Regional aspects of streamflow droughts in the Andean rivers of Patagonia, Argentina. Links with large-scale climatic oscillations

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ABSTRACT

Under the current global warming trend, droughts are expected to increase, with serious implications for water resources management. This study analyzed the regional aspects of droughts in terms of streamflow deficiencies over the Andean rivers of Patagonia, Argentina. Based on the variable threshold level method, the main characteristics of streamflow droughts were obtained for the hydrological years 1962/63–2014/15, considering three different severity levels over 11 representative basins. Two distinct regional behaviors were identified in terms of temporal variations of streamflow drought duration and its cumulative deficit volume, dividing the study area into North and Central Patagonia. The effects of the Southern Annular Mode (SAM), the El Niño–Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) on the interannual and interdecadal variability of streamflow droughts were assessed through an empirical decomposition applied to the regional time series. These large-scale climatic oscillations have a distinct regional and temporal behavior in terms of the modulation of streamflow drought variability. Considering the interannual streamflow drought variability, the El Niño signal is more consistent and contributes with humid conditions, especially over North Patagonia. The multi-decadal component of the streamflow drought time series is linked to the upward trend in SAM, particularly over Central Patagonia.

Key words | Andes, climate forcings, Patagonia, streamflow droughts, temporal variability, water resources

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INTRODUCTION

Extreme hydrometeorological events are recurrent natural hazards that generate negative impacts on ecosystems and human activities. From these events, droughts are one of the costliest and least understood natural disasters, with multiple regional aspects that highlight the vulnerability of societies. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), increases in intensity and/or duration of drought has been likely in many regions of the world since 1970 (IPCC 2013). This can be attributed to decreased precipitation and/or increased evaporation rates, factors that

have undergone important regional changes during the last 50 years.

Commonly, droughts are classified into four categories: meteorological drought, hydrological drought, agricultural drought, and socio-economic drought (Mishra & Singh 2010); with the first two categories being most attractive to scientists and researchers (Ye et al. 2016). Hydrological drought refers to a lack of water in the hydrological system, manifesting itself in abnormally low streamflow in rivers and abnormally low levels in lakes, reservoirs, and groundwater (Tallaksen & Van Lanen 2004). When rainfall

shortages propagate in the hydrological cycle and generate periods of streamflow deficits, usually it is hard to identify the beginning of this abnormal condition, its evolution, and end; this often leads to disagreement between scientists and policy-makers regarding drought declaration. From a scientific and practical point of view, understanding the changing characteristics of drought and wetness variations is of essential importance for improving integrated water resources management at the catchment scale and human mitigation of hydrological alterations (Ye *et al.* 2016). Therefore, a thorough knowledge of hydrological drought characteristics is relevant for the success of drought preparedness and mitigation, mainly in regions that exhibit a high dependency upon river flows. Moreover, an increased knowledge of the physical processes governing hydrological drought is needed in order to improve both monitoring tools and short- and long-term forecasts. Some of the challenges for hydrological drought research are summarized in Van Loon (2015).

Drought indices are important tools for drought characterization and prediction due to their abilities to simplify the complex interactions among various climate and climate-related variables (Zhu *et al.* 2016). Usually a drought index is essential for assessing the effect of drought and defining different parameters, including intensity, duration, severity, and spatial extent (Arabzadeh *et al.* 2016). The focus on hydrological drought is usually performed in terms of the assessment of streamflow drought, defined as a below-normal river discharge. Two kinds of indices are typically used when analyzing streamflow droughts: the threshold level method and the standardization of data into regularly used drought indices (Rangecroft *et al.* 2016). The threshold level method has the following advantages over the commonly used standardized indices, such as the standardized runoff index (SRI) (Shukla & Wood 2008) or the standardized streamflow index (SSI) (Vicente-Serrano *et al.* 2012): (1) no a priori knowledge of probability distributions is required and (2) drought characteristics such as frequency, duration, and severity are directly determined if the threshold is set using drought-affected sectors (Sung & Chung 2014). Moreover, the methodology should consider the daily variations of the hydrographs to define threshold levels, in order to quantify the hydrological cycle in a better way than considering a

