



Global Advanced Research Journal of Environmental Science and Toxicology (ISSN: 2315-5140) Vol. 3(2) pp. 025-037, July 2014
Available online <http://garj.org/garjest/index.htm>
Copyright © 2014 Global Advanced Research Journals

Full Length Research Paper

Characteristics and mechanism of extreme climate events under climate change background in Iran - part I: drought

M. Molanejad^{1, 2}, M. Soltani^{3, 4*} and A. Ranjbar SaadatAbadi⁵

¹Scientific Staff of Iranian Research Organization for Science and Technology (IROST)

²Director IORA- Regional Center for Science and Technology Transfer

³Indian Ocean Rim Association (IORA), Regional Center for Science and Technology Transfer (RCSTT), Tehran, Iran

⁴Department of Physical Geography, Faculty of Geography, University of Tehran, Iran

⁵Atmospheric Sciences and Meteorological Research Center (ASMERC) of I. R. of Iran Meteorological Organization (IRIMO), Tehran, Iran

*Corresponding author's email: soltani.clima@gmail.com

Abstract

Drought is a natural disaster that gives a lot of damage every year. It is one of the most dangerous natural hazards because it is very difficult to identify its onset. In this paper the *Standard Precipitation Index* (SPI) has been used to monitor drought in Iran. The SPI index is a powerful tool, requiring only rainfall data for its calculation, and delivering major dimensions of drought such as severity, magnitude, frequency etc. Thirty five years (1978 to 2012) of monthly precipitation data of 30 stations across Iran are used to calculate SPI values for a time-scale of 12 month period. The time series plots of SPIs indicated that a negative trend of drought (an increase in drought frequency) over the country except for the central and southeastern parts, where a positive trend and decrease in the frequency of drought observed for those areas. Furthermore, the year 2010 was detected as the driest year in terms of drought severity with values varying between -2.524 and -4.933 that approximately 80% of the stations had a negative trend in which 75% out of 80% was statistically significant during the examined period over Iran. The results also suggested that the drought severity is very critical in the Western areas in particular in Ilam region. As well as, we found that the mountainous regions, in general, are more vulnerable to drought phenomenon rather than other parts of the country. The synoptic features at 500 hPa and surface levels of the extremely dry (the severest drought) year *i.e.* 2010 proved that no suitable rising condition was provided during the mentioned year, because of the formation of a belt of high pressures over Iran as well as the expansion of the Siberian high pressure center southwestward. Consequently, no considerable amount of moisture transferred to the country, and as a result, the lowest amounts of the annual precipitation were recorded at the thirty selected stations during the examined period across Iran.

Keywords: Drought, standardized precipitation index, frequency, severity, synoptic pattern, Iran

INTRODUCTION

During the recent decades, Iran has been witnessing natural extreme events such as droughts, heavy floods, unexpected warm or cold weathers, storms and hails. Raising natural extreme events are mostly related to climate variables. Therefore, climate change has been a challenge facing humans in this century. The areas more affected by this change are agriculture, water resources, health, environment, etc., which should be recognized by the governments. Drought is a normal and recurrent feature of climate. It occurs in all climatic zones and its characteristics vary significantly from region to region. Iran is located in an arid and semi-arid region. Having an average annual precipitation of 250 mm, Iran receives less than one third of global average precipitation (*i.e.* 750 mm). In addition, the rainfall distribution pattern over the country is not the same everywhere. Bearing in mind such a climatic condition, many severe or mild droughts are inevitable to come up. Any drought can inflict a severe damage on the agricultural, domestic and industrial sectors of the country (Bazrafshan and Khalili, 2013). Iran is frequently hit by recurring droughts. The extreme drought of 1998–2001 was one of the worst ones in the last few decades with rainfall deficits consistently exceeding 60% of the mean annual rainfall in most of the country. The severity of this drought placed an extreme strain on water resources, livestock and agriculture. The Iranian Emergency Agency reported that 278 cities and 1050 villages had been affected.

In addition, the crops from a rain fed area of 4 million ha as well as those from an irrigated area of 2.7 million ha were completely destroyed. The total agricultural and livestock losses by the year 2001 were estimated to be US\$2.6 billion. Eighteen out of the 28 provinces of the country were affected, but the impact of the drought differed throughout the country and some of the provinces were more hit than others (Fahmi, 2001; Mir Abolghasemi *et al.*, 2001). Bazrafshan and Khalili (2013) analyzed the meteorological drought in Iran from 1965 to 2003. They found that: a) the maximum frequency of severe drought was 5.1 times and moderate drought was 23.1 times per 100 years; b) the most extensive droughts (more than 80% of the country) occurred during 1970–1971 (82.21%), 1988–1989 (92.05%), and 1999–2000 (96.27%); and c) drought spread in Iran beginning from the northwestern and southeastern regions, gradually extending to the central regions. Raziei *et al.*, (2008) regionalized the precipitation events and investigated the drought variability for western Iran. Their results suggested that five spatially homogenous sub-regions can be identified characterized by different precipitation regimes. The spatial pattern of seasonal precipitation seemed to be highly controlled by the wide latitudinal extent of the region and by the pronounced orographic relieves, and the time of occurrence of the maximum precipitation varies from spring in the north to winter in

the south. The time variability of dry and wet periods in the identified sub-regions was analyzed using the *Precipitation Index* (PI) and the existence of any long-term trend was tested. Results showed that the northern and southern regions of western Iran are characterized by different climatic variability. Furthermore, a negative long-term linear trend in the north and a weak positive trend in the south of the study area have been detected though they are not statistically significant.

Ahmadi and Houshyar (2013) investigated the synoptic patterns of the most severe droughts over watershed of Urumiyeh Lake. Their results showed that the event of a most severe drought in the watershed area has had an impact on all four synoptic patterns. Safari Shad *et al.*, (2013) studied the drought event using SPI index over Ghareh Chai and Karkheh basins. Results of their research showed that drought periods have taken place, and influenced water resources and few years were without drought, but in many years drought were occurred even for a short period. Vaghefi *et al.*, (2013) analyzed the impact of climate change on water resources components, drought and wheat yield in semiarid regions of Karkheh river basin in Iran. They found that in the northern part of KRB, freshwater availability will increase from 1716 to 2670 m³/capita/year despite an increase of 28% in the population in 2025 in the B1 scenario. In the southern part, where much of the agricultural lands are located, the freshwater availability will on the average decrease by 44%. Their results also indicated an increase of up to 25% in both frequency and length of dry periods in southern Karkheh, whereas increasing flood events could be expected in the northern and western parts of the region.

Lana, X., *et al.* (2001) used the SPI to analyze spatial and temporal behaviors of rainfall shortage and excess for Catalonia, Spain. Skaf and Mathbout (2010) studied the changes in drought over the last five decades in Syria, and found negative trends, which were statistically significant ($p = 0.05$ and $p = 0.01$) only for some stations by the Mann-Kendall test, but significant negative step changes were detected by Regime Shift Index (RSI) in annual SPI values for all regions. The study on drought duration using EDI showed a positive trend in dry days number, and dry spells seemed to be longer. Karavitis *et al.*, (2011) applied the *Standardized Precipitation Index* (SPI) to study the drought duration, magnitude and spatial extent in semi-arid areas of Greece. Their results underlined the potential that the SPI usage exhibits in a drought alert and forecasting effort as part of a drought contingency planning posture. Livada, I. *et al.* (2007) used monthly precipitation data from 23 stations to assess drought for Greece. In another effort, Sönmez, F.K. *et al.* (2005) examined the drought vulnerability of Turkey using the SPI. Wu, H. *et al.* (2005) indicated that the differences among the SPI values computed using

different lengths of records were not considerable, if the precipitation pattern is stable. In another effort they claim that the SPI users should be careful when adapting short time scale SPI values in arid locations and they should concentrate on the duration of the drought rather than on its severity.

