

Trends in meteorological and agricultural droughts in Iran

S. Golian · O. Mazdiyasi · A. AghaKouchak

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Abstract The aim of this paper is to investigate characteristics of meteorological and agricultural droughts and their trends in Iran, as well as several subregions with different climate conditions from 1980 to 2013. The Standardized Precipitation Index (SPI) and Standardized Soil Moisture Index (SSI) are used as the primary indicators of meteorological and agricultural droughts, respectively. This study assesses historical droughts using the Multivariate Standardized Drought Index (MSDI), which provides a composite model of meteorological–agricultural drought. Furthermore, this study discusses the behavior of MSDI relative to the other indices (SPI and SSI) over different climatic conditions ranging from humid, semiarid, and hyperarid regions. The Mann–Kendall trend test shows that the northern, northwestern, and central parts of Iran have experienced significant drying trends at a 95 % confidence level. However, no statistically significant drying trend was observed in the eastern part of Iran. The most severe drought across the country occurred between 1998 and 2001, with approximately 80 % of the country experiencing an exceptional drought (<2 % probability of occurrence). This event coincided with a prolonged cold phase El Niño–Southern Oscillation (La Niña) that led to persistently cold sea surface temperatures in the eastern Pacific and warm sea surface temperatures in the Indian and western Pacific.

1 Introduction

Drought is a recurring phenomenon that could lead to significant losses to societies and may affect different aspects of human life such as agriculture, food security, and the environment. A 38-year record (1970–2007), available from the Emergency Events Database (EM-DAT), indicates that drought led to over \$29.5 billion in damages in Asia alone (Kallis 2008; OFDA/CRED 2008; Guha-Sapir et al. 2004). Studies show that droughts and dry spells have been changing in different regions and may change under different climate change scenarios (Dai 2012; Wehner 2013; AghaKouchak et al. 2013; Hao et al. 2013; Trenberth 2001; Alexander et al. 2006).

The four classifications of droughts are meteorological, hydrological, agricultural, and socioeconomic (Wilhite and Glantz 1985; Wilhite 2000). A meteorological drought is defined as the deficit of precipitation relative to the average precipitation of long-term climatology. An agricultural drought is defined as a deficit in soil moisture, and a hydrological drought is defined as a period of time in which the amount of available water (streamflow, groundwater, and reservoir levels) is less than the normal condition. A socioeconomic drought, on the other hand, is described as an imbalance between demand and supply ratio (Heim 2002; Hill and Polsky 2007). Drought is a complex process, and numerous indicators have been developed to describe droughts based on different variables. The Standardized Precipitation Index (SPI; McKee et al. 1993) is one of the most commonly used indicators of meteorological drought monitoring and has been used extensively in the literature (e.g., Hayes et al. 1999; Mo 2008). The SPI has been found to be a valuable tool for the early detection of droughts and has been recommended by the World Meteorological Organization as a measure of meteorological droughts (Hayes et al. 2011; Shukla et al. 2011). The SPI has been used

S. Golian
Department of Civil Engineering, Shahrood University of
Technology, Shahrood, Iran

O. Mazdiyasi · A. AghaKouchak (✉)
Center for Hydrometeorology and Remote Sensing, Department of
Civil and Environmental Engineering, University of California,
Irvine, E4130 Engineering Gateway, Irvine, CA 92697-2175, USA
e-mail: amir.a@uci.edu

for both real-time drought monitoring (e.g., AghaKouchak et al. 2013) and climate change impact assessment (e.g., Wehner 2013). The concept of SPI can be applied to other climatic/land surface variables such as soil moisture: Standardized Soil Moisture Index (SSI; Hao and AghaKouchak 2013a). Soil moisture and, hence, SSI is typically used as an indicator of agricultural drought. Previous studies show that SPI is a suitable indicator for detecting drought onset, while soil moisture-based indices (e.g., SSI) describe drought persistence more reliably (Mo 2011; Hao and AghaKouchak 2013a).

Located primarily in semiarid regions, Iran's agriculture is very sensitive and vulnerable to extreme droughts. A number of studies have investigated droughts in Iran from different perspectives (e.g., Morid et al. 2006; Shiau and Modarres 2009; Bannayan et al. 2010; Tabari et al. 2012; Abbaspour and Sabetraftar 2005; Gohari et al. 2013; Madani and Mariño 2009; Raziei et al. 2011). Ghaffari 2006 argues that every 1 mm below average precipitation would result in approximately \$90 million in losses. Using the Palmer Drought Severity Index data set from 1951 to 2005, Zoljoodi and Didevarasl (2013) demonstrated that drought severity has increased over Iran, especially over the northwest and northeast parts of the country. Raziei et al. (2008) assessed the spatial distribution of precipitation patterns using the Precipitation Concentration Index to regionalize drought in western Iran and identified homogeneous regions with similar characteristics.