yearly fixed value. With this methodology, a drought event starts when the flow falls below the threshold, and ends when the threshold is exceeded or when the water deficit volume below the threshold has been replenished (Stahl 2001). For practical reasons, thresholds are often derived from percentiles of the flow duration curve, commonly ranging between the 70th and 95th percentile for perennial rivers (Van Loon 2015). The threshold level method has the ability to define drought characteristics in all possible hydrological variables in a uniform manner (Heudorfer & Stahl 2016).

East of the Andes Mountains, Argentinean Patagonia, located at the southern tip of South America, between 37°S and 55°S, covers almost one-third of the total continental surface of Argentina. The Andes strongly affect the regional climate features, mainly in terms of precipitation patterns, due to the changes in its mean elevation that interacts with the wind patterns and the incursion of moist air masses from the Pacific Ocean. There is a strong precipitation gradient that generates arid to semi-arid conditions east of the mountains, compromising the availability of water resources. In this sense, the rivers which are born in the higher elevations of the Andes, fed by snowmelt and rainfall, play an important role in the development of the region, with several hydropower plants providing a significant part of the electric power in Argentina (Seoane *et al.* 2005). The interannual variability of precipitation over the region has been partially associated with the El Niño–Southern Oscillation (ENSO) (González & Vera 2010), a climatic oscillation that also influences the streamflow variability on a seasonal basis mainly in the basins located in the northern portion of Patagonia (Scarpati *et al.* 2001; Seoane *et al.* 2005; Compagnucci & Araneo 2007). The leading pattern of circulation variability in the southern Hemisphere, i.e., the Southern Annular Mode (SAM), also plays an important role in the interannual variability of precipitation and streamflow over Patagonia, as previously shown by González & Vera (2010), Berman *et al.* (2012), and Mundo *et al.* (2012).

Despite such studies, much remains unknown or poorly understood about the interannual rainfall variability in Patagonia (González 2013) or the interdecadal variations of both precipitation and streamflow. Hydropower generation, irrigation for agricultural activities, and the availability of

water for human consumption are highly sensitive to the interannual variations in streamflows, with significant consequences in periods with hydrological drought conditions. The glaciers of the Patagonian Andes are currently shrinking rapidly, as a consequence of increases in atmospheric temperatures and reductions in precipitation (Davies & Glasser 2012). Recent studies assessed the future meteorological drought characteristics over southern South America, indicating that the Patagonia region will likely face a significant increase in the number of drought events during the 21st century, with significant decreases in its mean duration and non-significant changes in its severity (Penalba & Rivera 2013, 2016). The knowledge about hydrological drought in Patagonia has several gaps and uncertainties regarding the large-scale climatic drivers, the regional differences among the basins, and the methodologies used to define this extreme phenomenon. This kind of assessment is feasible since the streamflows over Patagonia have been measured since the beginning of the 20th century, and can provide relevant parameters to be considered in several engineering applications, such as the design of reservoirs and irrigation channels based on streamflow drought characteristics.

The objective of this paper is to depict the characteristics of streamflow droughts in the main rivers of Argentinean Patagonia and its links with the temporal variations of some of the main large-scale climatic oscillations that affect the hydroclimate of Patagonia. Understanding the temporal variabilities of streamflow drought characteristics and their regional patterns is relevant for decision-making processes regarding water distribution for irrigation and human consumption, hydropower generation, and environmental flows. The links between large-scale climatic oscillations and the main modes of streamflow drought variations will help in developing reliable hydrometeorological predictions, taking into account current trends and future drought projections over the region. The structure of the paper first provides details about the study area and hydrometeorological information, the definition of streamflow droughts and the methods for temporal assessment. The results obtained are separated between the streamflow drought climatology and the temporal assessment of streamflow drought characteristics. A discussion section provides links between the results and previous literature; finally,

the main conclusions and possible applications are summarized.