Khan and Gadiwala (2013) studied the drought event over Sindh (Pakistan) using SPI during 1951-2010, and found that the time scales less than 12 months had enormous fluctuations so that identifying drought and wet periods were not so clear. However, plots of 36 month SPI and 48 month SPI obviously could identify drought and wet periods of the region clearly. Their results also showed that the duration, attenuation, intensity and magnitude for any particular month during the historical records were time scale dependent. Rachchh and Bhatt (2014) investigated the drought events by SPI in Rajkot district, Gujarat, India. Their results suggested that the Rajkot region had felt severe drought in 1987 A.D. On an average there was a condition of drought in Rajkot district once in two years. They also concluded that since 2005 Rajkot district has not felt any major drought.

The purpose of this study is to analyze the statistical characteristics of drought events under climate change background in Iran. The objective is also extended to synoptically investigate the mechanisms responsible for the occurrence of the severest drought across the country. This paper is organized as follows: in Sect. 2 methodology is presented. Section 3 illustrates the main results and Sect. 4 provides the conclusions.

METHODOLOGY

Study Area and Data

Iran is located in an arid and semi-arid region. Iran is located in the south of Asia between $44^{\circ} 02'$ and $63^{\circ} 20'$ E longitudes and $25^{\circ} 03'$ to $39^{\circ} 46'$ N latitudes. The country covers an area of about 1.648 million square km, which it is mostly mountainous, where two major mountain chains, the Alborz Range and the Zagros Range dissect the country into climatic zones in which the topography ranges from around -26 to approximately above 4000 meters (Figure 1). Climatologically, of the total area, 13% has a cold and mountainous weather, 14% has a moderate climate and the remaining 73% is covered by dry weather. Water balance of the country according to 30 years of data shows that the average annual precipitation is 250 mm. 30% of the precipitation occurs in the form of snow and the rest in the form of rain (Alijani 1996). In this research, the daily precipitation data observed at 30 weather stations collected by *Islamic Republic of Iran Meteorological Organization* (IRIMO) are used to identify the dry (drought) periods using the *Standardized Precipitation Index* (SPI) during a 35-year (1978–2012) period across Iran (Table 1). In order to

investigate the synoptic mechanism of the extreme drought occurred in the year 2010 over Iran, the averaged relative vorticity (10^{-5} s^{-1}), geopotential height (m), *Sea Level Pressure* (SLP), u and v wind components (m/s) and relative humidity (%) datasets examined from the *National Centers for Environmental Prediction/National Center for Atmospheric Research* (NCEP/NCAR) reanalysis dataset (Kalnay et al., 1996), as well as averaged hourly total of precipitation (mm) data derived from the *European Centre for Medium-Range Weather Forecasts* (ECMWF). And then the charts produced using *Grid Analysis and Display System* (GrADS) program (Doty, 1996). Spatial distribution of 30 weather stations used in this research together with the topography map of Iran is shown in figure 1.

Methods

In order to study the characteristics of drought (dry spells) across Iran the *Standardized Precipitation Index* (SPI) has been applied. In fact, SPI is a tool which was developed primarily for defining and monitoring drought. It allows an analyst to determine the rarity of a drought at a given time scale (temporal resolution) of interest for any rainfall station with historic data. To analyze the mechanisms responsible for the severest (extreme) drought *i.e.* the drought of the year 2010, the weather charts at multiple levels of the atmosphere are synoptically analyzed. The SPI index was developed by McKee et al. (1993). A number of advantages arise from the use of the SPI index. First, the index is based on precipitation alone making its evaluation relatively easy (Cacciamani et al., 2007). Secondly, the index makes it possible to describe drought on multiple time scales (Tsakiris and Vangelis, 2004; Mishra and Desai, 2006; Cacciamani et al., 2007).

A third advantage of the SPI is its standardization which makes it particularly well suited to compare drought conditions among different time periods and regions with different climates (Cacciamani et al., 2007). A drought event occurs at the time when the value of the SPI is continuously negative; the event ends when the SPI becomes positive. Table 2 provides a drought classification based on SPI. The computation of the SPI requires fitting a probability distribution to aggregated monthly precipitation series (1, 3, 6, 12, 24, 48 months). The probability density function is then transformed into a normal standardized index whose values classify the category of drought characterizing each place and time scale (Cacciamani et al., 2007). The SPI can only be computed when sufficiently long (at least 30 years), and possibly continuous, time-series of monthly precipitation data are available (Cacciamani et al., 2007). In most cases the probability distribution that best models observational precipitation data is the Gamma distribution. The density probability function for the

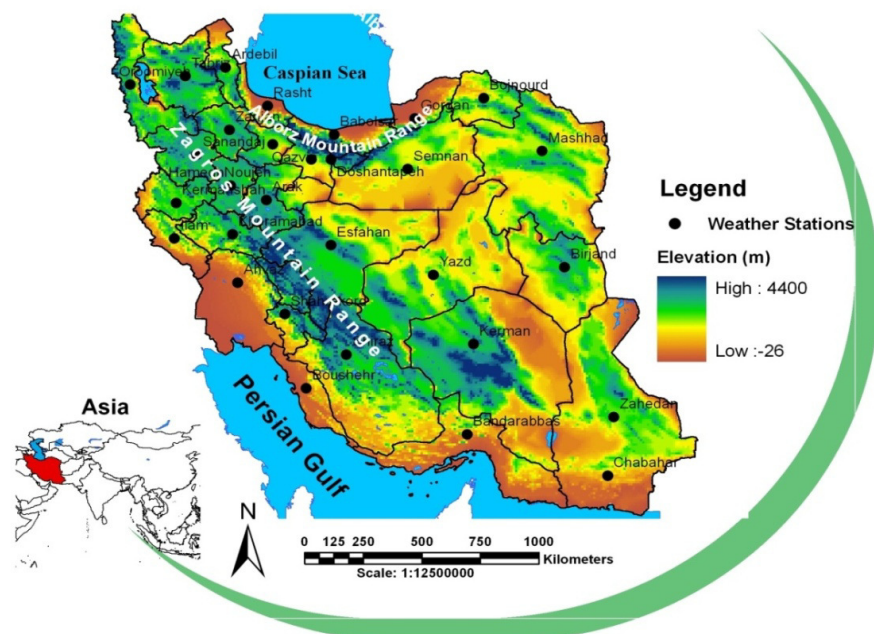


Figure 1. Topography map of Iran. Geographical locations of 30 weather stations examined in this project are labeled over the topography map

Table 1. Geographical characteristics of the selected weather stations across Iran during the period 1978-2012

