

DETECTING IMPACTS OF A CHANGING CLIMATE ON DROUGHT CHARACTERISTICS IN IRAN

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ABSTRACT:

The effect of changing climate on drought characteristics in Iran is investigated by comparing the time series of the Standardized Precipitation Index (SPI), the Reconnaissance Drought Index (RDI) and the Standardized Precipitation Evapotranspiration Index (SPEI) on 12-month time scale. Indices are computed for the common time period 1961–2005 using monthly data from 44 synoptic stations distributed throughout the country. Results suggest that the three drought indices strongly correlate with each other in northern and northwestern Iran where potential evapotranspiration is low due to the low temperatures compared with the other regions. In central and southern regions, while the correlations between the SPI and RDI remain high, the correlation coefficients between the SPI and SPEI noticeably decrease in most stations characterized by high temperatures and potential evapotranspiration, especially during the warm season. Moreover, it is found that though the RDI tends to correlate well with the SPI at all stations, several differences on the severity of dry/wet events occur. Differences in drought classes appear more evident when the SPI is compared to the SPEI, especially in central and southern regions. To analyse if the observed discrepancies are related to temperature increase in recent years, the annual mean temperature in selected stations is checked for long-term trend. Results show that temperature is noticeably increased during the last decade of the time section at several stations, mainly in central Iran, but this seems that does not necessarily imply low correlations between SPI and the other two drought indices. The effectiveness of using the RDI and SPEI in capturing the impact of increasing temperature and evapotranspiration in semi-arid regions on drought characteristics is evaluated and discussed.

1 INTRODUCTION

As an environmental hazard, drought has attracted the interest of many researchers in recent years, also for its higher occurrence probability expected under a changing climate. In analyzing drought phenomenon a drought index that is able to objectively quantify climate conditions is required. Along the years, several drought indices have

been proposed to monitor the different kinds of drought in different areas (Heim, 2002; Keyantash and Dracup, 2002). Among them, the Palmer Drought Severity Index (PDSI; Palmer, 1965) and the Standardized Precipitation Index (SPI; McKee et al., 1993) are the most widely used drought indices for monitoring purposes.

The PDSI is based on the supply-and-demand concept of the water balance equation for a two-layer soil model using monthly precipitation and evapotranspiration (ET). The index bases upon the calculation of the moisture departure between actual precipitation and the precipitation expected to occur for the average conditions of the climate, which implies performing a monthly water balance and the calibration of local monthly coefficients for the various terms of the water balance. In addition, the calibration of the index is required at local or regional level. The PDSI values depend upon the way how the soil water balance is computed, the soil available water capacity (AWC) of the underlying layer, the ET estimation method, and on the calibration procedures adopted. However, the PDSI is conceived differently from an aridity index, which is a merit to be recognized to its author. In view of updating the calculation procedures and improving the information provided through its use, a modification for Mediterranean conditions was produced, the MedPDSI (Pereira et al., 2007, Rosa et al., 2010), where actual ET is used instead of potential ET. Due to computation requirements and limitations on the PDSI (Alley, 1984; Karl and Knight, 1985), usually a “standardized” and “multi-scale” drought index, like the SPI, has been preferred to facilitate the quantitative comparison of drought events at different locations and time scales. The SPI is based on precipitation field alone. It was designed to quantify the precipitation deficit for multiple time scales, which reflect the impact of drought on the availability of the different water resources. The index computation for any location is based on the long-term precipitation record accumulated over the selected time scale. The long-term record is fitted to a probability distribution (usually a Gamma distribution, Guttman, 1999), which is then transformed through an equal-probability transformation into a normal distribution.

Recently, concerns have been raised by some authors on the suitability of the SPI in properly detecting the impact of a changing climate on drought characteristics. Drought is a relative concept (relative to some established norm) and originates from a deficiency of precipitation over an extended period of time. However, other climatic factors such as high temperature, high wind and low relative humidity, can aggravate its severity. The SPI is based on the assumption that drought variability is mainly controlled by variations in precipitation field alone. Thus, the lack of any information on temperature field, the basic variable for climate change studies, appears questionable. Tendencies towards increasing temperatures during the last decades have been observed in several regions around the world and it is expected that such long-term trends may affect the intensity and duration of drought events. The issue goes beyond this consideration and poses the question whether and how drought indices should be revised under climate change assumption (i.e. the variables of interest are not stationary).