In 2001 alone, approximately eight million hectares of Iran's agricultural lands were affected by a drought, causing millions of dollars in damages (Darvishi et al. 2008). Based on the similarity between the enhanced warm pool–La Niña composite and the climate anomalies of 1998–2001, Barlow et al. (2002) showed that the prolonged La Niña during this period was a major factor in the central and southwest Asia drought. Nazemosadat and Ghasemi (2004) argued that, during La Niña events, the probability of dry conditions is high and, during warm El Niño–Southern Oscillation (ENSO) phases, the risk of winter drought in the southeastern and northwestern parts of Iran is high, though the rest of the country receives above precipitation climatology. Raziei et al. (2009) investigated the relationship between El Niño and hydrological droughts in western Iran and concluded that there is no evidence of a clear and strong relationship between the two phenomena.

The objective of this study is to investigate the characteristics of meteorological and agricultural droughts and their trends in Iran. Moreover, the study investigates climatic conditions that led to a record drought during 1998–2001 affecting almost the entire country. This study utilizes National Aeronautics and Space Administration's (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA-Land; Reichle et al. 2011; Bosilovich et al. 2011; Rienecker et al. 2011) precipitation and soil moisture data to

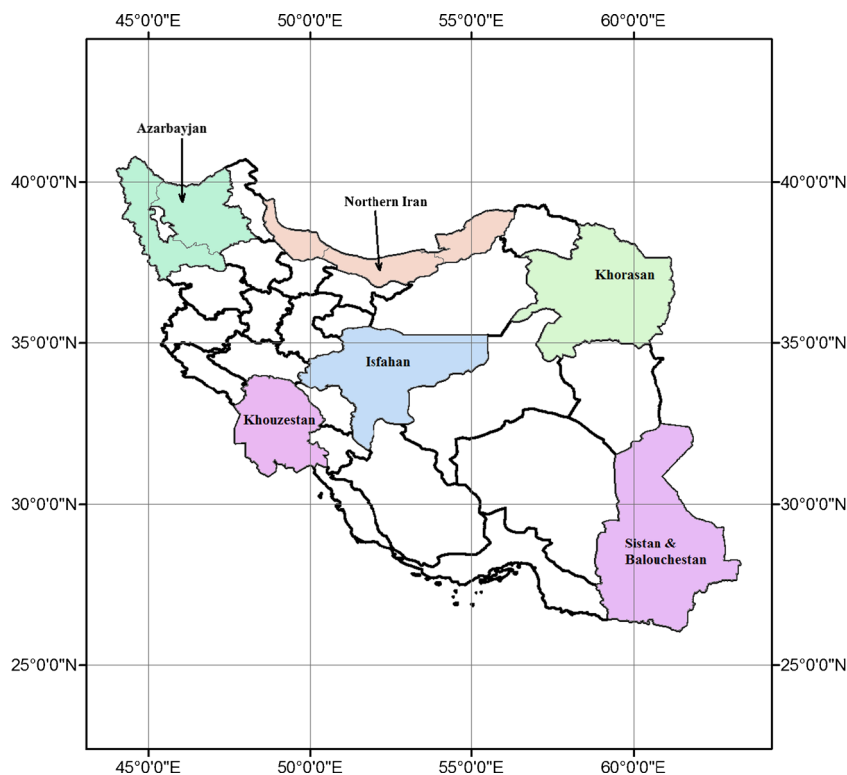
investigate meteorological and agricultural drought conditions in Iran over the past three decades. The SPI and SSI are used as the primary indicators of meteorological and agricultural droughts, respectively. Furthermore, the study assesses historical droughts using the Multivariate Standardized Drought Index (MSDI; Hao and AghaKouchak 2013b) which provides a composite model of meteorological–agricultural drought. Several studies argue that a single index may not be sufficient for a thorough characterization of droughts and a multi-index approach should be considered for comprehensive drought assessment (Quiring 2009; Keyantash and Dracup 2004; Hao and AghaKouchak 2013a). The MSDI offers a multi-index perspective by combining drought information based on precipitation and soil moisture. This study also discusses the behavior of MSDI, relative to the other indices (SPI and SSI) over different climatic conditions ranging from humid, semi-arid, and hyperarid regions.

This paper is organized into five sections. The study area and data sets are described in Section 2, while Section 3 describes the methodology. Section 4 documents the changes in trends of meteorological and agricultural droughts in Iran, followed by a discussion on the 1998–2000 drought. The last section contains a summary, conclusion, and closing remarks.

2 Study area and data resources

This study investigates droughts over Iran and several subregions across the country between 1980 and 2013. Figure 1 shows the location of the study areas. The selected subregions (provinces) have distinct climatic conditions. The northern part is a subtropical region, whereas the southeastern part (hereafter, Sistan and Balouchestan) is an arid/hyperarid region. The northwestern part (Azarbayjan) is a mountainous area with cold winters and warm summers. The southwest (Khouzestan) is a subhumid region with hot summers, while the central and northeast regions have arid and semiarid climate (Modarres 2006).

