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Identification of pluriannual periodicities in series of drought indexes and its relationship with macroclimatic indicators

Leticia Vicario [a,b,*], Érica Díaz [b], Carlos Marcelo García [b], Andrés Rodríguez [b]

[a] *National Institute of Water, Av. Ambrosio Olmos No. 1142, Córdoba, Argentina, X5000JGT*
[b] *Faculty of Exact, Physical and Natural Sciences, National University of Cordoba, Argentina*

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ABSTRACT

In Latin America, drought studies generally develop on climatic or hydrological approach and there are few studies available on the relationship between different kind of droughts and macroclimatic processes. The main objective of this paper was to relate the times series of droughts indexes to relevant macroclimatic indicators in Central Region of Argentina. For that, the Fourier analysis was used to identify the pluri-annual periodicities of macroclimatic indicators and representative indexes of hydrometeorological and hydrological droughts. The indexes were calculated with time series of precipitation and flow data of stations located in Carcarañá River basin. According to dominant frequencies, series with Fourier band-pass filters were filtered. Full and filtered series of indexes and indicators were compared through the correlation coefficient, for to identify and compare the time scale of the processes involved. A significant relationship in pluriannual periodicities of some droughts indexes and macroclimatic indicators was observed.

Introduction

The climate of a place is the average state of the atmosphere for a long time. There are several macroclimatic indices defined by equations with variables of the climate system such as pressure, temperature, precipitation and solar radiation, as well sea surface temperature or ice cover. These can explain part of the climate variability in a region.

Droughts are unavoidable events and still unpredictable (Kim et al., 2002) due to behavior of hydrologic processes that cause them. The identification and characterization of drought is complex, because is difficult to detect it (Tsakiris and Pangalou, 2009). Multidisciplinary analysis of this phenomenon involves meteorology, hydrology, geology and other geophysical sciences (Palmer, 1965) and needs to be characterized as widely as possible, identifying duration, intensity, magnitude and frequency. The kind of drought in all analyzes should be identified because there are differences between the processes of the meteorological and hydrological droughts (Hisdal and Tallaksen, 2003).

There are studies on different aspects of the drought phenomenon in the world and for several decades. Some examples of this are the relationship between hydrometeorological variables and different types of droughts in regions of Europe (Wong et al., 2013; Santos et al., 2015) or Asia (Wu et al., 2015). There are analyzes of droughts in areas with different spatial characteristics and the temporal evolution (Spain: Vicente-Serrano, 2006), as well as, works on the relationship between the occurrence of droughts and the climatic processes in different time scales (Australia: Chiew and McMahon, 2002; North Atlantic: Kushnir et al., 2010) and another studies related some characteristics of drougth with time periods of other natural phenomena involved (Özger et al., 2009). The influence of climate variability and drought periods in the availability of water resources in a basin (Lorenzo Lacruz et al., 2010) and water-related ecosystem services and how they are impacted by land use and climate change were evaluated (Bai et al., 2019).

Generally, in Latin America, drought studies are about a main aspect of it, such as climatic (Santos, 2011; Rivera, 2014), agricultural (Blain, 2012; Carrão et al., 2013) or hydrological (Wagner et al., 2012) but assessment of relationship between the processes involved are limited.

Argentina is one of the countries with the highest percentage of arid areas in Latin America (UNESCO, 2010), presents several climates and has wet and dry periods at annual level. So, extreme hydrological events occur in different regions at the same time and the drought research have predominantly a climatic and agricultural approach (Scian and Donnari, 1997; Hartmann et al., 2003; Havrylenko et al., 2013).

Implementation of a coherent policy mix is critical to achieve sustainable economic growth (Aldieri et al., 2019). Specifically, the Central

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[*] Corresponding author. Faculty of Exact, Physical and Natural Sciences, National University of Cordoba, Argentina.
E-mail address: lvicariotm@gmail.com (L. Vicario).

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Region of the Argentina has some of the most important cities with a high population density where knowledge about available water is essential for distribution and consumption and some economic activities, but the agricultural-livestock activity is one of the most important in regional economy and droughts cause significant economic losses, so it is more common to find information on agricultural droughts. (Ravelo et al., 2014; Thomasz et al., 2018). Also, studies on characterization of meteorological (Vicario et al., 2015) and hydrologic (Vicario and García, 2018) droughts have been made with representative indexes in basins of this region and in another study was observed that some macroclimatic indicators explain significantly the interannual variability of the streamflow in the main basins of Argentina (Diaz, 2016); but all these separately.

From the reviewed literature, a vacancy area in the evaluation of the relationship of the droughts and macroclimatic phenomena is observed.