For this purpose, recently, two new drought indices have been proposed: the Reconnaissance Drought Index (RDI) and the Standardized Precipitation Evapotranspiration Index (SPEI). The RDI (Tsakiris and Vangelis, 2005; Tsakiris et al., 2007) has been developed to estimate a water deficit. It is based on the ratio between precipitation and potential evapotranspiration, and can be computed for different time

scales. The index, in its standardized form, can be easily compared with the SPI. However, using potential ET instead of actual ET makes it the index to approach an aridity index. The SPEI (Vicente-Serrano et al., 2010) is based on the original SPI calculation procedure. In this case, the input variable is the difference between precipitation and potential evapotranspiration accumulated on a selected time scale, which is a simple measure of the theoretical water surplus or deficit for the analyzed month, but it performs like an aridity index because potential ET is used. The empirical statistical distribution of the input variable is fitted to a Log-logistic distribution and then, as in the SPI computation, transformed into a normal distribution. Both indices depend upon the ET equation adopted because actual ET is not estimated and used.

In investigating the potential capabilities of these indicators in capturing the possible impacts of temperature changes observed in recent decades on drought characteristics, in the present paper, an application of the aforementioned standardized drought indices (SPI, RDI and SPEI) is provided for Iran. Drought is a recurrent phenomenon in Iran, which is mostly characterized by arid and semi-arid climates due to its latitudinal extent. Morid et al. (2006) have applied several precipitation-based drought indices in Tehran province in northern Iran. Meteorological and hydrological droughts in Doroodzan Watershed and Reservoir in southwestern Iran have been assessed by Asghari Tabrizi et al. (2010) using SPI at different time scales and a threshold level method, respectively. A spatio-temporal variability analysis of hydrological drought was carried out by Raziei et al. (2009) for western Iran using SPI at 12-month time scale. By applying the SPI on 1-month time scale, Raziei et al. (2011a) studied the linkage between meteorological drought in western Iran and large-scale atmospheric circulation types. Moreover, Raziei et al. (2011b) assessed the spatial and temporal variability of drought over Iran using observations, gridded and reanalysis datasets. They identified four distinctive sub-regions of drought variability defined by the SPI at 12-month time scale. The sub-regions appeared to be almost stable with respect to the SPI time scale (Raziei et al., 2010). Recently, a comparative analysis was performed by Khalili et al. (2011) to investigate the similarities and differences between the SPI and RDI computed on 3-, 6- and 12-month time scale for 10 stations representative of different climates in Iran. The authors concluded that both indices exhibit an overall similar behaviour.

In the present paper a comparison of the SPI with the RDI and the SPEI is provided for the time period 1961–2005, by using 44 synoptic stations distributed relatively uniformly over Iran. The 12-month time scale is considered as it better illustrates the long-term behaviour of the indices and filtering out high frequency fluctuations. The aim is to study the effect of taking into account both precipitation and temperature information (through evapotranspiration) into drought indices.

2 DATA AND METHODS

Data used for the analysis are monthly precipitation and mean temperature used to compute ET with the climatic Thornthwaite method (Thornthwaite, 1948) from 44 main synoptic stations having the longest historical data records. The used stations are relatively regularly distributed over Iran so that all climate regimes of the country are represented (Fig. 1a). Station data are complete and were already quality controlled by

the Iranian Meteorological Organization. The few missing values in some stations were estimated from the neighbouring station time series using a linear regression method.

Dry and wet conditions at the selected stations have been assessed applying the SPI, RDI and SPEI. The SPI is widely used in drought monitoring centres and in several drought studies. It is a useful tool for capturing the climate variability associated with water shortage or surplus in different areas, and has several advantages (Keyantash and Dracup, 2002; Heim, 2002). It is based on precipitation alone and its computation requires a long-term precipitation record. For each month, the corresponding precipitation time series is fitted to a Gamma probability distribution (Guttman, 1999) that is normalised through an equal-probability transformation. SPI values between -0.99 and $+0.99$ denote near normal conditions, between -1 and -1.49 moderately dry, between -1.5 and -1.99 severely dry and less than -2 extremely dry conditions. The same applies to positive values, i.e., wet classes (Bordi and Sutera, 2004).

