Weather and Climate Extremes 1 (2013) 51–58

Contents lists available at ScienceDirect

Weather and Climate Extremes

journal homepage: www.elsevier.com/locate/wace

Recent trends and ENSO influence on droughts in Northern Chile: An application of the Standardized Precipitation Evapotranspiration Index ☆

Francisco J. Meza *

Centro Interdisciplinario de Cambio Global, Departamento de Ecosistemas y Medio Ambiente, Pontificia Universidad Católica de Chile, Aquasec, IAI Center of Excellence for Water Security, Av Vicuña Mackenna 4860, Macul, Santiago, Chile

ARTICLE INFO

Article history:
Received 19 January 2013
Received in revised form
16 July 2013
Accepted 17 July 2013
Available online 13 August 2013

Keywords:
Drought index
Dry spell trends
ENSO
Northern Chile

ABSTRACT

Northern and central Chile is one of the driest regions of the Arid-Americas with increasing demands on finite water supplies. The region faces recurrent droughts that cause important economic damages. The need to better monitor drought and study changes in their main properties is important for disaster risk management.

The aim of this work is to apply the Standardized Precipitation Evapotranspiration Index (SPEI) to detect trends of dry periods of different magnitude as well as to describe their association with El Niño phenomenon in the Coquimbo region.

Data shows that dry events are frequent in the region, and that spring and summer show negative trends (i.e. increasing dryness) in most of the stations analyzed. Significant trends for SPEI values are in the order of $-0.05\ \mathrm{yr}^{-1}$. The occurrence of dry conditions of different magnitude has increased over the last decades, and the duration of extreme climatic events has slightly increased as well. These results are consistent with future climatic projections and represent a major challenge for water resources management and the operation of existing reservoirs.

1. Introduction

The provision of water in sufficient quantity, adequate quality and appropriate timing is a necessary condition to ensure a sustainable development and build resilient ecosystems and represents the key element to define water security. Droughts are one of the most important environmental shocks that affect both ecosystem services and economic sectors, causing severe damages and even political instability. Unlike other extreme meteorological events, droughts are characterized by long periods of water scarcity that are triggered either by biophysical or man induced reasons (Paulo et al., 2006).

Under current climate conditions the relevance of droughts as natural disasters is predominant in many parts of the world. However, it is also known that future climate change increases the risk of potential damages, as it is expected that the frequency of extreme events will be affected due to global warming (Kabat et al., 2002; Trenberth et al., 2004).

The magnitude of the costs produced by such events, and the fact that droughts are regional phenomena, justifies the investment in early warning systems to act rapidly and alleviate their impact on society.

For the case of agriculture, it is important to bear in mind that severe water shortages are determined not only by the departure of precipitation from a particular threshold, but also by the intensity with which water is being demanded (evapotranspiration) and the amount of moisture that is available in soils for the growing season. Available soil moisture is the most important variable for the satisfaction of plant water demand. If water in the root zone is insufficient, yield reductions and even total crop failure, are observed. As a regional phenomenon, drought occurrence and intensity are spatially correlated; thus the impacts of agricultural droughts are then rapidly communicated to the regional economy.

A thorough assessment of the severity of droughts in agriculture requires detailed maps of soil texture, distribution of crop types and phenology, and a dense network of meteorological stations. However, soil moisture records are infrequent and/or their spatial coverage is limited. Although some of them can be indirectly obtained using proxy data from satellite images, it is not frequent to have all sources of information with the requested spatial and temporal resolution to analyze the onset of a particular event or to perform a frequency analysis of its main properties.

This is the main reason why meteorologists, hydrologists and agronomists have developed indices that combine hydrometeorological variables to represent the main properties of a

* Tel.: +56 223544137.
E-mail address: fmeza@uc.cl

2212-0947/$ - see front matter © 2013 The Author. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.wace.2013.07.002

drought. The Palmer Drought Severity Index (PDSI) is one of the most commonly used to measure the severity of a drought and to evaluate prolonged periods of wet and dry conditions (Palmer). For the evaluation of short term agricultural droughts Palmer (1968) proposed the Crop Moisture Index (CMI), which focuses on evapotranspiration deficits. However both have some limitations due to large number of parameterizations and the inability to detect droughts for a wider range of time scales (Alley, 1984; Vicente-Serrano et al., 2010).

The Standardized Precipitation Index (SPI) (McKee et al., 1993) is a drought index based on the precipitation amount and applied for periods up to 48 months. Values are transformed into a standard normal distribution with mean zero and variance of one, which facilitates the analysis for the time scales used.

Literature shows other examples and approaches that incorporate Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) and that can be applied for large scale regional analysis with the aid of Geographic Information Systems (Narasimhan and Srinivasan, 2005).

A comparable index is the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010). As the case of the PDSI, this index is also based in a water balance approach but is multiscalar, facilitating drought analysis and monitoring since it allows the user to examine wet and dry periods over different time scales. This index incorporates Potential Evapotranspiration calculated using Thornthwaite's formula (Thornthwaite, 1948), allowing to simultaneously evaluate water supply and plant water demand.

Moreover, Vicente-Serrano et al. (2010) showed that the SPEI was able to characterize recent drought in the arid regions that experienced significant warming over the last century. Thus it becomes an effective tool to assess whether trends in drought events are present.

The primary objective of this paper is to apply the SPEI and study trends of droughts of different magnitudes as well as to describe their association with El Niño phenomenon, a large a scale oceanic atmospheric pattern that is well known to influence the behavior of precipitation in Northern Chile. The underlying hypothesis of this work is that mild and moderate droughts have increased in frequency and duration over the last years, and that are influenced by the different phases of El Niño.