DATA AND METHODS

Study area and data base

The assessment of streamflow droughts was performed for the Argentinian portion of Patagonia, located between 37° and 46°S, which comprises the major rivers of Neuquén, Río Negro, and Chubut provinces (Figure 1). We discarded the analysis of the streamflow records of Santa Cruz province on the southern tip of Patagonia, given the lack of long and continuous records.

Most of Patagonia is dominated by air masses coming from the Pacific Ocean (Paruelo *et al.* 1998), creating a rain-shadow effect over northern Patagonia, where the Andes ranges possess higher elevations. The interaction between the semipermanent anticyclones of the Pacific and Atlantic Oceans and the subpolar low pressure belt and its seasonal variations defines the annual cycle of precipitation over the region. A steep west-to-east decrease in precipitation is observed. Over the Andes ranges and immediately to the east of the higher elevations, a maximum (minimum) in rainfall during the winter (summer) season is associated with the south–north displacement of the South Pacific High and the passage of moist air masses. East of the Andes, the climate turns semi-arid, with rainfall amounts less than 300 mm and a homogeneous distribution during the year. These climatic features drive the annual cycle of the Patagonian rivers, which show two annual maxima: one associated with the winter rainfalls and the other as a result of the snowmelt in spring and early summer (Figure 1). The streamflow annual cycle was defined as the period between 1st April and 31st March. A similar behavior is observed among the main rivers of the region (Figure 1), with a peak (or a succession of several peaks) between June and August and a secondary peak, usually larger than the winter one, between October and January. The main rivers that flow across Patagonia are (from north to south): Colorado, Neuquén, Negro, Limay, Chubut, and Senguerr.

The spatial distribution of the analyzed streamgauges and the main rivers in Patagonia is shown in Figure 1. Daily streamflow data from 20 streamgauges were obtained from the Hydrological Data Base belonging to the Water
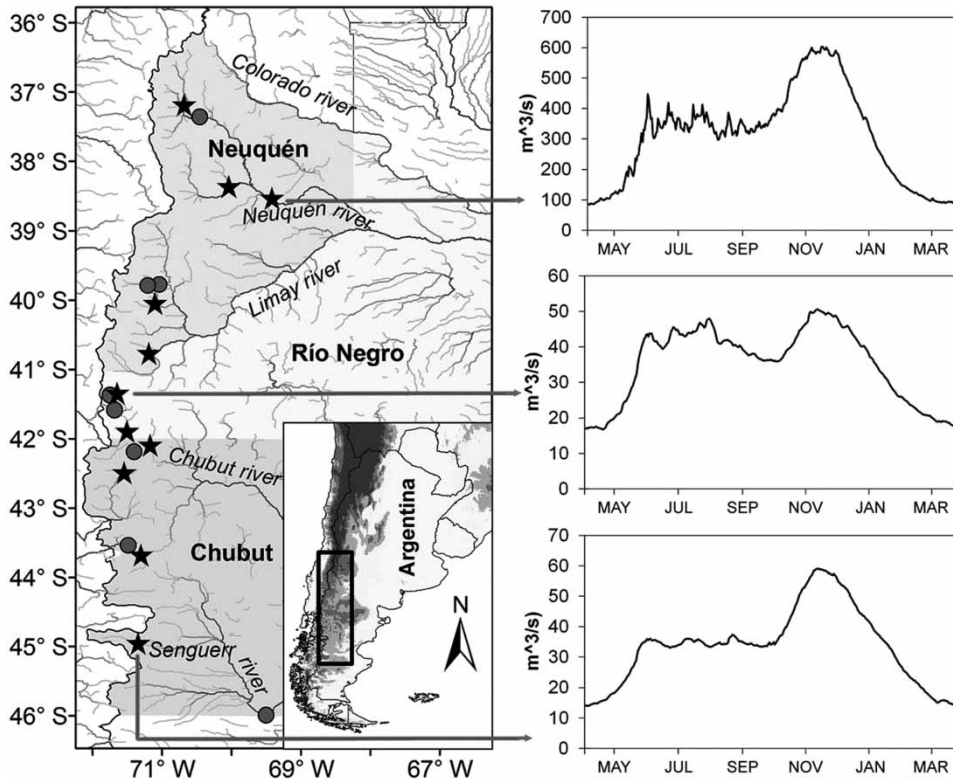
Figure 1 | Location of the study area, the main rivers selected for this study, and the spatial distribution of the hydrological stations. Stations marked with a star were used for the climatology of streamflow droughts. The hydrological annual cycle is shown for three selected rivers (from north to south: Neuquén, Manso, and Senguerr).

