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Note

Quantification with SPEI of historical Droughts and under probable climatic change in the climatological station Zacatecas, Mexico

Cuantificación con el SPEI de Sequías históricas y bajo cambio climático probable en la estación climatológica Zacatecas, México

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Abstract

The SPEI (Standardized Precipitation-Evapotranspiration Index) is a variant of the widespread SPI (Standardized Precipitation Index), it has greater potential as *drought index* since it is sensitive to climate change because it uses a more realistic measure of the water availability: the *climate balance*. This measure is evaluated by the difference between monthly precipitation and potential evapotranspiration. This study describes in detail the calculation of SPEI and its application to the monthly historical records of precipitation and average temperature available in the climatological station Zacatecas, located in the capital of the state of Zacatecas, Mexico. The data covers 86 years in the period from 1930 to 2015. For *historical droughts*, the results of SPEI indicate in light, moderate, severe and extreme droughts, the following approximate values: 32.2%, 11.5%, 5.0% and 1.3%. For this particular location, three scenarios of *climatic change* were proposed; the first one accepts a progressive and linear reduction of 20% in annual precipitation, the second one adopts a progressive and linear increase of 4 °C in the average temperature and finally, the third one, superimposes the two effects mentioned; being therefore the most critical. For the three proposed scenarios, results suggest that light and extreme droughts increase scarcely in number or percentage, and that moderate and severe droughts decrease, also in a slight way. Results are condensed on graphs of SPEI evolution of duration 12 months, historical and the third scenario, in which the times of occurrence of drought periods are clearly displayed, as well as the specific differences in the value of SPEI exposed. Based on these analyzes, the systematic application of SPEI in the characterization of historical and *future droughts* is recommended, its application on future droughts would lead to results merely indicative.

Keywords: SPEI index, Log-Logistic distribution, probability weighted moments, potential evapotranspiration, statistical homogeneity, climate change.

Resumen

El SPEI (Standardized Precipitation-Evapotranspiration Index) es una variante del ampliamente difundido SPI (Standardized Precipitation Index), que tiene un mayor potencial como *índice de sequías* al ser sensitivo al cambio climático, debido a que usa una medida más real de la disponibilidad de agua, el *balance climático*. Esta medida se evalúa con la diferencia entre la precipitación y la evapotranspiración potencial mensuales. En este estudio se describe con detalle el procedimiento operativo del SPEI y se aplica a los registros históricos mensuales disponibles de precipitación y temperatura media en la estación climatológica Zacatecas, ubicada en la capital del estado de Zacatecas, México, los cuales abarcan 86 años (1930-2015). Para las *sequías históricas*, los resultados del SPEI definen en las sequías leves, moderadas, severas y extremas, los valores aproximados siguientes: 32.2%, 11.5%, 5.0% y 1.3%. Para esta ubicación del país, se consideró conveniente formular tres escenarios del *cambio climático*, el primero acepta una reducción progresiva y lineal del 20% en la precipitación anual, el segundo adopta un aumento progresivo y lineal de 4°C en la temperatura media anual y el tercero, sobrepone los dos efectos citados; por lo tanto es el más crítico. En los tres escenarios planteados, se encuentra que las sequías leves y extremas aumentan someramente en número o porcentaje y que las sequías moderadas y severas disminuyen, también de manera mesurada. Se exponen los gráficos de evolución del SPEI de duración 12 meses, histórico y del tercer escenario, en los cuales se visualiza claramente las épocas de ocurrencia de los periodos de sequía, así como de las diferencias puntuales en el valor del SPEI. Con base en los resultados de estos análisis, se recomienda la aplicación sistemática del SPEI en la caracterización de las sequías históricas y *futuras*. En estas últimas, los resultados tienen únicamente un carácter orientativo.

Palabras clave: índice SPEI, distribución Log-Logística, momentos de probabilidad ponderada, evapotranspiración potencial, homogeneidad estadística, cambio climático.

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Introduction and Objective

Droughts are one of the main natural causes of damage to agriculture, to all economic activities and to the environment. Droughts occur after long periods of low precipitation and due to their slow evolution, it is difficult to specify their beginning and end, as well as to estimate their characteristics of magnitude, duration and territorial extent. On the other hand, due to the sustained growth of water demand for all uses and the threat of the climate change, in recent years the study of droughts has been intensified (Mishra & Singh, 2010; Vicente-Serrano, Beguería, & López-Moreno, 2010).

