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On the use of Standardized Drought Indices under decadal climate variability: Critical assessment and drought policy implications

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SUMMARY

Since the recent High Level Meeting on National Drought Policy held in Geneva in 2013, a greater concern about the creation and adaptation of national drought monitoring systems is expected. Consequently, backed by international recommendations, the use of Standardized Drought Indices (SDI), such as the Standardized Precipitation Index (SPI), as an operational basis of drought monitoring systems has been increasing in many parts of the world. Recommendations for the use of the SPI, and consequently, those indices that share its properties, do not take into account the limitations that this type of index can exhibit under the influence of multidecadal climate variability. These limitations are fundamentally related to the lack of consistency among the operational definition expressed by this type of index, the conceptual definition with which it is associated and the political definition it supports. Furthermore, the limitations found are not overcome by the recommendations for their application. This conclusion is supported by the long-term study of the Standardized Streamflow Index (SSI) in the arid north-central region of Chile, under the influence of multidecadal climate variability. The implications of the findings of the study are discussed with regard to their link to aspects of drought policy in the cases of Australia, the United States and Chile.

1. Introduction and study objective

Drought is one of the most widespread natural hazards in the world which, in conjunction with the societal vulnerability of the affected regions, has become the most significant natural disaster in terms of famines, human death and worldwide economic loss (Speranza et al., 2008; Sheffield and Wood, 2011). Thus, for the first time in history, a major international effort has recently been made to reach a political consensus that will allow this global scourge to be addressed (UNCCD-FAO-WMO, 2012a). Scientific knowledge, meanwhile, has advanced significantly in recent decades in the characterization, quantification, monitoring and economic assessment of droughts, as well as in the development of models for managing and adapting to it which are incorporated into public policies to combat it. However, in spite of these scientific advances and the social, economic and environmental impact of drought on a global level, only one country, Australia, has made systematic efforts to create, apply, and constantly reevaluate a National Drought Policy (White and Karssies, 1999; Botterill and Hayes, 2012; Kiem and Austin, 2013).

It is expected that the international effort already underway will spur a global push for the creation of national drought policies, along with a strengthening of scientific knowledge for designing and evaluating drought monitoring and early alert systems that provide operational support to these policies. With respect to these systems, drought monitoring and early warning systems have in large part have been based on the creation of Drought Indices (DI), of which the Standardized Precipitation Index (SPI) – a member of the Standardized Drought Indices (SDI) family – is the most important representative at the international level. Its purpose, as with the rest of the DI, is to provide an early alert of the occurrence of this silent, progressive, and pervasive disaster (Redmond, 2002;

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Sheffield and Wood, 2011). In this context, climate change and especially natural multidecadal climatic variability impose a great challenge to the creation, evaluation, selection and adoption of SDI. A particular challenge is assuring the existence of consistency, understood as the ability to be asserted together without contradiction (Merriam-Webster, 2013), among the conceptual definition that sustains SDI, the operational definition that they express and the political definition that they support (Smakhtin and Schipper, 2008; Botterill and Hayes, 2012). In this sense, the conceptual definition is understood as that which is expressed in general terms while the operational definition is that which allows to measure – by means of the selected Drought Index – the beginning, end and severity of the drought to be identified (Smakhtin and Schipper, 2008; WMO, 2005). Meanwhile the political definition is understood in terms of an explicitly stated declaration in a regulation that establishes when the event exists for the State and is linked to a public response, which is consistent with the term "legal definition" of drought suggested by López-Barrero and Iglesias (2009, p. 22) or the "legal concept" noted by the La Calle (2009, p. 48). Consistency among these definitions is considered to be of the utmost relevance in this work since the very ambiguity of the concept of drought constitutes one of the main obstacles to the creation of drought policies (Smakhtin and Schipper, 2008; La Calle, 2009; Whitney, 2013).

Thus, this work aims to analyze the applicability of the Standardized Streamflow Index (SSI), (Vicente-Serrano et al., 2012) as a natural extension of the SPI, to hydrological droughts, in the context of multidecadal climate variability and its relationship with international recommendations for the appropriate use of SDI. Thus, the work is structured in the following way: In Section 1, a background of drought in the world and international initiatives to fight it is given, DI are presented with an emphasis on SDI, and the properties, advantages and limits of SPI are reviewed. It concludes with the role of multidecadal climate variability in drought occurrence and the potential effects of the appropriate use of SDI. In Section 2, a case study that supports this work is presented and justified, and the analysis methods used are detailed. In Section 3, the results related to the effect of record length and reference period on the distributional properties and recurrence of drought events estimated by the SSI are presented. The work concludes with Section 4, with a discussion of the results and an analysis of their implications in drought policy in representative cases at the international level.

1.1. Drought and international initiatives to fight it

Drought has been, is and will very likely continue to be one of the most significant natural disasters affecting society and the environment in a large part of the world. In spite of the controversy that exists as to the occurrence and projections of drought frequency at the global level (Dai, 2012; Sheffield et al., 2012), an objective fact is that this hydrometeorological phemonenon caused more than half of the deaths associated with natural disasters in the twentieth century and was, after floods, the natural disaster that affected the greatest number of people, with a direct global cost of more than 80 billion dollars (Below et al., 2007; Sheffield and Wood, 2011). Although it is recognized that drought affects virtually every climate regime (Wilhite and Buchanan-Smith, 2005), the drylands of the earth, which cover 41% of the surface of the planet and sustain the lives of 35% of the global population, with one of the highest poverty rates (45%), are the most seriously affected (Toni and Holanda, 2008; Speranza et al., 2008; Sheffield and Wood, 2011; FAO et al., 2011). The impact of drought in the arid and semiarid regions of the world, within the drylands, is precisely what has motivated the primary international efforts against it. For example, the droughts that occurred in sub-Saharan Africa spurred the creation of the United Nations Sudano-Sahelian Office (UNSO) in 1973 (Stringer, 2008). In 1991–92, UNSO assisted countries under its jurisdiction in the Sudano-Sahelian region to prepare for the United Nations Conference on Environment and Development (UNCED). This was an intermediate step that contributed to the subsequent creation in 1994 of the United Nations Convention to Combat Desertification (UNCCD) which, although it has focused on desertification as a fundamental global problem, has also included drought as a relevant component (UNDP, 2013). At present and again making reference to the droughts that are significantly impacting in the Horn of Africa and the Sahel, an international effort to cope with the global impacts of drought has been organized. This effort is the High Level Meeting on National Drought Policy (HMNDP), coordinated by the United Nations Convention to Combat Desertification (UNCCD), the Food and Agriculture Organization (FAO) and the World Meteorological Organization (WMO) (UNCCD-FAO-WMO, 2012a) and held in Geneva in March, 2013.

The HMNDP has been convened to initiate a dialogue for the creation and adoption of national drought policies at the global level. The scientific purpose of this initiative comprises 39 elements, associated with the following five spheres of activity, (UNCCD-FAO-WMO, 2012b):

(a) Promoting standard approaches to vulnerability and impact assessment.
(b) Implementing effective drought monitoring and early warning systems.
(c) Enhancing preparedness and mitigation actions.
(d) Implementing emergency response and recovery measures that reinforce national drought management policy goals.
(e) Understanding the cost of inaction.

Along with the proposal, a ten-step planning process which has been a key tool in providing guidance in the development of drought preparedness and mitigation plans is presented. Step 7 of the planning process refers explicitly to "*Integrating science and policy aspects of drought management*", a topic directly related to the present work (UNCCD-FAO-WMO, 2012b, p. 11).

