DESERT

DESERT
Online at http://jdesert.ut.ac.ir

DESERT 18 (2013) 89-97

Monitoring Meteorological Drought in Iran Using Remote Sensing and Drought Indices

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Received: 2 June 2013; Received in revised form: 9 September 2013; Accepted: 14 September 2013

Abstract

Drought is a major environmental disaster in many parts of the world. Knowledge about the timing, severity and extent of drought can aid planning and decision-making. Drought indices derived from *in-situ* meteorological data have coarse spatial and temporal resolutions, thus, obtaining a real-time drought condition over a large area is difficult. This study used advanced very high resolution radiometer (AVHRR) images to evaluate the efficacy of NOAA-AVHRR data for monitoring drought in Iran for the 1997-2005 (March-July) time period. Ten-day maximum normalized difference vegetation index (NDVI) maps were produced and a vegetation condition index (VCI), vegetation health index (VHI) and temperature condition index (TCI) for the same period was calculated. Precipitation data from 47 synoptic meteorological stations was collected to calculate the standardized precipitation index (SPI) as a meteorological drought index. Analysis and interpretation of these maps revealed that the spatial extent of the satellite-derived drought-indices and SPI generally confirm each other. Based on the statistical analysis, higher correlations were found among the satellite-derived indices while lesser or no relationships were found between the satellite-derived indices and SPI. The results revealed that high correlations were found among TCI and VHI, VCI and VHI in dry, normal, and wet years (0.662 to 0.813). Iran suffered from severe drought during 1999-2001.The results of remotely-sensed indices and the SPI index for 2002-2005 most of the region show that it experienced normal conditions.

Keywords: Drought monitoring; Iran; NOAA-AVHRR; SPI

1. Introduction

Assessing the relationship between environmental parameters and vegetation cover is essential in arid and semi-arid regions for advanced planning (Tavili, *et al.,* 2009). Drought is a water-related natural disaster that affects environmental factors and agriculture, vegetation, humans and wild life, and localeconomies(Jeyaseelan, 1999; Azarakhshi, *et al.,* 2011; Dastorani and Afkhami, 2011). Droughts are complex natural phenomena for which there is no universally accepted definition. In general terms, a drought is considered to exist when the rainfall over a determined period of time is inferior to the mean rainfall for the same period of time calculated for a series of reference years (Gonzalez *et al.,* 2003). From 1967 to 1991, 50% of the 2.8 billion people who experienced natural disasters were victims of drought; it killed 35% of the 3.5 million victims who died over that time period. In recent years, large-scale intensive drought has been observed on all continents and has led to economic loss, destruction of ecological resources, food shortages, and starvation for millions people (Kogan, 2001).

Satellite data has been successful for early detection and monitoring of drought and its impact on crops and pastures in China, Greece,

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Mongolia, Brazil, and others (Kogan*et al.,* 2005). For more than a decade, remote-sensing techniques have been used to identify and monitor drought-affected areas on regional, national, and global scales with satisfactory results (Tucker and Choudhury, 1987; Kogan, 1997). Drought in different regions of Spain during 1987-2001 was evaluated using remote sensing data with good results (Gonzalez *et al.,* 2003).

Iran is a country with an arid and semi-arid climate. From 1999 through 2000, Iran experienced drought (United Nations, 2001). Global climate change envisages increased frequency and duration of drought for this region, but there is currently no systematic way to determine the onset of drought over such a large area in a timely manner. Several climatic drought indices have been developed and employed for drought monitoring. These indices are derived from climatic data such as precipitation thatis frequently scattered or insufficient and unavailable for timely drought detection, monitoring and decision-making (Unganai and Kogan, 1998). Morid*et al.* (2006) studied drought conditions by comparing seven drought indices (Deciles index, percent of normal, standardized precipitation index (SPI), China-Z index (CZI), modified CZI, Z-score, and effective drought index (EDI)) in Tehran province, Iran. They found that SPI, CZI and Z-Score performed similarly for drought identification and SPI and EDI could detect the commencement of a drought condition. The present study compared different remotely-sensed indices with a meteorological index (SPI) for meteorological drought monitoring from 1997 to 2005 across Iran.