2. Study area and climatology

As many other Mediterranean and semi-arid locations, northern and central Chile (29–35S) is characterized by strong seasonality, with hot and dry summers and winter rains. One of the main controllers of climate in this region corresponds to the strength and position of the South Pacific Anticyclone (SPA). When this semi-permanent high pressure system is displaced towards the south, as it occurs in spring and summer, it blocks westerly frontal systems, producing clear skies and stable conditions. During wintertime the SPA is located towards the north and allows the occurrence of precipitation Garreaud and Aceituno (2002).

The region under study, known as the Coquimbo region, is characterized by a strongly seasonal semi-arid climate. Besides the SPA, the region is also influenced by the cold Humboldt current that runs along the Pacific coast. Four major geographic features are present, and become relevant to understand topoclimatic modifications of regional climate as well as the seasonality of river discharges. These features are the Andes on the east, whose high elevation allow the accumulation of water as snow, the middle mountains on the west (locally known as the “Cordillera de la Costa”), the coastal band and the Transverse Valleys of Elqui, Limarí, and Choapa where most of the agriculture is developed.

Fig. 1 shows the main characteristics of the region under study.

Interannual climate variability strongly affects this region. It is well known that El Niño-Southern Oscillation (ENSO) has a distinguishable footprint on the precipitation regime of the region. During El Niño events, positive rainfall anomalies can be observed, whereas below normal conditions are more likely to occur when the opposite phase is present (Aceituno, 1988; Montecinos and Aceituno, 2003; Pittock, 1980; Quinn and Neal, 1983). Specifically for the region under study, Verbist et al. (2010) showed that a simultaneous ENSO index regressed on May–August total precipitation was able to explain 32% of station variability.

The region, particularly the central valley, is also characterized by an almost permanent presence of clear skies allowing incoming solar radiation to be one of the highest in the country. In addition, the relatively low relative humidity and clear skies result into a significantly high diurnal temperature range. These situations make the evaporative demand of the atmosphere to be quite high, particularly between October and March.

High evaporative demands and variable rains make drought a recurrent phenomenon. Paleoecological records (Maldonado and Villagrán, 2006) show that this region experienced extreme aridity conditions until approximately 5700 cal yr BP. Several records show the existence of alternating wet and dry periods (Jenny et al., 2002; Maldonado and Villagrán, 2002; Villagrán, 1982; Villa-Martínez et al., 2004).

3. Methodology and data

3.1. Climate data

Daily climatic data of precipitation, maximum, and minimum temperature was collected from the Chilean Directorate General of Water (DGA) for five representative stations, whose locations are presented in Fig. 1. Table 1 summarizes the main monthly statistics of these values. The region is characterized by a strong interannual variability. Monthly coefficients of variation can be as high as five times the observed mean in the dry period, and in the same order of magnitude of the average precipitation in the winter season.

The period of record is variable among the stations, some of them have been operating since 1943, whereas others cover a more recent period. This is why most of the analysis is focused on the 1970–2011 period.

3.2. Calculation of monthly totals of precipitation and potential evapotranspiration

The main input variables for the calculation of the SPEI are monthly totals of Precipitation (Pp) and Potential Evapotranspiration (PET). The calculation of potential evapotranspiration was carried out in the following manner:

a) First calculate the extraterrestrial solar radiation (R_{SO}; MJ m^{-2} day^{-1}) as

$$R_{SO} = 37.4[\sin(\phi)\sin(\delta)h_s + \cos(\phi)\cos(\delta)\sin(h_s)] \quad (1)$$

where ϕ corresponds to the latitude of the location, δ is the declination angle, and h_s corresponds to the solar angle at sunrise (sunset).

b) Then calculate the solar global radiation (R_G; MJ m^{-2} day^{-1}) using Allen's equation (Allen, 1997)

$$R_G = 0.17[Tx - Tn]^{0.5} R_{SO} \quad (2)$$

c) Due to the lack of humidity data it is not possible to calculate long wave emissivities of the air and the surface. Therefore, the estimation of net radiation is done under the assumption that air