The computation of RDI is based on the ratio of precipitation totals (P) to potential evapotranspiration (PET) accumulated over the selected time scale (k). On the annual basis (k=12), we have:

$$a^{(i)} = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} PET_{ij}}, \quad (1)$$

with p_{ij} and PET_{ij} the precipitation and potential evapotranspiration of the j-th month of the i-th year. The standardized RDI is computed following a similar procedure to the one used for the SPI computation (Tsakiris et al., 2007), and is given by:

$$RDI_{(k)}^{(i)} = \frac{y_k^{(i)} - \overline{y_k}}{\sigma_{y_k}}, \quad (2)$$

with $y^{(i)} = \ln(a^{(i)})$, $\overline{y_k}$ is the arithmetic mean and σ_{y_k} is its standard deviation. It

should be noted that the above expression is based on the assumption that $a^{(i)}$ values follow a lognormal distribution. The P/PET ratio is in fact an aridity index, which ties the RDI to describe the aridity dynamics as an estimator of dry/wetness conditions.

The computation of the SPEI is based on the original SPI calculation procedure, but differently from SPI the input variable is the difference between monthly precipitation and potential evapotranspiration, as:

$$D_j = P_j - PET_j, \quad (3)$$

where j denotes the j-th month of the year. The D_j values are then accumulated on the selected time scale. The D_j values denote excess or deficit of precipitation when the climatic demand over the period of calculation is represented by PET. Thus, the index is also a kind of aridity index (see the Thornthwaite aridity index; Thornthwaite, 1948). As

in the SPI computation, the empirical probability density distribution of the difference for a given month and time scale is fitted to the three parameter log-logistic distribution. Finally, through an equi-probability transformation the fitted distribution is transformed into a normal one (Vicente-Serrano et al., 2010). Both RDI and SPEI are standardized, thus the interpretation of their values can be the same as for the SPI (i.e., same classification).

Calculation of the PET, which is required for computation of both RDI and SPEI, has to reflect climatic conditions and not vegetation/crop potential demand like when using a reference ET equation. Therefore, as did Palmer for the PDSI, the Thornthwaite method (Thornthwaite, 1948) is used for large-scale drought analysis.

3 RESULTS

Time series of SPI, RDI and SPEI on 12-month time scale have been computed for all the 44 considered stations (Fig. 1a). Results suggest that the time behaviours of the three indices are in close agreement in those stations located in the north and north-west of the country, while they show noticeable differences in central, southern and eastern Iran, especially when SPEI is compared to the SPI and RDI. The correlation between the SPI and the RDI appears good all over the country (correlation coefficients between 0.92 and 0.99). This is clearly evident from Fig. 1b–d where the correlation maps between SPI and RDI, SPI and SPEI, and SPEI and RDI are shown.

Recently, Raziei et al. (2011), by applying the Principal Component Analysis to the SPI on 12-month time scale, have identified four sub-regions with different drought variability in Iran (bold lines in Fig. 1a). In the present paper, for illustrative purposes, two stations for each of the sub-regions have been considered. The indices time series are shown in Fig. 2, while scatter plots of the SPI vs SPEI and RDI are illustrated in Fig. 3. As can be seen, though the SPI and RDI show similar time behaviours (i.e., high correlation), several discrepancies are found on the magnitude of dry/wet events, especially in central and southern regions. However, the major differences occur between SPI (and RDI) and SPEI in central and southern regions. In some cases, as for Tabas station, the discrepancies are so remarkable that there is a change in the long-term tendency of the SPEI with respect to the other two indices.

In investigating the impact of possible temperature changes (through evapotranspiration) on the new drought indices, the Principal Component Analysis (PCA) of the annual mean temperature field has been performed. The first loading and the associated principal component score time series (PC-1) are shown in Fig. 4. It can be seen that the highest positive loading values, meaning high positive correlation between temperature anomalies in the stations and PC-1 time series, are mainly located in the central part of the country. The PC-1 time series shows a change in the last decade of the time record characterized by positive temperature anomalies. Such a change hardly affects the long-term linear trend characterizing the PC-1 time series that accounts for about 28% of the total variance of the signal. This behaviour is found in most of the time series of the annual mean temperature of the selected stations (see Fig. 5). A tendency towards higher temperatures is observed in all stations with the exception of Anzali (Caspian Sea region) and Ghazvin (north-western region).