2. Materials and Methods

2.1. Study area

Iran is located in the Middle East, a recognized geographical region of southwestern Asia. Iran (latitude 25–40 N and longitude 45–63 E) covers an area of about 1.6 million square km, which makes it one of the largest countries in the region. The country is bordered by the Caspian Sea, Persian Gulf and Gulf of Oman, and by the countries of Iraq, Turkey, Azerbaijan, Turkmenistan, Afghanistan and Pakistan (Figure 1). Iran is a rugged country of plateaus and mountains dominated by the Elburz Mountains in the north and the Zagros Mountains along its western border. Iran's climate is mostly arid and semi-arid. The central and eastern portion is covered by the Iranian plateau. Dasht-e Kavir is a salty sandstone desert plateau; in the summer, it is one of the hottest places on the planet. In the summer, the different regions of Iran can be cool as well as warm.

2.2. Satellite data

The satellite data taken from the AVHRR onboard the NOAA satellite were preprocessed using the satellite analysis and research system (STARS) software for HRPT/APT AVHRR (Sea Scan International Inc.) The original study plan included a temporal range of 9 years (1997-2005) covering 5 months (March–July). For each month, 3 images were selected at 10 day intervals to produce vegetation drought indices.

2.3. Digital Image Processing

The five bands of the raw AVHRR images were extracted using STARS software and radiometric calibrations were performed on images using calibration coefficients provided by NOAA (www.noaa.gov). Geometric corrections for the images were performed in two subsequent stages using ephemeris data and ground control points in Geomatica software.

The methodology was based upon the evolution of the normalized difference vegetation index (NDVI), vegetation condition index (VCI), temperature condition index (TCI), and vegetation health index (VHI), derived from AVHRR images during 1997-2005. The SPI was used to monitor meteorological drought.

2.3.1. Normalized difference vegetation index

Researchers have been able to determine thestatus of vegetation indices such as the NDVI, (Di *et al.,* 1994; John *et al*., 1998; Malingreau and Belward, 1992; Marsh *et al*., 1992; Reed *et al*., 1994). The NDVI approach is based on healthy vegetation having low reflectance in the visible portion of the electromagnetic spectrum because of absorption by chlorophyll and other pigments, and high reflectance in the NIR because of the internal reflectance of the mesophyll spongy tissue of a green leaf (Campbell, 1987). Several studies have found that the NDVI can facilitate observance of drought in time series satellite data and provide further analysis of the relationships between rainfall, soil water conditions, and the

NDVI (Kogan, 1990; Di *et al*., 1994). NDVI can be calculated as the ratio of red (0.58 to 0.68 µm) and the NIR (near infrared: 0.725 to 1.10 µm) bands of a sensor system and as represented by:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

where NIR and RED are near infrared reflectance and red reflectance, respectively. TheNDVI values range from -1 to +1 (Lillesand and Kiefer, 2004). In this study, the original data was the 10-day NDVI maximum value composite (MVC) images from March to July for the years 1997 to 2005. Table 1 shows the classification of NDVI on the basis of land cover density conditions.

Fig. 1. Location of Iran

Table 1. Classification of NDVI according to land cover density conditions*

NDVI Values	< 0.05	0.05 to 0.20	0.20 to 0.60	> 0.60
Land Cover Density	Bare	Sparse	Moderate	Dense

*Holben, 1986

2.3.2. Vegetation condition index

NDVI has been used successfully to identify stressed and damaged crops and pastures, but interpretive problems may arise when these results are extrapolated over non-homogeneous areas. In such areas, differences between levels of vegetation can be related to differences in environmental resources (i.e. climate, soil, vegetation, relief). For example, under similar vegetation conditions, a region with abundant resources shows NDVI values twice as large as those for adjacent regions with insufficient resources (Kogan, 1987). The VCI wasdeveloped by Kogan (1995) and has been used to estimate the impact of weather on vegetation. The weather-related NDVI envelope is linearly scaled to 0 for minimum NDVI and 1 for maximum NDVI for each grid cell and weekly NDVI. It is defined as:

$$VCI = \frac{NDVIi - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \times 100 \quad (2)$$