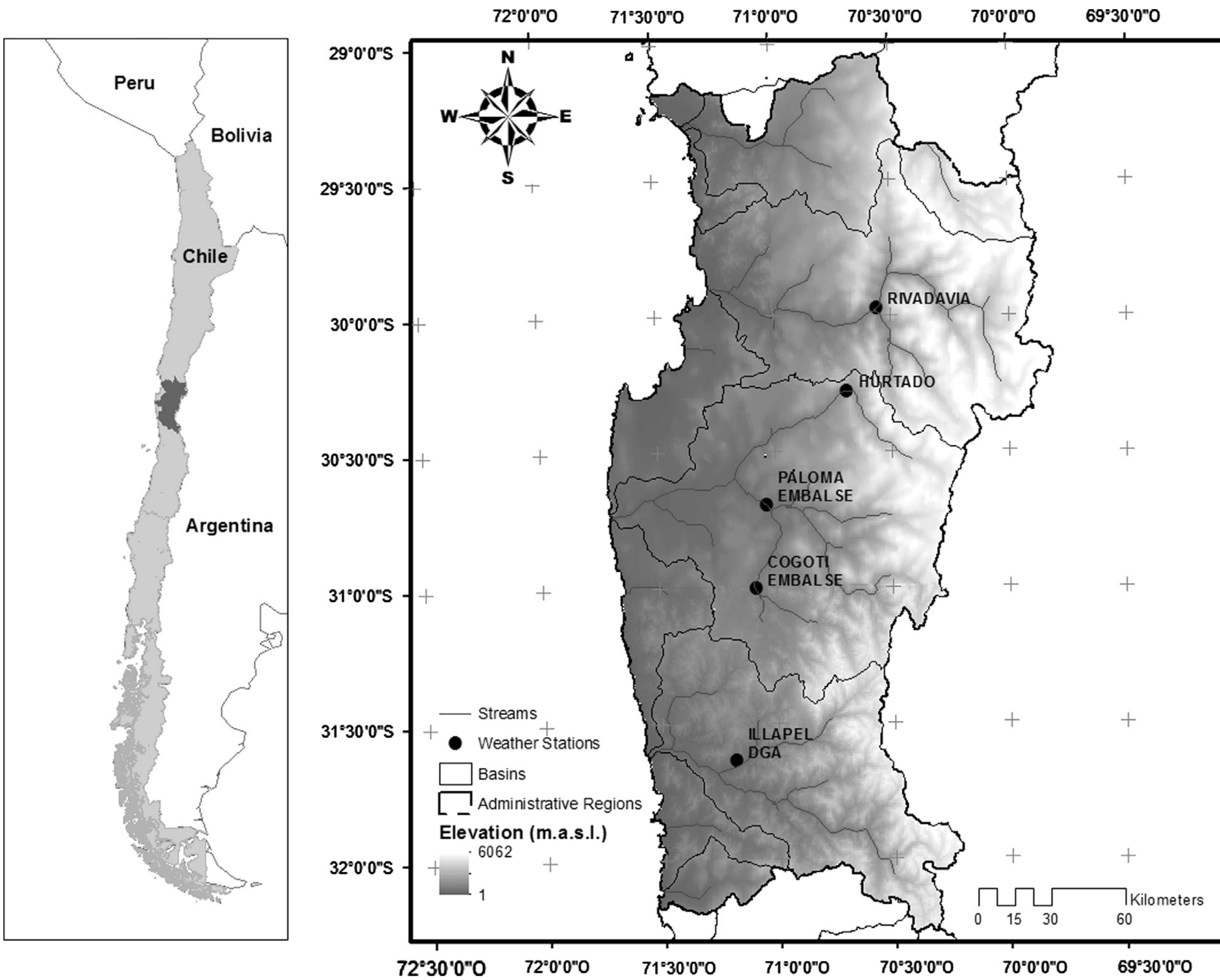

Fig. 1. General characteristics and location of selected stations in the region under study.

Table 1
Mean values of total monthly precipitation (*Pp*) maximum temperature (*Tx*) minimum temperature (*Tn*), and coefficient of variation of monthly precipitation (*CV*).

Location	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cogotí	*Tx*	27.9	27.8	26.5	24.3	21.7	18.9	18.2	19.6	21.3	23.8	25.6	27.1
	Tn	14.3	14.1	12.9	10.5	8.4	6.8	6.1	6.8	7.8	9.7	11.4	13.2
	Pp	1.1	0.4	3.6	15.4	45.6	56.1	66.0	41.1	18.8	9.9	4.3	2.4
	CV	562	649	422	307	190	121	136	126	186	235	449	772
Hurtado	*Tx*	28.3	28.5	27.6	25.2	22.6	20.6	19.8	21.4	22.5	25.2	26.6	27.7
	Tn	12.6	12.6	11.8	9.7	8.0	6.7	5.9	6.5	6.8	8.5	10.1	11.6
	Pp	1.4	9.0	2.7	13.0	25.5	47.6	63.5	30.0	11.9	5.5	4.3	3.1
	CV	599	496	425	242	172	131	171	125	186	211	378	619
Illapel	*Tx*	28.5	28.4	27.0	24.2	21.2	18.6	17.9	18.9	20.8	23.3	25.5	27.3
	Tn	12.2	12.2	11.0	8.7	6.9	5.5	4.9	5.8	7.0	8.1	9.5	11.2
	Pp	1.5	0.1	3.7	11.9	25.2	51.9	64.5	32.1	17.8	9.6	5.4	0.0
	CV	624	608	231	219	112	114	122	117	165	231	317	N/A
La Paloma	*Tx*	29.3	29.0	27.4	24.2	21.1	18.9	18.1	19.7	21.7	24.6	26.5	28.2
	Tn	13.5	13.3	12.2	10.2	8.5	7.0	6.4	7.1	8.0	9.1	10.6	12.2
	Pp	0.9	5.9	6.1	14.9	35.8	46.9	52.8	31.9	15.0	6.3	5.0	3.6
	CV	537	758	514	340	193	126	139	125	209	229	481	741
Rivadavia	*Tx*	29.2	29.1	28.4	26.0	23.6	21.6	21.0	22.4	24.0	26.1	27.5	28.5
	Tn	13.0	12.8	11.8	10.0	8.9	8.0	7.4	8.0	8.6	9.5	10.6	12.0
	Pp	0.3	1.4	4.3	9.7	18.2	34.8	51.1	24.3	10.6	3.9	1.5	3.2
	CV	538	515	392	283	207	139	165	144	201	287	437	682

and surface (i.e. vegetation canopy) have similar emissivities and that they are in thermal equilibrium. Thus one can estimate net radiation as being 80% of solar global radiation. Since SPEI is a standardized value that allows us to compare months and identify drought occurrence, a systematic bias in the estimation of net radiation does not substantially affect the rank of obtained indices.

d) Finally the equation of Priestley–Taylor was applied to estimate Potential Evapotranspiration (PET; kg m^{-2} day^{-1} = mm day^{-1}) at a daily basis. Although the SPEI method uses Thornthwaite equation for PET, no major differences could be expected as Priestley and Taylor equation is also sensitive to temperature.

$$PET = A\frac{\Delta}{\Delta+\gamma}\frac{R_N}{\lambda} \tag{3}$$

With Δ being the slope of the saturation vapor pressure with respect to temperature (kPa C^{-1}), γ is the psicrometric constant (kPa C^{-1}) and λ is the latent heat of vaporization (approximately 2.5 MJ kg^{-1}). The empirical coefficient of this equation ($A=1.1$) was recalibrated to better represent semi-arid conditions.