1.2. Drought indices as a tool for supporting drought policies

As mentioned in Section 1.1, using effective monitoring and early warning systems is a fundamental component in a drought policy, since these systems allow responses to and management of drought to be improved (Botterill and Hayes, 2012). As of the Declaration of the Heads of State and Government, drafted during the HMNDP, an increase can be expected in the global dissemination and adoption of national drought monitoring systems and, especially, the adoption of Drought Indices and drought triggers, which are the basis of drought management plans (Steinemann and Cavalcanti, 2006; Zargar et al., 2011; Botterill and Hayes, 2012). In this context, there have been great advances in the last two decades in the creation and design of DI for drought monitoring in their various forms of expression (Keyantash and Dracup, 2002; Heim, 2002; Quiring, 2009; Zargar et al., 2011). From the wide range of available DI, the SPI has been recognized as one of the most appropriate for drought monitoring, and is the most globally widespread DI at both the research and operative levels, even though it is surpassed in its attributes by the rainfall deciles method, which is widely used in Australia. The SPI belongs to the probability-based SDI family, all of which are sensitive to factors and assumptions that govern probabilistic hydrology (Hosking and Wallis, 1997). This family includes, in addition to the SPI, the Standardized Precipitation Evapotranspiration Index (SPEI) for meteorological drought, the Standardized Runoff Index (SRI) and the Standardized Streamflow Index (SSI) – evaluated in this work – for hydrological drought monitoring and the Standardized Growndwater Index (SGI) in the case of groundwater (Shukla and Wood, 2008; Vicente-Serrano et al., 2010; Vicente-Serrano et al., 2012; Bloomfield and Marchant, 2013). Recently, a standardized alternative to the Palmer Drought Severity Index, one of the oldest and most recognized drought indices in the world, has even been proposed, illustrating the increasing interest in SDI as tools for drought monitoring and management (Sheffield et al., 2012; Dai, 2012; Ma et al., 2013).

Although complete details of SDI calculation procedures can be found in other works (Lloyd-Hughes and Saunders, 2002; Vicente-Serrano et al., 2010; Vicente-Serrano et al., 2012), that which is common to the calculation of different SDI, including the SSI evaluated in this study, are summarized hereafter.

SDI are simply the transformation of time series of the hydrological variable of interest to a standardized normal distribution. SDI are computed by adjusting a probability density function to the frequency distribution of the analyzed variable, added to different time scales of interest (Lloyd-Hughes and Saunders, 2002). This is calculated separately for each month, time scale and place. Each adjusted probability density function is then transformed into a standardized normal distribution for which it is common to use a numerical approximation (Vicente-Serrano et al., 2010). Finally, the standardized value is interpreted in the context of a set of anomaly categories that define how wet or dry the event is with respect to normal conditions, for the available historical records. The equations that describe SDI are the following:

$$Z = \mathrm{SDI} = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad \text{for} \quad 0 < \mathrm{H}(x) < 0.5 \tag{1}$$

$$Z = \mathrm{SDI} = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad \text{for} \quad 0.5 < \mathrm{H}(x) < 1 \tag{2}$$

where,

$$t = \sqrt{\ln\left[\frac{1}{(\mathrm{H}(x))^2}\right]} \quad \text{for} \quad 0 < \mathrm{H}(x) < 0.5 \tag{3}$$

$$t = \sqrt{\ln\left[\frac{1}{1 - (H(x))^2}\right]} \quad \text{for} \quad 0.5 < \mathrm{H}(x) < 1 \tag{4}$$

and $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$, x is the variable to analyze for the time scale, month and place of interest and $\mathrm{H}(x)$ is the accumulated probability obtained for x from the probability distribution of best fit.

The recognition given to the SPI, as the main example of SDI, has recently led an expert panel to recommend to national meteorological and hydrological services that it be adopted as a universal meteorological drought index, and to request that the WMO take the necessary measures to implement this recommendation (Hayes et al., 2011). This request has already been responded to (WMO, 2012) and it is expected that in many parts of the world, drought monitoring based on SPI – as well as other indices in the SDI family – will constitute an important tool for putting the drought policies suggested by the HMNDP into place. In fact, the SPI is a key index of the US Drought Monitor in the United States (Svoboda et al., 2002) and recently has been integrated into official drought management plans in countries such as Mexico and Chile, and recommended to a series of Mediterranean countries by the Mediterranean Drought Preparedness and Mitigation (MEDROPLAN), to name a few examples (DGA, 2012; SEMARNAT-IMTA, 2013).

1.3. Recognized advantages and limitations of the SPI

The advantages that have promoted the global acceptance of the SPI have been outlined in a series of works (Guttman, 1999; Hayes et al., 1999; Keyantash and Dracup, 2002, Heim, 2002; Wu et al., 2007; Quiring, 2009; Mishra and Singh, 2010).

However, various limitations associated with the calculation and use of the SPI have also been noted, the majority of which stem from the probabilistic nature of the index, like record length, record period and probability model used in the distributional adjustment described in Section 1.2 (Agnew, 2000; Blain et al., 2009; Hayes et al., 1999; Redmon, 2002; Mishra and Singh, 2010).

The sensitivity of the SPI to record length has been demonstrated by Wu et al. (2005). WMO (2012) recommends a minimum record length of 20–30 years for the calculation of the SPI and the preference for records of greater length, consistent with the assumption that the root mean square error of the estimated quantiles decreases linearly with the square root of the sample size (Guttman, 1994; Hosking and Wallis, 1997). In the case of the reference period, its effect has been indicated by Agnew (2000) and Blain et al. (2009), demonstrating the sensitivity of the SPI to this factor.

Regarding the probability distribution model, there are two relevant aspects to consider: the probability model selected and the procedure used in the estimation of its parameters. In the first case, there has been a trend of moving from the use of two-parameter Gamma distribution, as part of the conventional calculation of the SPI (McKee, 1993), to the use of generalized three-parameter probability models, which is currently recommended, even as the selection of the model of best fit in the calculation of the SDI remains a challenge to its application in arid zones (Guttman, 1999; Wu et al., 2007; Vicente-Serrano et al., 2010; Pietzsch and Bissolli, 2011; Vicente-Serrano et al., 2012; Stagge et al., 2013).

With respect to the method of estimating the distribution parameters, the SPI uses the maximum likelihood procedure. However, due to the limitations of this method for small samples and advances in the development of new procedures, new adjustment method designs for the SDI have emerged (McKee et al., 1993; Edwards and McKee, 1997; Giles and Feng, 2009). Among them, the L-moments method has been more and more adopted for estimating parameters of the SDI due to its demonstrated superiority relative to other probabilistic adjustment methods in hydrology (Hosking, 1990; Hosking and Wallis, 1997; Vicente-Serrano et al., 2010; Vicente-Serrano et al., 2012; Eslamian et al., 2012; McRoberts and Nielsen-Gammon, 2012; Lorenzo-LaCruz et al., 2013). In a similar way, the regional frequency analysis approach based on L-moments has also demonstrated its superiority with respect to conventional at-site distribution adjustment methods, which are commonly used in the calculation of SDI (Hosking and Wallis, 1997). However, even when there are recommendations for its use in the calculation of the SPI (Faergemann, 2012), it has not been routinely implemented, even though various works have reported on its application in the study of meteorological droughts, particularly in arid regions (Núñez et al., 2011, Eslamian et al., 2012; McRoberts and Nielsen-Gammon, 2012).

1.4. Droughts in the context of multidecadal climate variability

Although various studies have attributed the severity and duration of the droughts of recent decades to global warming (Burke et al., 2006; Sheffield and Wood, 2008) and a debate has been opened on their recurrence and severity during the 20th century and the beginning of the 21st (Dai, 2012; Sheffield et al., 2012), some authors attribute an increasingly significant role in this recurrence and severity to natural climate variability, especially of the multidecadal type (Cai et al., 2010; Kiem and Austin, 2013). This can be explained by the importance of internal climate variability in uncertainty analyses of projections based on global climate models, especially for hydrological variables (Deser et al., 2012a). Thus, natural climate variability will continue to be an important aspect of future regional climate and the occurrence, severity and frequency of droughts, even in the presence of long-term secular changes (Sheffield and Wood, 2011; Deser et al., 2012b). This evidence, therefore, imposes the need to evaluate the temporal statistical properties of SDI against the occurrence of these natural climate variability modes (Redmond, 2002). It is widely recognized that a major ocean–atmosphere driver that determines, on a global scale, the interannual variability of hydrological variables is the El Niño Southern Oscillation (ENSO). At the same time, there is a growing consensus on the existence of other sea surface temperature patterns, such as the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO), acting as forcings of variability of the hydrological system and drought recurrence in decadal or even larger time scales (Sheffield and Wood, 2011). Various studies have shown the influence of multidecadal climate variability modes on, and their associations with, hydrology and drought recurrence in different parts of the world. For the purposes of this work, those found in the western United States (Goodrich, 2007; Timilsena et al., 2009), Mexico and Central America (Méndez and Magaña, 2010) and north-central Chile (Núñez et al., 2013) are addressed, although it is recognized that the effects of multidecadal climate variability are of a global scale, with some regions more sensitive than others to these changes (Sheffield and Wood, 2011). In these cases, the international promotion of SDI should be complemented with recommendations for a complete evaluation of their statistical properties against the most plausible scenarios of local climate variability, as an integral part of their adoption process by national meteorological and hydrological services.