Where $NDVI_i$,$NDVI_{max}$ and $NDVI_{min}$ are the smoothed weekly NDVI, long-term period maximumNDVI, and multi-year minimum NDVI, respectively, for each grid cell. VCI ranges from 0 to 100 depending on the changes in vegetation from extremely unfavorable to optimal (Kogan, 1995).

2.3.3. Temperature condition index

To remove the effects of cloud contamination in the satellite assessment of vegetation, Kogan (1995) proposed the temperature condition index. The TCI is derived from the brightness temperature (BT) and its algorithm is similar tothat for VCI. It is defined as:

$$TCI = \frac{BT_{max} - BT_i}{BT_{max} - BT_{min}} \times 100 \quad (3)$$

Where BT_i, BT_{min} and BT_{max} are the seasonal averagesfor weekly brightness temperature, multi-year absolute minimum BT, and maximum BT, respectively.

It is important to note that BT was calculated from Ch4 (10.3–11.3µm); Ch4-measured radiance is more representative of drought because it is less responsive to the amount of water vapor in the atmosphere than is Ch5. Although BT only partially represents land surface conditions, analysisshowed that, during the years of drought, BT was much higher than during normal and wet years (Kogan, 1997).

2.3.4. Vegetation health index

TCI is a complementary tool to VCI for drought detection and mapping. When used together, they provide a reliable additive drought detection and crop condition assessment scheme (Kogan 2001). The additive expression for vegetation assessment and drought mapping, VHI, is defined as:

$$VHI = a(VCI) + b(TCI) \quad (4)$$

Where a and b are coefficients quantifying the contributions of VCI and TCI in the combined condition. Since the moisture and temperature contributions during vegetation cycle was not known, it was assumed that the share of VCI and TCI was equal (Kogan, 2001). VCI, TCI and VHI classifications proposed by Kogan (2001) were used toassess the drought-affected areas (Table 2).

Table 2. Classification of VCI,TCI and VHI drought conditions*

VCI,TCI,VHI values	<10	10-20	20-30	30-40	40-60	> 60
Drought Conditions	Extreme	Severe	Moderate	Mild	Normal	Wet

*(Kogan, 2001)

2.4. Standardized precipitation index

McKee *et al.* (1993, 1995) proposed the SPI to assess anomalous and extreme precipitation. This study used a 6-month SPI to quantify the precipitation deficit for 1997-2005 (March-July). Since precipitation data are mostly skewed, to compute SPI, precipitation data were normalized using a gamma function.

The SPI is based on the probability of precipitation for any desired time scale and spatially invariant indicator of drought (Guttman, 1998, 1999). It involves fitting a gamma probability density function to a given frequency distribution of precipitation totals for a station (Edwards and McKee, 1997). The SPI is computed by dividing the difference between the normalized seasonal precipitation and its long-term seasonal mean by the standard deviation. It can be written as:

$$SPI = \frac{X_{ij} - X_{im}}{\sigma} \quad (5)$$

where, X_{ij} is the seasonal precipitation at the i^{th} raingauge station and the j^{th} observation, $X_{im}$is the long-term seasonal mean, and σ is its standard deviation.

Since drought is a regional phenomenon, to demarcate its spatial extent, SPI values for the 47 synoptic weather stations in Iran were interpolated using inverse distance weighted (IDW) interpolation in ArcView 3.2a. SPI classificationsfor the present study are recorded in Table 3.