Precipitation and soil moisture data from NASA's MERRA-Land (Reichle et al. 2011) data are used for assessing meteorological and agricultural droughts. MERRA data are generated by assimilation of in situ and remote sensing observations into numerical models of the global land–atmosphere. MERRA-Land provides hydrologic and land surface data from January 1980 onward, at a spatial resolution of $2/3^\circ \times 1/2^\circ$. MERRA provides two-dimensional products including surface fluxes and land states at an hourly resolution and three-dimensional atmospheric analyses at six-hourly intervals. In this study, monthly averaged MERRA data are used for drought analysis. Drought information based on MERRA data, used in this study, is available through the Global Integrated Drought Monitoring and Prediction System (Hao et al. 2014; Hao and AghaKouchak 2013a).

Fig. 1 Study areas

3 Methodology

Drought is a complex phenomenon, and a single variable (or indicator) may not be able to fully represent/describe its features. Because droughts affect multiple variables (e.g., precipitation, runoff, and soil moisture), we use a multi-index approach for drought assessment. These indices include (1) SPI as a measure of meteorological drought, (2) SSI as a measure of agricultural drought, and (3) MSDI which combines both meteorological and agricultural drought information. The MSDI can be considered as a composite model based on precipitation and soil moisture. The selected drought indices are computed as follows:

- SPI and SSI: In this study, the SPI and SSI are computed using a nonparametric approach presented in Hao et al. (2013). In summary, empirical probabilities are derived using the Gringorten plotting position formula (Gringorten 1963). The empirical probabilities are then standardized using the standard normal distribution.
- MSDI: The concept of MSDI is based on extending the commonly used SPI into a bivariate form (here, based on precipitation and soil moisture). Assuming precipitation (P) and soil moisture (S), MSDI can be obtained by standardizing the joint probability distribution function of precipitation and soil moisture: $\Pr(P \leq p, S \leq s) = C[F(P), G(S)] = p_{ps}$, where $F(P)$ and $F(S)$ are the marginal cumulative distribution functions of variables P and S ,

respectively, and C is the empirical copula. From the cumulative joint probability of precipitation and soil moisture (P_{ps}), the MSDI can be derived as: $\text{MSDI} = \varphi^{-1}(p_{ps})$, where φ is the standard normal distribution function.

All three indices are standardized in which negative (positive) values indicate dry (wet) conditions. Two important characteristics for each drought event are duration and severity. Drought duration is the time period when the drought indicator (e.g., SPI) is below the choice of drought threshold (truncation level), and drought severity is the deviation below the climatological mean as represented by SPI, SSI, and MSDI. Standardized indices can be derived for different time-scales. In this study, the common 6-month SPI, SSI, and MSDI are used for drought assessment.

The study investigates trends and temporal changes in droughts over the selected regions. The nonparametric Mann–Kendall test is applied to the drought time series to examine the presence of trends. Mann (1945) originally developed this test and Kendall (1975) subsequently derived the test statistics distribution. The null hypothesis $H(0)$ indicates that there is no significant trend in the examined time series. This hypothesis is rejected if the p value of the test is less than the significance level (e.g., 0.05 indicating a 95 % confidence level). This test has demonstrated good performance for trend detection in hydrology (Burn and Hag Elnur 2002) and has been previously applied in drought studies (e.g., Damberg and AghaKouchak 2013).