Values of PET and Pp were aggregated to compute their respective monthly totals. If a month did not contain sufficient data to perform this calculation, its value was replaced by a linear interpolation between the precedent and subsequent month. If two or more consecutive months were missing, the sequence was excluded from the time series.

3.3. Calculation of SPEI

Following the methodology presented by Vicente-Serrano et al. (2010), for each month i, a difference between monthly precipitation and Potential Evapotranspiration was calculated

$$D_i = Pp_i - PET_i \tag{4}$$

Then a Pearson III distribution was fit using L-moments (Hosking, 1990) according to what is described by Singh et al. (1993). The Cumulative distribution function of the variable D is given by

$$F(D) = \left[1+\left(\frac{\alpha}{D-\gamma}\right)^{\beta}\right]^{-1} \tag{5}$$

The final step was to standardize the probabilities using an inverse normal function (Abramowitz and Stegun, 1965; Vicente-Serrano et al., 2010). The average value of each standardized time series is zero, negative values represent drier than normal conditions, whereas positive values correspond to wetter than normal conditions indicate wetter than normal conditions.

Monthly values of SPEI are correlated with ENSO indices for the region 3–4 (EN34). These indices were obtained from NCEP NOAA.

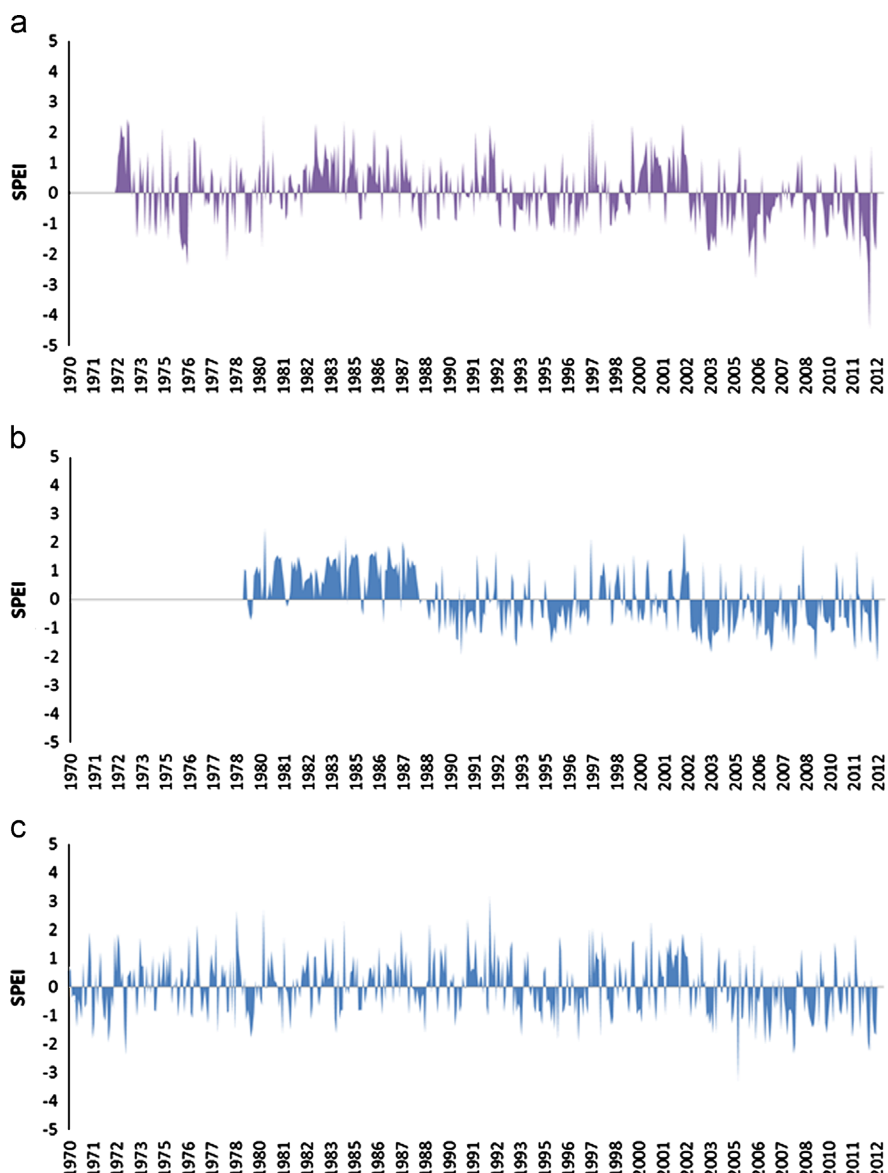

Fig. 2. Time series of monthly values of SPEI for stations of Rivadavia at Elqui Valley (a); Hurtado at Limarí Valley (b); and La Paloma at Limarí Valley (c).

Trend detection for individual months was performed using simple regression analysis on SPEI data (a normalized variable). Generalized linear models were used to analyze the influence of time, and EN34 on different drought properties.