Table 3. Classification of SPI drought conditions*

SPI Values	≥ 2.0	1.5 to 1.99	1.0 to 1.49	-0.99 to .99	-1.0 to -1.49	-1.5 to -1.99	≤ -2
Drought conditions	extremely wet	very wet	moderately wet	near normal	moderately dry	severely dry	extremely dry

*(McKee *et al.*,1993)

3. Results

3.1. Vegetation indices

Figure 2 shows theNDVI values calculated for 1997-2005 (March-July). The figure shows that the vegetation cover density decreased from 1999 to 2001, especially in 2000, when many regions faced severe drought. In 2002, the vegetation cover increased, it then decreasedin 2003 and 2004, and increased again in 2005.

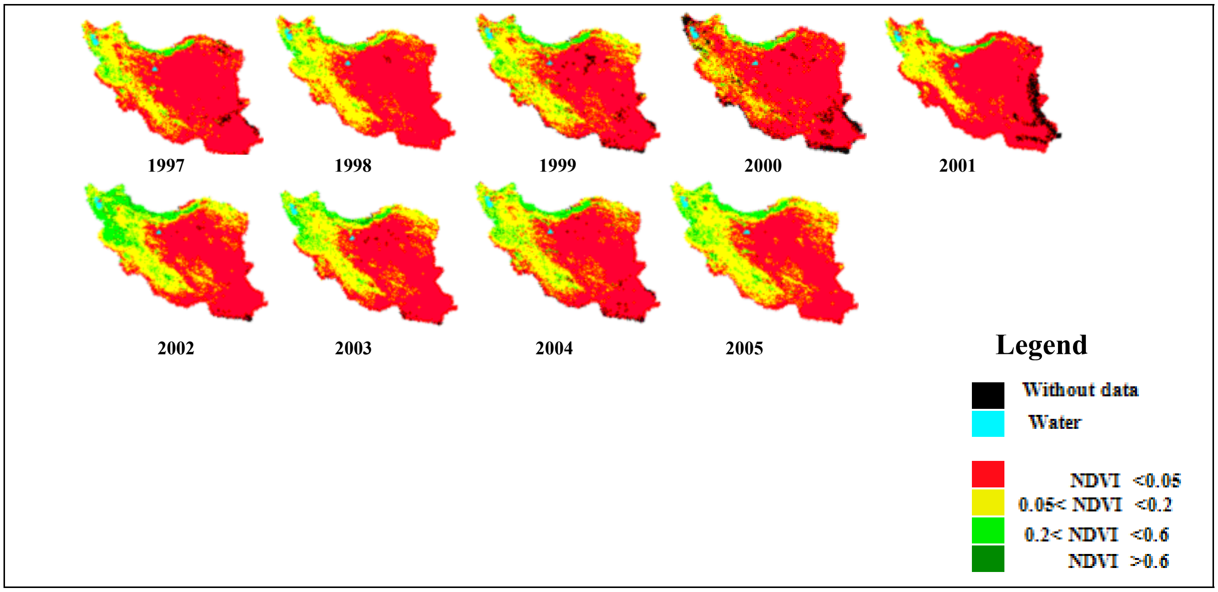

Fig. 2. Averaging monthly values of NDVI during 1997-2005

VCI, TCI, and VHI values were computed for the study area for 1997–2005 by averaging monthly values (Figure 3). In 1997, the northwestern, northeastern, and central parts of Iran were affected by severe to extreme moisture-stress, but favorable thermal conditions helped vegetation to maintain its health and checked the intensity of drought and its spatial extent. In 1998, favorable thermal conditions accompanied good moisture in vegetation. In 1999, the northern, northwestern and western parts of Iran experienced extreme thermal-stress and mild to moderate moisturestress. In 2000, while the eastern, southeastern, and central parts of Iran experienced almost no moisturestress, the rest of the region suffered extreme moisturestress. In 2001, severe to extreme moisturestress occurred in the southern, eastern, northeastern, and some northern parts; in the other regions, drought was restricted to mild-to-moderate intensities. In 2000 and 2001, the largest area of moisturestress over the 9 periodoccurred; for both years,the whole region was almost free of thermalstress. In 2002-2005, a good moisture condition prevailed in the entire region. Also in 2005,the whole region was almost free of thermalstress, making 2005 a wet year with good thermal and moisture conditions. In 2002, the southern, eastern, and some northern parts were affected by thermalstress. In 2003 and 2004, some parts of the region suffered mild to moderate thermal stress (Figure 3).