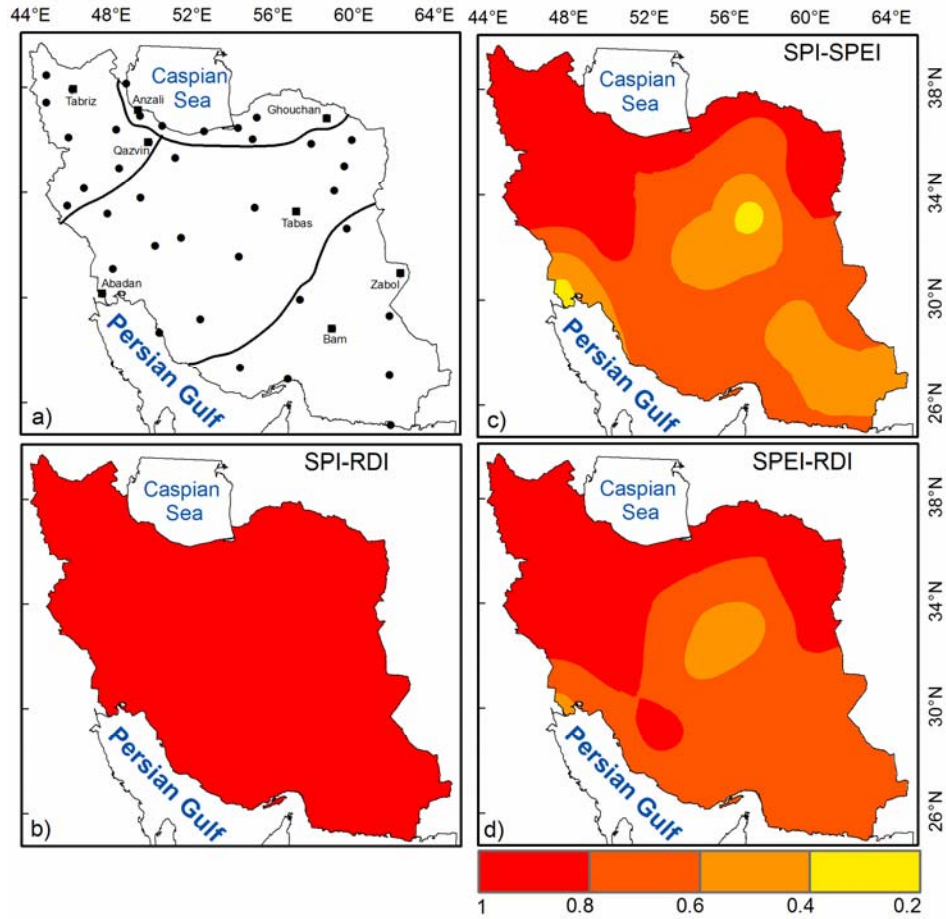


Figure 1. (a) Synoptic stations used in the study with bold lines denoting the four sub-regions with different drought variability according to the SPI on 12-month time scale (from Raziei et al., 2011). Only names of the stations selected as representative of the sub-regions are provided in the map. Correlation maps between: (b) SPI and RDI, (c) SPI and SPEI, (d) SPEI and RDI.

Thus, a concern rises about the role played by temperature changes in driving the differences between the SPI and the SPEI and RDI. A matter of fact is that even though in Tabriz (north-western region) and Abadan (central region) a similar temperature change is observed, the SPEI is in one case in a satisfactory agreement (i.e., high correlation) with the SPI, while in the other case does not. Moreover, though Ghouchan station is characterized by a statistically significant linear trend accounting for about 52% of the total variance, high correlation between SPI and SPEI (RDI) is found, also in recent years when the temperature change reaches its maximum over the record. The correlation map (here not shown) between SPI and SPEI obtained by considering the shorter period 1961–1990 (thus, excluding temperature changes occurred in recent years) supports these findings. There is, in fact, no substantial improving of the correlation coefficients between SPI and SPEI.