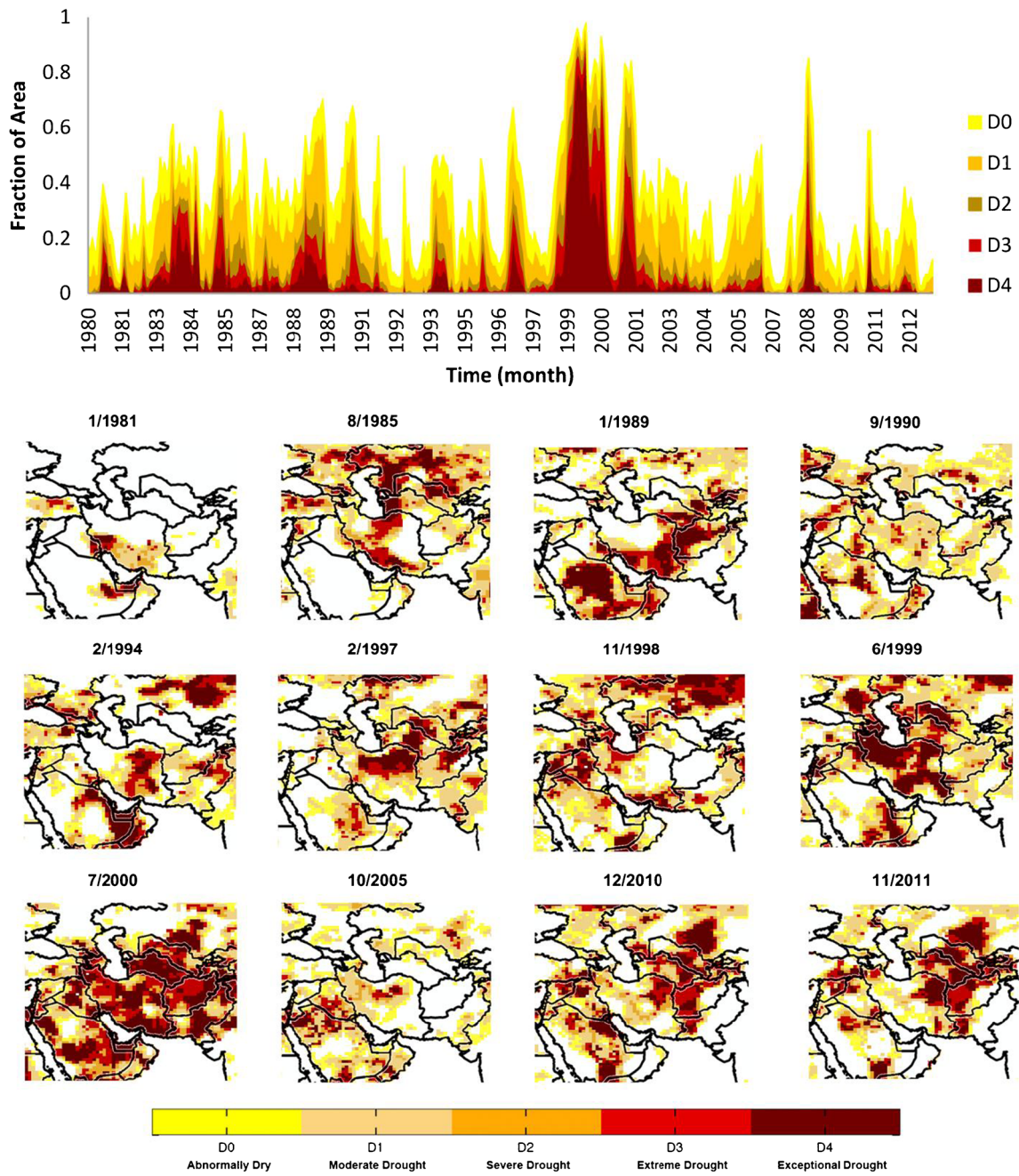


Fig. 2 The fraction of Iran under drought for different drought severity levels (*top*), and spatial patterns of drought at several time steps based on the MSDI

Fig. 3 Time series of the 6-month SPI, SSI, and MSDI over Iran

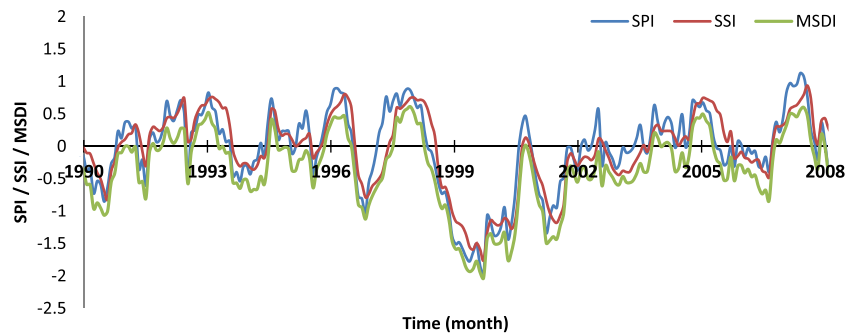


Table 1 The result of the Mann–Kendall trend test for the time series of meteorological and agricultural drought indices in Iran and the selected subregions

	Index	H(0)	<i>p</i> value	Trend
Iran	SPI	False	0.162	No
	SSI	False	0.320	No
Azarbayjan	SPI	True	0.025	Yes
	SSI	True	4.8E-06	Yes
Isfahan	SPI	True	0.032	Yes
	SSI	True	0.0178	Yes
Khorasan	SPI	False	1	No
	SSI	False	0.673	No
Khouzestan	SPI	True	0.001	Yes
	SSI	True	6.7E-12	Yes
Northern Iran	SPI	True	0.017	Yes
	SSI	False	0.5027	No
Sistan and Balouchestan	SPI	False	0.248	No
	SSI	True	0.008	Yes

The Mann–Kendall test does not take into account the magnitude of the values, but instead depends on the rank of values in historical observations. In this test, each value x_i x_n , from a time series with n values is compared with all other values. For a positive difference between the data points, the so-called S statistic is increased by +1, while it is decreased by -1 for a negative difference. The S statistics remains unchanged for a zero difference (Eqs. 1 and 2):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i), \quad (1)$$

where:

$$\text{sgn}(x_j - x_i) \begin{cases} +1, & (x_j - x_i) > 0 \\ 0, & (x_j - x_i) = 0 \\ -1, & (x_j - x_i) < 0 \end{cases}. \quad (2)$$

Thus, a large positive value of S indicates a strongly increasing trend and a large negative value of S indicates a strongly decreasing trend. The nonparametric assumption of

Mann–Kendall's test, when applied to a time series with a large number of values, allows the use of a regular Z test to determine whether a trend is significant or not (Yue et al. 2002):

$$Z = \begin{cases} \frac{S-1}{\sqrt{\frac{n(n-1)(2n+5) - \sum_{j=1}^q t_j(t_j-1)(2t_j+5)}{18}}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\frac{n(n-1)(2n+5) - \sum_{j=1}^q t_j(t_j-1)(2t_j+5)}{18}}}, & \text{if } S < 0 \end{cases}$$

Here, n is the sample size; q is the number of zero-difference groups (ties) in the data set; and t_j is the number of data points in the j th zero-difference group. Throughout this study, a p value of 0.05 (confidence level of 95 %) is used as the criterion of statistical significance of a trend. The Mann–Kendall test returns an H value of 1 if a statistically significant trend is detected (i.e., the null hypothesis of no trend is rejected). Consequently, the test returns an H value of 0 if the null hypothesis of no trend cannot be rejected at a significance level of $p=0.05$.

