., Tallaksen, L.M., Gudmundsson, L., Van Loon, A.F., Stahl, K., 2015. Candidate distributions for climatological drought indices (SPI and SPEI). Int. J. Climatol. 35, 4027–4040.

Stahle, D.W., Fye, F.K., Cook, E.R., Griffin, R.D., 2007. Tree-ring reconstructed megadroughts over North America since A.D. 1300. Climatic Change. https://doi.org/10.1007/s10584-006-9171-x.

Tabari, H., Hosseinzadeh Talaee, P., 2011. Analysis of trends in temperature data in arid and semi-arid regions of Iran. Global Planet. Change. https://doi.org/10.1016/j.gloplacha.2011.07.008.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. https://doi.org/10.2307/210739.

Trenberth, K.E., Dai, A., Rasmussen, R.M., Parsons, D.B., 2003. The changing character of precipitation. Bull. Am. Meteorol. Soc. https://doi.org/10.1175/BAMS-84-9-1205.

Tsakiris, G., Pangalou, D., Vangelis, H., 2007. Regional drought assessment based on the reconnaissance drought index (RDI). Water Resour. Manag. https://doi.org/10.1007/s11269-006-9105-4.

Unep, 1997. World Atlas of Desertification 2ED. United Nations Environ. Program.

Vaghefi, S.A., Keykhai, M., Jahanbakhshi, F., Sheikholeslami, J., Ahmadi, A., Yang, H., Abbaspour, K.C., 2019. The future of extreme climate in Iran. Sci. Rep. https://doi.org/10.1038/s41598-018-38071-8.

Van Rooy, M.P., 1965. A rainfall anomaly index independent of time and space. Notos.

Vicente-Serrano, S.M., Beguer\'\ia, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J. Clim. 23, 1696–1718.

Vicente-Serrano, S.M., Beguería, S., 2016. Comment on "Candidate distributions for climatological drought indices (SPI and SPEI)" by James H. Stagge et al. Int. J. Climatol. https://doi.org/10.1002/joc.4474.

Vicente-Serrano, S.M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J.J., López-Moreno, J. I., Azorin-Molina, C., Revuelto, J., Morán-Tejeda, E., Sanchez-Lorenzo, A., 2012. Performance of drought indices for ecological, agricultural, and hydrological applications. Earth Interact. https://doi.org/10.1175/2012EI000434.1.

Weghorst, K., 1996. The reclamation drought index: guidelines and practical applications. In: North American Water and Environment Congress & Destructive Water.

Wehner, M., Easterling, D.R., Lawrimore, J.H., Heim, R.R., Vose, R.S., Santer, B.D., 2011. Projections of future drought in the continental United States and Mexico. J. Hydrometeorol. https://doi.org/10.1175/2011JHM1351.1.

Wells, N., Goddard, S., Hayes, M.J., 2004. A self-calibrating palmer drought severity index. J. Clim. 2 https://doi.org/10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO.

Who, 2009. Experts Agree on a Universal Drought Index to Cope with Climate Risks. WMO Press release, p. 872.

Yue, S., Pilon, P., Phinney, B., Cavadias, G., 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol. Process. https://doi.org/10.1002/hyp.1095.

Zehtabian, G., Karimi, K., Nakhaee nezhad fard, S., Mirdashtvan, M., Khosravi, H., 2013. ComparabilityAnalyses of the SPI and RDI meteorological drought indices in south khorasan province in Iran. Int. J. Adv. Biol. Biomed. Res. 1, 981–992.

Zoljoodi, M., Didevarasl, A., 2013. Evaluation of spatial-temporal variability of drought events in Iran using palmer drought severity index and its principal factors (through 1951-2005). Atmos. Clim. Sci. https://doi.org/10.4236/acs.2013.32021.