Thus, the main objective of this study is to analyze the effect that multidecadal climate variability has on the applicability of SSI (Vicente-Serrano et al., 2012; Lorenzo-Lacruz et al., 2013), as an example of the application of SDI on hydrological droughts, according to international recommendations on record length and reference period used in the calculation. The measurement used to judge the applicability of the SSI is related to the Drought Declaration Recurrence estimated by the index, as an expression of its operational definition, and its consistency with the conceptual definition of drought it is associated with and the political definition it supports.

2. Case study: hydrological drought in the north-central region of Chile

2.1. Case study justification

As a case study, hydrological drought in the north-central region of Chile is analyzed. This case study is justified because (a) hydrological droughts, associated with human water use, are increasingly more important and especially relevant in a large part of the arid regions of the world with mountainous areas, of which the area of study is representative (Sheffield and Wood, 2011; FAO et al., 2011), (b) the study area, as well as others recognized for their vulnerability to multidecadal climate variability such as western North America and northwestern Mexico, are experiencing extreme droughts, the monitoring and management of which are supported by the use of SDI to trigger public responses (Svoboda et al., 2002; SEMARNAT-IMTA, 2013; DGA,2012) and (c) it has recently been demonstrated that in the study area, snowmelt-driven streamflows at the stream gauge stations used for official drought monitoring in Chile exhibit multidecadal variability associated with the Pacific Decadal Oscillation (Núñez et al., 2013).

2.2. Study area and data sources

The case study is located in north-central Chile, between 29.5–34° S latitude and 70°–71° W longitude, and covers an area of ca. 72379 km^2. According to Verbist et al. (2006) this area spans the arid regions at its northern boundary, with 9–10 dry months per year, through the semi-arid regions on the southern boundary, with 7–8 dry months per-year. Elevation ranges from sea level to 6206 m at the highest part of the Andes Cordillera over very short distances (e.g. 250 km). Mean annual precipitation shows both a north–south and an east–west gradient, with a minimum of 51 mm of annual precipitation in the far north and a maximum of 680 mm at the southern edge of the study area. The snowmelt-driven streamflows, which have their source in the Andes Cordillera, exhibit strong seasonality, with maximum values in southern spring (October, November and December), and are the main source of water for economic, social and environmental activities in this region of the country (Núñez et al., 2013).

Six stream gauge stations with monthly records were available, with data provided by the General Water Directorate of Chile and the Maipo River Canal Water Users Association. The stream gauge stations and their location characteristics are presented in Table 1. The available record period spans 93 years, between January 1914 and December 2006.

2.3. Methods

2.3.1. Calculation of distributional properties

The accumulated streamflow series were calculated in three consecutive months (CS-3ijk) where CS-3 is the time series of accumulated streamflows in 3 months for i = record length (10, 20,. . ., 80), j = month (Jan, Feb, . . ., Dec) and k = stream gauge station.

For each CS-3ijk series, its L-moment ratios were determined (L-CV, L-Skewness and L-Kurtosis) as representative estimators of the form of the probability distribution of the series (Hosking, 1990; Hosking and Wallis, 1997) and the probability model of best fit based on the Z|DIST| statistic was selected (Hosking and Wallis, 1997). The probability models tested were the three-parameter Generalized Extreme Value (GEV), Generalized Normal (GNO), Generalized Pareto (PAR), Pearson Type III (PE3), and Generalized Logistic (GLO) models (Hosking and Wallis, 1997). Finally, for each month and station the model of best fit (from among the Exponential, Lin-

Table 1
Descriptive statistics of the stations used in this study.

ID	Station name	Abbreviation	Lat (°S)	Lon (°W)	Height (m.a.s.l.)	Annual mean value (m^3/s)
			Stream gauge			
a	Río Turbio en Varillar[a]	RTV	29.95	70.53	860	8.16
b	Río Claro en Rivadavia[a]	RCR	29.98	70.55	820	4.65
c	Río Elqui en Almendral[a]	REA	29.98	70.90	395	12.98
d	Río Hurtado en Angostura Pangue[a]	RHAP	30.44	71.00	485	3.57
e	Río Choapa en Puente Negro[a]	RCHPN	31.69	71.27	200	13.34
f	Río Maipo en la Obra[b]	RMELO	33.59	70.47	776	102.98

[a] Provided by the Chilean General Water Directorate.
[b] Provided by the Maipo River Canal Water Users Association.

ear, Logarithmic and 2nd Degree Polynomial models), the equation of best fit and R2 of the relation between record length and L-Skewness (L-Kurtosis) were determined in order to confirm the assumption that the properties of the distribution model tend to stabilize as the record length increase. Only these two L-moment ratios were considered because they are regularly used in the selection of the probability model of best fit, both graphically and statistically (Hosking and Wallis, 1997; Guttman, 1999; Vicente-Serrano et al., 2012).

2.3.2. Calculation of the SSI for 3 months (SSI-3) according to reference period

For each month, station, and reference period, the SSI of 3 consecutive months (SSI-3) was calculated using the L-moments method for parameter adjustment (Vicente-Serrano et al., 2012). SSI-3 was calculated for the entire record period (1914–2006) using four reference periods (RP-I:1914–2006, RP-II: 1971–2000, RP-III:1944–1976 and RP-IV:1977–2000). RP-1 corresponds to the case of conventional SPI calculation where the reference period coincides with the record period. RP-II uses a standard reference period (Faergemann, 2012) and RP-III and RP-IV are reference periods consistent with the recent phases of PDO cool and PDO warm, respectively (Núñez et al., 2013). GLO distribution was used to adjust the SSI-3 series, since it was the most appropriate and flexible, in prior tests, for adjusting 12 monthly series with only one distribution, similar to the results of comparable studies (Vicente-Serrano et al., 2012).

2.3.3. Drought declaration

For official drought declaration, the political definition of Chile was used, which states that drought occurs when "average monthly streamflows of the last 3 consecutive months have a drought indicator of less than −0.84" (DGA, 2012, p. 2).

2.3.4. Structural stability analysis of the SSI-3 series

For each station, using the entire record period (1914–2006), the structural stability, understood as the constancy of the regression coefficients in the linear regression model of the SSI-3 Series with respect to time, was analyzed using the OLS-CUSUM type generalized empirical fluctuation test (Ploberger et al., 1989; Zeileis et al., 2002).

2.3.5. Modified standardized streamflow index (MSSI-3)

An alternative form of the SSI called the modified standardized streamflow index was proposed, in which decadal and long-term variability modes were extracted. From here, the MSSI-3 was calculated in a manner similar to the SSI-3. This MSSI-3 time series was created by decomposing the original monthly streamflow time series using the Ensemble Empirical Mode Decomposition procedure (EEMD) (Wu and Huang, 2009; Núñez et al., 2013), extracting the decadal and long-term oscillation modes from the decomposed series, reconstructing the streamflow series with only the subdecadal oscillation modes and finally, calculating the SSI-3 with the reconstructed streamflow series.

3. Findings

3.1. Effect of record length

Fig. 1 shows the L-Skewness and L-Kurtosis values of the CS-3 time series for each month and stream gauge station. The general pattern was that (a) lower L-Skewness (L-Kurtosis) values for 30 or 80 years of record length and greater values for 50–60 years occurred, (b) the L-moments ratios were lower in southern autumn–winter (JJA) and greater in spring-summer (ONDJF) and (c) this general pattern was more characteristic in stations located at lower latitudes (more arid) and less evident in the Rio Choapa en Puente Negro and Rio Maipo en la Obra stations, both of which are located at higher latitudes (less arid). Both L-moment ratios exhibited a parabolic relationship to record length which is inconsistent with the expected asymptotic association (Guttman, 1994; Hosking and Wallis, 1997). This parabolic relationship was confirmed by the evaluation of the models of best fit between L-Skewness (L-Kurtosis) and record length, for each station and month of the year. In each case, the model of best fit was a 2nd degree polynomial with a negative slope, with an average annual R^2 of 0.71 and 0.59 for L-Skewness and L-Kurtosis, respectively. Likewise, the probability model of best fit varied according to record length and did not stabilize with increases in sample size. This implies that, under the influence of multidecadal climate variability associated with the PDO (Núñez et al., 2013), the use of records of greater length does not produce stability in the statistical properties of the distribution model, as is expected of the recommendations for the use of this type of drought index (Guttman, 1999; WMO, 2012).