WMO Number	Sub-Regions	Station Name	Latitude (N)	Longitude (E)	Elevation (m)
40712	Northwest	Oroomiyeh	37°32′	45°05′	1315.9
40706		Tabriz	38°05′	46°17′	1361
40708		Ardebil	38°15′	48°17′	1332
40729		Zanjan	36°41′	48°29′	1663
40731		Qazvin	36°15′	50°03′	1279.2
40768	North	HamedanNojeh	35°12′	48°43′	1679.7
40747		Sanandaj	35°20′	47°00′	1373.4
40788		Gorgan	36°51′	54°16′	13.3
40736	North	Babolsar	36°43′	52°39′	-21
40719		Rasht	37°12′	49°39′	3607
40745	Northeast	Mashhad	36°16′	59°38′	999.2
40723		Bojnourd	37°28′	57°19′	1091
40780		Ilam	33°38′	46°26′	1337
40766	West	Kermanshah	34°21′	47°09′	1318.6
40782		Khoramabad	23°26′	48°17′	1147.8
40769		Arak	34°06′	49°46′	1708
40798	Central	Shahrekord	32°17′	50°51′	2048.9
40754		Tehran-Mehrabad	35°41′	51°19′	1190.8
40751		Dooshantapeh	35°42′	51°20′	1209.2
40757	Central	Semnan	35°35′	53°33′	1130.8
40821		Yazd	31°54′	54°17′	1237.2
40800	East	Esfahan	32°37′	51°40′	1550.4
40809		Birjand	32°52′	59°12′	1491
40811	Southwest	Ahvaz	31°20′	48°40′	22.5
40858		Boushehr	28°59′	50°50′	19.6
40848		Shiraz	29°32′	52°36′	1484
40875	South	Bandarabass	27°13′	56°22′	9.8
40898		Chabahar	25°17′	60°37′	8
40856	Southeast	Zahedan	29°28′	60°53′	1370
40841		Kerman	30°15′	56°58′	1753.8

Table 2. Drought classification based on SPI (McKee *et al.*, 1993)

SPI values	Drought intensity
$SPI \leq -2$	Extremely dry
$-2 < SPI \leq -1.5$	Severely dry
$-1.5 < SPI \leq -1$	Moderately dry
$-1 < SPI \leq 1$	Near normal
$1 < SPI \leq 1.5$	Moderately wet
$1.5 < SPI \leq 2$	Severely wet
$SPI \geq 2$	Extremely wet

Gamma distribution is given by the expression (Cacciamani *et al.*, 2007):

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta}, \quad \text{for } x > 0 \quad (1)$$

where $\alpha > 0$ is the shape parameter, $\beta > 0$ is the scale parameter and $x > 0$ is the amount of precipitation. $\Gamma(\alpha)$ is the value taken by the standard mathematical function known as the Gamma function, which is defined by the integral (Cacciamani *et al.*, 2007):

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx \quad (2)$$

In general, the Gamma function is evaluated either numerically or using the values tabulated depending on the value taken by parameter α . In order to model the data observed with a gamma distributed density function, it is necessary to estimate parameters α and β appropriately. Different methods have been suggested in the literature for the estimate of these two parameters. For example, Thom (1958) approximation is used for maximum probability in Edwards and McKee (1997):

$$\hat{\alpha} = \frac{1}{4A} \left(1 + \sqrt{1 + \frac{4A}{\pi}} \right) \quad (3)$$

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \quad (4)$$

where for n observations:

$$A = \sum_{i=1}^n \ln(x_i) \quad (5)$$

The estimate of the parameters can be further improved by using the interactive approach suggested in Wilks (1995). After estimating coefficients α and β the density of probability function $g(x)$ is integrated with respect to x and we obtain an expression for cumulative probability $G(x)$ that a certain amount of rain has been observed for a given month and for a specific time scale (Cacciamani *et al.*, 2007):

$$G(x) = \int_0^x g(x) dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \quad (6)$$

The Gamma function is not defined by $x = 0$ and since there may be no precipitation, the cumulative probability becomes (Cacciamani *et al.*, 2007):

$$H(x) = q + (1 - q)G(x) \quad (7)$$

where q is the probability of no precipitation and $H(x)$ is the cumulative probability of precipitation observed. The cumulative probability is then transformed into a normal standardized distribution with null average and unit variance from which we obtain the SPI index. The above approach, however, is neither practical nor numerically simple to use if there are many grid points of many stations on which to calculate the SPI index. In this case, an alternative method is described in Edwards and McKee (1997) using the technique of approximate conversion developed in Abramowitz and Stegun (1965) that converts the cumulative probability into a standard variable Z . The SPI index is then defined as (Cacciamani *et al.*, 2007):

$$Z = SPI = - \left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right), \quad \text{for } 0 < H(x) \leq 0.5 \quad (8)$$

$$Z = SPI = + \left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right), \quad \text{for } 0.5 < H(x) < 1 \quad (9)$$

Where

$$t = \sqrt{\ln \left[\frac{1}{(H(x))^2} \right]} \quad \text{for } 0 < H(x) \leq 0.5 \quad (10)$$

And

$$t = \sqrt{\ln \left[\frac{1}{(1 - H(x))^2} \right]} \quad \text{for } 0.5 < H(x) < 1 \quad (11)$$

where x is precipitation, $H(x)$ is the cumulative probability of precipitation observed and $c_0, c_1, c_2, d_0, d_1, d_2$ are constants with the following values:

$$\begin{aligned} c_0 &= 2.515517 & c_1 &= 0.802853 & c_2 &= 0.010328 \\ d_0 &= 1.432788 & d_1 &= 0.189269 & d_2 &= 0.001308 \end{aligned}$$

THE RESULTS AND DISCUSSION

Time Series and SPI Trends

The time series and trends of SPI coefficients in six stations *i.e.* Tabriz, Babolsar, Mashhad, Ilam, Esfahan and Birjand for a 35-year period (1978-2012) from different geographic regions of Iran is shown in figure 2. In the northwest area of the country, as Tabriz station indicates, the general trend is negative with a slope of –