4. Results

Figs. 2 and 3 show the time series of monthly SPEI values for the five stations considered in this study. Data show the presence of alternative dry and wet periods, but with no regular annual shifts. With the exception of La Paloma station, the rest show clearly the dominance of a wet period in the decade of 1980 and the predominance of drier conditions in the last decade. SPEI values fluctuate between a value of $+2$ and -2 in the majority of the occasions. In the Limarí Valley, the station of La Paloma and Cogotí show SPEI values around -3 around year 2003 indicating a severe dry period affecting the Valley.

4.1. Trends and ENSO influence on SPEI values

We studied time trends in SPEI values for each month. Table 2 shows the slope of a regression between monthly SPEI values and year since 1970. Bold values indicate trends that are statistically significant, according to traditional Student *t*-test. Almost all slope values are negative, indicating that there is a trend towards increasing dryness in the valleys. Three stations show values that are statistically significant for spring (October–December) and summer periods (January–March). Illapel station shows significant trends only in two months, whereas La Paloma station does not present trends that can be considered different from zero. A recent paper by Souvignet et al. (2012) shows that the valley has experienced a significant positive trend in temperature and a downward trend in precipitation at centennial scales (a positive trend can be found in recent decades). Since evapotranspiration increases as temperature rises, and considering the reduction in precipitation that can be affecting the last 40–50 years, the observed SPEI values are explained by hotter and drier conditions, and the region is more likely to experience droughts in spring and summer periods.

Drought monitoring indices are usually applied at longer time scales to detect trends at seasonal (6 months), annual (12 months) or even interannual (24 or 48 months) scales. Data was aggregated at 6 and 12 months periods and the trend analysis was repeated. The stations of Cogotí, Hurtado, and Rivadavia showed significant time trends when analyzing 6 month periods (slopes: -0.044; -0.067; -0.047 respectively). At longer time scales (12 months) the trend only remains significant at stations of Hurtado and Rivadavia (slopes: -0.06; -0.05 respectively).

Since this region has a strong seasonality in its precipitation regime, it is difficult to compare SPEI results with other standardized

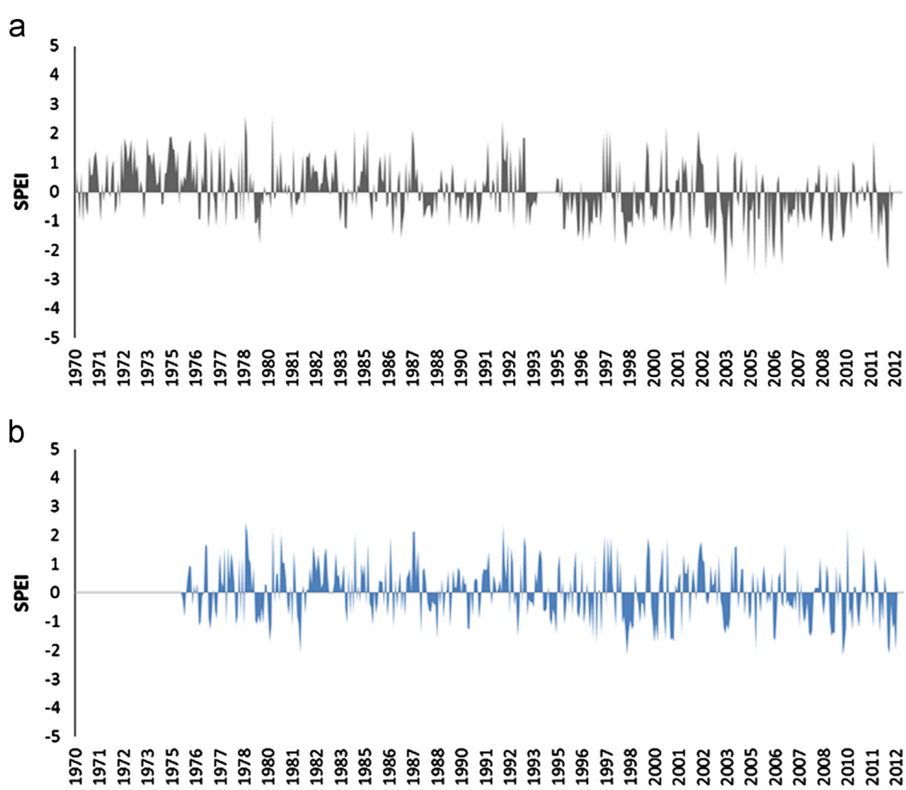

Fig. 3. Time series of monthly values of SPEI for stations of Cogotí at Limarí Valley (d); and Illapel at Choapa Valley (e).

Table 2
Slope values of monthly SPEI (yr^{-1}) for the region under study. Bold values indicate magnitudes that are significantly different from zero.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cogotí	**−0.04**	**−0.05**	**−0.05**	**−0.03**	−0.01	0.01	−0.02	0.00	**−0.03**	**−0.04**	**−0.05**	**−0.05**
Hurtado	**−0.08**	**−0.07**	**−0.07**	**−0.06**	−0.01	0.00	−0.03	−0.02	**−0.05**	**−0.07**	**−0.07**	**−0.08**
Illapel	−0.01	−0.01	**−0.04**	−0.02	−0.02	0.02	−0.03	0.01	−0.01	−0.02	**−0.05**	−0.02
La Paloma	−0.02	−0.01	−0.02	−0.02	0.01	0.01	−0.01	0.01	−0.01	−0.02	−0.02	−0.02
Rivadavia	**−0.04**	**−0.03**	**−0.03**	0.01	0.00	0.00	−0.02	0.00	−0.02	**−0.04**	**−0.03**	**−0.05**

indices based on precipitation only like SPI. This is because the calculation of SPI involves fitting a Gamma distribution function that requires values to be greater than zero. In this region it is quite common to find long periods five and up to seven months where no monthly precipitation is observed. Since SPEI incorporates PET as a variable, even for extreme dry periods (precipitation equal to zero) it will be possible to determine fluctuation in the index due to changes in potential evapotranspiration and re-express them as a Gaussian variable. Thus SPEI can be a better monitoring index for arid and semiarid regions.