3.2. Effect of reference period

Fig. 2 presents the historical SSI-3 series. The figure shows that the occurrences of wet (blue) and dry (red) periods are distinct in the 6 stations, according to reference period used in the calculation of the SSI-3. This effect is similar to that found in other studies in the case of the SPI (Agnew, 2000; Blain et al., 2009). Table 2 shows the effect of reference period on the Drought Declaration Recurrence (DDR = percentage of time in which SSI-3 < −0.84) and Dryness Condition Recurrence (DCR = percentage of the time in which SSI-3 < 0) for three periods of interest (Conv = Conventional, PDOC = PDO cool and PDOW = PDO warm). The threshold value (SSI-3 = −0.84) proposed by the Chilean policy is based on the assumption that the value is associated with a DDR of 20%, equivalent to a probability of 0.2 or a five-year return period, validated in Chile on a database associated with the period 1976–2006 (DICTUC, 2009). For RP-IV and PDOW, similar to the record period used to draft the Chilean policy, the average DDR of the 6 stations (Average = 20%) was equivalent to that expected by the Chilean policy. In the long term, this value is similar to that obtained for RP-I and Conv (Average = 21%) estimated with an extensive record length and somewhat greater than that obtained for PR-II and Conv (Average = 17%) if an approach based on standard reference period is used. In these three cases, the estimated DDR is close to that expected by the policy. However, when specific periods of interest associated with recent phases of the PDO are analyzed, significant differences of magnitude of DDR are observed. For RP-IV and PDOC, for example, the average DDR is almost twice (Average = 38%) that which was expected, with a maximum value of 49% (St. Rio Elqui en Almendral). This DDR is associated with a return period of approximately 2 years. A similar result occurs for RP-I and PDOC, where the average DDR is almost double (38%) the estimated DDR for PDOW and Conv, equivalent to a return period of 2–3 years. In terms of dryness, for RP-IV and PDOC, the DCR is close to 80% (Average = 78%). Only when RP-III, characterized by the occurrence of the lowest streamflows of the whole series, is used, does DCR exhibit lower values for Conv (Average = 36%) and PDOW (Average = 30%), though it is greater for PDOC (Average = 53%). These results demonstrate that, in conditions of PDO cool, using reference periods that include phases associated with PDO warm, DDR equivalent to a return period of 2 years or DCR around 80% can be obtained. These values can be interpreted as permanent or long-term droughts, which would not be appropriate given that it contradicts the conceptual definition of drought, understood as a phenomenon of temporary nature (Wilhite and Buchanan-Smith, 2005; Smakhtin and Schipper, 2008; Strosser et al., 2012).

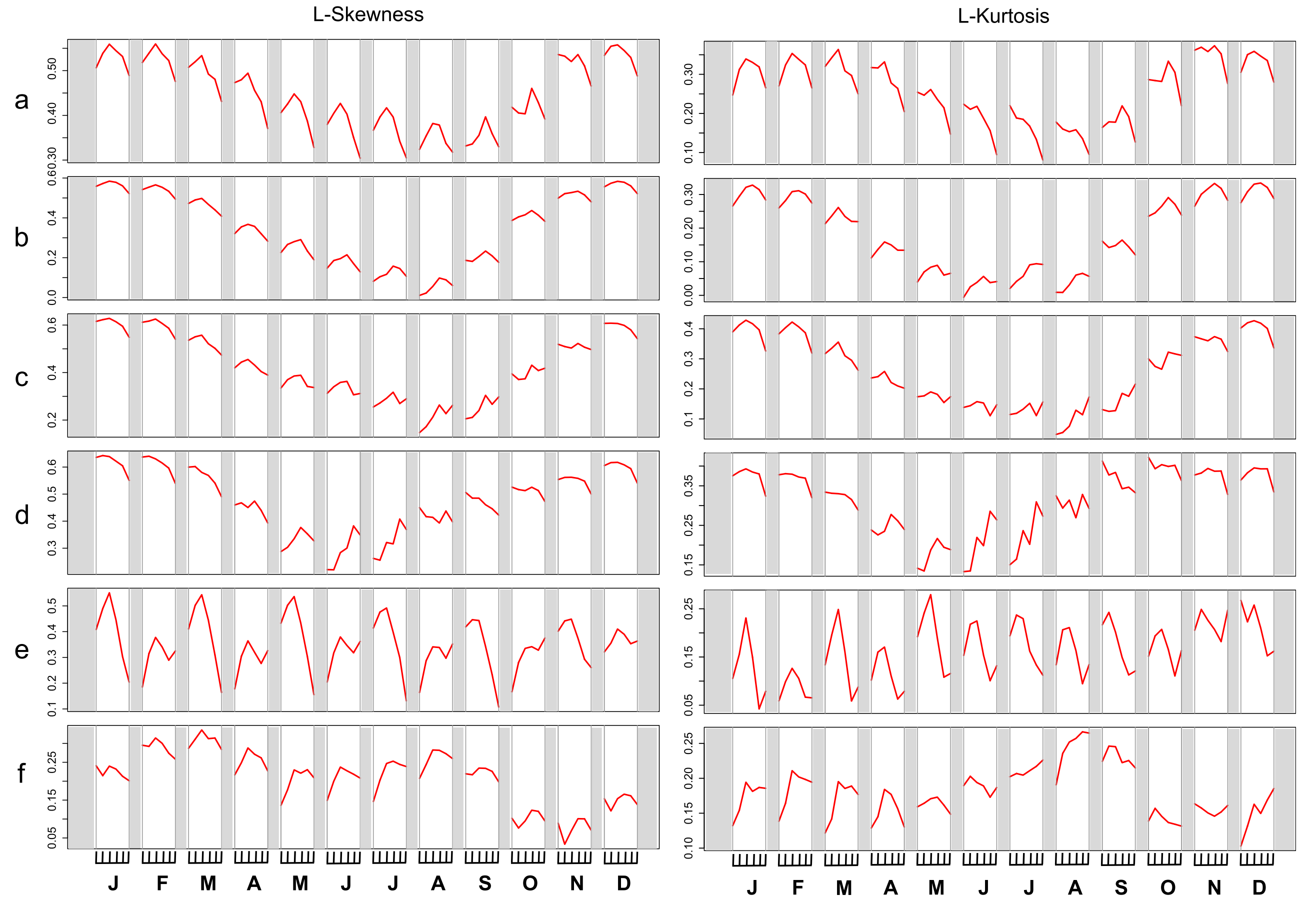

Fig. 1. L-Skewness and L-Kurtosis as function of Record Length for each month and stream gauge station (a = St. Río Turbio en Varillar, b = St. Río Claro en Rivadavia, c = St. Río Elqui en Almendral, d = St. Río Hurtado en Angostura Pangue, e = St. Río Choapa en Puente Negro, f = St. Río Maipo en La Obra). Axes for each month span record length from 30 to 80 year. Stream.

3.3. Structural stability of the SSI-3 series

One explanation of the findings presented in Sections 3.1 and 3.2 stems from the analysis of Fig. 3, which shows the Empirical Fluctuation Processes graphs of the SSI-3 series for the entire record period. This figure shows the fluctuation in standardized residuals cumulative sums of the linear regression model of each SSI-3 series with respect to time. All stations exhibit structural change beyond the 5% significance level for a stationary process (Kuan and Hornik, 1995; Zeileis et al., 2002), with greater deviation at the stations located at lower latitudes (more arid). This structural change has been found to be significantly correlated with the phases of the PDO, and its action mechanisms could be associated, hypothetically, with multidecadal changes in the intensity, position and extension of the South Pacific Subtropical Anticyclone off the coast of Chile, as well as changes in the speed of zonal winds that transport humid air masses to high positions in the Andes cordillera, reducing snow cover and average long-term streamflows during PDO cool phases and causing an inverse effect during the PDO warm phase (Núñez et al., 2013).