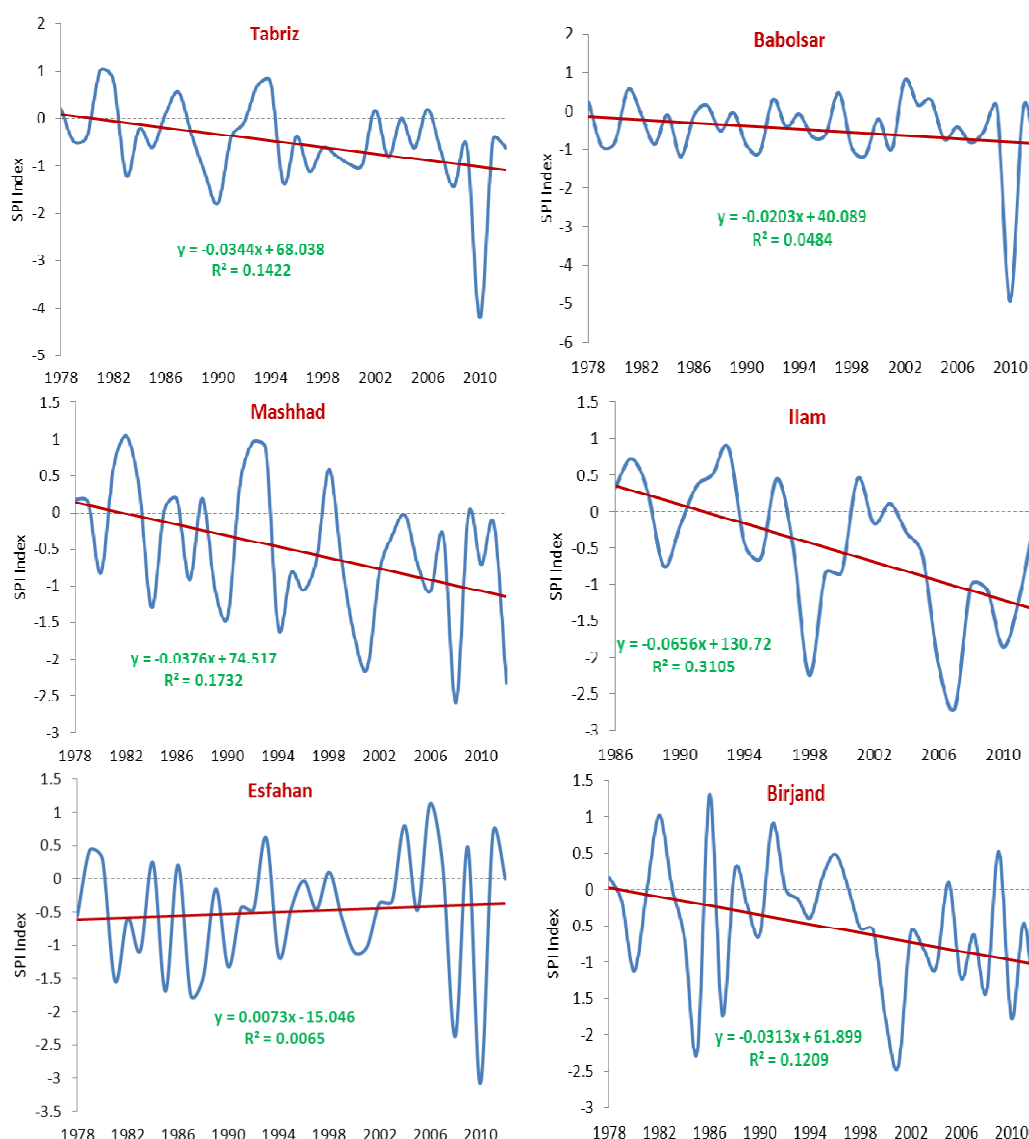


Figure 2. The time series and trends of SPI index coefficients in the selected stations across Iran during the period 1978-2012. Each individual station acts as a representative for the individual sub-regions in the country as follows: Tabriz (northwest); Babolsar (north); Mashhad (northeast); Ilam (west); Esfahan (central) and Birjand (east).

0.034 specifically in Tabriz station in which indicating that the dry years (periods) are continuously occurring with high magnitudes in the region. Based on the chart, in 10 out of 35 years the SPI coefficient was positive, which indicates a *Near Normal* condition in terms of drought severity, meanwhile only 1 out of 10 positive years indicated a *Moderately Wet* condition with a SPI index of 1.014 in the year 1981. On the contrary, the year 2010 was detected as the driest year and *Extremely Dry* in terms of drought severity with a negative SPI value of -4.197 for Tabriz station in the examined period (see

Tabriz in the Fig. 2). The dryness and drought condition in the north of Iran was detected mostly *Near Normal* condition (29 out of 35 years), as shown in Babolsar station. Meanwhile, 5 years identified as *Moderately Dry* in terms of drought severity in the north of the country. Similar to Tabriz station, In Babolsar station also the year 2010 was detected as *Extremely Dry* with a negative SPI coefficient of -4.933. On the whole, the general SPI trend of the region (Babolsar) is almost normal, although a negative trend of -0.020 was identified. Interestingly, no *Wet* condition (moderate or extreme) was detected in the

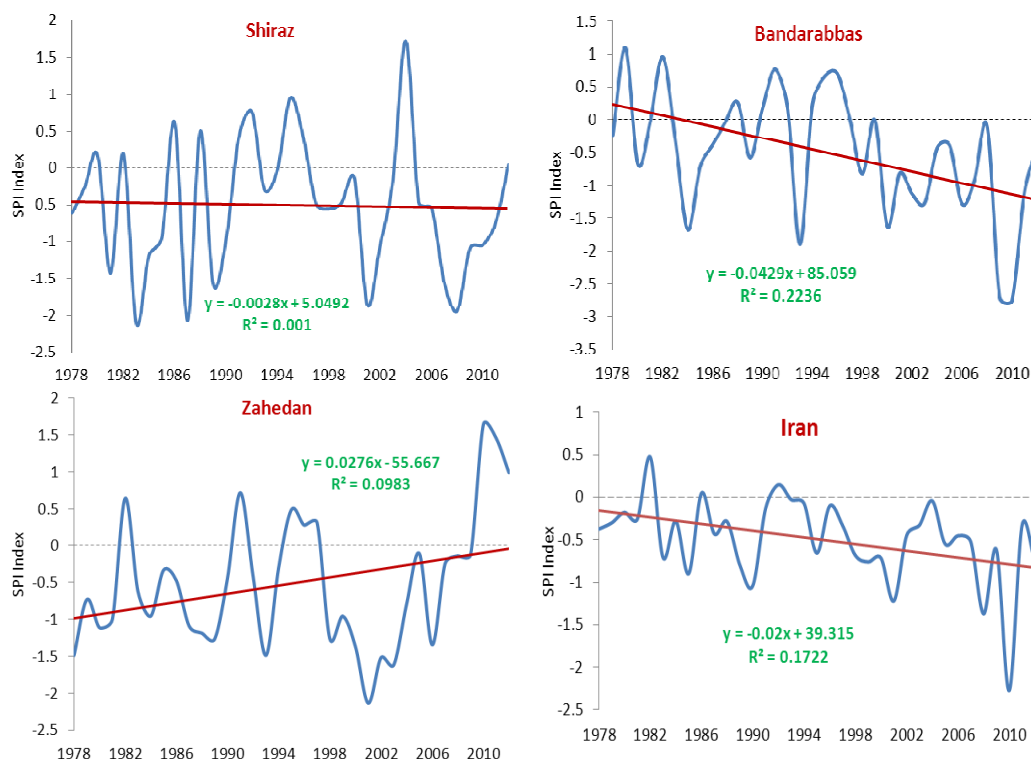


Figure 3 Same as Figure 2, but for: Shiraz (southwest); Bandarabbas (south); Zahedan (southeast) and Iran (30 selected stations across Iran).

region (see Babolsar in the Fig. 2). The SPI coefficients in the northeast of the country (Mashhad) indicated a very fluctuating trend. The SPI index only in the year 1982 was detected as *Moderately Wet* (with a value of 1.048) in terms of drought severity and in 10 out of 35 years the drought severity was detected as *Moderately* (5-years) and *Severely* (2-years) and *Extremely* (3-years) *Dry*. The general SPI trend of the northeast of the country (Mashhad) was identified negative with a slope of -0.037, which indicates that the drought condition in the northern half of Iran is more severe in the northeastern region of the country (see Mashhad in the Fig. 2).

The severest drought among the all stations was detected in the west of Iran i.e. Ilam station with a negative SPI trend of -0.065. The year 2007 was identified as the driest year in terms of drought severity as *Extremely Dry* (SPI value -2.698). The years 1998 (-2.248) and 2006 (-2.101) also were detected as *Extremely Dry* condition. Meanwhile, 19 out of 35 years recorded a *Near Normal* condition in terms of drought severity (see Ilam in the Fig. 2). Opposed to the northwest, north, northeast and west of the country, the central region of Iran (Esfahan station) indicated a positive SPI trend with a value of 0.007. Approximately 6 out of 35 years indicated a *Moderately Dry* and 3 out of 35 years showed *Severely Dry* condition. Meanwhile, the

SPI coefficients in the years 2008 (-2.372) and 2010 (-3.077) was detected as *Extremely Dry* condition. The rest of the years i.e. 22 out of 35 years recorded a *Near Normal* condition in terms of drought severity in the central (Esfahan) region (see Esfahan in the Fig. 2). In contrast to the central region, the eastern areas of the country (Birjand) indicated a negative trend of SPI index with a value of -0.031. In 2 out of 35 years (i.e. 1982 and 1986) recorded a *Moderately Wet* condition with positive values of 1.019 and 1.310 respectively in the east of Iran. The *Extremely Dry* condition was detected in the years 1985 (-2.248) and 2001 (-2.427). 23 years also indicated a *Near Normal* condition in terms of drought severity (see Birjand in the Fig. 2).