Resources Agency of Argentina (http://bdhi.hidricosargentina.gov.ar/). The names and relevant particulars of the selected streamgauges are summarized in Table 1, showing records ranging from 24 to 112 years. From these records, 11 time series were selected as representative for the climatology of streamflow droughts (marked with a star in Figure 1), based on the quality of the data, the spatial representativeness, and the length of data. A common period between the hydrological cycles of 1962/63 and 2014/15 was considered to obtain the climatological features of streamflow droughts. Following Penalba *et al.* (2014), several methods were used to evaluate the consistency of the time series. Data outliers, identified as the streamflow values which were away from the daily average value over a range greater than four standard deviations, were associated with typing errors and corrected. We applied several infilling methods – polynomial interpolation, linear regression interpolation – depending on the size of the gap, the hydrological conditions at the site when the gap occurred and the availability of nearby gauging stations, following the recommendations made by WMO

(2008) and the methodology used by Rivera *et al.* (2016) for the Central Andes of Argentina. In this sense, we used nine stations exclusively to fill data gaps, which explain more than 80% of the temporal behavior of streamflow in the stations selected for the climatological assessment. After these procedures, the time series selected for the climatological assessment has less than 2% of missing data during the period 1962/63–2014/15 (53 years, Table 1), with the exception of Nacimiento station (Senguerr River, Table 1).

We used several climatic indices in order to identify the main drivers of streamflow droughts at an interannual to interdecadal level. The Oceanic Niño Index (see http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml for details) was considered to define El Niño and La Niña events, as periods when the three-month running means of Extended Reconstructed Sea Surface Temperature (ERSST) v4 anomalies in the Niño 3.4 region (5°N–5°S, 120°–170°W) were above 0.5°C or below −0.5°C for five consecutive months or more. The Pacific Decadal Oscillation (PDO) index, defined as the leading empirical orthogonal

Table 1 | Geographical characteristics of the selected stations, period of record, percentage of missing data, and mean streamflow value