4. Discussion and implications of the findings in relation to political aspects of drought management

4.1. Record length

The findings associated with the effect of record length on the distributional properties of the CS-3 series under the influence of multidecadal climate variability are relevant since, to date, the international recommendation has been to use the most extensive records available (WMO, 2012) However, this recommendation is not appropriate under conditions of change in the structural stability of hydrological variables with respect to time, associated with the influence of multidecadal climate variability. Studies that relate the mean square error reduction with the proportional increase in record length are based on the assumption that the records comprise an independent and identically distributed data sample, free of trends, periodic variations or serial dependence, and that the events observed in the past will be similar to those expected in the future (Guttman, 1994; Hosking and Wallis, 1997). Various methods have recently been developed to tackle the problem of distributional fit of hydrological variables in light of drifts from this assumption, such as those found in this work, including methods with applications for the calculation of SDI (López and Francés, 2013; Russo et al., 2013). However, if these methods are considered complex for operative use in the calculation of SDI (the simplicity of which is one of their advantages), though they may be robust, they could face significant entry barriers to their adoption by the meteorological or hydrological services responsible, in many cases, for the official calculation of SDI (Stendinger and Griffis, 2008). In the cases in which the series do not exhibit structural change in their distributional properties, one recommendation is the use of the Regional Frequency Analysis based on L-moments approach as a basis for the calculation of the SPI with stations of various record lengths (Núñez et al., 2013; Faergemann, 2012).

4.2. Reference period

Unlike the internationally recommended climate normals (Arguez and Vose, 2011), the use of standard reference periods

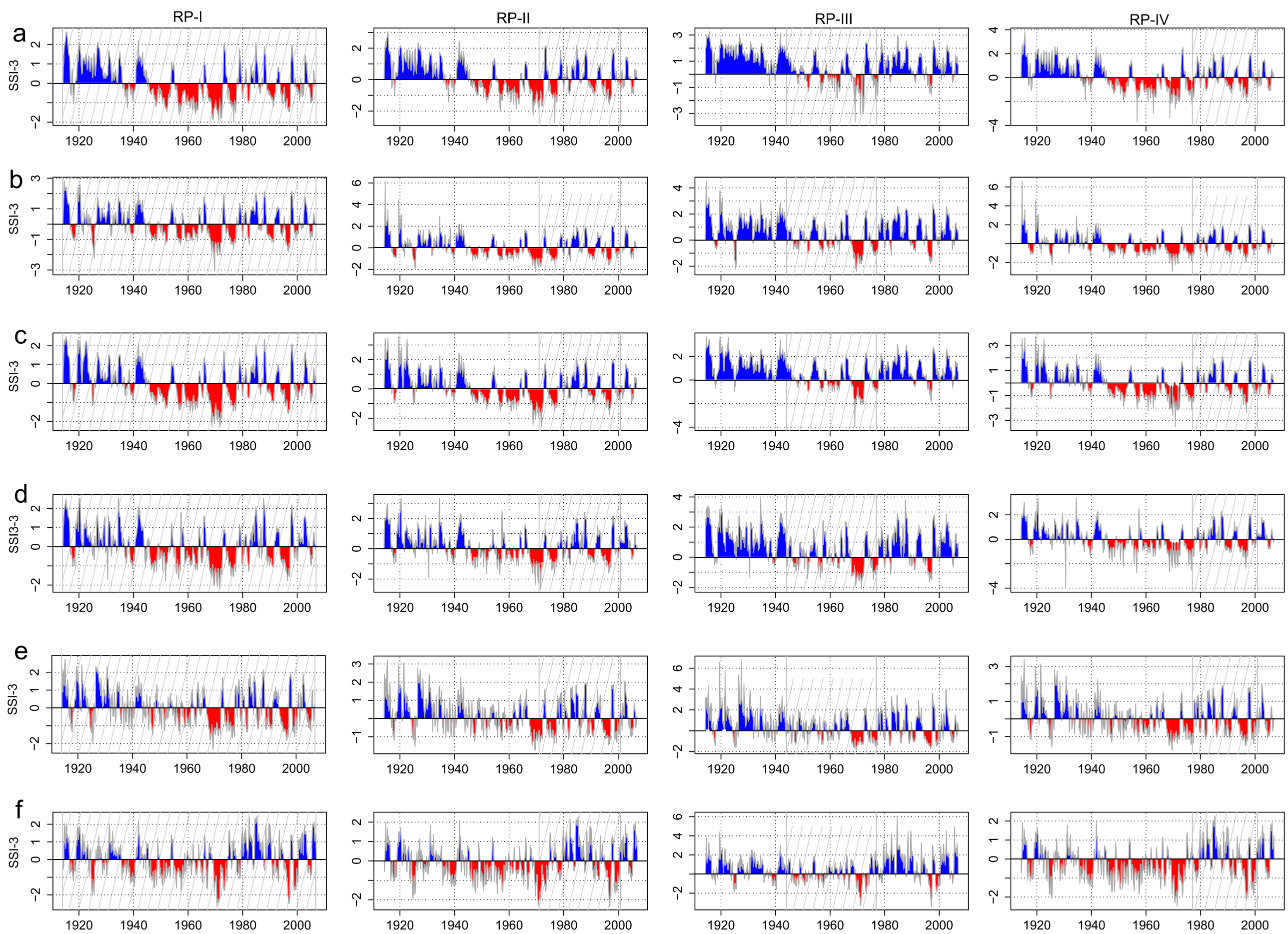

Fig. 2. SSI-3 time series as function of the reference period and stream gauge station. a: St. Río Turbio en Varillar, b: St. Río Claro en Rivadavia, c: St. Río Elqui en Almendral, d: St. Río Hurtado en Angostura Pangue, e: St. Río Choapa Puente Negro and f: Río Maipo en La Obra.

for the calculation of Standardized Drought Indices has not been promoted. Conventionally, the SPI is calculated with all available data series, although there exist operative monitoring systems, such as the Global Precipitation Climatology Centre drought index, in which the SPI values are estimated based on a standard reference period (Ziese et al., 2013). Some authors, such as the Water Scarcity and Drought Expert Group strongly recommend using the period January 1971–December 2010 as reference period for the calculation of the SPI (Faergemann, 2012). However, it is currently recognized that the approach based on reference periods suffers from limitations associated with so-called climate normals (Arguez and Vose, 2011). This is consistent with the results of this study, in which the use of a standard reference period (RP-II) does not solve the problem of magnitude difference in the DDR between the PDO cool and PDO warm periods. The results are similar to those found in an evaluation of the Exceptional Circumstances of Drought policy in Australia in the early 90s, which came to the conclusion that the system of indices and triggers was inappropriate for a changing climate, in which the years with exceptionally low precipitation were highly dependent on the analysis period, due to the high climate variability between decades (Hennessy et al., 2008; Botterill and Hayes, 2012). The root problem leading to this type of conclusion is the lack of consistency among the operational, conceptual and political definitions of drought as a result of multidecadal climate variability, which will be addressed below.

4.3. Consistency among the conceptual, operational and political definitions of drought

The main limitation stemming from the findings presented in this study is the loss of consistency between the conceptual, operational and political definitions of drought under the influence of multidecadal climate variability. In the case of the first, although the absence of one conceptual definition of drought in the scientific community is universally acknowledged (Smakhtin and Schipper, 2008), one of the most referenced is that proposed by Wilhite and Buchanan-Smith, 2005, p6-7), who state that "Drought is a temporary aberration, unlike aridity, which is a permanent feature of the climate" and by definition, "cannot occur 100% of the time". This definition is similar to that proposed by (UNISDR, 2009, p. 8) which states that drought is "a deficiency of precipitation over an extended period of time, usually a season or more, which results in a water shortage for some activity, group, or environmental sectors". A key element for the use of the conceptual definition of drought is the precision of the time scale that differentiates the temporary from the permanent (Maliva and Missimer, 2012), a relevant aspect because this type of conceptual ambiguity forms part of the obstacles to an adequate implementation of drought policies (Smakhtin and Schipper, 2008; Whitney, 2013). An advance in this sense is the recent proposal within the framework of the European Union Water Scarcity and Drought Policy review (Strosser et al., 2012), to categorize drought in terms of a subdecadal time scale,

Table 2
Drought declaration recurrence (DDR) [%] and Drought deficit condition (DDC) [%] for SSI-3 and MSSI-3. Numbers refer to: SSI-3 DDR|SSI-3 DDC/(MSSI-3 DDR|MSSI-3 DDC).