Interestingly, the SPI coefficient in the southwest of Iran (Shiraz station) indicated a slightly negative trend with a slope of -0.002, which can be negligible so that it may be stated that there is not a specific trend in the region. Similar to the northeast regions (Mashhad station), in the southwestern areas of the country (Shiraz station) the SPI index also showed a very fluctuating trend, which mostly are negative. The years 1983 (-2.094) and 1987 (-2.065) were detected as *Extremely Dry*, while in four other years a *Severely Dry* condition was identified (see Shiraz in the Fig. 3). Like most of the regions in the country, the south of Iran (Bandarabbas

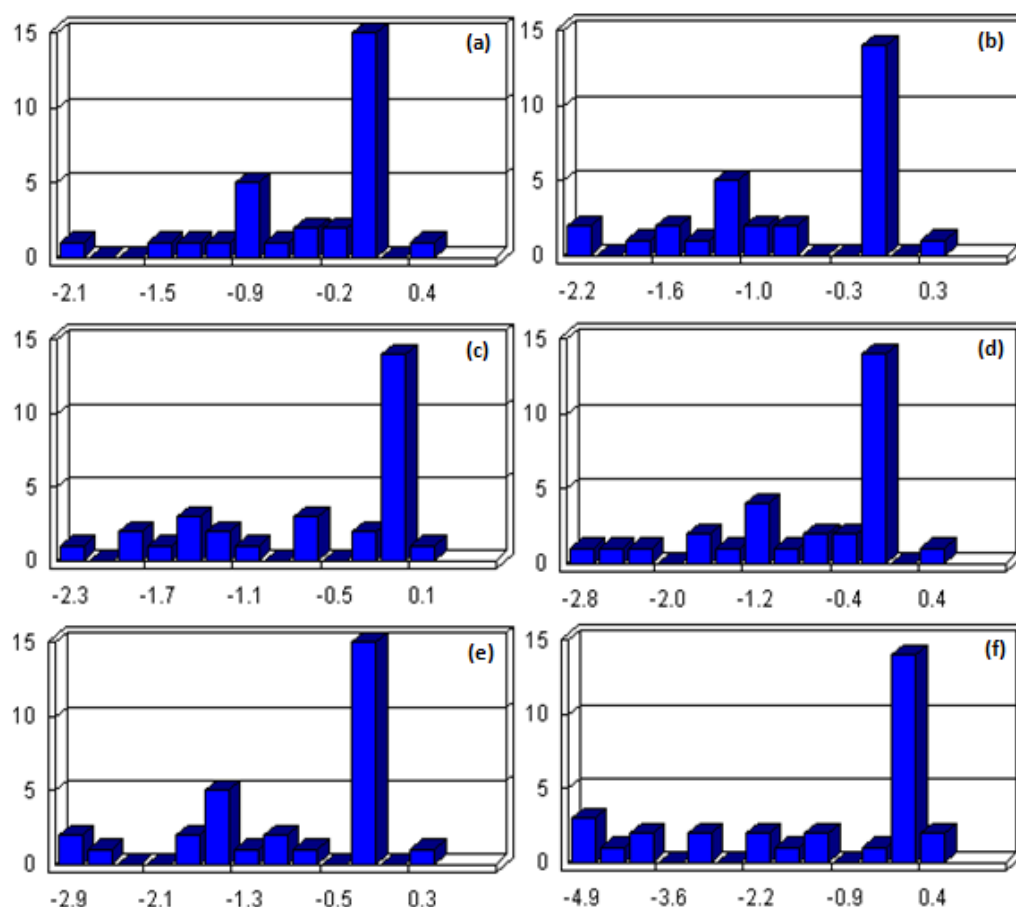


Figure 4. Frequency distribution of SPI trend magnitudes for the severest droughts during the period 1978-2012 across Iran: (a) 1983; (b) 1985; (c) 1990; (d) 2001; (e) 2008; (f) 2010. The x-axis indicates the SPI coefficient magnitudes and y-axis shows the frequency of the SPI index.

station) indicated a negative SPI coefficient, which is very sharp with a value of -0.042. Only the year 1979 the SPI index was identified as *Moderately Wet* condition with value of 1.090. Meanwhile, in 7 out of 35 years *Moderately* (4 years) and *Severely* (3 years) *Dry* condition were detected. The *Extremely Dry* condition also was found in the years 2009 (-2.696) and 2010 (-2.7565). Other years *i.e.* 23 out of 35 years showed a *Near Normal* condition in terms of drought severity (see Bandarabbas in the Fig. 3). The SPI coefficient in the southeastern parts of the country (Zahedan station), similar to the central regions (Esfahan), indicated a general positive trend with a slope of 0.027, which this is mainly due to the positive values at the end of the examined period *i.e.* 2010 (1.641) and 2011 (1.454) which were detected as *Moderately Wet* and *Very Wet* conditions in terms of drought severity in the region, respectively. In contrast, the year 2001 with a value of -2.135 was identified as *Extremely Dry* condition. In 9 out of 35 years a *Moderately Dry* condition was found, while

in the years 2003 (-1.519) and 2003 (-1.615) a *Severely Dry* was detected (see Zahedan in the Fig. 3). Finally, the SPI coefficient indicated a negative trend with a slope of -0.02 throughout the country (Iran). The year 2010 was detected as *Extremely Dry* condition with a SPI value of -2.273 in the whole country. On the whole, in only three years of 1982 (0.475), 1986 (0.049) and 1992 (0.149) a positive SPI index were found, while in 32 out of 35 years a negative trend was detected in the averaged thirty selected stations across Iran (see Iran in the Fig. 3).

Frequency Distribution

Figure 4 indicates the frequency distribution of SPI index trend at 30 selected stations across Iran for the years that have recorded the severest drought condition during a 35-year period *i.e.* 1983, 1985, 1990, 2001, 2008 and 2010. On the whole, all of the selected years had decreasing SPI trend for the whole region, but it is

statistically significant at some stations. In the year 1983, large number (85%) of SPI coefficient was negative and more than 30% out of 85% of the frequency of SPI had a statistically significant trend, meanwhile only 15% of SPI index showed a positive trend, but statistically insignificant in 1983 (Fig. 4a). About 90% of the SPI index was negative and around 48% out of 90% was statistically significant in the year 1985. Meanwhile, 10% of the SPI coefficient had a positive trend with no value statistically significant (Fig. 4b).

In addition, in the drought conditions of the years 1990, 2001 and 2008, about 95% of SPI coefficient (55%, 65% and 70% statistically significant, respectively) had negative trends. While, only 1% of SPI index showed positive trend that is statistically insignificant in the three mentioned years (Fig. 4c, 4d and 4e). As mentioned earlier, the year 2010 was detected as the extremely dry during the examined period. Approximately 80% of SPI index had negative trend in which 75% out of 8% was statistically significant. But, 5% of the SPI index possessed a positive trend with 2% out of 5% statistically significant (Fig. 4f). The linear trends of these extreme droughts have also shown in the figure 3 (Iran chart).