Number	River	Station name	Lat (˚S)	Lon (˚W)	Altitude (masl)	Number of years of record (time period)	Missing data (%)	Mean streamflow (m³/s)
2036	Neuquén	Andacollo	37° 11′ 8.0″	70° 40′ 48.0″	1,000	44 (1971–2015)	0.80	110.77
2059*	Neuquén	Rahueco	37° 21′ 22.0″	70° 27′ 15.0″	879	24 (1984–2008)	2.60	201.29
2010	Agrio	Bajada del Agrio	38° 21′ 55.0″	70° 01′ 59.0″	660	62 (1953–2015)	0.00	74.66
2004	Neuquén	Paso de Indios	38° 31′ 55.5″	69° 24′ 48.9″	498	112 (1903–2015)	0.00	306.52
2032*	Malleo	Malleo	39° 46′ 41.0″	71° 02′ 22.0″	800	40 (1973–2013)	7.63	33.42
2005*	Chimehuín	Naciente	39° 47′ 27.0″	71° 12′ 23.0″	875	42 (1971–2013)	15.65	64.08
2040	Quilquihue	Junín de los Andes	40° 02′ 60.0″	71° 05′ 60.0″	750	53 (1962–2015)	0.00	33.63
2021	Cuyín Manzano	Cuyín Manzano	40° 46′ 32.0″	71° 05′ 60.0″	675	44 (1971–2015)	0.73	10.10
1807	Manso	Los Moscos	41° 20′ 51.7″	71° 11′ 10.0″	792	69 (1946–2015)	0.00	35.04
1806*	Manso	Los Alerces	41° 22′ 25.4″	71° 44′ 45.4″	728	62 (1951–2013)	1.75	44.32
1812*	Roca	Los Alerces	41° 22′ 36.0″	71° 45′ 00.0″	780	30 (1985–2015)	2.56	6.87
1814*	Manso	Confluencia	41° 35′ 12.6″	71° 41′ 01.2″	400	48 (1965–2013)	4.10	80.77
1811	Quemquemtreu	Escuela N° 139	41° 53′ 53.7″	71° 30′ 08.0″	750	59 (1956–2015)	0.87	9.19
2206	Chubut	El Maitén	42° 05′ 59.0″	71° 10′ 11.8″	680	72 (1943–2015)	0.34	19.91
2208*	Epuyén	La Angostura	42° 11′ 20.0″	71° 24′ 00.0″	290	62 (1951–2013)	6.40	14.48
2204	Carrileufú	Cholila	42° 29′ 44.0″	72° 32′ 28.0″	535	58 (1957–2015)	1.57	48.39
2288*	Carrenleufú	Puente de Hierro	43° 32′ 38.8″	71° 29′ 10.1″	439	25 (1990–2015)	0.00	52.44
2202	Carrenleufú	La Elena	43° 41′ 02.0″	71° 18′ 03.1″	802	61 (1954–2015)	0.81	33.10
2215	Senguerr	Nacimiento	44° 57′ 30.9″	71° 20′ 31.9″	925	74 (1952–2015)	14.97	33.51
2297*	Senguerr	Los Molinos	45° 59′ 27.0″	69° 30′ 00.0″	320	29 (1986–2015)	0.00	50.57

Note: Stations with an asterisk were used to complete the records of neighbor stations.

function of mean November through March sea surface temperature (SST) anomalies for the Pacific Ocean to the north of 20°N latitude (Mantua *et al.* 1997), was obtained through the JISAO web page (http://research.jisao.washington.edu/data_-sets/). The large-scale climate phenomenon known as SAM was identified using the Marshall station-based index (Marshall 2003), following the recommendation by Ho *et al.* (2012) for hydroclimatic investigations prior to 1979 (i.e., without satellite data). This SAM index measured the monthly mean difference between normalized mean sea level pressure at six stations close to 40°S and six stations close to 65°S, and was obtained at http://www.nerc-bas.ac.uk/icd/gjma/sam.html.

Streamflow drought definition

A streamflow drought event was defined using the daily varying threshold level approach, a methodology widely applied in drought analysis (Fleig *et al.* 2006; Sung & Chung 2014; Wanders *et al.* 2015) but relatively novel over southern South America (Rivera *et al.* 2016). The threshold levels, also referred to as the truncation levels, were derived from the flow-duration curve as the flow equaled or exceeded for 70% (Q70), 80% (Q80), and 90% (Q90) of the time. The use of different thresholds is useful to indicate various drought severity levels (in this case moderate, severe, and extreme streamflow drought) that can be related to drought impacted sectors, as for example, irrigation for agriculture or hydropower generation levels. Also, they can be used to inform water users about current river discharges, to help declare an alert or emergency conditions and to support the application of drought contingency plans. The streamflow drought condition is defined as the period when the flow is below the selected threshold, allowing definition of the onset and end of the drought event and

other commonly used statistics, such as: (i) the number of drought events; (ii) the drought mean duration; and (iii) the cumulative deficit volume (severity). The following annual drought parameters were derived for the 1962/63–2014/15 period (Hisdal *et al.* 2001):

- ANDD: annual number of days below the selected threshold (drought days);
- ACDV: annual cumulative deficit volume standardized by seasonal mean flow (days);
- NDE: number of drought events per year.