As droughts are a natural phenomenon and threat, their best characterization is carried out using *indicators* which are climatic, hydrological, agricultural and/or socio-economic variables showing numerically the potential of droughts regarding the deficiencies and damages that they produce. A *drought index* is a method based on statistical calculations using indicators and seeks to quantify droughts, thereby enabling their comparison in climates and dissimilar hydrological regimes;

also favor the development of correct and efficient mitigation actions of their negative impacts (Mishra & Singh, 2010; Fuchs, Svoboda, Wilhite, & Hayes, 2014).

Another important aspect of droughts is their character of multiple time scales (*multiscaler*), which is caused by the *delays* that occur in the use of water in the different hydraulic systems, so that deficiencies in precipitation are first visible in temporary agriculture, then in irrigation supply, hydroelectric power generation and other water uses, and finally, in social, economic and environmental impacts. Due to the above, droughts are classified as: *meteorological*, *agricultural*, *hydrological* and *socio-economic*. The latter include environmental damage (Pandey, Sharma, Mishra, Singh, & Agarwal, 2008; Vicente-Serrano *et al*., 2010; Fuchs *et al*., 2014).

Since the end of the last century, drought studies and the development of their warning and monitoring systems have been based on the PDSI (Palmer Drought Severity Index) and SPI (Standardized Precipitation Index); the first one based on a soil moisture balance (Palmer, 1965; Wells, Goddard, & Hayes, 2004) and the second in a probabilistic approach of precipitation (McKee, Doesken, & Kleist, 1993; Wu, Svoboda, Hayes, Wilhite, & Wen, 2007). The PDSI has been criticized for not having multiscalar character in the time nor a simple calculation, besides not being sufficiently sensitive to induced changes in precipitation and temperature. The SPI has shown an efficient use of the available information and its main criticism is to use only monthly precipitation data, thereby ignoring other indicators of drought, such as temperature and potential evapotranspiration.

Since droughts are a complex and natural phenomenon with wide impacts, their characterization has recently been sought through indices based on multiple variables. Hao and Singh (2015) describe the various approaches to constructing *multivariate indices*, among the best known are the use of the soil water balance and the latent or *hidden variables*. A hidden variable is formed with a difference or quotient of variables that have great physical significance in drought; for example, precipitation and potential evapotranspiration, and thus the RDI (Reconnaissance Drought Index) was proposed with the quotient of such variables (Tsakiris & Vangelis, 2005; Campos-Aranda, 2015) and the SPEI (Standardized Precipitation-Evapotranspiration Index) with its difference, which implies a condition of water deficit or excess. The SPEI is a new drought index proposed by Vicente-Serrano *et al*. (2010) and Beguería, Vicente-Serrano, Reig and Latorre (2014) of calculation similar to the SPI, which is multiscalar and sensitive to induced alterations in the historical records of precipitation and temperature, according to the expectations presented by the climate change in such zone or region. An application of the SPEI with such approach has been exposed by Törnros and Menzel (2014) for a zone of Middle East.

The *objective* of this study is to describe in detail the operational procedure of the SPEI and to apply it to the available historical record of precipitation and average temperature of the climatological station Zacatecas, located in the capital city of the same name of the state of Zacatecas, Mexico. This record covers 86 years in the span of 1930 to 2015. Nine durations of drought ranging from 3 to 48 months are processed and three scenarios are analyzed for the probable climate change, the first considers a progressive and linear reduction that reaches 20% of the annual precipitation, the second adopts a progressive and linear increase that reaches 4°C in the average annual temperature and the third, the most critical, combines the negative effects of both alterations. Based on the percentages defined by SPEI for light, moderate, severe and extreme droughts, the contrast of results are made and the conclusions are formulated.