Mean Annual Precipitation and Drought Severity Interpolation

The interpolation maps of mean annual precipitation and the drought severity classification derived from SPI index for a 35-year period (1978-2012) are shown in figure 5. The distribution of annual precipitation pattern, as figure 5a indicates, is highly in good agreement with the distribution of topography in Iran, meaning that the Alburz and Zagros Mountain ranges receive almost the highest amount of precipitations except for the southern coasts of Caspian Sea in which the highest precipitation (with more than 1300mm) is absolutely recorded in the southwestern border of the Caspian Sea southern coasts (e.g. Rasht station). In addition to the leeward side (northern) of Alburz mountain range (Caspian Sea southern coasts), the western half of the country (Zagros mountain range) also receives a considerable amount of annual precipitation ranging from 350mm to 700mm. On the contrary, the lowest precipitation occurrence is found in the eastern and in particular in the southeastern regions of the country, where the precipitation values varied between 60mm – 200mm (Fig. 5a). According to the SPI index drought severity, as figure 5b indicates, the drought condition is very critical in the western areas in particular in Ilam station with values ranging from -0.4704 to -0.3831. The SPI index in the eastern and southeastern areas is less critical and has a better condition, meaning that although all parts of the country are suffering from drought condition, this phenomenon has had less impact over the mentioned areas. Interestingly, the findings from the interpolation maps are quite in good agreement with

those of trend analysis in figures 2 and 3. For example, the severest negative SPI trend was detected in Ilam station, which it is shown in the interpolation map (Fig. 5b) as the most critical point (station) across the country. Whereas, the stations like Zahedan, indicated a positive trend (Fig. 3) and the least dryness and drought condition in the country. In general, it seems that the mountainous regions in Iran are more vulnerable to drought phenomenon, while the opposite is true for the arid and semi-arid areas (e.g. eastern and southeastern regions) of the country as well as the southern coasts of Caspian Sea (Fig. 5b).

Synoptic Analysis of Weather Charts

In this section, the weather charts for the severest drought during the examined period *i.e.* the year 2010 drought, are analyzed on the basis of the synoptic condition over Iran. Thus, the averaged weather charts for individual period *i.e.* cold and warm periods, will be examined to identify the mechanisms responsible for the occurrence of the extreme drought in 2010 across Iran.

Weather Charts Analysis of Cold Seasons

The averaged weather charts in cold seasons (*i.e.* autumn and winter seasons) indicate that at 500-hPa level, a low center with central height 5200-hPa is closed over the northern Europe (*i.e.* Scandinavia) resulted in the positive relative vorticity values to be increased varying between $0.5 \times 10^{-5} \text{ s}^{-1}$ - $2 \times 10^{-5} \text{ s}^{-1}$ over most European countries. Simultaneously, a belt of high pressures are dominant over the middle and lower latitudes including Iran. As a result, the relative vorticity is either zero or negative over lower latitudes. In such synoptic condition, there is not a suitable rising condition, and therefore there is a little chance for the air parcels to rise (Fig. 6a). Correspondingly, at surface chart it can be seen that the Siberian high pressure center extended largely southwestward, so that Iran is affected by the ridges of this high center. On the contrary, the low pressure centers can be found over the European countries (Fig. 6b). The synoptic features at 500 hPa and surface levels prove that no suitable rising condition was provided during the cold seasons of the year 2010. The wind streams at 850 hPa, as figure 6c indicates, were transferring the moisture sources from Mediterranean Sea to the central and northern parts of the country in such a way that the relative humidity varied between 50%-100% over the area, and a precipitation amount ranging from 15mm to 30mm over the region (Fig. 6d). At the same time, due to an anticyclonic circulation over the Saudi Arabia peninsula, some moisture of the Persian Gulf transferred to the south of Iran (Fig. 6c), which

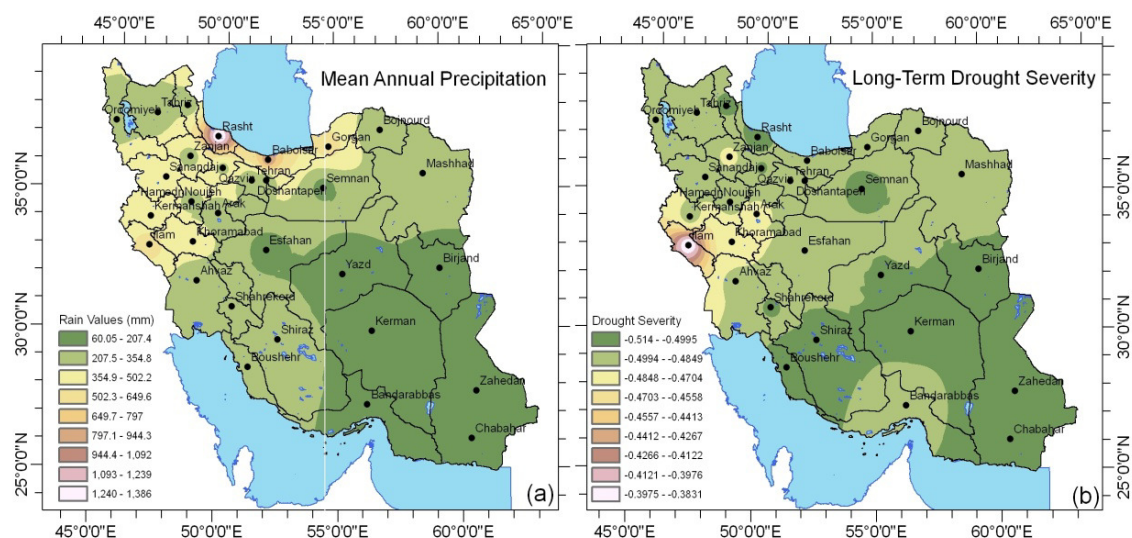


Figure 5 (a): Distribution of mean annual precipitation (mm), (b): Interpolation of SPI index drought severity across Iran during the period 1978-2012