Prior to the threshold level calculation, a moving average filter of 7 days length was applied to the streamflow time series as a pooling procedure to define an independent sequence of deficits. In order to eliminate minor droughts that can alter the streamflow drought characteristics over the basins, all drought events with a duration of less than 10 days were excluded from the analysis.

Temporal analysis

Based on the annual indices described above, we summarized the interannual and interdecadal variations of streamflow drought characteristics as regional averages. Rotated principal components analysis (RPCA) (Richman 1986) was applied in S-mode, which allowed us to obtain a spatial regionalization and temporal patterns of the streamflow drought annual indices in the studied domain. Varimax rotation (Kaiser 1958) was applied to obtain consistent spatial patterns, retaining the orthogonality and enhancing the interpretability of the results. The number of components to retain was obtained using the Kaiser criterion (Kaiser 1958), considering the eigenvalues greater than 1, and also the scree test of Cattell (1966). In order to define the homogeneous regions, each station was assigned to the component upon which it loads most highly.

Once the regional temporal patterns were obtained, we applied the complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) (Colominas *et al.* 2014) in order to find the main modes of temporal variability present in the time series of the annual indices. This method decomposes a time series into a finite number of components, called intrinsic mode functions (IMF), which can be linked to climatic oscillations. The CEEMDAN has

proved to be an important improvement of the original empirical mode decomposition (EMD) (Huang *et al.* 1998), retaining the advantages of the original methodology, such as robustness in the presence of non-stationary data and adequacy for the assessment of non-linear variations. The full description of the CEEMDAN and its main advantages with respect to EMD and the ensemble EMD can be found in Colominas *et al.* (2014). The use of this methodology for the identification of the main modes of variability present in hydrometeorological variables over southern South America has received some attention recently, as shown in the studies by Rivera & Penalba (2014), Antico *et al.* (2016), and Rivera *et al.* (2016).

RESULTS

Streamflow drought characteristics at individual basins

The streamflow drought characteristics, i.e., number of drought events, mean drought duration, and mean drought severity, for the 11 selected stations during the 1962/63–2014/15 period are shown in Figure 2, considering the three different truncation levels. A general result from the evaluation of the number of drought events and its mean duration indicates that there is a relationship between drought frequency and duration: the basins with more (less) numbers of streamflow drought events have short (large) mean duration. This is also observed considering the drought severity, which means that streamflow droughts with longer mean duration have large cumulative deficit volumes. The location of the stations with the larger values in each of the streamflow drought characteristics is dependent upon the selected threshold, showing a highly variable spatial pattern.