The United Nations (United Nations, 2001) reported that the study area experienced drought from 1999 to 2001, which is in agreement with the VCI map for 2000 and 2001and TCI for 1999 (Figure 3). The time series for VCI and TCI show that they correspondedin some years andcounteredone another in other years; this determined the occurrence and severity of drought as reflected in the VHI. For example, in 2000, severe-to-extreme drought (VHI<20) covered about 20% of the region and mild-to-moderate drought (20<VHI<40) covered about 25%; the rest of the region was free from drought. The VHI map for 2000 was not in agreement with the drought recorded for this year. Tables4, 5, and 6 show the drought-affected areas (in percent) using classification of yearly VCI, TCI and VHI images, respectively, on the basis of percentage of DN values.

Figure 4 compares the drought-affected area of classified data for yearly VCI, TCI, and VHI for the above 60 (>60) category. It shows that VCI and VHI indices confirmed each other for most year’s overthe TCI index. For example, in 2005, 85% of the country experienced a wet year for VCI and 64% of the country experienced VHI of more than 60; only 24% of the country showed a wet year for TCI for more than 60 category.

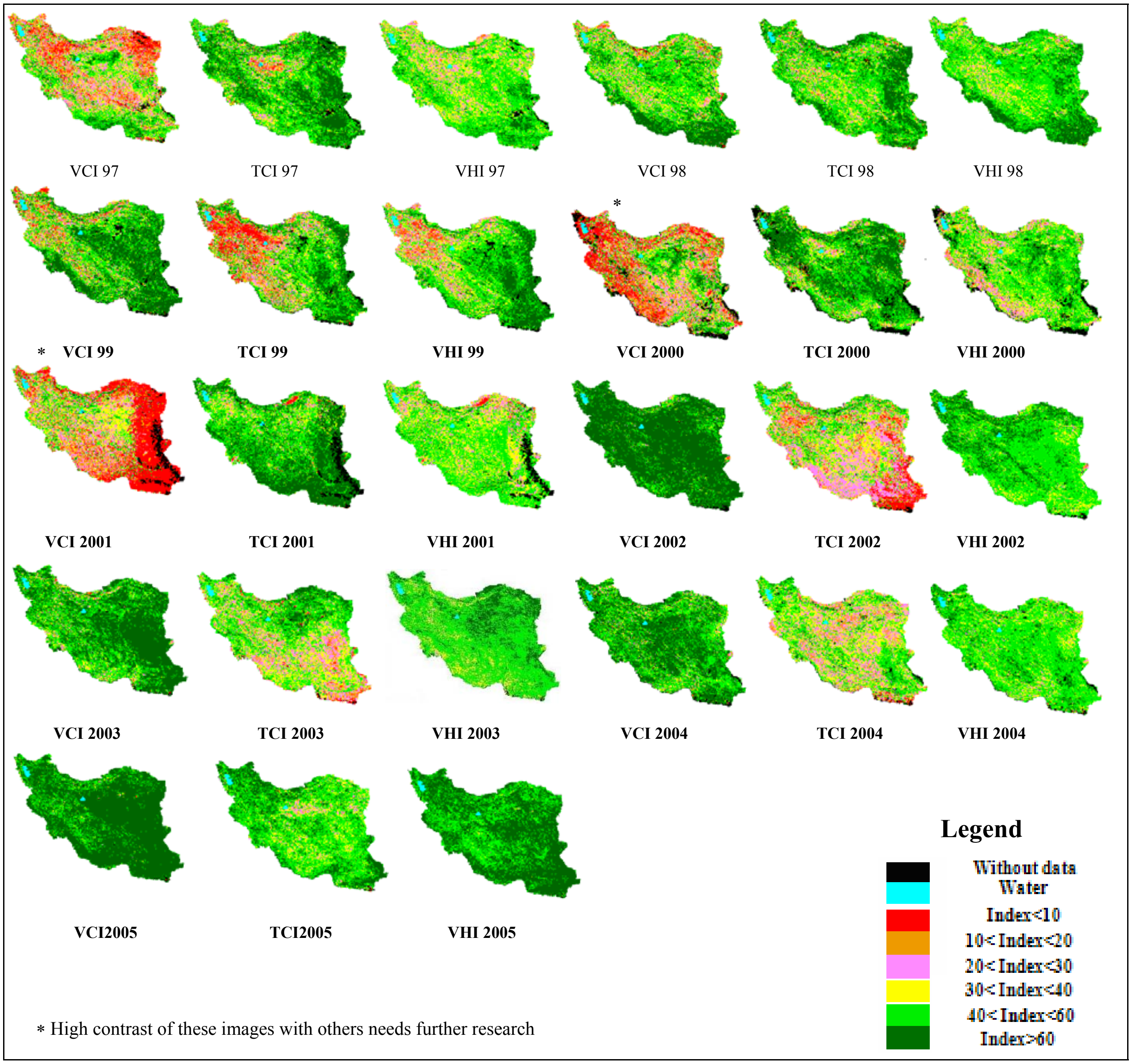

Fig. 3. Averaging monthly values of VCI,TCI and VHI during 1997-2005