Summary of the Operational Theory

SPEI calculation

The SPI has been applied using various *durations k* of droughts, which varied from three to 72 months (Vicente-Serrano *et al*., 2010). The monthly precipitation record is processed under the *moving sum* scheme, so that for the duration of 3 months, the first sequence is obtained by adding the historical data one, two and three, the second sequence is the sum of the data two, three and four and so on until the last sequence, which is made up of the antepenultimate, penultimate and last data. Then the number of *ns* sequences that can be formed depends on *k* and is defined by expression:

$$ns = 12 \cdot NA - k + 1 \tag{1}$$

in which, NA (for its Spanish initials) is the number of completed years of the processed record (> 30 years). The fundamental difference between the calculation of SPI and SPEI is that the second uses as historical data the differences ($D_{j,i}$) between the monthly precipitation ($P_{j,i}$) and the monthly potential evapotranspiration ($ETP_{j,i}$, for its Spanish initials), that is:

$$D_{j,i} = P_{j,i} - ETP_{j,i} \tag{2}$$

Logically, *j* varies from one to 12 and *i* from one to NA. In order to proceed with the calculation of the SPEI, firstly, the sequences of differences designated by D_l^k are formed in which *t* varies from one to *ns*. When taking into account that the differences D_l^k are most of them negative, there is a need to use a probabilistic model of three fit parameters whose location parameter *u* is less than the smallest of the sequences to be processed. Vicente-Serrano *et al*. (2010) and Beguería *et al*. (2014) contrasted four distributions: Log-Normal, Pearson type III, General of Extreme values and Log-Logistics; recommend the latter, fitted by the method of biased weighted probability moments (βs), whose equations are (Stedinger, Vogel, & Foufoula-Georgiou, 1993; Vicente-Serrano *et al*., 2010):

$$\beta_s = \frac{1}{ns}\sum_{l=1}^{ns}(1 - F_l)^s \cdot D_l^k \ con\ s = 0, 1, 2, \tag{3}$$

being:

$$F_l = \frac{l - 0.35}{ns} \tag{4}$$

In equation 3 the sequences are used ordered in increasing form $\left(D_1^k \leq D_2^k \leq \Lambda \leq D_{ns}^k\right)$. Beguería *et al*. (2014) have proposed to use the unbiased βs, when biased estimators do not lead to a numerical solution. Stagge, Tallaksen, Gudmundsson, Van Loon, & Stahl (2015) have suggested using the General Distribution of Extreme Values, fitted with the maximum-likelihood method. The equation of the cumulative probability distribution function [*F* (*x*)] of the Log-Logistic distribution is (Haktanir, 1991):

$$F(x) = \left[1 + \left(\frac{x-u}{a}\right)^{-1/\gamma}\right]^{-1} \quad (5)$$

being, $\gamma > 0$, $\alpha > 0$ and $u < x_{mo}$ the parameters of form, scale and location. x_{mo} is the minimum sequence observed. The values of the fitting parameters are estimated with the following expressions (Haktanir, 1991):

$$\gamma = 3 - \frac{2\cdot(\beta_0 - 3\cdot\beta_2)}{(\beta_0 - 2\cdot\beta_1)} \quad (6)$$

$$\alpha = \frac{(\beta_0 - 2\cdot\beta_1)}{\gamma\cdot\Gamma(1+\gamma)\cdot\Gamma(1-\gamma)} \quad (7)$$

$$u = \beta_0 - \alpha \cdot \Gamma(1+\gamma) \cdot \Gamma(1-\gamma) \quad (8)$$

in which Γ (·) is the Gamma factorial function, it was estimated with the formula of Stirling (Davis, 1972):

$$\Gamma(\varepsilon) \cong e^{-\varepsilon}\, \varepsilon^{\varepsilon-1/2}\, \sqrt{2\pi}\, \left(1 + \frac{1}{12\cdot\varepsilon} + \frac{1}{288\cdot\varepsilon^2} - \frac{139}{51840\cdot\varepsilon^3} - \frac{571}{2488320\cdot\varepsilon^4} + \Lambda\right) \quad (9)$$

Calculated the three fit parameters (γ, α, u) of each duration *k* analyzed, equation 5 is applied with x = D_t^k to estimate the non-exceedance probabilities *F*(*x*) corresponding to each difference. Then, the rational numerical approximation is used, developed by Zelen and Severo (1972), and exposed by Campos-Aranda (2015), to convert *F*(*x*) into the standardized normal variable Z of zero mean and unit variance, which corresponds to SPEI. Light, moderate, severe and extreme droughts are defined when the SPEI ranges from zero to -1.00, from -1.00 to -1.50, from -1.50 to -2.00 and when it is less than -2.00, respectively.