Pearson correlation coefficient was calculated for each month between SPEI values and simultaneous EN34 and PDO data. The correlation coefficient (r) has a standard error ($s.e.$) equivalent to

$$s.e. = \sqrt{\frac{1-r^2}{n-2}} \quad (6)$$

The significance of the linear associations between SPEI and El Niño data is evaluated using a Z-test. The null hypothesis is that observed r values are not different from zero.

Fig. 4 shows the seasonal behavior of the correlation coefficient between SPEI and EN34 data for selected stations. Because of the sample size used, values above $+0.3$ and below -0.3 can be classified as significantly different from zero.

As reported by Verbist et al. (2010), the region is under a strong influence of El Niño. It is well known that during warm events precipitation increases. This influences SPEI, reducing the probability of experiencing dry periods. Although Meza (2005) reported influences of El Niño in reference evapotranspiration in a basin located south from the region of the study this effect could be observed here only in summer, whereas most of the influence of ENSO on droughts in is due to the decreases in precipitation associated with La Niña phase.

4.2. Observed trends on dry conditions

The Palmer Drought Severity Index can be used to determine the severity of a drought and to study different properties such as its recurrence (occurrence), duration, and severity. Individual values of the index can be used to assess its intensity (Alley, 1984).

In this case, different SPEI thresholds were used to classify months as under scarcity or not, allowing the study of trends on the occurrence of events below a threshold and their duration. The aim of this exercise is to prove the sensitivity of the occurrence of these events to the independent variables and not to officially declare the presence of drought. That is why the event is referred to as dry conditions.

A threshold of SPEI equal to 0 was first considered for this classification, note that McKee et al. (1993) uses the category of mild drought when SPI values are found in the range 0 to -0.99 for periods of 3 months. Then months were classified as under deficit (1) or above normal (0). With this, SPEI data was transformed into a binary time series that can be analyzed using binomial distribution. Normally, these distributions have only a parameter that is the frequency of occurrence of the event under examination (p). Generalized linear models are used to fit this parameter, allowing it to be dependent on additional variables. Since droughts depend on climatic conditions that show seasonality and often have “memory” the first variable considered was the occurrence of dry conditions in the preceding 1 and 2 months. Then EN34 data and time were added. A stepwise generalized regression that selected models based on the Akaike Information Criterion (AIC) was implemented. Table 3 shows the result of this analysis.

In almost all stations, the occurrence of dry conditions depends on the occurrence of dry conditions in the previous month. Data shows that El Niño event has a negative influence on the occurrence of dry conditions in three of the stations. During warm episodes is less likely to experience values below the selected threshold. Interestingly, a temporal trend can be detected in all stations. In recent years the probability of experiencing a drought has increased.

This analysis can be repeated for more severe dry conditions. To achieve that, the classification of months has to be done using a more negative SPEI value. Similar results were found for dry conditions defined with a -0.5 threshold. However it was found that for the occurrence of dry conditions with SPEI values below -1 and -1.5 the value of the precedent month is less important, the influence of El Niño weakens. Time trends are still present in

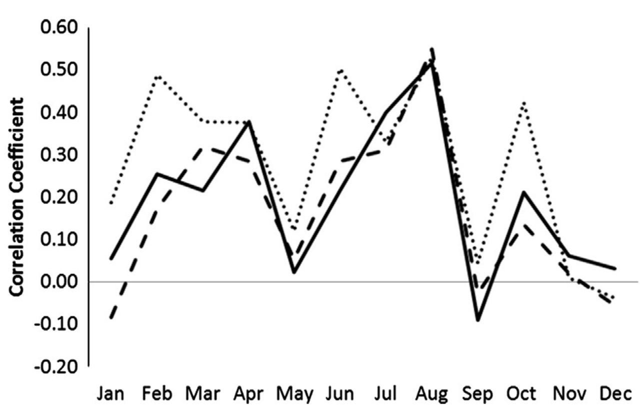

Fig. 4. Monthly correlation values between SPEI and EN34 data. Solid line corresponds to Rivadavia station, dashed line is La Paloma and dotted line is Illapel.

Table 4
Coefficients of a generalized model of the Poisson parameter for dry spell length. Bold values in italics are significant at 0.1% level. Bold values are significant at 1% and regular values are significant at 5%.

	SPEI=0		SPEI=−0.5	
	Intercept	Time	Intercept	Time
Cogotí	−0.309273	***0.028279***	−0.47279	***0.023264***
Hurtado	0.007648	**0.028167**	−0.92515	0.03367
Illapel	−0.352606	**0.023448**	0.61506	
Paloma	0.303462	**0.013382**	−0.6083	
Rivadavia	−0.073884	**0.020014**	−0.153922	0.017066

Table 3
Generalized linear model coefficients for a binomial distribution of the occurrence of dry conditions. Bold values in italics are significant at 0.1% level. Bold values are significant at 1% and regular values are significant at 5%.