In this paper, the pluriannual periodicities in series of meteorological and hydrological droughts indices were identified in Carcarañá River basin into Central Region of Argentina and were compared with periodicities of macroclimatic indicators. The main objective is to correlate these time series and identify the processes involved with each other and provide a basis for future water resources policies in the study area.

Materials and methods

Study area

Carcarañá River Basin is located in the Pampas region of Argentina, in central-southeast of Córdoba province and crosses the southern of Santa Fe province to discharge into the Parana River. The Carcarañá River drains an area of 60000 km^2. The availability of hydrological information and assessment of water resources is poor in the basin (Romagnoli et al., 2017), for this reason only two data series were used (Fig. 1): Río Cuarto (rainfall station) and Pueblo Andino (hydrometric station). Both series have a good quality and length for the study objective.

Meteorological and hydrological droughts indexes

Standardized precipitation index (SPI) was designed to improve the detection of the beginning of a meteorological drought and its monitoring. The SPI index summarizes properly the characteristics of drought as a natural phenomenon, because the rainfall is the principal variable of the hydrological cycle (Velasco and Aparicio, 2004). This index is based on probabilities of occurrence of precipitation using a long serie of records (World Meteorological Organization, 2012). A probability distribution is applied for the precipitation series and it is normalized, so SPI average for a location and period of time used, is zero (Edwards and McKee, 1997), and climates wet as dry can be represented similarly. SPI index can characterize droughts in different time scales: three, six, nine, twelve, and twenty four months according to objective of the study. Classification intervals for SPI are presented in Table 1. The start of the drought is defined when SPI value is −1.0 or less, and it continues until the SPI becomes positive. The drought duration is the interval between the beginning and the end of the period.

The World Meteorological Organization (2012) indicates the following advantages of this index:

- It is flexible: it can be calculated for various time scales
- For short time scales, the SPI index provides early alerts of drought and helps to assess the severity of it.
- The SPI index has spatial coherence, because it allows comparisons between locations with different climates.
- The probabilistic origin of the SPI index gives a historical context. This is suitable for decision making.

Streamflow Drought Index (SDI) developed by Nalbantis (2008) was used to analyze hydrological droughts. The SDI index allows the determination and classification of droughts in a basin. However, sufficiently long series of data is required data to estimate the frequency of drought events. Nalbantis (2008) indicated that SDI index is based in the analyze of the accumulated values of flows, volumes or runoff in three, six, nine

Table 1
Characteristic values of Standardized Precipitation Index (SPI).

SPI	Category drought
>2.00	Extremely wet
1.99 to 1.50	Very wet
1.49 to 1.00	Moderately wet
0.99 to −0.99	Normal
−1.00 to −1.49	Moderate drought
−1.50 to −1.99	Severe drought
<-2.00	Extreme drought

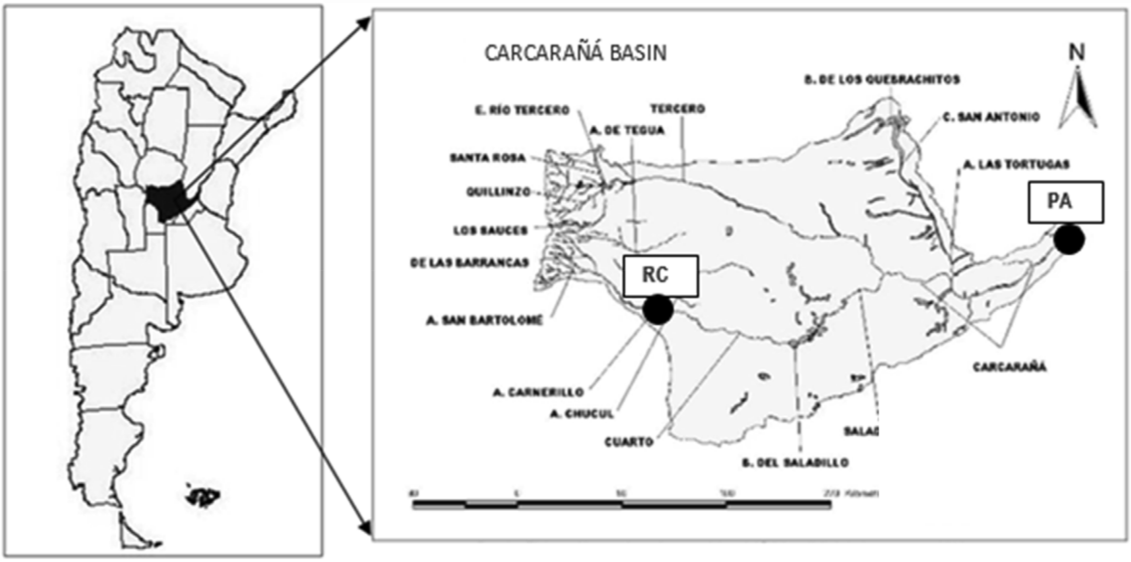

Fig. 1. Location Carcarañá River Basin in Argentina. RC: Rio Cuarto, rainfall station. PA: Pueblo Andino, hydrometric station. (Source: National Secretary of Water Resources).

