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Variability of the standardized precipitation index over México under the A2 climate change scenario

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RESUMEN

En este estudio se presenta una aplicación del índice de precipitación estandarizada de 12 meses (SPI, por sus siglas en inglés) como una herramienta para identificar y evaluar la severidad en eventos de sequía en México durante el periodo 1949-2098, bajo la proyección del escenario de emisiones A2 del Panel Intergubernamental sobre Cambio Climático. El análisis indica un incremento en la ocurrencia y severidad de eventos de sequía en México, con una tendencia negativa en los valores proyectados del SPI de 12 meses, concluyendo que las proyecciones de eventos de sequía superan la duración, magnitud y frecuencia de aquellos eventos modelados en la segunda mitad del siglo XX.

ABSTRACT

The 12-month Standardized Precipitation Index (SPI) is used to identify and assess drought severity in México during the 1949-2098 period under the A2 emissions scenario of the Intergovernmental Panel on Climate Change (IPCC). The analysis indicates more frequent and severe drought events in México, shown by a negative trend of the 12-month projected SPI time series. Furthermore, this study concludes that projected future drought events would surpass the time-length, magnitude and frequency of those modelled during the second half of the 20th Century.

Keywords: Drought, SPI, climate change, A2 scenario.

1. Introduction

Precipitation patterns over México are influenced by tropical and middle-latitude systems, for example: easterly waves, tropical cyclones on both Atlantic and Pacific coasts, the summer monsoon in the northwest, and the midsummer drought on the south. Besides, during winter the westerlies bring precipitation to the northwest part of México. Generally, the maximum of rainfall patterns is achieved from May through October, depending on the specific region of the country (Mosiño and García, 1974), whereas during the winter the warm subtropical high pressure systems cause dry conditions over most of México.

Meteorological drought defines the degree and duration of dryness of a specific region as a result of high deficits of precipitation compared to its average amount (Wilhite and Glantz, 1985); although it is a regular feature of climate variability, combined with climate change conditions, it can have devastating effects. Therefore, it is important to estimate future precipitation conditions under climate change circumstances over México, especially in regions where urban settlements highly depend on water coming from lakes, rivers, lagoons and reservoirs which water levels have a strong dependence on rainfall patterns.

Recent studies (Solomon *et al.*, 2007), indicate that more intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics; furthermore, increased drought has contributed to higher temperatures and reduced precipitation over land.

The IPCC (1990, 1992) developed long-term emissions scenarios to support climate modelling, the analysis of climate change and its impacts and to help generate options to mitigate and adapt to climate change. We chose the A2 emissions scenario since it is one of the most commonly used to represent the higher end, although it is not the highest, of climate changes within the IPCC set of scenarios; therefore it will give us information about the greater impacts that may occur due to global warming.

The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and considers preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines (IPCC, 2000). Besides, the A2 scenario estimates an increase of global average surface temperature (likely range is 2.0 to 5.4 ºC), and a sea level rise (likely range is 0.23 to 0.51 m, excluding dynamical changes in ice flow) at the end of the 21st century (Solomon *et al.*, 2007).

The analysis of drought events may incorporate different indices and methodologies that consider meteorological and hydrological variables such as rainfall, soil moisture, evapotranspiration, ground and surface water levels. We have chosen the Standardized Precipitation Index (McKee *et al.*, 1993) which has been used as a tool to identify and assess drought events in many countries (Paulo *et al.*, 2003; Vicente-Serrano *et al.*, 2004). The main advantage of this drought analysis technique is its simplicity and temporal flexibility, because it only uses one parameter: the precipitation data over time.

In this study, the SPI methodology has been used for México, covering a period of 150 years, from January 1949 through December 2098. The first 51 years (January 1949 to December 1999) has been simulated with the observed changes in radiative forcing, while the second period (January 2000 to December 2098), a climate projection, has been simulated considering the greenhouse gases concentrations of the A2 Emissions Scenario.

2. Data and methods

The SPI (McKee *et al.*, 1993,1995) is based on the probability of precipitation for a number of consecutive months, and its main objective has been to represent a deficit of precipitation over a local area on a specific time scale relative to its climatology. Although the SPI is not a drought prediction tool, the SPI methodology has been used to identify dryness and wetness conditions, and to evaluate their impact in the water resources and management. This study computes SPI values within the area shown on Figure 1, where the spatial resolution is 2º longitude by 2º latitude.

Monthly precipitation data were acquired from 15 climate models of the IPCC Fourth Assessment Report (AR4), under the A2 scenario. The simulation data were downloaded from the Earth System Grid webpage at Los Alamos National Laboratory (www.earthsystemgrid.org).