4 Results

The time series of the fraction of Iran under drought based on MSDI is shown in Fig. 2 (top). For better visualization, drought severity is provided in the so-called D scale (Svoboda et al. 2002): D0 (abnormally dry), D1 (moderate drought), D2 (severe drought), D3 (extreme drought), and D4 (exceptional drought). The aforementioned drought categories represent the following ranges in standardized indices: -0.5 to -0.7 (D0), -0.8 to -1.2 (D1), -1.3 to -1.5 (D2), -1.6 to -1.9 (D3), and -2.0 or less (D4). Figure 2 shows that the most severe drought in the past 30 years occurred between 1998 and 2001 (see also the example spatial patterns in Fig. 2). In August 1999, for example, approximately 90 % of the country was under drought, with approximately 70 % of the country

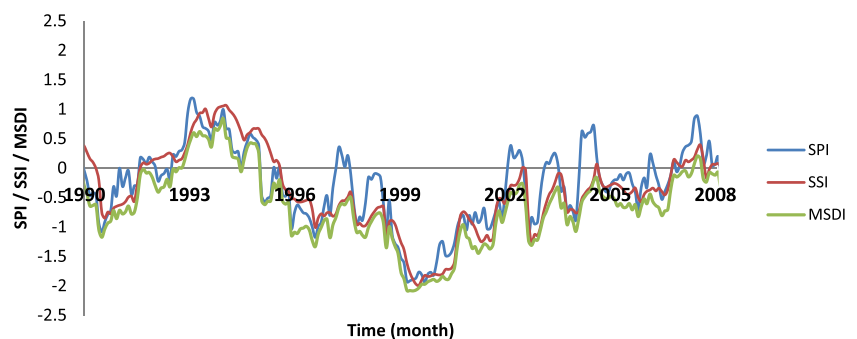
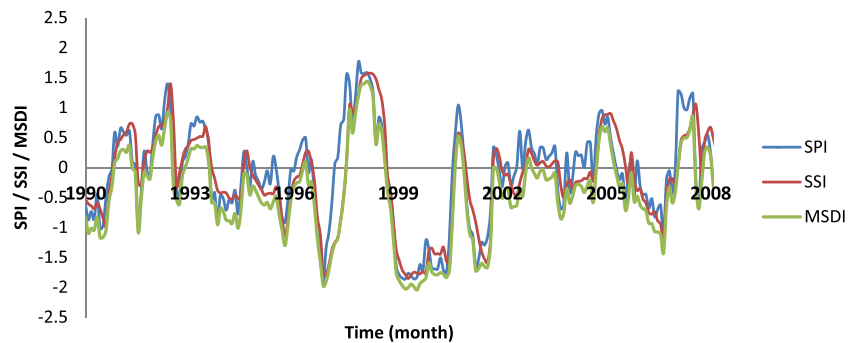
Fig. 4 Time series of the 6-month SPI, SSI, and MSDI over Azarbayjan

Fig. 5 Time series of the 6-month SPI, SSI and MSDI over Khorasan



under exceptional drought (D4 category or SPI, SSI, and MSDI below -2.0).

During the same period, droughts occurred across other parts of Asia, Europe, and the USA. In this period, the sea surface temperatures in the eastern Pacific were persistently cold, while the sea surface temperatures in the Indian and western Pacific were warm (Hoerling and Kumar 2003). Numerous studies have focused on the effects of sea surface temperatures on droughts in the USA and Europe (Kiladis and Diaz 1989; Barlow et al. 2002). However, limited studies have addressed this issue over Iran. Figure 2 shows that the 1998–2001 drought in Iran may have resulted from anomalous sea surface temperatures related to ENSO. ENSO substantially alters precipitation patterns across the tropics and parts of the midlatitudes. In 1999, 2000, and 2001, the average precipitation in Iran was 72 %, 62 %, and 80 % below the long-term climatology, respectively (Darvishi et al. 2008). This clearly highlights that the cold phase of the ENSO (La Niña) phenomenon significantly affects precipitation patterns across Iran (Nazemosadat and Ghasemi 2004).

Analyzing drought duration and severity, it was deduced that SPI recognized 23 drought events lasting 2 months or more. Consistent with previous studies, the most severe drought in the record in Iran started in August 1998 and lasted 27 months until November 2000. SSI indicated 20 drought events where the most severe one started November 1998 and lasted for 25 months until December 2000. The MSDI, on the other hand, detected 19 drought events with the record drought starting July 1998 ending November 2000, 28 months. For the 1998–2001 event, the SPI detects the drought onset

earlier than SSI, which is consistent with the findings of Hao and AghaKouchak (2013b). Also, it is noted that the MSDI detects the drought onset 1 month earlier than SPI, and hence, it may be a better indicator for drought early onset detection.