Table 2
SDI index: Classification of hydrological drought.

Description	Criterion
No drought	$SDI_{I,k} > 0$
Soft drought	$-1 \leq SDI_{I,k} < 0$
Moderate drought	$-1.5 \leq SDI_{I,k} < -1$
Severe drought	$-2 \leq SDI_{I,k} < -1.5$
Extreme drought	$SDI_{I,k} < -2$

or twelve months within for each hydrological year, called k_1, k_2, k_3 and k_4 respectively. These intervals allow to analyze the evolution of droughts in the annual period considered.

SDI index is calculated as:

$$V_{i,k} = \sum_{j=1}^{3k} Q_{ij} \ldots\ldots\ldots\ldots i = 1, 2, \ldots, n; j = 1, 2, \ldots, 12; k = 1, 2, 3, 4,$$

$Q_{i,j}$ are streamflow volume values where i denote the hydrological year and j month within a hydrological year. We can obtain $V_{i,k}$ cumulative of streamflow volume for the i year and k reference period. Then:

$$SDI_{i,k} = \frac{V_{i,k} - V_k}{s_k}$$

$SDI_{i,k}$ is a hydrological drought index for the i year and k reference period. V_k and s_k are, respectively, the mean and standard deviation of volume data for k interval considered. Classification of hydrological droughts trough SDI index are shown in Table 2.

Two time series are analyzed in this paper. Average monthly rainfall serie of the Río Cuarto station were used to calculate SPI index (12 month) in period 1980–2009, and SDI (k4) index, was calculated with average monthly flows registered in Pueblo Andino station, in period 1981–2013 (Table 3).

Macroclimatic indicators

The macroclimatic indicators used in this work are (Table 4):

TSA (Tropical Southern Atlantic Index): It is the average of anomalies of the sea surface temperature between the coordinates Ecuador-20 S and 10 E − 30 W.

AMM (Atlantic Meridional Mode): It describes the meridional variability in the tropical Atlantic Ocean.

SOI (South Oscillation Index): It is an indicator of the difference of atmospheric pressure in Tahití y Darwin.

SS (Sunspots): The sunspots are zones of the sun with lower temperature than others.

These are dynamic and variable in time and some studies explain its influence on different atmospheric variables (Dölling, 2014).

ONI (Oceanic Niño Index): It is based on 3 month moving average of the temperature anomaly in the Niño 3.4 region (5°N-5°S, 120°-170°W).

Niño 2 + 1: It is the average temperature of sea surface in Niño 1 + 2 region and it represents the atmospheric variability in the Pacific coast of South America.

The set of indicators AMM, ONI, SOI, NIÑO 1 + 2 and TSA were obtained from the website NOAA (National Oceanic and Atmospheric Administration, 2016), and Sunspots data (SS) was obtained from SILSO (Sunspot Index and Long-term Solar Observations, 2016).

Table 4
Macroclimatic indicators series.

Indicator	Description	Period
TSA	Tropical South Atlantic Index	1948–2013
AMM	Atlantic Meridional Mode	1948–2001
SOI	Southern Oscillation Index	1951–2013
SS	Sunspots	1700–2013
ONI	Oceanic Niño Index	1950–2012
Niño 1 + 2	Average temperature of the sea surface in regions 2 + 1	1950–2013

Table 5
Correlation coefficients between SPI series of Río Cuarto station and macroclimatic indicators series. Correlation coefficient greater than 0.5 are highlighted.

SPI series	TSA	AMM	Niño 1 + 2	ONI	SOI	SS
Full	0.13	0.08	−0.05	−0.17	0.06	0.09
filtered Nbd	***−0.54***	0.28	***0.72***	−0.08	***−0.53***	***0.51***
filtered N11	−0.38	***−0.59***	0.34	−0.16	−0.07	0.33
filtered N5	0.30	0.17	−0.13	−0.19	0.17	−0.02

Spectral analysis

The analysis to obtain the energy spectrum of the time series used and identify the dominant frequencies in each of them, was based on the following concepts.