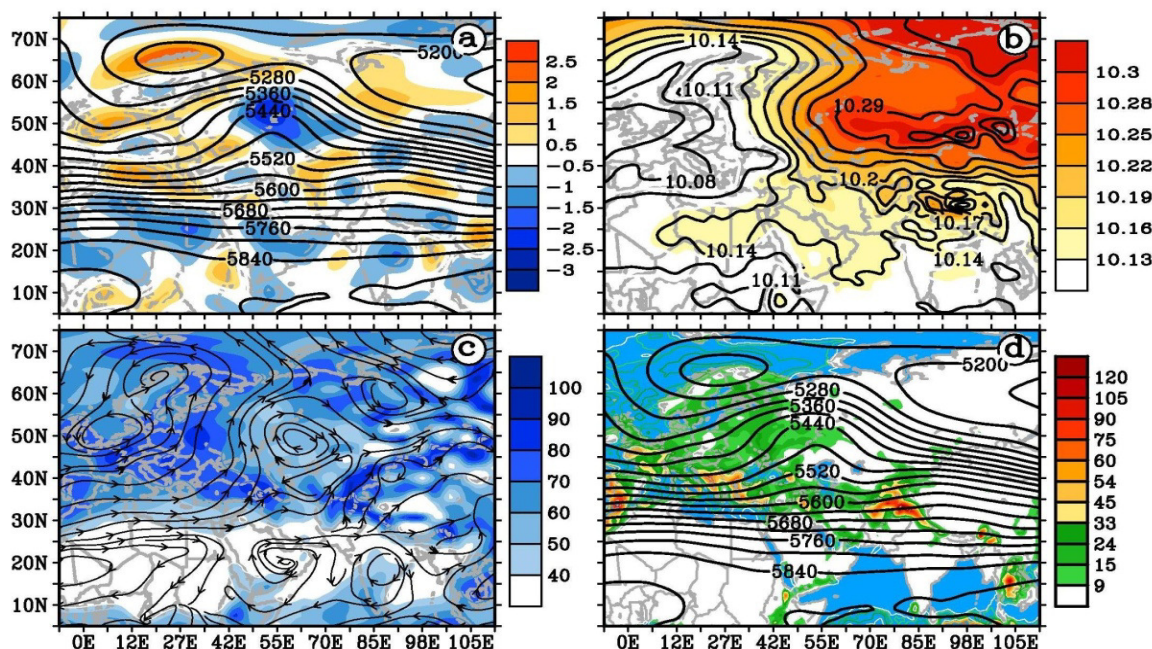


Figure 6. Analysis of averaged charts derived from NCEP/NCAR reanalysis dataset for: (a) 500hPa geopotential height contours (m) and relative vorticity ($10^{-5}s^{-1}$) in shading; (b) SLP in hectopascal pressure (contours and shading); (c) relative humidity (%) at 850hPa (shaded) and streamlines in black barbs (m/s). (d) Daily precipitation (mm) derived from ECMWF (shaded) and daily geopotential height (m) at 500 hPa (solid contours). Figures are valid for cold seasons *i.e.* autumn and winter 2010.

resulted in occurring of some light precipitation (Fig. 6d). These amounts of precipitation over Iran are far less than

those of the mean semiannual (*i.e.* autumn and winter) values.

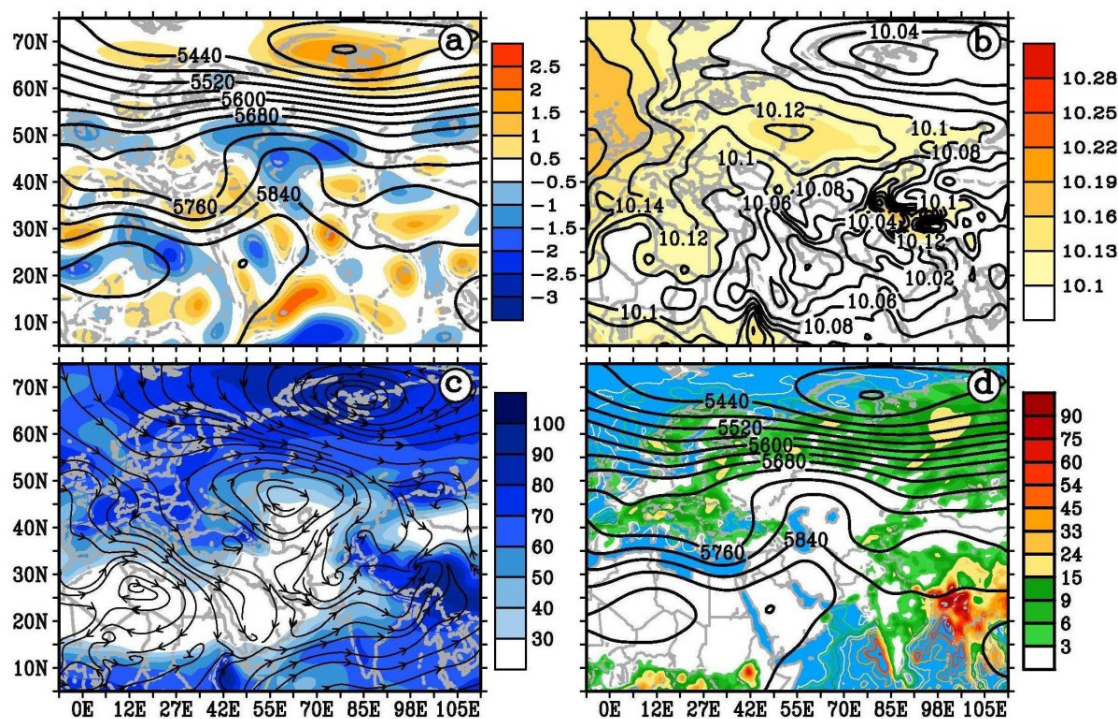


Figure 7. Same as Fig. 6, but valid for warm seasons *i.e.* spring and summer 2010

Weather Charts Analysis of Warm Seasons

It can be clearly seen that, as 500 hPa chart in the figure 7a indicates, a strong ridge is extended over middle latitudes including Iran as a result of the expansion of a closed low center headquartered over Africa northeastward. Between the latitudes 50°N and 70°N the pressure gradient is very intensive, as it is located between two low belts in the tropical and high latitudes in which a suitable condition is provided for rising the air parcels. The opposite is true for 500 hPa circulative condition over Iran due to the placing a powerful ridge over the country (Fig. 7a). The synoptic condition at surface chart in the warm periods of the year 2010, as shown in figure 7b, is almost opposite of those of in cold periods. On the other hand, during the warm seasons a ridge of a closed high pressure center located over Western Europe extended highly eastward in such a way that a closed high center formed over the north of Caspian Sea, which was negatively affected Iran (Fig. 7b). The amount of relative humidity over Iran, as figure 7c indicates, is less than 30% mostly because of the anticyclonic circulation due to the exist of the closed high pressure center over the north of Caspian Sea. As a result, almost no precipitation was recorded during the spring and summer seasons across Iran. Meanwhile, the amount of precipitation over the southeast of Asia including India is considerable due to the Monsoon phenomenon (Fig. 7d).

CONCLUSIONS

The actual rainfall expressed as percent deviation from normal (long-term average) is the most commonly used drought indicator, although it has limited use for spatial comparison due to its dependence on the mean. The *Standardized Precipitation Index* (SPI) expresses the actual rainfall as a standardized departure from rainfall probability distribution function. This index has gained importance in recent years as a potential drought indicator since it permits comparisons across time and space (Naresh Kumar *et al.*, 2009). In this study, we investigated the characteristics and mechanisms of drought events under climate change background in Iran for a 35-year period (1978-2012). The SPI index was used to identify the dry spells as well as to analyze the severity and extent of droughts across the country. The time behaviors of annual SPI time series in the identified sub-regions showed a similar climatic variability *i.e.* negative trend of drought (an increase in drought frequency) over the country except for the central and southeastern parts in which indicated a positive trend and decrease in the frequencies of drought occurrence for those areas. Meanwhile, a long-term decreasing trend towards dry periods is detectable in the northern and western regions, while an increasing weak long-term trend has been observed in the southeastern area, which it is statistically significant at the end of the examined period.

The most negative trend in terms of drought occurrence among the sub-regions of the country was detected in the Western Iran with a negative slope of -0.065. In more than 22 out of 30 stations (approximately 73%) the year 2010 was detected as extremely dry in terms of drought severity with a negative SPI coefficient varying between -2.524 and -4.933, although the averaged SPI trend for the whole country (30 selected weather stations) showed that the year 2010 was the driest year over the past 35 years in Iran. The frequency distribution of SPI trend magnitudes confirmed that the year 2010 recorded the severest drought in Iran, which approximately 80% of SPI index had negative trend in which 75% out of 80% was statistically significant. But, 5% of the SPI index possessed a positive trend with 2% out of 5% statistically significant. On the whole, all of the selected years had decreasing SPI trend for the whole region, but it was statistically significant at some stations. The interpolation maps of mean annual precipitation showed that the southern coasts of Caspian Sea as well as the Western Iran receive the highest amounts of annual precipitation ranging from 350mm to 700mm. On the contrary, the lowest precipitation occurrence was found in the eastern and in particular in the southeastern regions of the country, where the precipitation values varied between 60mm – 200mm. Meanwhile, the drought condition was very critical in the Western areas in particular in Ilam region with values ranging from -0.4704 to -0.3831. On the whole, it was found that the mountainous regions in Iran are more vulnerable to drought phenomenon rather than the arid and semi-arid areas (e.g. eastern and southeastern regions) of the country as well as the southern coasts of Caspian Sea.