The time series of the SPI, SSI, and MSDI averaged over the entire country is shown in Fig. 3. In the rest of this paper, for better visualization and to better illustrate the differences between the drought indices, only the results for 1990–2008 are shown. The Mann–Kendall test applied to nonoverlapping SPI and SSI data indicates no significant trend at 95 % confidence level (see also Table 1). This indicates that, in the period of analysis, no significant change in drying/wetting patterns is observed. It is noted that, in all regions, the entire record of data (1980–2013) is used for trend analysis. One can see that the three indices are generally consistent; however, at several time steps, there are discrepancies between the three indices. Typically, soil moisture responds to precipitation deficit with some lag time. For this reason, precipitation is a better indicator for detecting the drought onset (Mo 2008). On the other hand, soil moisture exhibits less variability compared to precipitation and, hence, better describes drought persistence (Hao and AghaKouchak 2013a; Changnon 1987). This study offers the opportunity to investigate the behavior of the indices (SPI, SSI, and MSDI) over different climatic conditions (e.g., northern Iran with humid climate vs. southeast with arid and semiarid climate).

In the following, the subregions shown in Fig. 1 are discussed in more detail. Figures 4, 5, 6, 7, 8, and 9 show the time series of SPI, SSI, and MSDI for the selected subregions.

Fig. 6 Time series of the 6-month SPI, SSI, and MSDI over Sistan and Balouchestan

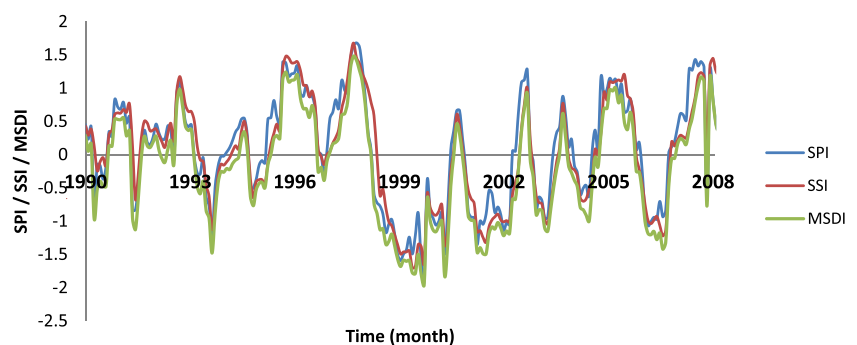
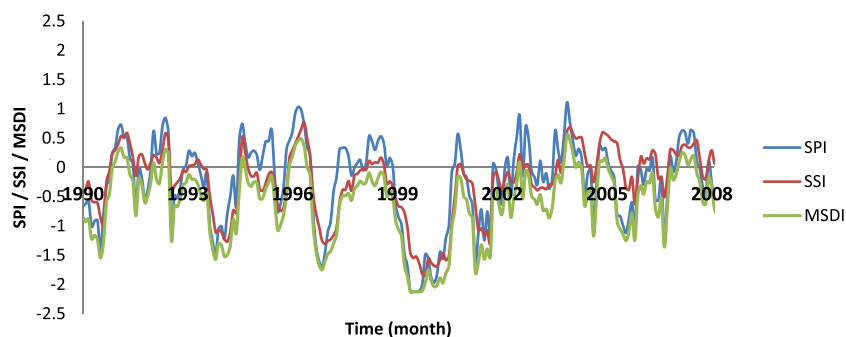


Fig. 7 Time series of the 6-month SPI, SSI, and MSDI over Isfahan



In Azarbaijan, located northwest of Iran (Fig. 4), the most severe drought occurred in 1999 which is consistent with previous studies in this region (Parvin 2011). In this region, precipitation is highly variable. Often, short and heavy precipitation events occur, changing the SPI drought signal (from negative to positive), while they may not be sufficient to terminate agricultural droughts. As shown, in several time steps (e.g., 1997, 2004), SPI shows positive values indicating a wet period from meteorological viewpoint, while the SSI continues to show a dry spell. This may occur when a large volume of precipitation happens over a short time, while the rest of the month remains dry. For this reason, droughts should be investigated with multiple indices.

Figures 5, 6, and 7 show the three indicators for Khorasan, Sistan and Balouchestan, and Isfahan Provinces, all of which are located in semiarid and arid regions. The figures show that, relative to the northwest, droughts have shorter durations. Unlike in the Azarbaijan region, these regions show that the three indices are more consistent throughout the study period. Previous studies in the USA showed that soil moisture-based drought indices often respond to meteorological droughts with a delay of a couple months. In these three regions, however, the figures show that meteorological and agricultural droughts occur at approximately the same time. This can be explained by the fact that these regions have semiarid and arid climate and that the soil moisture is lost quickly.