Time series of indices and indicators have fluctuations generated by quasi periodic processes of different frequencies. These frequencies may be determined through the energy spectrum $Gxx(f)$, because it represents the energy or variance contributed by the fluctuations of different frequencies.

To obtain $Gxx(f)$ of droughts indexes and macroclimatic indicators series, Fourier finite transform (Bendat and Piersol, 2000) was used. The function is:

$$Gxx(f) = \frac{2}{T} |X(f, T)|^2 \qquad \text{(C)}$$

Then:

Frequency $f = 1/T$
T: period of time
X (f,T): Fourier Discrete Transform (FDT) obtained with Fourier fast transform (FFT) which allows the transformation of a time function in a frequency function. It is used for spectral analysis of time dependent variables since it optimizes the original function reducing operations to minimum (Cooley and Tukey, 1965). Periodogram function available in the @MATLAB program libraries was used, to obtain *Gxx(f)*.

Correlation of observed fluctuations in macroclimatic indicators and drought indexes series

Fluctuations of different frequencies and random fluctuations in macroclimatic indicators series and drought indexes series, can affect the correlation analysis. Therefore, they were filtered using a Fourier pass-band filter. It takes the energy of fluctuations to zero for the frequency ranges not included in the filter band used. The filtrate was made for the following frequency ranges or characteristic periods:

Table 3
Characteristics of the stations and series of drought indexes.

Station name	Geographical coordinates		Altitude (masl)	Series		
	Latitude	Longitude		Index	Time scale	Length (years)
Río Cuarto	−33,07	−64,1	421	SPI	mensual	34
Pueblo Andino	−32,67	−60,87	18	SDI	anual	29

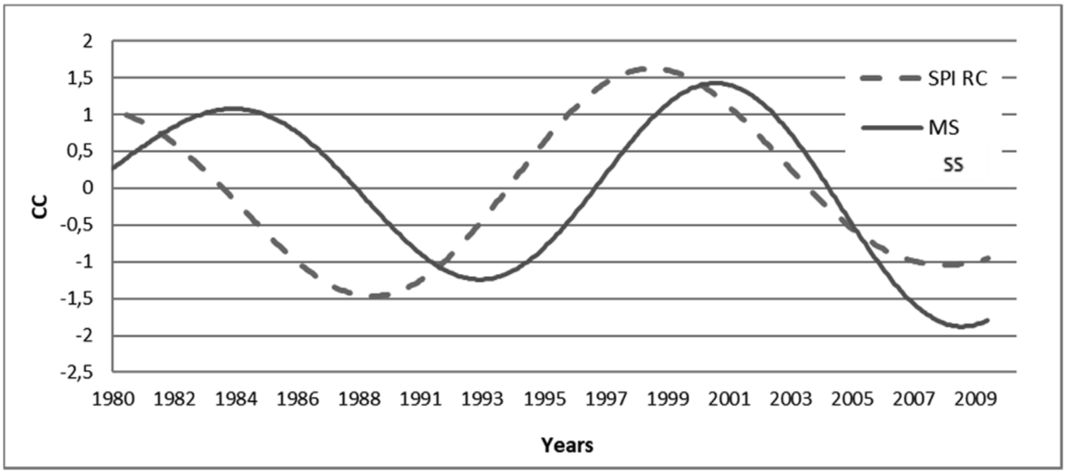

Fig. 2. Standardized SPI index of Río Cuarto station (SPI RC) and SS indicator for band-pass filter 13–35 years.

Table 6
Correlation coefficients between SDI (k4) series of Pueblo Andino station and macroclimatic indicators series. Correlation coefficient greater than 0.5 are highlighted.

SDI series	TSA	AMM	Niño 1 + 2	ONI	SOI	SS
full	−0.34	−0.23	−0.08	0.06	−0.25	0.34
filtered Nbd	***−0.55***	***−0.67***	0.24	0.43	−0.37	0.00
filtered N11	***−0.72***	***−0.56***	−0.17	0.19	−0.35	***0.55***
filtered N5	−0.23	0.28	0.12	0.11	−0.10	−0.09

N5: fluctuations with periods of 3–7 years (frequencies from 0.14 to 0.33 1/year).
N11: fluctuations with periods of 7–13 years (frequencies from 0.08 to 0.14 1/year).
Nbd: fluctuations with periods of 13–35 years (frequencies from 0.03 to 0.08 1/year).

Finally, the correlation coefficient between the time series of filtered drought indexes (Nbd, N11, N5) and filtered macroclimatic indicators in the same bandwidth was calculated. Then, the series with the best correlations were plotted.

3. Results

In monthly SPI indexes of Río Cuarto station, dominant frequencies about of 1/3 and 1/7 year (0.012 and 0.028 1/month respectively) were found.