<table>
<tr><th></th><th colspan="4">Reference period</th></tr>
<tr><th>Period of interest</th><th>RP-I
(1914–2006)</th><th>RP-II
(1971–2000)</th><th>RP-III
(1944–1976)</th><th>RP-IV
(1977–2000)</th></tr>
<tr><td>St. Río Turbio en Varillar</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Conv: 1914–2006</td><td>21|55/(11|52)</td><td>17/48/(16|47)</td><td>8|25/(34|55)</td><td>23|51/(16|48)</td></tr>
<tr><td>PDOC:1944–1976</td><td>43|82/(1|42)</td><td>36/79/(4|35)</td><td>19|49/(18|45)</td><td>46|80/(4|36)</td></tr>
<tr><td>PDOW:1977–2000</td><td>18|60/(10|58)</td><td>14 /50/(15|52)</td><td>5|21/(42|59)</td><td>20|54/(16|53)</td></tr>
<tr><td>St. Río Claro en Rivadavia</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Conv: 1914–2006</td><td>21 |53/(18|50)</td><td>16|51/(14|36)</td><td>9|31/(3|56)</td><td>23| 57/(13|35)</td></tr>
<tr><td>PDOC:1944–1976</td><td>38|76/(1|43)</td><td>29|74/(0|24)</td><td>18|50 (19|52)</td><td>40|80/(0|24)</td></tr>
<tr><td>PDOW:1977–2000</td><td>19|51/(32|63)</td><td>16|49/(24|51)</td><td>9|32 (52|67)</td><td>21|53/(20|49)</td></tr>
<tr><td>St. Río Elqui en Almendral</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Conv: 1914–2006</td><td>21|53/(14|54)</td><td>17|49/(15|38)</td><td>7|25 (32|55)</td><td>24|53/(15|34)</td></tr>
<tr><td>PDOC:1944–1976</td><td>43|79/(0|51)</td><td>37|77/(0|25)</td><td>17|51 (15|51)</td><td>49|79/(0|18)</td></tr>
<tr><td>PDOW:1977–2000</td><td>15|53/(19|64)</td><td>13|50/(23|55)</td><td>5|19 (54|64)</td><td>16|55/(22|51)</td></tr>
<tr><td>St. Río Hurtado en Angostura Pangue</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Conv: 1914–2006</td><td>21|51/(15|50)</td><td>14|48/(16|40)</td><td>9|30 (40|59)</td><td>18|52/(14|36)</td></tr>
<tr><td>PDOC:1944–1976</td><td>39|79/(0|37)</td><td>29|76/(0|18)</td><td>20|51 (18|55)</td><td>33|79/(0|15)</td></tr>
<tr><td>PDOW:1977–2000</td><td>20|52/(22|58)</td><td>12|48/(25|55)</td><td>9|33 (54|64)</td><td>19|51/(21|51)</td></tr>
<tr><td>St. Río Choapa en Puente Negro</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Conv: 1914–2006</td><td>24|51/(15|53)</td><td>15|46/(24|55)</td><td>19|38 (31|53)</td><td>19|52/(24|58)</td></tr>
<tr><td>PDOC:1944–1976</td><td>32|66/(4|53)</td><td>19|61/(11|56)</td><td>25|52 (19|52)</td><td>24|68/(12|59)</td></tr>
<tr><td>PDOW:1977–2000</td><td>33|53/(10|51)</td><td>22|49/(24|52)</td><td>26|44 (38|52)</td><td>25|53/(24|55)</td></tr>
<tr><td>St. Río Maipo en la Obra</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Conv: 1914–2006</td><td>20|52/(22|50)</td><td>20|57/(9|35)</td><td>12|36 (31|55)</td><td>25|62/(8|34)</td></tr>
<tr><td>PDOC:1944–1976</td><td>30|74/(12|47)</td><td>30|77/(4|26)</td><td>18|53 (20|52)</td><td>37|81/(3|26)</td></tr>
<tr><td>PDOW:1977–2000</td><td>18|41/(41|63)</td><td>16|47/(22|53)</td><td>13|30 (52|66)</td><td>19|50/(19|51)</td></tr>
<tr><td>Mean</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Conv: 1914–2006</td><td>21|53/(16|52)</td><td>17|50/(16|42)</td><td>11|31/(34|55)</td><td>22|54/(15|41)</td></tr>
<tr><td>PDOC:1944–1976</td><td>38|76/(3|45)</td><td>30|74/(3|31)</td><td>20|51/(18|51)</td><td>38|78/(3|30)</td></tr>
<tr><td>PDOW:1977–2000</td><td>21|52/(23|59)</td><td>15|49/(22|53)</td><td>11|30/(49|62)</td><td>20|53/(20|52)</td></tr>
</table>

Conv = Conventional, PDOC = PDO cool, PDOW = PDO warm.

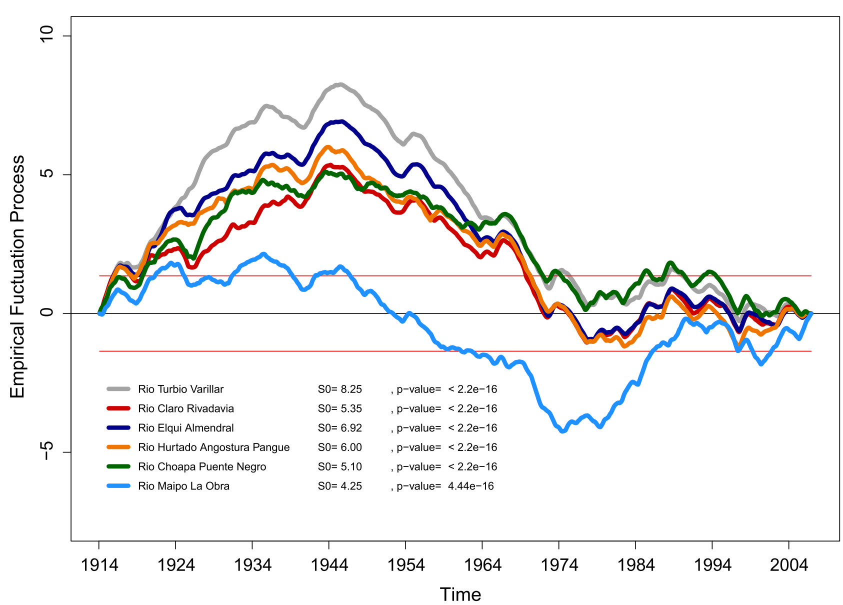

Fig. 3. Empirical fluctuation process of SSI-3 time series as function of stream gauge station. S_0 = statistical significance and p-value for stationary process.

thus describing it as a temporary and natural water imbalance that can last for months, seasons or years. This categorization allows the definition of drought to be separated from related concepts such as dry spell (the duration of which is days or weeks) and aridity (the duration of which is decades) (Strosser et al., 2012). Although it may seem arbitrary, this approach is consistent with recent works on the study of changes in global aridity using decadal periods (Dai, 2012; Spinoni et al., 2013). But still more relevant is that it is also consistent with the argument that persistent drought events can indicate the appearance of dryness conditions, due to climate change, that require the reevaluation of what is normal, at least in the time scale of water management and political decision-making (Maliva and Missimer, 2012; Whitney, 2013). In this sense, the precision of the subdecadal time scale for establishing the conceptual definition of drought allows the evaluation of consistency among SDI, with the conceptual definition that they sustain and, depending on the regulatory context in which they are applied, with the political definition that they support.