Monthly *ETP* calculation

Mavromatis (2007) found that the use of simple or complex methods for estimation of $ETP_{j,i}$, leads to similar results when applying drought indices such as that of Palmer. Based on this result, Vicente-Serrano *et al*. (2010) adopt a simple approach to estimate the $ETP_{j,\ i}$, through the Thornthwaite formula, whose expression is:

$$ETP_{j,i} = 16 \cdot Fc \cdot \left(\frac{10 \cdot Tt_{j,i}}{IC_i}\right)^m \qquad (10)$$

in which, *Fc* is a corrective factor function of the latitude of place (LAT) and of number of days in the month (*ndm*), its formula is:

$$Fc = \left(\frac{N}{12}\right) \cdot \left(\frac{ndm}{30}\right) \qquad (11)$$

where, N is the maximum sunshine or maximum number of hours with average monthly sun. For its estimation in the Mexican Republic, Campos-Aranda (2005) developed the following empirical expression:

$$N = A + B\,[sen\,(30\,nm + 83.5)] \quad (12)$$

where nm is the number of month, with 1 for January and 12 for December; A and B are constants function of LAT in degrees, with the following expressions:

$$A = 12.09086 + 0.00266 \cdot LAT \quad (13)$$

$$B = 0.2194 - 0.06988 \cdot LAT \quad (14)$$

$Tt_{j,i}$ is the average monthly temperature in °C and IC_i is an annual heat index, equal to the sum of the 12 monthly indices, which are:

$$icm = \left(\frac{Tt_{j,i}}{5}\right)^{1.514} \quad (15)$$

Finally, the exponent m is function of IC_i with the following empirical equation:

$$m = 6.75 \cdot 10^{-7} \cdot IC_i^3 - 7.71 \cdot 10^{-5} \cdot IC_i^2 + 1.792 \cdot 10^{-2} \cdot IC_i + 0.4924 \quad (16)$$

For values of $Tt_{j,i}$ higher than 26.5 °C there is no influence of IC_i, so $ETP_{j,i}$ is only function of $Tt_{j,i}$ and is tabulated in Campos-Aranda (2005).

Hypothetical scenarios of climate change

Vicente-Serrano *et al*. (2010) and Ma *et al*. (2014) have suggested that as a consequence of climate change processes, at least two scenarios must be studied, the first is a reduction in precipitation and the second, an increase in average temperature. Based on quantitative analyses done by these authors and the climatic projections for Mexico by Montero, Martínez, Castillo and Espinoza (2010), three scenarios were established for analysis: (1) a progressive and linear reduction of 20% in annual precipitation of the historical record; (2) a progressive and linear increase of 4 °C in the average annual temperature record and (3) the superimposition of both changes in the historical record. The changes mentioned have a direct impact in the severity and duration of droughts (Fuchs *et al*., 2014). The correction of the monthly precipitation record ($PM_{j,i}$) is made based on the following equation:

$$PM_{j,i} = PM_{j,i} - \left(\Delta_P \cdot i \cdot PM_{j,i}\right) \qquad (17)$$

in which, Δ_P is the slope of reduction and therefore equals to the quotient of 0.20 between the number of years NA and *i* is the year counter, ranging from 1 to NA. The average monthly temperature correction (TM_{ij}) is carried out with equation:

$$TM_{j,i} = TM_{j,i} + (\Delta_T \cdot i) \qquad (18)$$

now, Δ_T is the slope of the increase and therefore equal to the quotient of 4 °C between NA.

Processed data and their Results

Historical records available

The climatological station Zacatecas is located in the city of the same name, which is the capital of the state of Zacatecas, Mexico, which according to historical information provided by the Local Office of the National Water Commission (CONAGUA), has operated continuously and has not undergone changes of location, so the records can be considered reliable. Its geographical coordinates are as follows: latitude 22° 45' N, longitude 102° 34' W.G. and altitude 2485 m.a.s.l. Its available monthly precipitation (mm) records and average temperature (°C) in the Excel files of CONAGUA of Zacatecas, started in January 1953 and are available until December 2015, with missing data in April 1986 and several months of the years 2010 to 2013.