The correlation coefficients (CC) between the full and filtered (for three frequency ranges) series of SPI index in Río Cuarto station and the macroclimatic indicators are shown in Table 5 where correlation coefficients greater than 0.5 are in bold type. The negative correlations with the TSA and SOI indicators at the bidecadal level and with the AMM at the decadal level are highlighted, as well as, the positive correlations with the Niño 1 + 2 and SS indicators at the bidecadal level. An example of CC between Sunspots (SS) indicator and SPI index for a bandpass filter of 13–35 years, is shown in Fig. 2.

The previous procedure was applied to SDI (k4) serie of Pueblo Andino station. The dominant frequencies are about 1/7 and 1/13 years (0.08 and 0.14 1/year, respectively).

The correlation coefficients between the full and filtered (for three frequency ranges) series of the SDI index in Pueblo Andino station and the macroclimatic indicators are shown in Table 6 where correlation coefficients greater than 0.5 are in bold type. The negative correlations with the TSA and AMM indicators at the bidecadal and decadal level are highlighted, therefore positive phases of these indicators could be associated with dry hydrological cycles. Also, the positive correlation with SS indicator at the decadal level (Fig. 3) is highlighted.

The proactive approach entails planning necessary measures to prevent or minimize drought impact in advance and it is based on short and long term measures and includes monitoring systems for a timely

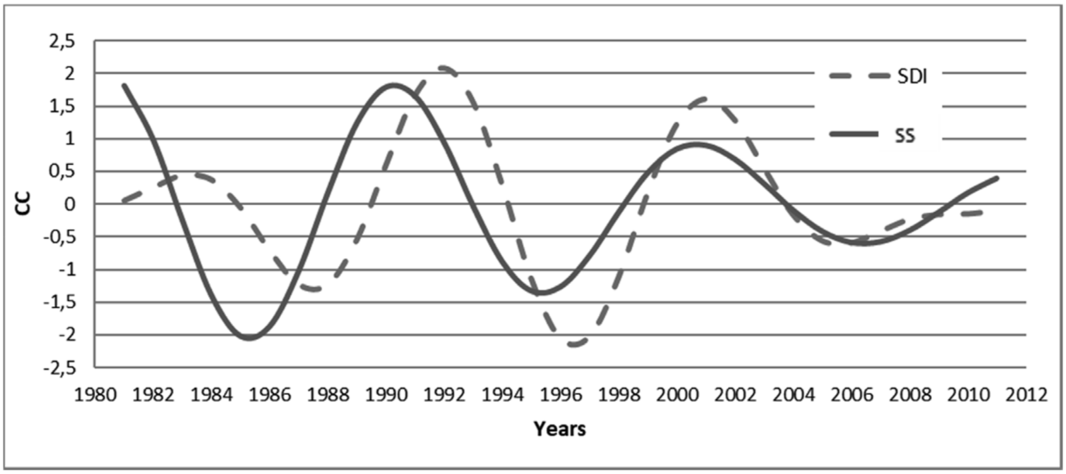

Fig. 3. Standardized SDI index of Pueblo Andino station and SS indicator for band-pass filter 7–13 years.

warning of drought conditions (UNDRR, 2019). In this respect, the drought indexes allow monitoring of local and regional droughts at different time scales, but also from the correlation between series of drought indexes with some macroclimatic indicators, it is possible to have a long term analysis (more than 10 years). For the period N5 (less than a decade) no acceptable correlations were observed.

Using the globalized information of certain macroclimatic indicators would allow the evaluation of future management and planning policies of water resources in regions with scarce hydrometeorological information and would be an important complement to studies about different aspects of droughts.

4. Conclusions

In Carcarañá river basin of Central Region of Argentina, pluriannual periodicities of meteorological (SPI) and hydrological (SDI) droughts indexes were identified with spectral analyzes.

A high correlation between SPI indexes of Río Cuarto station with macroclimatic indicators TSA, SOI, SS and Niño 1 + 2 in bidecadal period and AMM in decadal period, was observed.

A high negative correlation between SDI indexes of Pueblo Andino station and macroclimatic indicators TSA and AMM at decadal and bidecadal level was observed, and a good positive correlation with SS indicator at decadal level, too.

In summary, an important relationship between drought indexes SPI and SDI with macroclimatic indicators of the Atlantic and sunspots in decadal and bidecadal level were observed, in two stations of Carcarañá River basin, but the correlation coefficients were not acceptable for periods less than a decade.

This type of analyzes is recommended to defined long term policies for planning and management of water resources to prevent and mitigate the effects of the extreme hydrological phenomena in a community and its environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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