Synoptic analysis of weather charts for the year 2010 drought during the cold period indicated that a low center is closed over the northern Europe (i.e. Scandinavia), which resulted in the positive relative vorticity values to be increased varying between $0.5 \times 10^{-5} \text{s}^{-1}$ - $2 \times 10^{-5} \text{s}^{-1}$ over most European countries. Simultaneously, because of formation of a belt of high pressures over the middle and lower latitudes including Iran, the relative vorticity was mostly negative over lower latitudes. Correspondingly, at surface chart the Siberian high pressure center was extended largely southwestward, so that Iran was affected by the ridges of this high center. The synoptic features at 500 hPa and surface levels proved that no suitable rising condition was provided during the cold seasons of the year 2010. Furthermore, the moistures of Mediterranean Sea as well as Persian Gulf were transferring to the country to some extent. As a result, some precipitation ranging from 15mm to 30mm recorded across Iran during the cold period of the year 2010. In contrast during the warm period, a strong ridge at 500 hPa is extended over middle latitudes including Iran as a result of the expansion of a closed low center headquartered over Africa northeastward. Meanwhile, at surface a ridge of a closed high pressure center located

over Western Europe extended highly eastward in such a way that a closed high center formed over the north of Caspian Sea, which was negatively affected Iran e.g. no considerable amount of moisture transferred to the country. As a result, almost no precipitation amount was recorded during the warm period across Iran.

ACKNOWLEDGEMENTS

The daily precipitation data was provided by *I. R. of Iran Meteorological Organization* (IRIMO). The NCEP/NCAR reanalysis dataset was provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA (<http://www.cdc.noaa.gov>), as well as the hourly total of rainfall values derived from the *European Centre for Medium-Range Weather Forecasts* (ECMWF).

REFERENCES

- Abramowitz M, Stegun A (1965). Handbook of Mathematical Formulas, Graphs, and Mathematical Tables. Dover Publications, Inc., New York, USA.
- Ahmadi H, Houshyar A (2013). Reviews of the Synoptic Patterns of the Most Severe Droughts, Watershed of Urumiyeh Lake, EUROPEAN ACADEMIC RESEARCH, VOL. I, ISSUE 6/ SEPTEMBER 2013.
- Alijani B (1996). Climate of Iran, Payam-e-Nour University press, Tehran, Iran (in Persian).
- Bazrafshan J, Khalili A (2013). Spatial Analysis of Meteorological Drought in Iran from 1965 to 2003, DESERT 18 (2013) 63-71.
- Cacciamani C, Morgillo A, Marchesi S, Pavan V (2007). Monitoring and Forecasting Drought on a Regional Scale: Emilia-Romagna Region. Water Science and Technology Library 62(1): 29-48.
- Dotty B (1996). The Grid Analysis and Display System (GrADS), V1.5.1.12, 145p. [<http://www.iges.org/grads/gadoc/users.html>].
- Edwards DC, McKee TB (1997). Characteristics of 20th Century Drought in the United States at Multiple Scales. Atmospheric Science Paper: 634.
- Fahmi H (2001). Assessment of the 1998–2000 Drought Spell on Water Resources of Iran. Ministry of Energy: Teheran; 49.
- Kalnay E, 21Co-authors, (1996). The NCEP/NCAR 40-year reanalysis project, *Bulletin of the American Meteorological Society*, 77: 437-471.
- Karavitis Ch A, Alexandris S, Tsesmelis DE, Athanasopoulos G (2011). Application of the Standardized Precipitation Index (SPI) in Greece, *Water* 2011, 3, 787-805; doi:10.3390/w3030787.
- Khan MA, Gadiwala MS (2013). A Study of Drought over Sindh (Pakistan) Using Standardized Precipitation Index (SPI) 1951 to 2010, *Pakistan Journal of Meteorology*, Vol. 9, Issue 18: Jan 2013.
- Lana X, Serra C, Burgueño (2001). A. Patterns of monthly rainfall shortage and excess in terms of the standardized precipitation index for Catalonia (NE Spain). *Int. J. Climatol.* 2001, 21, 1669-1691.
- Livada I, Assimakopoulos VD (2007). Spatial and temporal analysis of drought in Greece using the standardized precipitation index (SPI). *Theor. Appl. Climatol.* 2007, 89, 143-153.
- McKee TB, Doesken NJ, Kleist J (1993). The Relationship of Drought Frequency and Duration to Time Scales, Paper Presented at 8th Conference on Applied Climatology. American Meteorological Society, Anaheim, CA.
- Mir Abolghasemi H, Morid S, Ghaemi H (2001). Integrated drought plans, the lost component in water management of Iran. In *Proceeding of the First National Conference on "Water Crisis Mitigation Strategies"*, Zabol; 443–454.
- Mishra AK, Desai VR (2006). Drought forecasting using feed-forward recursive neural network. *Ecological Modeling* 198(1-2): 127-138.

- Naresh Kumar M, Murthy SC, Sessa Sai MVR, Roy PS (2009). On the use of Standardized Precipitation Index (SPI) for drought intensity assessment, *Meteorol. Appl.* 16: 381–389 (2009).
- Rachchh R, Bhatt N (2014). Monitoring of Drought Event by Standard Precipitation Index (SPI) in Rajkot District, Gujarat, India, *International Journal of Engineering Development and Research*, Volume 2, Issue 1 (2014).
- Raziei T, Bordi I, Pereira LS (2008). A precipitation-based regionalization for Western Iran and regional drought variability., *Hydrol. Earth Syst. Sci.*, 12, 1309–1321, 2008.
- Skaf M, Mathbout S (2010). Drought changes over last five decades in Syria. In : López-Francos A. (comp.), López-Francos A. (collab.). Economics of drought and drought preparedness in a climate change context. Zaragoza: CIHEAM/FAO/ICARDA/GDAR/CEIGRAM/MARM, 2010. p.107-112 (Options Méditerranéennes: Série A. Séminaires Méditerranéens; n. 95).
- Sönmez, FK, Kömüscü AÜ, Erkan A, Turgu E (2005). An analysis of spatial and temporal dimension of drought vulnerability in turkey using the standardized precipitation index. *Nat. Hazards* 2005, 35, 243-264.
- Thom HCS (1958). A note on gamma distribution. *Monthly Weather Rev.* 86, 117–122.
- Tsakiris G, Vangelis H (2004). Towards a Drought Watch System based on spatial SPI. *Water Resources Management* 18 (1): 1-12.
- Vaghefi SA, Mousavi SJ, Abbaspour KC, Srinivasan R, Yang H (2013). Analyses of the impact of climate change on water resources components, drought and wheat yield in semiarid regions: Karkheh river basin in Iran, *Hydrol. Process.* (2013) DOI: 10.1002/hyp.9747.
- Wilks DS (1995). Statistical methods in the atmospheric sciences an introduction, Academic, San Diego, 467.
- Wu H, Hayes MJ, Wilhite DA, Svoboda MD (2005). The effect of the length of record on the standardized precipitation index calculation. *Int. J. Climatol.* 2005, 25, 505-520.