As expected, the number of drought events decreases as the severity level increases: there are between 100 and 170 drought events considering moderate drought conditions, 80–140 reach the severe drought category and 40–70 extreme conditions (Figure 2(a)). The stations located on the Quemquemtreu, Chubut and Carrileufú rivers have a large number of streamflow drought events, with more than 150 events in the 53 hydrological years for the Q70 threshold. Regarding streamflow drought duration, the
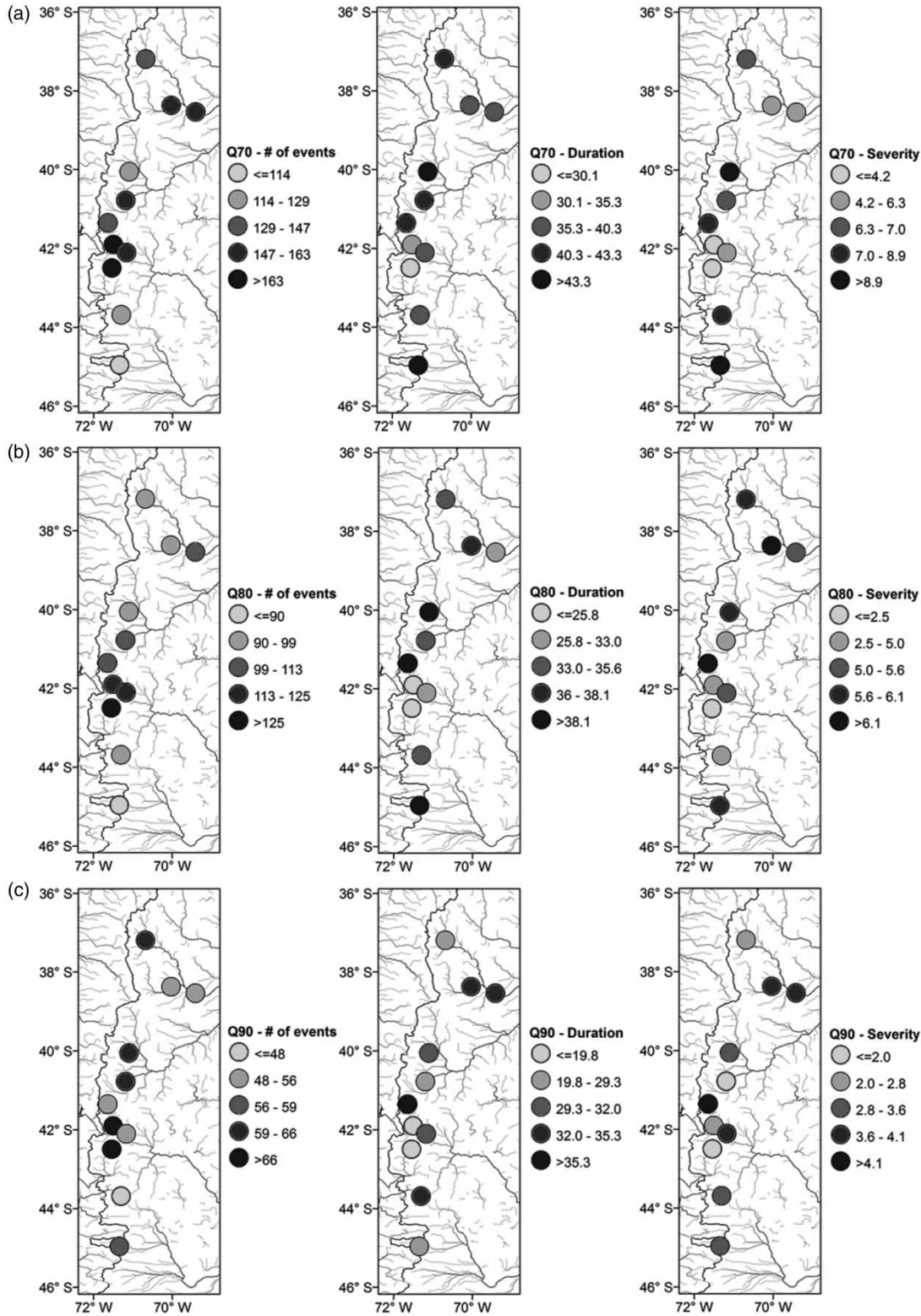
Figure 2 │ Streamflow drought indicators for the stations selected for the climatological assessment: (left panel) number of drought events in the period 1962/63–2014/15, (center panel) mean drought duration (in days), and (right panel) mean drought severity (in days) for (a) Q70, (b) Q80, and (c) Q90 thresholds.