With respect to the political definition of drought, there exists a close relationship between it and the indices and triggers used to make it operational (Botterill and Hayes, 2012). Australia is the only country that has developed a national drought policy and gained adequate experience in its application as public policy. Although there is currently a debate on the necessity of modifying Australian drought policy, which is currently suspended and under review (Kiem and Austin, 2013), some of its aspects are relevant within the framework of this discussion, particularly its relationship with SDI. The basis for Australia's National Drought Policy was its definition as a set of criteria for the Declaration of Exceptional Circumstances of Drought (DECD) that allowed financial support to be provided to those affected (White and Karssies, 1999). The first of the three criteria of the DECD establishes that "the event must be rare and severe"..."and of a scale to affect a significant proportion of farm businesses in a region" (Hennessy et al., 2008, p 4). This criterion is associated, therefore, with the concept of an extreme event, and consequently, with the definition of triggers to activate a response to the occurrence of the event. In the case of Australia, an Exceptional Drought was associated with a return period of 20–25 years, that is, an event with a DDR of 5% (Hennessy et al., 2008), while in the case of Chile, it is associated with a return period of 5 years, with a DDR of 20%. The fact that DDR, in both cases, are influenced by multidecadal climate variability and can be much greater than expected for the respective political definitions, generates contradictions that appear because the time scales of the hydroclimatic time scales are not necessarily coupled with the related time scales of water management and political decision making (Smakhtin and Schipper, 2008). This contradiction or absence of consistency stems, for example, from changes in the structural stability of the time series, such as that shown for the SSI-3 in Section 3.3 of this study. In this sense, the third criterion of the Australian DECD is crucial for an appropriate interpretation of SDI under conditions of multidecadal climate variability. This criterion establishes that "the event must not be predictable or part of a process of structural adjustment" (Hennessy et al., 2008, p 4). Under this concept, the use of SDI without considering the effects of structural change associated with multidecadal climate variability proves inadequate, especially when the predictability of these changes has been significantly improving (Meehl et al., 2009). To tackle this problem, the analyst could resort to three alternatives: (a) at the cost of sacrificing the simplicity of the SDI calculation, include the effect of the temporal variability of the distributional properties in the procedure to estimate the distribution parameters of best fit, (b) calculate the SDI with a model adjusted for the structural stability conditions of the current hydrological regime or (c) extract from the time series those components of temporal subdecadal variability consistent with the definition of drought, prior to the calculation of the index. For the first alternative there is recent experience associated with the calculation of the SPI (Russo et al., 2013). The second alternative is, seemingly, the simplest and most plausible of all. It is derived from the fact that, in agreement with Table 2, as well as RP-IV/PDOW and RP-III/PDOC, both combinations exhibit a DDR = 20%, consistent with the conceptual and Chilean political definitions. This implies that the restoration of consistency between the SSI and the definitions with which it is associated is based on constructing the SSI with records located within the same period of structural stability. This finding alone seems to be significant in terms of balancing the simplicity of the calculation of the index with the need to maintain its robustness and consistency. However, its adoption has an associated cost: the political cost of assuming a new normality of greater dryness (Arguez and Vose, 2011; Maliva and Missimer, 2012), transferring the management of that risk to the users, a matter with which Australians have a long experience. The third and final approach, for which there are no available references of its application in drought monitoring indices, is addressed in Section 4.4

4.4. Extraction of multidecadal climate variability

Recognizing the existing difficulties in reaching an accord on a universal definition of drought and recent advances in defining a temporal subdecadal time scale for this natural disaster (Strosser et al., 2012), an alternative to attempt to restore the consistency of the SDI (or others of a probabilistic nature) with the conceptual and political definitions with which they are associated, is to extract those modes of variability that are decadal or greater from the time series of the variable to be analyzed, Based on this approach, in Fig. 4, the MSSI-3 series of the case study are presented. Compared to the original SSI-3 series, the MSSI-3 series do not exhibit the pattern of dryness characteristic of the 1944–1976 PDO cool phase, although it is observed that the reference period effect remains. The observation is confirmed by the results presented in Table 2 (values in parentheses). In the original SSI-3 the highest DDR values are associated with PDOC conditions, while in the MSSI-3 series, the highest values are found in Conv and PDOW conditions. For some stations (Rivadavia, Almendral and Angostura Pangue) the DDR is zero in three of the four reference periods analyzed (RP-I, RP-II and RP-IV). For RP-IV, similar to the Chilean policy, the DDR in PDOC conditions is significantly lower (Average = 3%) than that registered by the corresponding SSI-3 (Average = 30%), and is also associated with a return period of 33–34 years. On the other hand, the occurrence of extraordinarily dry MSSI-3 values (MSSI-3 < 3) is observed in all of the stations, which could be due to a lack of specification of the probability distribution model used in the adjustment (GLO). In consequence, although the extraction of the multidecadal and long-term variability modes eliminates the problem of high DDR values in PDO cool conditions in some stations, some difficulties emerge in the estimation and interpretation of the index in this approach, which require additional research. Thus, an approach based on "calculating the SDI with a model adjusted for the structural stability conditions of the current hydrological regime" seems to be a simple, operative and reasonable method, even though the probabilistic adjustment of SDI in arid zones remains a permanent challenge (Vicente-Serrano et al., 2012; Wu et al., 2007; Mishra and Singh, 2010; Pietzsch and Bissolli, 2011; Stagge et al., 2013).

4.5. Implication of the findings with respect to national drought policies

The implication of the findings of this study, in the context of "Integrating science and policy aspects of drought management" in the ten-step process of development of National Drought Policies (UNCCD-FAO-WMO, 2012b, p. 11), depends precisely on the link between drought policy and indices, as a means of making these policies operational (Botterill and Hayes, 2012). To argue this statement, the potential implications that the findings of this study could have in three application cases, in Australia, the US and Chile, are discussed.

The National Drought Policy of Australia and its ongoing review have been more and more based on the concept of climate risk management (Botterill and Hayes, 2012; White et al., 2001). As a country with a strong globalized and liberalized economy, it has focused drought policies on the elimination of the concept of natural disaster and the transference of the risk of drought from the

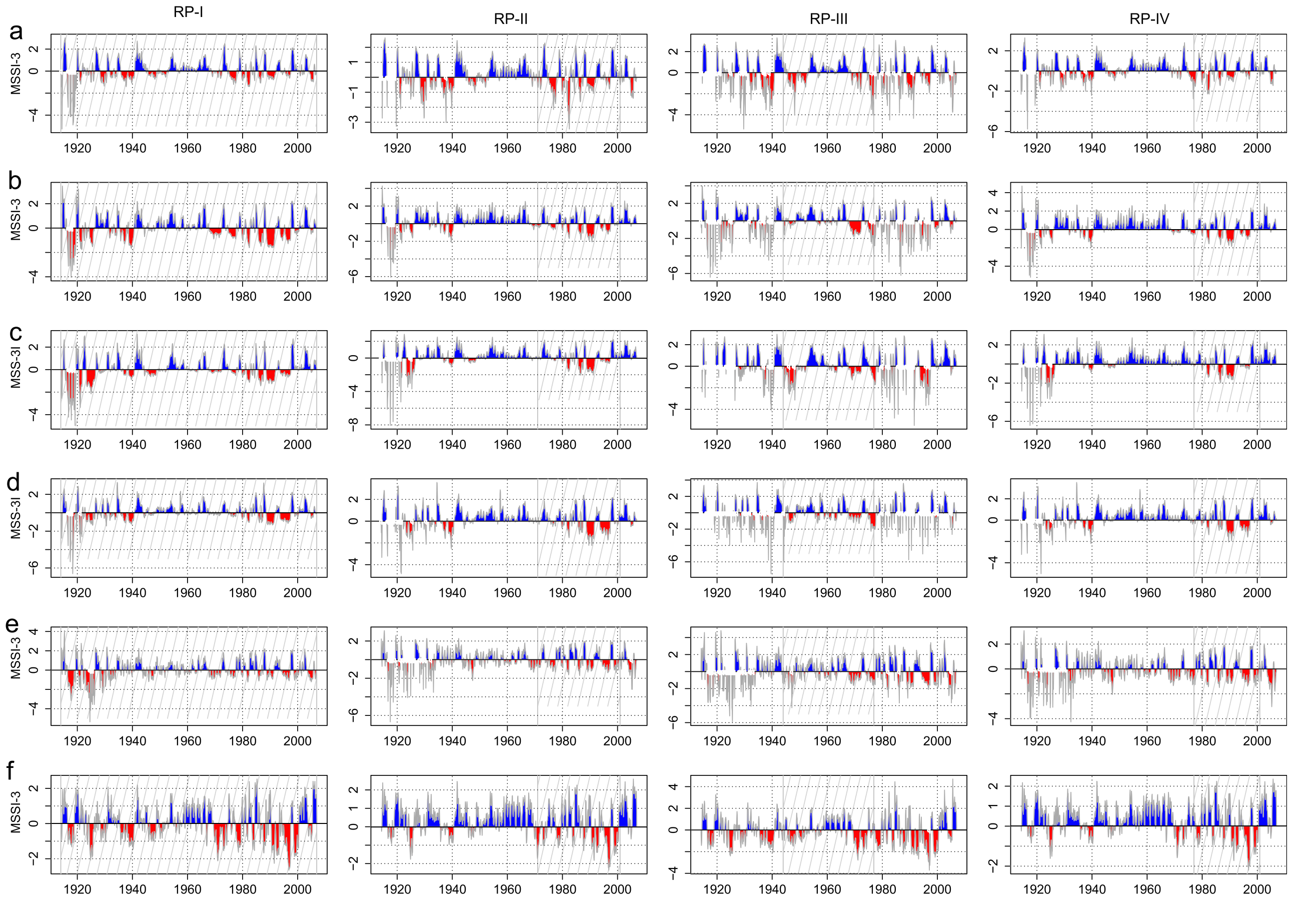

Fig. 4. MSSI-3 time series as function of reference period and stream gauge station. a: St. Río Turbio en Varillar, b: St. Río Claro en Rivadavia, c: St. Río Elqui en Almendral, d: St. Río Hurtado en Angostura Pangue, e: St. Río Choapa Puente Negro and f: St. Río Maipo en La Obra.