The first missing data were adopted equal to the monthly averages and the rest was considered equal to the values recorded in the same months in the climatological station Guadalupe, which is approximately 6 km in a straight line and is located inside of the same geographical sub-region. This was considered acceptable due to the similarity that both records show at annual level, both in precipitation and in average temperature. On the other hand, in the Climatological Bulletin No. 3 (SARH, 1980) of the Hydrological Region No. 37 (El Salado), the available records of the Zacatecas station of the monthly precipitation and average temperature begin in January of 1930 and go up to December of 1978. Then, the period from January 1930 to December 1952, without missing data, was taken from such Bulletin and with it a joint record of NA = 86 years was integrated. The twelve monthly average values of the integrated precipitation record are: 16.2, 9.6, 5.7, 7.5, 17.7, 80.0, 102.1, 97.9, 85.4, 35.4, 12.8 and 12.0, whose sum is 482.2 mm, magnitude corresponding to the average annual precipitation. Values of the average monthly temperature record are: 11.7, 12.7, 14.8, 17.1, 19.0, 19.0, 17.5, 17.6, 17.0, 16.1, 14.1 and 12.3, with an annual average value of 15.7 °C.

Homogeneity tests

Starting from the monthly historical records, the annual values of precipitation and average temperature were integrated, to which three basic tests (Helmert, Sequences and Von Neumann) and six specific ones were applied: two of persistence (Anderson and Sneyers), two of trend (Kendall and Spearman), one of them of change in the variability (Bartlett) and another of change in the mean, that of Cramer. These tests can be consulted in WMO (1971); Campos-Aranda (2005), and Machiwal and Jha (2012).

The annual precipitation record is perfectly homogeneous, since no general or specific test detected any deterministic components. On the other hand, the mean annual temperature record was not homogeneous because, according to the basic and specific tests, shows persistence and change in mean. This evidence of lack of homogeneity justifies the approach of scenarios related to climate change.

SPEI values with the historical records

For this study it was decided to analyze the following nine durations *k* of droughts: 3, 6, 9, 12, 18, 24, 30, 36 and 48 months. In Table 1 the results obtained with available historical records were concentrated for each duration according to four concepts: (1) those related to the statistical properties of the sequences formed, (2) those corresponding to the fitting of the Log-Logistics distribution, (3) those associated with the statistical indicators of SPEI and (4) those belonging to the defined drought types.

The first group of results gives an idea of the variability and bias of the sequences formed with the criterion of moving sums; in such a way that the second group, which are the fit parameters of the distribution, are related to such behavior. The third group of results is the most important, because it defines the quality of the fit achieved and therefore the reliability of the estimates made with the SPEI, since its mean, variance and percentage of droughts that it defines should be zero, the unit and 50%. As such indicators approximate the values quoted, the estimate will be better or more reliable.

As Table 1 shows, the most accurate estimates were those of durations of 12, 24 and 36 months, defining approximate percentages of 32.2, 11.5, 5.0 and 1.3 of light, moderate, severe and extreme droughts, respectively.

Figure 1a shows the historical evolution of SPEI with duration of 12 months, observing that in general there is alternation of wet and dry periods. The longest duration drought began towards the sequence 153 (September 1941) and ended in the 416 (August 1963). The date corresponding to a sequence is obtained by clearing from Equation 1 the value of NA in years, which is added to the initial year of the record. In this period the value of the most extreme SPEI occurs, with -2.742 in sequence 321 (October 1954).

Table 1. SPEI results with the monthly historical data of the climatological station Zacatecas, Mexico.

Numerical concepts:	Duration in months of the analyzed sequences								
	3	6	9	12	18	24	30	36	48
Of sequences									
Number of sequences	1030	1027	1024	1021	1015	1009	1003	997	985
Minimum moving sum	-255.0	-389.6	-513.3	-668.6	-867.1	-1059.0	-1322.5	-1487.3	-1923.4
Maximum moving	385.4	398.7	352.1	284.2	429.7	295.2	310.5	43.8	-276.6