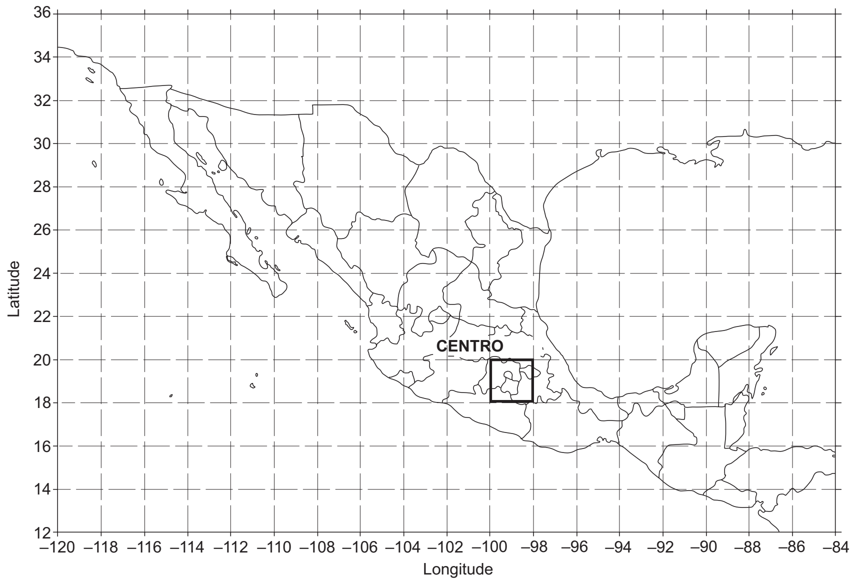

Fig. 1. Domain used to compute the Standardized Precipitation Index with 2º latitude by 2º longitude resolution as shown in the grid. The Centro zone centered at 19º N, 99º W is enclosed by a thick square.

To develop a homogeneous resolution precipitation database, and since each model has different gridded precipitation data, a multi-model ensemble with a uniform spatial resolution of 2º by 2º was generated. Afterwards, cumulative annual precipitation data (in mm year^{-1}) were calculated as an average of the 15 models, together with their respective standard deviations from 1949 to 2098.

The general procedure in every grid-cell is as follows:

1) The 12-month SPI is computed from the 1949-1999 (historic period) modeled precipitation for each grid-cell, obtaining the probability density function, being the gamma distribution the best fitting (Thom, 1966). The mathematical method is explained in appendix 1.
2) The 12-month SPI is computed for the 2000-2098 (future period) modeled precipitation using, for each grid-cell, the linear relationship between the 12-month SPI values and the annual cumulative rainfall during 1949-1999.

This procedure has allowed a direct comparison between the historic and future rainfall variability.

Based solely on the amount of precipitation recorded in a specific location, the SPI gives a better representation of abnormal wetness and dryness than other indices of drought severity (Guttmann, 1998). Negative SPI values imply dryer than normal conditions, while positive ones, indicate wetter than normal conditions. Values from –1 to –1.5 represent moderate drought, while from –1.5 to –2 and less than –2 represent severe and extreme drought conditions respectively.

3. Results

The database obtained by the ensemble of 15 models of the IPCC AR4 includes annual precipitation data and its corresponding standard deviation into 216 grid-cells. The time series of 12-month SPI for the grid-cell centered at 19º N, 99º W (Centro zone) is shown on Figure 2 for the historic period, together with the extrapolation of the relationship between the 12-month SPI and the annual precipitation for the historic period projected to the future period. Thin lines correspond to this signal plus or minus the standard deviation associated to the variability of the IPCC climate models. In 2098, the strong decay of the projected precipitation, reaching –3.95 SPI-units, is considered an extreme drought event. In addition, there is a steady increase in frequency and intensity of dry events; 2059 is the last year with an above average precipitation, while the average signal of climate models during 2060-2098 shows negative SPI values, which would have important socio-economic consequences, since this region contains the main population and some of the most important economical activities in México.