Figures 8 and 9 show the three indices over Khouzestan (southwest) and northern Iran. Khouzestan receives high precipitation in its mountainous regions and has very hot and often humid summers. The selected region in northern Iran is

humid, with the annual precipitation ranging from 400 to 1,500 mm. In these two regions, unlike the semiarid and arid regions, the SSI (agricultural drought) responds to SPI (meteorological drought) with a couple of months of delay. The figure shows that MSDI is consistent with the SPI's drought onset, but describes the drought persistence similar to SSI. Based on Figs. 4, 5, 6, 7, 8, and 9, one can conclude that, in arid and hyperarid regions, the SPI and SSI are quite similar with respect to the drought onset, while in wet climatic conditions, SPI detects the drought onset earlier. In all areas, the MSDI indicates drought onset similar to precipitation and persistence similar to soil moisture.

In the selected regions, as well as the rest of Iran, the presence of a trend is evaluated using the Mann–Kendall test. Table 1 provides the summary statistics including p values of the trends at 95 % confidence level (0.05 significance level). Nonoverlapping data samples are used for trend analysis to avoid serial dependence. One can see that, in the eastern parts of Iran (with arid and semiarid climate), no significant trend is observed. In contrast, over Azarbaijan, a significant drying trend is observed based on MERRA-Land data. This is consistent with the findings of Damberg and AghaKouchak (2013) where a significant drying trend is detected at 95 % significance level in northwestern Iran using a satellite-based model-independent precipitation data record (AghaKouchak and Nakhjiri 2012). The results are also consistent with the reported trends in the northwest of Iran using ground-based measurement (Tabari and Hosseinzadeh Talaei 2011). Over northern Iran where the average rainfall is much higher than the rest of the county, MERRA precipitation exhibits a

Fig. 8 Time series of the 6-month SPI, SSI, and MSDI over Khouzestan

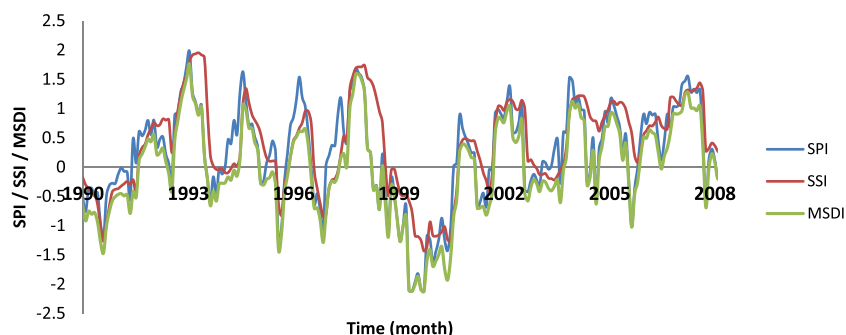
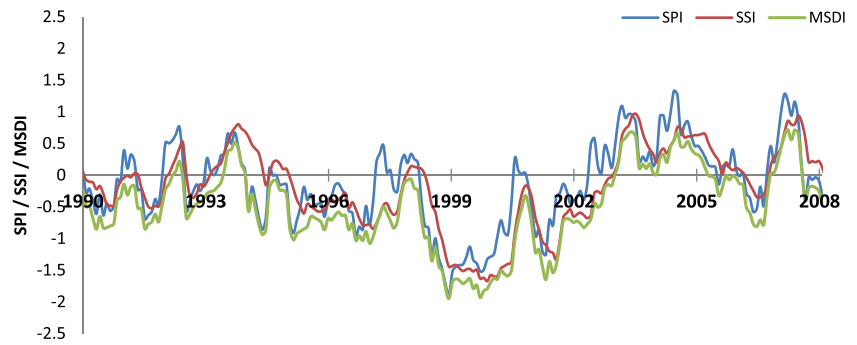


Fig. 9 Time series of the 6-month SPI, SSI, and MSDI over northern Iran



significant trend. A similar trend has been observed using a satellite precipitation data (Damberg and AghaKouchak 2013). However, soil moisture data does not indicate the presence of a significant trend. This can be explained by the fact that the average rainfall is high in northern Iran (between 400 and 1,500 mm/year) and at some time steps, even with precipitation being below the climatology, rainfall is sufficient to keep the soil wet.

Table 2 summarizes the characteristics of extreme drought events that occurred in the regions shown in Fig. 1. Based on each index, the table shows the start time, length, and minimum value of drought indices (most severe conditions) of the top 3 most severe droughts. In this table, drought is defined as the index below the abnormally dry (D0) threshold which

corresponds to -0.5 in standardized scale. As shown, in most regions, the record drought of the late 1990s and early 2000s was even two or three times longer than the second worst drought in some of the regions, especially over Azarbayjan (northwestern Iran). It is worth pointing out that the drought duration and start month is not the same based on different indicators because different drought indices focus on different aspects of drought. One can see, however, that the drought duration based on MSDI is typically longer than both SPI and SSI since it combines information from both indices. Also, the table shows that the MSDI minimum values are slightly smaller than both SPI and SSI, indicating a more severe condition. This is because MSDI emphasizes drought condition when both indicators are below the choice of drought