sum									
Arithmetic mean	-67.6	-135.4	-203.9	-273.1	-412.9	-552.7	-692.2	-832.2	-1110.7
Standard deviation	100.2	135.0	150.4	156.4	214.5	234.5	278.2	289.4	337.9
Asymmetry coefficient	1.000	0.799	0.640	0.548	0.525	0.539	0.546	0.451	0.234
Of the FDP (LL3)									
Shape parameter (γ)	0.170	0.148	0.109	0.097	0.080	0.090	0.090	0.084	0.063
Scale parameter (α)	306.08	488.25	756.28	892.86	1488.13	1436.10	1701.99	1910.52	3054.05
Location parameter (*u*)	-388.3	-641.0	-974.3	-1178.8	-1915.2	-2006.6	-2415.2	-2763.0	-4181.4
Of SPEI									
Arithmetic mean	-0.0008	-0.0006	-0.0033	-0.0042	-0.0061	-0.0049	-0.0050	-0.0053	-0.0070
Variance	0.9994	0.9939	0.9956	0.9987	0.9966	0.9979	0.9980	1.0011	1.0079
Minimum value	-2.438	-2.287	-2.311	-2.742	-2.247	-2.334	-2.445	-2.405	-2.408
No. of negative values	539	519	524	517	496	508	510	504	501
% of droughts	52.3	50.5	51.2	50.6	48.9	50.3	50.8	50.6	50.9
Of the types of droughts									

% of light droughts	36.2	32.0	33.5	32.8	29.4	32.0	33.6	33.0	29.7
% of moderate droughts	8.5	12.2	10.6	11.8	13.3	11.3	10.7	11.4	17.5
% of severe droughts	6.0	5.6	5.8	4.8	5.2	5.7	4.9	4.2	2.1
% of extreme droughts	1.6	0.8	1.3	1.3	1.0	1.3	1.7	1.9	1.5

Table 2. Characteristic values of the historical climatic records and their hypothetic versions according to the probable climate change, in the climatological station Zacatecas, Mexico.

Annual record of:	historical value		minimum		Maximum		average value
	initial	final	value	year	value	year	
Historical precipitation (mm)	630.9	1019.0	169.3	1969	1019.0	2015	482.2
Average temperature (°C)	15.2	16.2	14.2	1985	16.8	1962	15.7
ETP (mm) with the Thornthwaite (THW) method	736.6	763.9	704.7	1985	792.9	1962	752.8
Precipitation with reduction of 20% (mm)	629.4	815.2	145.3	2011	880.9	1935	432.9
Average temperature with increase to 4°C	15.2	20.2	15.1	1931	20.4	2006	17.8
ETP (mm) of THW and temperature	738.1	950.7	735.5	1931	975.3	2006	833.6

with increase							

Table 3. SPEI results with the monthly altered records with combined effects (reduction of precipitation and increase of average temperature), in the climatological station Zacatecas, Mexico.

Numerical concepts:	Duration in months of the analyzed sequences								
	3	6	9	12	18	24	30	36	48
Of sequences									
Number of sequences	1030	1027	1024	1021	1015	1009	1003	997	985
Minimum moving sum	-324.9	-474.3	-632.2	-766.5	-1143.5	-1409.6	-1827.0	-2035.6	-2487.3
Maximum moving sum	374.1	382.3	278.9	165.0.	395.9	259.6	265.5	-4.2	-347.8
Arithmetic mean	-100.2	-200.4	-301.1	-402.3	-606.4	-810.2	-1013.7	-1217.2	-1622.9
Standard deviation	92.8	127.1	147.8	161.3	225.3	261.8	315.6	349.8	435.1
Asymmetry coefficient	0.858	0.799	0.658	0.586	0.671	0.663	0.639	0.596	0.542
Of the FDP (LL3)									
Shape parameter (γ)	0.111	0.115	0.090	0.076	0.084	0.078	0.074	0.070	0.086
Scale parameter (α)	445.43	594.79	892.73	1164.48	1462.82	1816.87	2325.00	2725.99	2784.61