Table 4. Drought affected areas (in percent) using classification of yearly VCI images

YEAR	<10	10-20	20-30	30-40	40-60	> 60
1997	9.96	16.56	21.14	21.28	24.58	6.48
1998	1.03	3.39	8.77	18.51	44.58	23.72
1999	2.37	4.82	7.91	11.65	32.26	40.99
2000	19.07	17.23	18.71	16.75	19.62	8.62
2001	31.19	14.46	18.87	20.12	12.50	2.86
2002	0.08	0.22	0.51	1.51	12.22	85.46
2003	0.14	0.65	2.42	6.83	33.52	56.44
2004	0.04	0.51	2.31	6.71	37.59	52.84
2005	0.00	0.00	0.15	0.98	14.31	84.56

Table 5. Drought affected areas (in percent) using classification of yearly TCI images

YEAR	<10	10-20	20-30	30-40	40-60	> 60
1997	0.83	2.20	5.45	12.14	40.59	38.80
1998	0.51	1.99	6.11	15.99	46.56	28.81
1999	9.46	11.06	12.84	15.45	30.99	20.21
2000	0.80	1.53	4.90	10.75	37.22	44.78
2001	0.69	0.88	3.19	9.48	37.77	48.06
2002	7.88	12.20	29.68	26.85	19.91	3.55
2003	0.68	5.41	17.23	26.15	38.64	11.84
2004	0.58	6.94	23.63	32.50	32.68	3.67
2005	0.01	0.48	3.68	14.75	57.20	23.79

Table 6. Drought affected areas (in percent) using classification of yearly VHI images

YEAR	<10	10-20	20-30	30-40	40-60	> 60
1997	0.15	1.84	10.07	27.46	52.12	8.36
1998	0.06	0.59	3.90	16.45	57.74	21.26
1999	1.78	5.77	10.58	16.36	40.65	24.86
2000	0.60	3.57	11.35	24.31	48.46	11.71
2001	0.73	2.65	10.76	29.46	51.97	4.43
2002	0.04	0.19	1.24	8.70	66.34	23.49
2003	0.03	0.19	1.77	11.63	65.53	20.85
2004	0.01	0.18	2.81	16.49	69.71	10.80
2005	0.01	0.03	0.05	0.68	35.39	63.84