State to the productive sectors, especially the agricultural sector (Botterill and Hayes, 2012). In light of the current suspension and review and its national drought policy, it is clear that this approach intends to consolidate, abolishing the concept of Exceptional Circumstances of Drought and strengthening the concept of preparedness in the face of variability and climate change. In these circumstances, the use of probabilistic indices and their limits in the face of decadal climate variability should not have an impact with respect to drought policies, since aim of supplying information about climate conditions is to improve climate risk management on the part of farmers through structural changes in their production systems and is not a mechanism for triggering responses (Botterill and Hayes, 2012). Furthermore, the findings reinforce the Australian conclusion that the temporal variability of biophysical variables that supported the Declaration of Exceptional Circumstances made these indices and triggers inappropriate in a changing climate (Hennessy et al., 2008). These indices are even less appropriate, as has been shown in this study, if they are calculated in the conventional manner.

In the United States, the approach has been quite different than that of Australia (White et al., 2001; Botterill and Hayes, 2012). The US has established its international leadership in drought management based on a strong development of climatic monitoring systems, with the US Drought Monitor being the operative tool supporting the drought management plans (Svoboda et al., 2002). The severity categories of the US Drought Monitor are based on six key indicators and supplementary indicators. The SPI is one of them, but other indicators of a probabilistic nature, such as CPC Soil Moisture Model Percentiles, U.S. Geological Survey (USGS) Daily Streamflow Percentiles and the Percent of Normal Precipitation, are also used. The fact that the SPI has exhibited various limitations to its application in various regions of the US (Wu et al., 2007), and that a large part of the country, especially the American west, is susceptible to the influence of multidecadal climate variability on precipitation and streamflows (Goodrich, 2007; Timilsena et al., 2009), allows us to presume that the results of this study could be applicable in there (as well as in Mexico, its neighbor, which has recently adopted a national drought management framework based on the use of SDI and is also affected by multidecadal climate variability). The impact that the limitations of the SPI or other probability-based indices of the US drought monitor could exhibit under the growing influence of multidecadal climate variability in the American west could depend on the recurrence of the declarations triggered by the system, with respect to the recurrence expected by the institutions responsible for responding to these events. However, the problems of consistency among the conceptual, operational and political definitions of drought that could be exhibited in the US are only one portion of the factors that complicate the development of a national drought policy in that country (Folger et al., 2013). Some of these factors include, especially in the American West, to get more operative its drought management system within a growing water scarcity and highly variable climate (Ingram and Malamud-Roam, 2013). Similarly, Western US must reconcile its own water management with its neighbor Mexico where, in addition to the above problems, important cross-border institutional asymmetries must be considered (Prichard and Scott, 2013; Varady et al., 2012). These experiences will be highly valuable, especially in the context of increasing demands for water security, not only in America (Scott et al., 2013), a region in which the study area of this research is located, but in similar areas of the world. In the case of Chile, internationally recognized as one of the most liberal countries in the world with respect to private water management (Bauer, 2004), the implications of the results could be immediate, due to the significant water deficit currently experienced by the north-central region of the country associated with multidecadal climate variability consistent with the phases of the PDO (Núñez et al., 2013). Under these circumstances and in light of the evidence that suggests that this condition could lengthen to a more permanent process of aridization (Spinoni et al., 2013), it is expected that the estimations of the SSI-3 (or those of the SPI) that support the official response of Chile to drought events (DGA, 2012), future estimations of the SSI-3 will be more recurrent than what is expected by the policy. Although the international response to these declarations is not related to the mobilization of economic resources, it does have a direct link to the ability of users to access new sources of surface water and groundwater without having to secure the associated legal use rights, which could generate future problems in management and sustainability of water resources if this becomes a permanent condition. Chile, on the other hand, has a second official drought response mechanism, independent of that analyzed in this study and with a focus on climate risk management in line with the Australian trend. Which of the two management models will dominate the triggering of the public response to drought events in the future is uncertain. Therefore, for Chile, it is fundamental to resolve this type of definition, since the governance, institutions and policies that are developed around the management of water are critical determinants for the construction of adaptive capacities of society to respond in an efficient manner to extreme hydroclimatic events such as drought (Engle and Lemos, 2010). Although there have been attempts to improve drought management through the development by the Ministry of Agriculture of a Climate Risk Observatory, these efforts still seem to be insufficient to properly address water scarcity. The significant increase of the latter has been triggered a general consensus to generate relevant changes to the water management model in Chile. This is due not only to an increase in drought conditions over the last decade (Meza, 2013) but also to higher water demand. Perhaps even more importantly, and similar to what happened in US during the great drought that hit the country during the 1990s, there has been a recognition that "attempts to understand and address the failures of water management during droughts would be unsuccessful unless shortcomings in the larger context of water management are also understood and addressed" (Werick and Whipple, 1994). Thus, the current drought that Chile is facing has unveiled the structural weaknesses of the Chilean water management model under great scarcity, where free market – only driven by economic efficiency – has not been able to ensure sustainable water allocation considering social and environmental issues (Bauer, 2004).

The analyzed cases, and others that can have similar results, representative of dry mountainous zones of the globe, with national drought management systems where SDI have a relevant role, and located in regions affected by multidecadal climate variability, are examples in which the findings of the present study can have a direct an immediate application. In these cases, the results of this study should at least be considered, both by those who promote the use of SDI and those who have the responsibility of adopting them to mobilize public resources or inform the affected parties in order to strengthen their own management of the climatic risk. In this way, science can contribute directly to drought policy matters, helping to construct capacities that reduce the vulnerability of society to its occurrence, a primary objective of a National Drought Policy (UNCCD-FAO-WMO, 2012a).

5. Conclusions

The present study evaluates the limitations that the SSI, a member of the Standardized Drought Indices family, exhibits under conditions of changes in structural stability of streamflow series associated with multidecadal climate variability. Taking the north-central region of Chile as a case study representative of the drylands in mountainous regions, the findings show that the limitations are related to the lack of consistency among the operational definition of drought expressed by the SSI, the conceptual definition that sustains it and the political definition that it supports. Through an analysis of the effects of record length and reference period, and considering the recent phases of the Pacific Decadal Oscillation that have been associated with the streamflow regime in the study area, it is demonstrated that all of these factors affect Drought Declaration Recurrence, and that the international recommendations for the use of the SPI are insufficient for overcoming this limitation. To confront the lack of consistency among the definitions, the following options are proposed: (a) consider the temporal changes in the distributional properties of the analyzed time series in the SDI calculation procedure, (b) calculate the SDI with a model adjusted for the structural stability conditions of the current hydrological regime or (c) extract temporal subdecadal variability modes from the time series prior to the calculation of the index. The second approach is a simple and effective option. Finally, the implications of the findings on the capacity of SDI to support national drought policies are discussed in the context of their potential effects in Australia, the United States and Chile. Accordingly, the potential impact of the limitations of SDI under the influence of multidecadal climate variability depends on the interrelation between drought policy and the indices used to make it operative. In any case, the results of this study should be considered both in the promotion of SDI and in its adoption for drought management, thus contributing to link science with policy issues, one of the crucial elements in the development of a National Drought Policy.

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