Location parameter (*u*)	-554.2	-807.6	-1204.9	-1576.6	-2084.64	-2643.53	-3357.2	-3962.4	-4438.5
Of SPEI									
Arithmetic mean	-0.0053	-0.0041	-0.0062	-0.0081	-0.0070	-0.0080	-0.0085	-0.0091	-0.0061
Variance	1.0015	0.9958	0.9968	0.9991	0.9989	0.9988	0.9990	0.9999	1.0001
Minimum value	-2.810	-2.486	-2.444	-2.401	-2.569	-2.453	-2.700	-2.456	-2.154
No. of negative values	521	516	498	500	509	499	510	500	484
% of droughts	50.6	50.2	48.6	49.0	50.1	49.5	50.8	50.2	49.1
Of the types of droughts									
% of light droughts	34.3	33.6	29.7	30.4	33.1	32.3	33.1	32.1	30.8
% of moderate droughts	8.7	9.6	12.0	11.4	9.9	10.9	10.1	9.8	10.2
% of severe droughts	4.9	5.6	5.4	5.3	5.0	4.5	6.2	7.1	7.2
% of extreme droughts	2.7	1.4	1.6	2.0	2.1	1.8	1.5	1.1	1.0

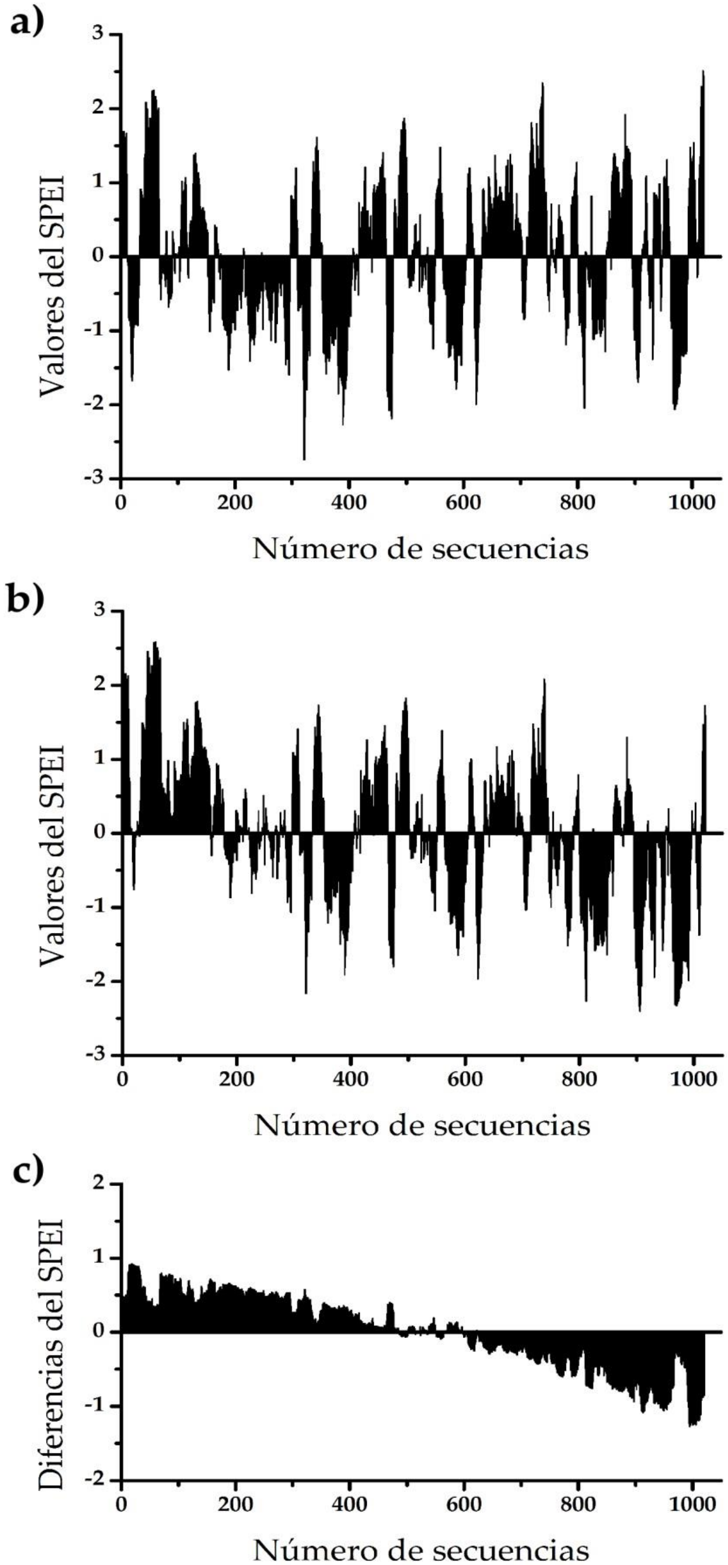
a)
Valores del SPEI
Número de secuencias
b)
Valores del SPEI
Número de secuencias
c)
Diferencias del SPEI
Número de secuencias

Figure 1. (a) SPEI evolution of 12 months duration in the climatological station Zacatecas, of the state of Zacatecas, Mexico; (b) SPEI evolution (k = 12 months) with reduction of 20% in the annual precipitation and increase of 4 °C in the average annual temperature and (c) Differences between the SPEI shown (b - c).