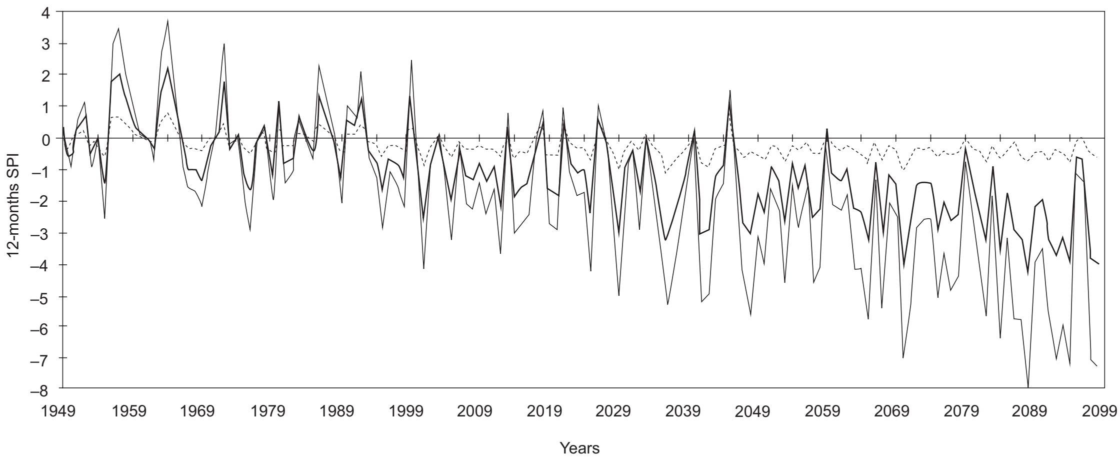

Fig. 2. Time series of modelled precipitation results: 12-month SPI values for the Centro zone (thick line). Thin lines correspond to this signal plus or minus one standard deviation. The vertical scale is in multiples of the SPI-unit for this region.

The procedure to obtain Figure 2 was repeated on every grid-cell of the study area and results for years 1949, 1998, 2048 and 2098 are summarized in Figure 3, where bluish scale represents wet circumstances, while reddish-brown areas illustrate drought conditions; white areas indicate a normal situation. In 1949 and 1998, most grid-cells are in normal condition, whereas in 2048 and 2098 most of the areas have moderate or extreme drought events. In 2048 and 2098 the value of the 12-month SPI revealed an increase in intensity of dry events mainly over the southeast part of México, as well as over the central-Pacific coast of the country.

The domain-average of the 12-month SPI for each decade from 1950s up to 2090s is presented in Figure 4 together with their dryness categories. As it is shown, moderate drought is projected, on average, over the whole domain for the 2050s to 2070s decades, while severe drought conditions are projected for the 2080-2098 period.

4. Conclusions

In this study, the 12-month SPI was computed for the 1949-2098 period, and it has been used as a tool to assess frequency and severity of drought events under the climate change emissions scenario A2 over México.

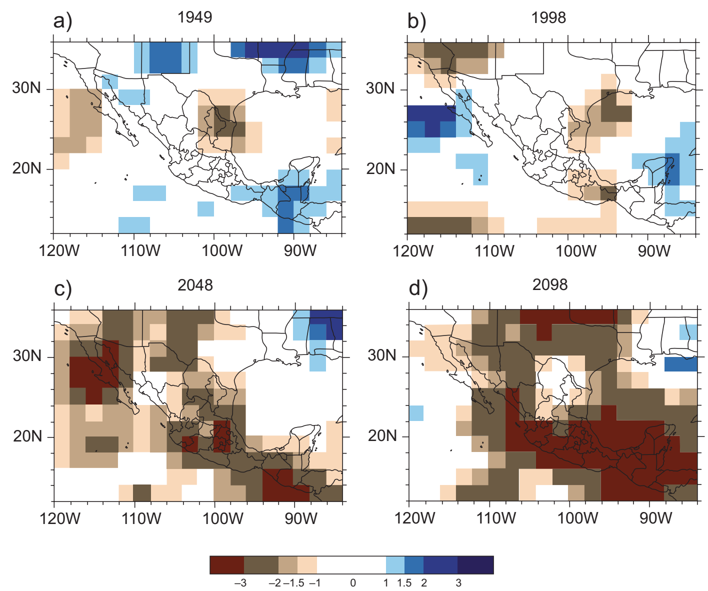

Fig. 3. Maps of modelled precipitation results, 12-month SPI for: a) 1949, b) 1998, c) 2048, and d) 2098. The label bar units are in multiples of 1 SPI. The domain-averaged of 12-month SPI for each panel is: a) 0.13 (normal), b) –0.17 (normal), c) –1.25 (moderate drought), d) –1.73 (severe drought).