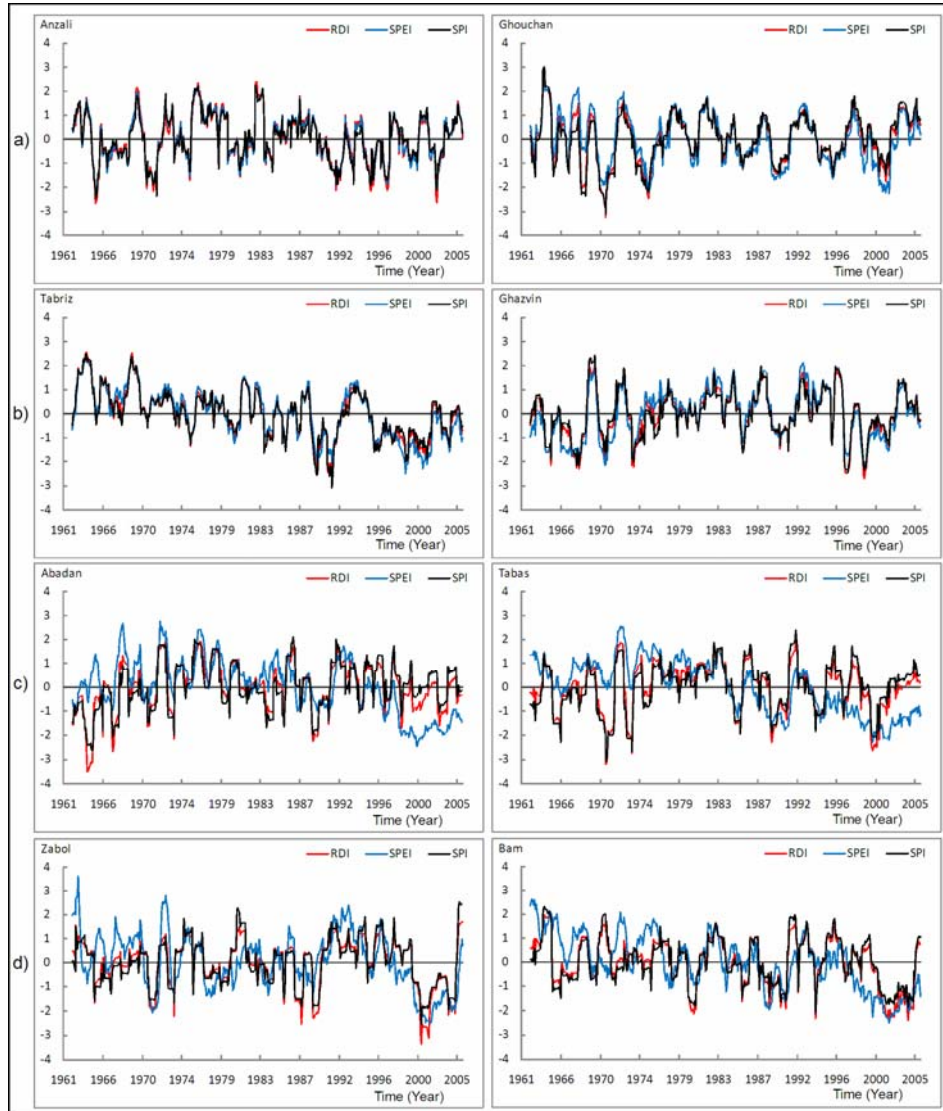


Figure 2. Time series of the SPI, RDI and SPEI for the stations selected as representative of the four sub-regions having different drought variability: (a) Northern region, (b) north-western region, (c) central region, (d) south-eastern region.

Since the basic variables of RDI and SPEI are P/PET and $D = P - PET$, respectively, it is of interest to show the time behaviour of the annual mean of P , PET , D and P/PET for Tabriz and Abadan stations (Fig. 6). It can be noted that for Tabriz both D and P/PET follow the behaviour of precipitation, while for Abadan the difference D does not. This example suggests that while the ratio P/PET follows the P behaviour, the difference D is hardly affected by PET variations and amount. Thus, in locations where PET largely exceeds P (in our case central and southern Iran characterized by high

temperatures) noticeable differences between SPI and SPEI are expected. At this stage of the analysis, which standardized index is more suitable for monitoring the impacts of recent temperature changes on drought remains an open question because of the underlying assumption concerning the most appropriate basic variable to be used for drought assessment (P, P/PET or D) that still nowadays is debated.