Table 2 Characteristics of most significant drought events in selected regions shown in Fig. 1 (several snapshots of the spatial patterns of these historical events are provided in Fig. 2)

Index		Event 1			Event 2			Event 3		
		Start month	Duration (month)	Min index	Start month	Duration (month)	Min index	Start month	Duration (month)	Min index
Azarbayjan	SPI	Oct 98	41	-1.94	Mar 96	12	-1.18	Apr 89	6	-1.47
	SSI	Dec 97	52	-1.99	Mar 96	19	-1.01	Nov 90	9	-0.85
	MSDI	Dec 97	53	-2.09	Dec 95	23	-1.33	Jul 90	16	-1.17
Isfahan	SPI	Mar 99	19	-2.12	Mar 90	10	-1.41	Jun 05	7	-1.12
	SSI	Mar 99	21	-1.84	Dec 96	9	-1.30	Jan 94	9	-1.27
	MSDI	Feb 99	22	-2.12	Jun 89	20	-1.55	Nov 96	10	-1.75
Khorasan	SPI	Feb 99	20	-1.86	Dec 88	12	-1.23	Mar 01	9	-1.67
	SSI	Feb 99	21	-1.85	Dec 88	12	-1.04	Apr 01	8	-1.58
	MSDI	Jan 99	22	-2.04	Nov 88	27	-1.37	Dec 93	11	-1.01
Khouzestan	SPI	Mar 99	19	-2.12	Feb 88	21	-1.72	Oct 83	13	-2.03
	SSI	Dec 85	47	-1.54	Mar 83	20	-1.83	Jul 99	16	-1.43
	MSDI	Mar 85	56	-1.87	Feb 99	22	-2.12	Feb 83	21	-2.08
Northern Iran	SPI	Aug 98	25	-1.89	Feb 83	7	-1.6	May 85	7	-1.59
	SSI	Nov 98	25	-1.67	Apr 04	17	-1.32	Apr 83	9	-1.12
	MSDI	Jul 98	30	-1.95	May 95	27	-1.08	May 85	19	-1.63
Sistan and Balouchestan	SPI	Jul 98	18	-1.91	Mar 01	15	-1.36	Jan 88	8	-1.21
	SSI	Sep 98	24	-1.7	Mar 01	16	-1.32	Oct 87	12	-1.28
	MSDI	Jul 98	26	-1.95	Mar 01	17	-1.49	Nov 88	13	-1.73

threshold. It is acknowledged that model simulations and satellite observations used to derive SPI, SSI, and MSDI are subject to uncertainties.

5 Conclusion

Every year, droughts affect agriculture, water resources, and ecosystems of Iran. Most parts of Iran suffer from water scarcity, and droughts can substantially exasperate the pressure on the water resource systems. Water resource systems are sensitive to climatic change and variability (Nazemi et al. 2013) and, hence, changes in droughts could affect water availability. Using precipitation and soil moisture data from NASA's MERRA-Land, this study investigates the trends and patterns of meteorological and agricultural droughts in Iran and several subregions with different climatic conditions. The meteorological and agricultural droughts are assessed using the SPI and SSI, respectively. Using a composite model, known as the MSDI, the overall meteorological–agricultural drought conditions are also evaluated. The findings can be summarized as follows:

1. The results indicate that the hypothesis of no trend could not be rejected in the eastern and northeastern Iran (Khorasan and Sistan and Balouchestan). However, in the northern, northwestern, and central parts of Iran, a significant drying trend at 95 % confidence level has been observed. Over the entire country, the drought indicators do not show any significant trend.
2. The most severe drought across the county and the selected regions occurred between 1998 and 2001. Nearly the entire country was under drought for a couple of months during this period. For example, in summer 1999, approximately two thirds of the country experienced exceptional drought (D4 category), with approximately 90 % of the country being under D0–D4 drought conditions. This coincides with a cold phase ENSO, La Niña, that led to persistently cold sea surface temperatures in the eastern Pacific and warm sea surface temperatures in the Indian and western Pacific. Consequently, droughts occurred in many parts of the world including Iran. This clearly highlights that the ENSO phenomenon (particularly, prolonged La Niña) significantly alters precipitation patterns across Iran and is one of the main drivers of droughts.
3. This study investigated the newly developed MSDI over different climatic conditions from humid to hyperarid. In humid regions (e.g., northern Iran) and also areas with high precipitation variability (e.g., Azarbayjan), the use of multivariate indicators such as MSDI is of particular importance. The main reason is that, in humid and semihumid regions, soil moisture levels may remain high even long after precipitation. In such regions/climates,

typically, precipitation detects the drought earlier and soil moisture better describes the persistence. MSDI, detects the drought onset similar to SPI, but describes the drought persistence more similar to SSI. However, in arid and hyperarid regions (e.g., Sistan and Balouchestan and Khorasan), the three indices (SPI, SSI, and MSDI) were more consistent, and MSDI did not provide additional information. The main reason is the fact that, in arid and hyperarid regions, after each rainfall event, soil moisture evaporates relatively quickly. In such regions, soil moisture level is typically very low and meteorological and agricultural droughts occur at about the same time.

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