	Intercept	Occur. Lag 1	Occur. Lag 2	EN34	Time
Cogotí	−***2.005546***	0.482668	0.41791		***0.036264***
Hurtado	−***5.08461***	***1.7677***			***0.08506***
Illapel	−**1.53953**			−***0.4805***	0.02683
Paloma	−***1.077737***	***0.659451***		−0.253493	0.017114
Rivadavia	−***1.664735***	0.502989		−0.218078	**0.026019**

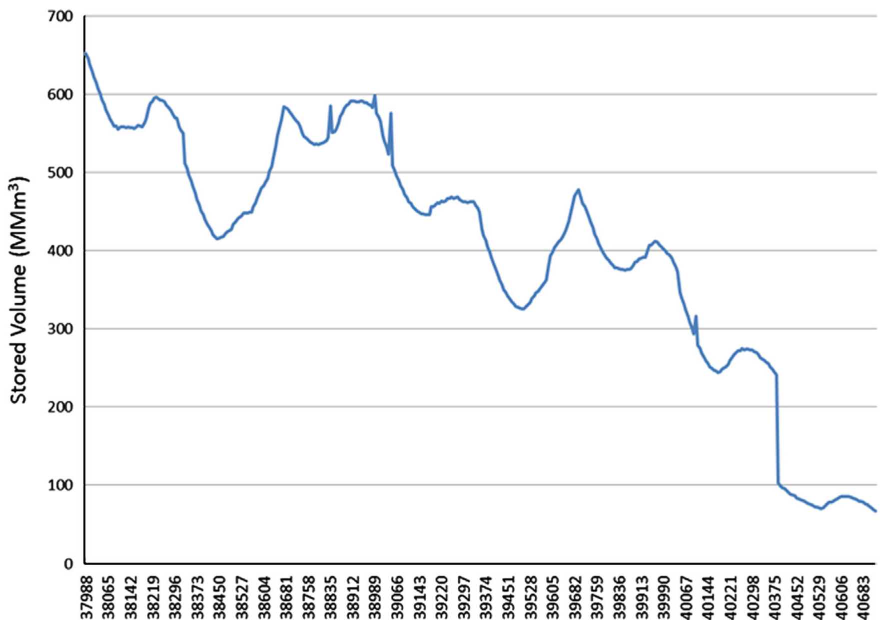

Fig. 5. Changes in stored volume of the Paloma reservoir in recent years.

three of the stations that belong to the Limarí valley (Cogotí, Hurtado and La Paloma).

As in the case of flood frequency analysis, in which a "peak over threshold" is used (Stedinger and Cohn, 1986), for these extreme events it is important to determine the duration once a dry period has occurred. For this analysis a Poisson distribution was assumed, since events were counted in discrete months. In this case, trend detection was be done only on dry periods defined with SPEI values of 0 and -0.5 because not enough data was available as a more severe criterion for drought classification was implemented. Table 4 presents the result of time trends on dry spell duration.

There is a small but significant trend towards increasing dry spell duration in all stations. For more severe threshold values (SPEI$=-0.5$) the trend is present only in three stations (two of them belonging to the Limarí Valley). These values complement and confirm the analysis of Souvignet et al. (2012) and are also consistent with climate change projections for the region Vicuña et al. (2011).

5. Concluding remarks

This analysis evaluated the SPEI index in a semi-arid region of Northern Chile evaluating the presence of temporal trends and the influence of El Niño on several drought properties. It is well known that a weakening (strengthening) in the subtropical anticyclone is observed during El Niño (La Niña) events allowing the displacement (blocking) of frontal storms to more northern locations (Garreaud and Battisti, 1999). As a consequence the El Niño footprint is observed in the occurrence of droughts.

Data shows that extreme dry events are present in the region, and that SPEI values show temporal trends, particularly in the spring summer seasons. These seasons climatologically correspond to the dry period, so detected trends imply that temperature changes are affecting water demand and putting additional pressure over already scarce water resources.

Data also reveals that there is a trend towards increasing drought frequency, particularly in the Limarí Valley, increasing risk of climate extremes. This feature must be considered for disaster risk management strategies since the region presents a wide variety of exposed sectors, ranging from high value crops depending on irrigation to goat shepherds that depend on pasture wet periods for pasture availability. In addition there is a slight trend towards increasing dry spell duration and therefore the magnitude of these extreme events and the economic damages associated are likely to be higher in the future.

This and other studies (Verbist et al., 2010; Souvignet et al., 2012; Stedinger and Cohn, 1986) reveal that the region is facing great challenges to maintain sectorial productivity. Recent years have been slightly below normal in terms of precipitation; however data show a relatively large period of negative SPEI values. Water is already a limiting resource and existing reservoir levels are falling. Fig. 5 illustrates the effects of this consecutive dry period on the levels of Paloma Reservoir. Year by year stored volume is decreasing as the demand for irrigation has to be met to maintain perennial crops.

Most of the agriculture in the region is under irrigation, and therefore it is difficult to correlate SPEI trends with crop yields. Nevertheless when looking at NDVI data (a reasonably good proxy for plant productivity) obtained from MODIS images (data not shown), a slight decreasing trend is observed. This confirms the impact that current hydroclimatic conditions are producing on the region and highlights the relevance of integrated water resources management to effectively deal with changing climate.

Acknowledgments

This work was carried on with the support of the Inter-American Institute for Global Change Research under grant No. SGP-CRA#005 and with the aid of Fondecyt Grant 1110297. The author expresses his gratefulness to Dr. Willem van Leeuwen, Dr. Pablo Alvarez, Eduardo Bustos, and Fidel Maureira for their valuable comments and help during the elaboration of this manuscript.