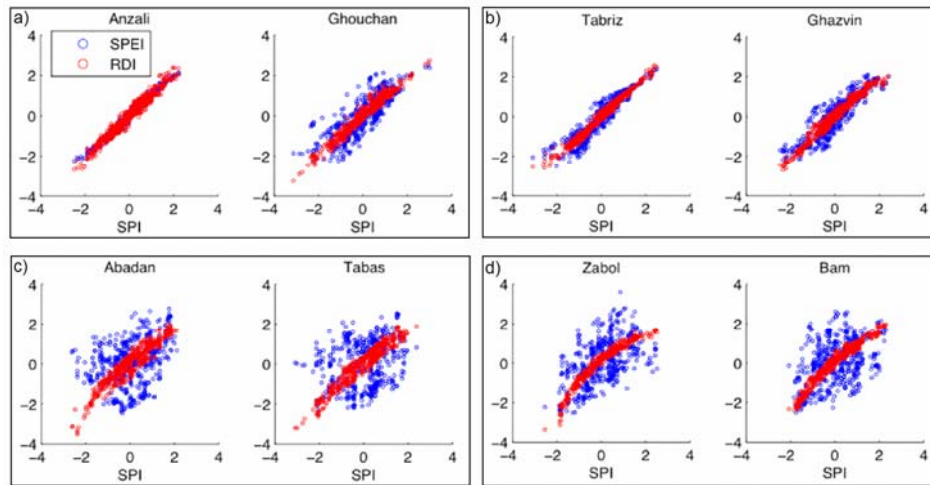


Figure 3. Scatter plots of the SPI and SPEI, RDI for the eight stations selected as representative of the four sub-regions having different drought variability (same of Fig. 2 above).

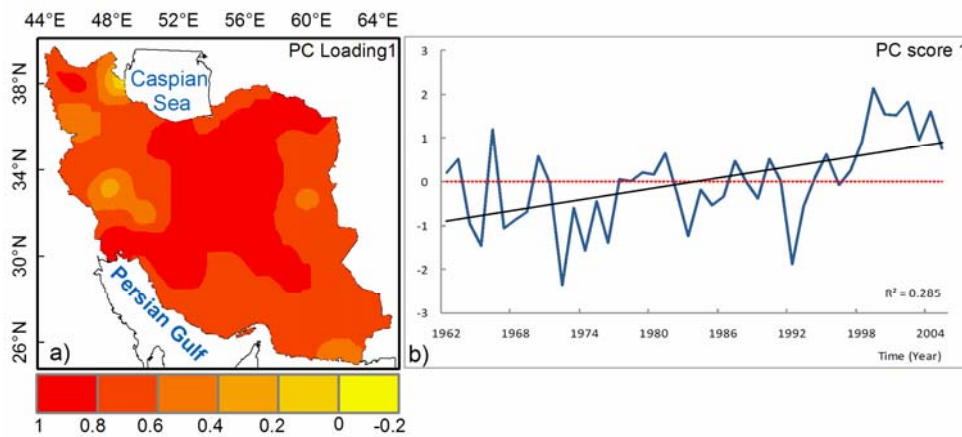


Figure 4. Principal component analysis of annual mean temperature field: (a) First loading, (b) first principal component score time series. Explained variance is 54.9%.

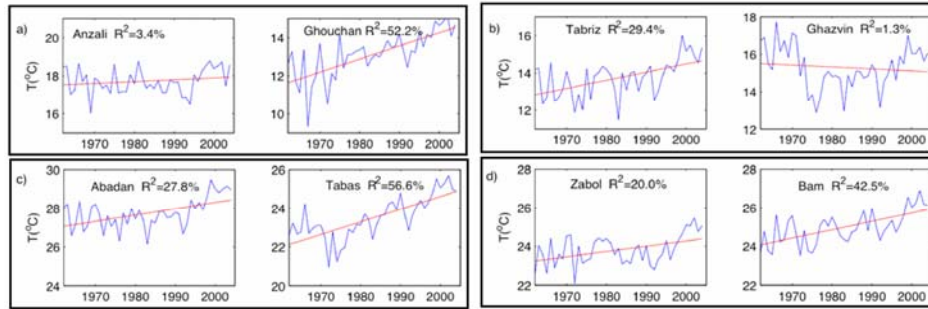


Figure 5. Time series of annual mean temperature at the eight stations selected as representative of the sub-regions (same of Fig. 2 above). Red lines denote the fitted linear trend.