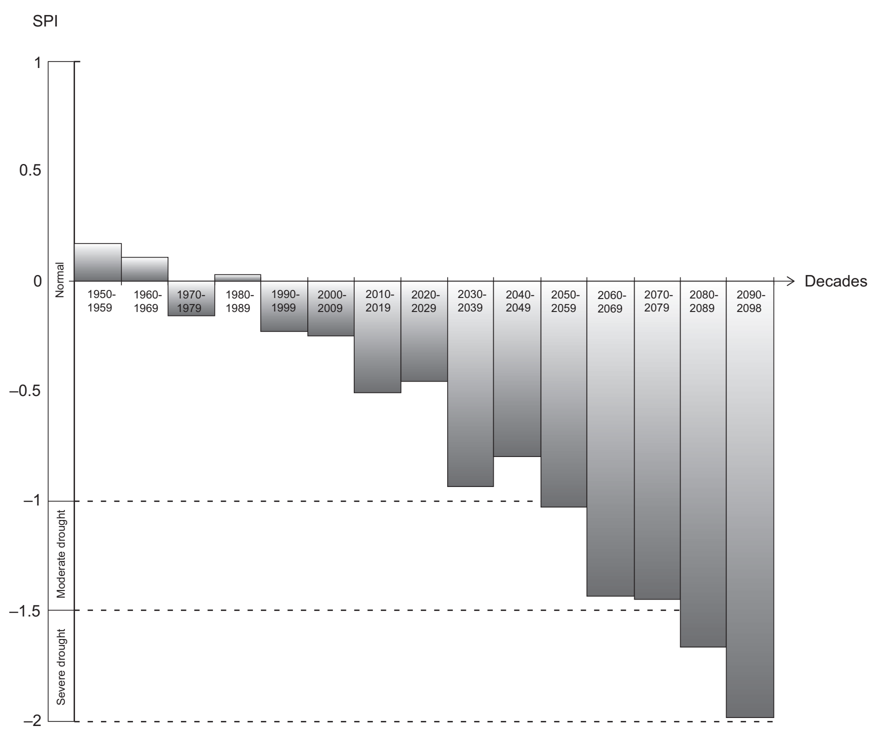

Fig. 4. Decadal average of 12-month SPI from 1950s to 2090s for the region shown in Figure 1.

Analysis of the time series of the Standardized Precipitation Index revealed that during the historic period (1949-1999), there is not a clear trend for a drier or wetter climate, however for the future period (2000-2098), the tendency over most of mainland México is towards drier conditions. Moderate drought is projected, on average, over the whole domain by the mid-21st century; afterwards a severe drought condition becomes evident. In individual cells such as the one over the Chiapas State in southeast México (centered at 19º N, 95º W), the SPI average for the 2075-2098 period is –3.48 which represents extreme drought conditions.

The mean of model projections has a clear tendency towards drier conditions for México, which can be categorized as moderate drought from 2050 to 2079, and severe drought from 2080 to 2098; these results are obtained from simulations that participated on the IPCC-4AR being the most accepted projection data available at the present time. These projected drier conditions would have important consequences for millions of people, reducing their access to water. Therefore it is necessary to implement adaptation measures on water management, agriculture, cattle rising and urban development. It is also essential to carry out mitigation processes in order to reduce greenhouse gas emissions. Since the projections show a tendency towards extreme climate conditions, it is necessary to produce, on the short term, more detailed quantitative studies of projected precipitation patterns over the country, using the newest higher resolution versions of climate models. This information will be indispensable for government authorities and social scientist in order to promote new human settlements that can provide better conditions for inhabitants affected by droughts.

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Appendix I

The gamma distribution is defined by its frequency or probability density function as:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \text{ for } x>0 \qquad \text{(A1)}$$

Where:

$\alpha > 0$ α is a shape parameter

$\beta > 0$ β is a scale parameter

$x > 0$ x is the precipitation amount

$$\Gamma(\alpha)=\int_0^{\infty} y^{\alpha-1}e^{-y}\,dy \qquad \Gamma(\alpha) \text{ is the gamma function} \qquad \text{(A2)}$$

The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given month and time scale. The cumulative probability is given by:

$$G(x)=\int_0^x g(x)\,dx=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}\int_0^x x^{\alpha-1}e^{-\frac{x}{\beta}}\,dx \qquad \text{(A3)}$$

Letting $t=\frac{x}{\beta}$ the equation becomes the incomplete gamma function:

$$G(x)=\frac{1}{\Gamma(\alpha)}\int_0^x t^{\alpha-1}e^{-t}\,dt \qquad \text{(A4)}$$

Since the gamma function is undefined for x=0 and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$H(x) = q + (1-q)G(x) \qquad \text{(A5)}$$

Where, q is the probability of zero. Finally, the cumulative probability $H(x)$ is then transformed to the standard normal random variable Z with mean zero and variance of one, which is the value of the SPI (McKee *et al.*, 1993; Guttmann, 1999).