References

Abramowitz, M., Stegun, I.A., 1965. Handbook of Mathematical Functions, with Formulas, Graphs, and Mathematical Tables. Dover Publications, Mineola, NY, USA, p. 1046.

Aceituno, P., 1988. On the functioning of the Southern Oscillation in the South American sector. Part I: surface climate. Monthly Weather Review 116, 505–524.

Allen, R., 1997. Self-calibrating method for estimating solar radiation from air temperature. Journal of Hydrologic Engineering 2, 56–67.

Alley, W.M., 1984. The Palmer drought severity index: limitations and applications. Journal of Climate and Applied Meteorology 23, 1100–1109.

Garreaud, R., Aceituno, P., 2002. Atmospheric circulation over South America: mean features and variability. In: Young, K. (Ed.), The Physical Geography of South America. Oxford University Press, Oxford, UK.

Garreaud, R.D., Battisti, D.S., 1999. Interannual (ENSO) and interdecadal (ENSO-like) variability in the Southern Hemisphere tropospheric circulation. Journal of Climate 12, 2113–2122.

Hosking, J.R.M., 1990. *L*-moments: analysis and estimation of distributions using linear combinations of order statistics. Journal of the Royal Statistical Society 52B, 105–124.

Jenny, B., Valero-Garcés, B.L., Villa-Martínez, R., Urrutia, R., Geyh, M.A., Veit, H., 2002. Early to mid-holocene aridity in Central Chile and the Southern Westerlies: the Laguna Aculeo record (34°S). Quaternary Reseach 58, 160–170.

Kabat, P., Schulze, R.E., Hellmuth, M.E., Veraart, J.A. (Eds.), 2002. Coping with Impacts of Climate Variability and Climate Change in Water Management: A Scoping Paper. International Secretariat of the Dialogue on Water and Climate, Wageningen.

Maldonado, A., Villagrán, C., 2002. Paleoenvironmental changes in the semiarid coast of Chile (~32°S) during the last 6200 cal years inferred from a swamp-forest pollen record. Quaternary Research 58, 130–138.

Maldonado, A., Villagrán, C., 2006. Climate variability over the last 9900 cal yr BP from a swamp forest pollen record along the semiarid coast of Chile. Quaternary Research 66, 246–258.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales: In: Proceedings of the 8th Conference of Applied Climatology. Anaheim, California, January 17–22, 1993. American Meteorological Society, Boston, MA, pp. 179–184.

Meza, F.J., 2005. Variability of reference evapotranspiration and water demands. Associations to ENSO in the Maipo river basin, Chile. Global and Planetary Change 47 (2–4), 212–220.

Montecinos, A., Aceituno, P., 2003. Seasonality of the ENSO related rainfall variability in central Chile and associated circulation anomalies. Journal of Climate 16, 281–296.

Narasimhan, B., Srinivasan, R., 2005. Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. Agricultural and Forest Meteorology 133 (1–4), 69–88.

Palmer, W.C. Meteorologic drought. U.S. Weather Bureau. Research Paper no. 45, 58 pp.

Palmer, W.C., 1968. Keeping track of crop moisture conditions, nationwide: the new crop moisture index. Weatherwise 21 (4), 156–161.

Paulo, A., A., Pereira, L.S., 2006. Drought concepts and characterization. Water International 31 (1), 37–49.

Pittock, A.B., 1980. Patterns of climatic variation in Argentina and Chile. Part I: precipitation, 1931–1960. Monthly Weather Review 108, 1347–1361.

Quinn, W., Neal, V., 1983. Long-term variations in the Southern Oscillation, El Niño and the Chilean subtropical rainfall. Fishery Bulletin 81, 363–374.

Singh, V.P., Guo, H., Yu, F.X., 1993. Parameter estimation for 3-parameter log-logistic distribution (LLD3) by Pome. Stochastic Hydrology and Hydraulics 7, 163–177.

Souvignet, M., Oyarzún, R., Verbist, K., Gaese, H., Henrich, J., 2012. Hydro-meteorological trends in semi-arid north-central Chile (29–32°S): water resources implications for a fragile Andean region. Hydrological Sciences Journal 57 (3), 479–495.

Stedinger, J.R., Cohn, T.A., 1986. Flood frequency analysis with historical and paleoflood information. Water Resources Research 22, 785–793.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geographical Review 38, 55–94.

Trenberth, K.E., Overpeck, J.T., Solomon, S., 2004. Exploring drought and its implications for the future. Eos, Transactions, American Geophysical Union 85, 27.

Verbist, K., Robertson, A., Cornelis, W.M., Gabriels, D., 2010. Seasonal predictability of daily rainfall characteristics in Central Northern Chile for dry-land management. Journal of Applied Meteorology and Climatology 49, 1928–1955.

Vicente-Serrano, S., Beguería, S., López-Moreno, J., 2010. A multiscalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. Journal of Climate 23, 1696–1718.

Vicuña, S., Garreaud, R., McPhee, J., 2011. Climate change impacts on the hydrology of a snowmelt driven basin in semiarid Chile. Climatic Change 105, 469–488.

Villa-Martínez, R., Villagrán, C., Jenny, B., 2004. Pollen evidence for late-Holocene climatic variability at Laguna de Aculeo, Central Chile (lat. 34°S). The Holocene 14, 361–367.

Villagrán, C., 1982. Estructura floristica e historia del bosque pantanoso de Quintero (Chile, V Región) y su relación con las comunidades relictuales de Chile Central y Norte Chico. Actas del III Congreso Geológico 3, 377–402.