SPEI values with altered climate records

Based on equations 17 and 18, the historical records were modified to incorporate a progressive and linear decrease of 20% in annual precipitation and a progressive and linear increase of 4 °C in the average annual temperature. Table 2 shows various relevant values of the historical records and those of the altered or modified records according to possible climate change, as well as the annual values of the *ETP* estimated with the Thornthwaite method.

Similar to Table 1, in Table 3, the SPEI results for the altered record according to the third scenario are presented, i.e., considering the combined effect of both modifications. Due to space limitation the results of the SPEI with reduction of precipitation, and with increase in average temperature are not shown, but they are available with the author. Based on all the SPEI results, the duration of 24 months was defined as the ideal for the contrast between the values obtained with the historical record and the altered ones. This contrast is shown in Table 4.

Table 4. Number of events and percentages of each drought type obtained with SPEI of 24 months of duration in the historical records (Table 2) and their contrast with the altered ones (Table 3).

Types of drought and SPEI	Table 2	Reduction of precipitation	Reduction of precipitation	Combined effects

Light	323 (32.0%)	357 (35.4%) >	356 (35.3%) >	326 (32.3%) >
Moderate	114 (11.3%)	90 (8.9%) <	88 (8.7%) <	110 (10.9%) <
Severe	58 (5.7%)	53 (5.3%) <	60 (5.9%) >	45 (4.5%) <
Extreme	13 (1.3%)	21 (2.1%) >	18 (1.8%) >	18 (1.8%) >
SPEI minimum	-2.334	-2.401	-2.547	-2.453

The results shown in Table 4 indicate that, in general, light and extreme droughts will increase as a result of probable climate change; in contrast, moderate and severe droughts will decrease. In these conclusions there is an anomaly in the severe droughts of the record with increase of temperature, which also increase. Regarding the extreme values of the SPEI, they are considered in agreement with the modifications imposed to the historical records. For the third scenario, the most critical, it is defined in Table 3 as more accurate results those of the 18-month duration, with the following percentages for the four types of droughts sought: 33.1, 9.9, 5.0 y 2.1.

Figure 1b shows the evolution of the SPEI of 12- month duration in the record that includes both effects of climate change; it is clear how droughts will increase in duration and severity towards the end of the record, significantly reducing the wet periods. Finally, Figure 1c shows the SPEI differences of Figure 1b minus 1a.

Conclusions

The results of the SPEI with the historical records of the climatological station Zacatecas (Table 1), located in the capital of the same name, in the state of Zacatecas, Mexico, define approximately 32.2%, 11.5%, 5.0% and 1.3% of light, moderate, severe and extreme droughts, respectively. These percentages and the following ones were obtained based on the drought durations of 12 to 30 months.

In the three scenarios of climate change, it is generally found that light and extreme droughts increase briefly and that moderate and severe droughts decrease, also scarcely in small number or percentage. They are defined globally for the third scenario (Table 3), the most critical, for combining precipitation reduction and average temperature increase, 32.7%, 10.5%, 4.8% and 2.0% for each type of drought.

The evolution graphs of SPEI, as those shown in Figure 1 for a 12-month drought duration, allow for accurate visualization and definition of drought periods, as well as their maximum or extreme point values; the before mentioned, both in the historical record and in the altered records by probable climatic change.

Taking into account, the consistency of the results of this study, the systematic application of SPEI in the quantification of historical and future droughts is recommended; the first based on the available historical records and the second ones, in their modified versions, that must be considered, according to the possible effects of climate change in each zone or region of the country.

In the climate change scenarios that are considered feasible to occur, SPEI results can help to put into perspective the impact on the water balance of a region. However, being uncertain how exactly droughts will evolve in the future, the SPEI results can only be considered as guidelines.

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