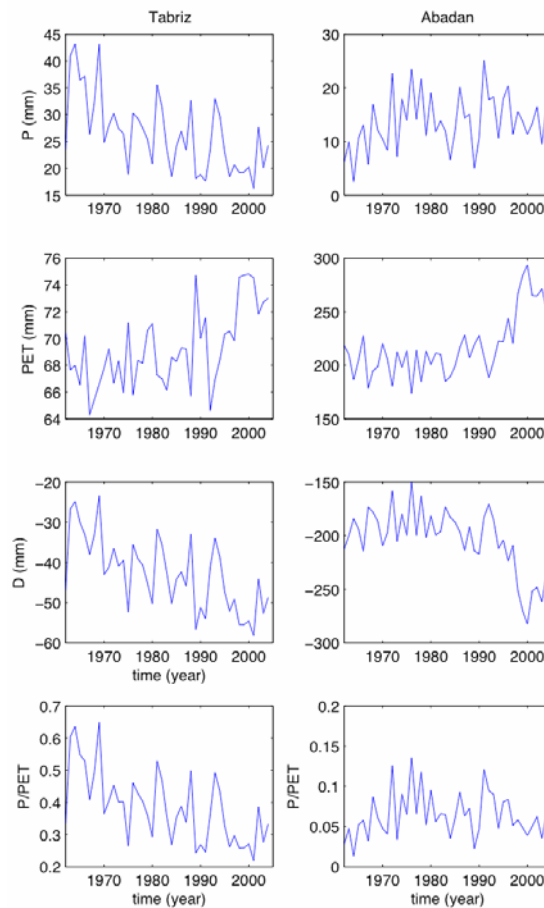


Figure 6. Annual mean time series of precipitation (P), potential evapotranspiration (PET), the difference between P and PET (D) and the ratio P/PET for Tabriz (north-western) and Abadan (central). Units for P, PET and D are mm, P/PET is dimensionless.

Results indicate that indices based upon P/PET and, mainly, D are very much influenced/representing aridity, thus indicating more the dynamics of the demand for water than drought itself. In other words, these indices refer more to impacts of droughts than to the severity of droughts, despite both are inter-related.

4 CONCLUSIONS

The study provides an application of the SPI and two new drought indices (RDI and SPEI) for Iran by using 44 synoptic stations distributed nearly uniformly over the country. At variance with the SPI that is based on precipitation field alone, the new drought indices take into account both precipitation and temperature through potential evapotranspiration. For this reason they have been recently proposed as alternatives to the PDSI because more easy to be computed and supposed to be adequate for assessing climate change impacts on drought characteristics. This study provides an inter-comparison of these indices and a first understanding of the observed discrepancies.

Correlation maps between SPI and RDI suggest that there is a good agreement between the two indices over all the country even if some differences on the magnitude of drought events are detectable (i.e. differences in dry/wet classes). Differently, the correlation map between SPI and SPEI suggests a good agreement in the north and less agreement in central and southern regions. In investigating the origin of such discrepancies, the PCA of the annual mean temperature has been performed. Results show that most of the stations, particularly in the central part of Iran, are characterized by a long-term trend towards higher temperatures, mainly driven by a change occurred in the last decade of the time section. An in depth inspection of the temperature time series at the eight stations selected as representative of different drought variability sub-regions shows that having a long-term trend in temperature does not necessarily imply the occurrence of greater discrepancies between SPI and RDI (SPEI). For example Tabriz in the north-western and Abadan in the central region are characterized by similar temperature change, but in the first station there is a good correlation between SPI and SPEI while in the second station does not. From an analysis of the basic variables of SPEI (P and PET), it can be noted that the differences between SPI and SPEI is controlled (by definition) by the imbalance between precipitation and evapotranspiration. In particular, when evapotranspiration greatly exceeds precipitation (regions with high temperatures like the arid and semiarid regions of central and southern Iran) the differences between SPI and SPEI becomes noticeable (differences in magnitude and time behaviour).

The study suggests that taking into account an increasing temperature, as expected in climate change studies of a few tenths of a degree, should not affect much drought time behaviour evaluated through the SPI, while there is an impact on the magnitude of dry/wet events when climate aridity dominates. Arid and semiarid regions, which are characterized by high temperatures and PET, have a great imbalance between P and PET leading to noticeable discrepancies between the SPI and SPEI. In the case of the RDI, the ratio between P and PET usually follows precipitation providing limited discrepancies with the SPI. At this stage of the analysis two key questions remain open. They concern: i) what is the basic variable to properly assess drought conditions, and ii) how drought indices, like the ones here used, should be revised for applications under

climate change conditions. The first question involves the definition of drought and the identification of the most important factors affecting the severity of an event. The approach by Palmer seems appropriate since actual ET is considered together with actual precipitation. The second question is related to the presence of long-term trends in the variables of interest that affect the stationarity of the coefficients of the probability distributions underlying drought indices definitions. The statistical methods used for the corresponding assessment are also of importance. Both issues will be topics for further investigations.

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