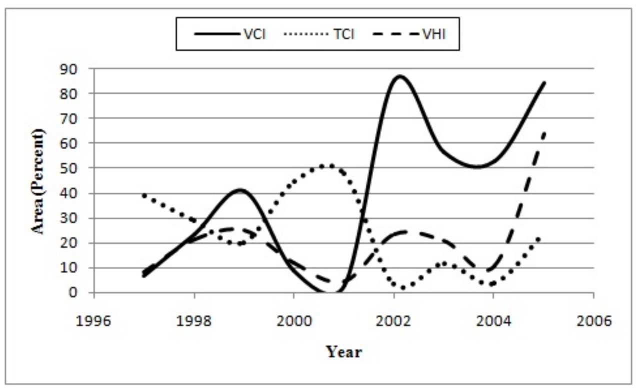

Fig. 4. Comparison of drought affected area of yearly VCI, TCI and VHI for > 60 data

3.2 Meteorological drought index

In March 1997, the centraland northern regions were affected by moderatetoextreme drought and the rest of the region was free from drought. In March toJuly 1997, the size of the affected area decreased; in July 1997, the whole region was nearly free of drought.During March to July 1998, the whole region was free of drought and some parts were wet. From March to July 1999 the northwestern parts of the region experienced moderate to severe drought and the rest of the region was free from drought. In March and April 2000, moderate to severe drought occurred in all parts of the region, except the northwestern, northern and southeastern parts. During May to July of 2000,the whole region experienced near-drought conditions. In July 2000, Iran recorded the largest area of severe drought forthe preceding 5 months of this year. In March 2001, the whole region experienced near-drought conditions. During April to June of 2001, the intensity of the drought and size of the affected area increased; in July 2001 the intensity and the area experiencing drought decreased. For 2002-2005, most of the region experienced normal conditions.

4. Discussion and Conclusion

The spatial satellite-derived droughtindices and the meteorological-based SPI generally confirm each other, but it was observed that drought occurred in spite of a positive SPI. Negative SPI anomalies did not always correspond to drought. The correlation matrix (r) is presented in Tables 7, 8, and 9 for dry (2000), normal (2004) and wet

(2005) years, respectively. Statistical analysis showed higher correlations for the satellite-derived indices and lesser relationships between the satellite-derived indices and SPI. High correlations were found between TCI and VHI, VCI and VHI in dry, normal, and wet years (0.662 to 0.813).

Table 7. Correlation coefficient between indices of April of 2000 (Dry year)

	SPI	VHI	TCI	VCI
SPI	1.000	0.363	0.350	0.208
VHI	0.363	1.000	0.813	0.744
TCI	0.350	0.813	1.000	0.216
VCI	0.208	0.744	0.216	1.000

Table 8. Correlation coefficient between indices of May of 2004 (Normal year)

	SPI	VHI	TCI	VCI
SPI	1.000	0.131	0.200	-0.028
VHI	0.131	1.000	0.745	0.662
TCI	0.200	0.745	1.000	-0.007
VCI	-0.028	0.662	-0.007	1.000

Table 9. Correlation coefficient between indices of April of 2005 (Wet year)

	SPI	VHI	TCI	VCI
SPI	1.000	0.167	0.095	0.144
VHI	0.167	1.000	0.742	0.668
TCI	0.095	0.742	1.000	-0.003
VCI	0.144	0.668	-0.003	1.000

Factors such as soil moisture, temperature, wind, cloud cover, and temporal distribution of rainfall influence drought. Satellite-derived drought-indices are influenced by these factorsand meteorological-based indices such as SPI depend upon the amount of rainfall and spatial distribution. This confirms that satellite-derived drought-indices can be reliable.

It is clear that no single indicator or index is sufficientto monitordrought on a regional scale; instead, a combination of integrated monitoring tools is preferable to producing regional or national drought maps. The results of this study showed thatIran suffered from severe drought from 1999-2001, which is in good**agreement with**those obtained from the United Nations (2001) and Morid*et al.* (2006). The results of remotely-sensed and SPI indices for the years 2002 to 2005 showed thatmost of the region experienced normal conditions. Quantifying thepercentage of contributions from VCI and TCI combined is an important subject of future study.

Acknowledgement

We would like to thank the I.R. of Iran Meteorological Organization (IRIMO) for providing us with meteorological data**.**

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