mean values decrease as the severity category increases, given that the time in which the river flows below the defined threshold decrease. Mean drought duration considering the Q70 threshold is between 25 and 50 days, decreasing to 20–45 days for Q80 and 15–40 days for Q90 (Figure 2(b)). For example, mean drought duration greater than 40 days for the Q70 threshold was observed for the stations located in the western portion of Neuquén province and in the headwaters of Senguerr River (Figure 2). The same spatial distribution is observed for the stations with higher severity, i.e., larger cumulated deficit, with values greater than 6 days. The cumulative deficit is expressed as days given that it is standardized by the mean flow, resulting in a variable denoting the number of days with mean flow needed to compensate the deficit (Van Loon 2015). The severity values decrease as the threshold increases, typically ranging from 1–5 days for the Q90 threshold to 3–10 days considering the Q70 level (Figure 2(c)).

Regional assessment of streamflow drought annual indices

From the streamflow drought characteristics during the period 1962/63–2014/15, we built three annual indices to evaluate the interannual and interdecadal behavior of streamflow droughts over Patagonia. In this sense, we summed the number of streamflow drought events; the number of days below the selected threshold as a measure of streamflow drought duration and its corresponding cumulative deficit volume – the difference between the observed flow and the threshold – standardized by the mean flow as a measure of streamflow drought severity. A regionalization performed through RPCA applied to the ANDD allowed us to identify two geographically consistent regions: North Patagonia, comprising the Neuquén, Agrio, Quilquihue, and Cuyín Manzano river basins; and Central Patagonia, encompassing the Manso, Quemquemtreu, Chubut, Carrileufú, Carrenleufú, and Senguerr river basins (Table 1, Figure 1). Even when previous work showed a homogeneous behavior among the annual streamflows over the study area (Compagnucci & Araneo 2005), the streamflow drought characteristics have two distinct regional features. The same results were obtained considering the ACDV (not shown), indicating a strong relationship between the temporal variabilities of streamflow drought duration and severity. This is further verified in Figures 3 and 4, where the temporal evolution of the regional annual indices is shown. The behavior of both ANDD and ACDV regional averages over the basins of North Patagonia (Figure 3) indicate a large interannual variability. Dry years with more than 200 days with streamflow drought conditions were recorded in 1962/63, 1968/69, 1989/90–1990/91, 1996/97, 1998/99, and 2012/13. A large proportion of those years were under severe and extreme drought conditions; except for 1989/90, all the years had more than 100 days with extreme streamflow drought conditions. The above-mentioned years were coincidental with high streamflow deficits observed over the region, ranging from 40 days to over 100 days in 1998/99. In fact, the 1998/99 hydrological year recorded the higher ANDD in the three selected thresholds (307, 288, and 241 days in Q70, Q80, and Q90, respectively) and the higher ACDV (112, 79, and 42 days). Regarding the NDE, a large interannual variability is observed, with values reaching 3 to 6 regional streamflow drought events in the drier years. The relation between the NDE and both ANDD and ACDV is not straightforward given that one single streamflow drought event can produce a greater number of dry days and cumulative deficit than several events with short duration. In some of the years, the values of the NDE were higher for the extreme drought category in comparison with the severe and moderate categories, which is related to the occurrence of dry pulses.

The regional average of the indices for Central Patagonia is shown in Figure 4. Interannual variations are not as marked as in the case of North Patagonia. Just three years have more than 200 days with streamflow drought conditions: 1988/89 and 1998/99–1999/00. This indicates that droughts have shorter durations with respect to the results observed for North Patagonia, a result also evident when comparing the mean drought duration values among the basins in Figure 2. Two distinct dry periods are observed in the second half of the 1980 decade and between 1998 and 2000. The higher ACDV is observed in the years 1998/99 and 1999/00, with more than 60 days considering the Q70 threshold. On average, there are between 3 and 4 streamflow drought events per year, with a higher NDE after 1981/82 in relation to the previous period. This is in line with an increase in both ANDD and ACDV.
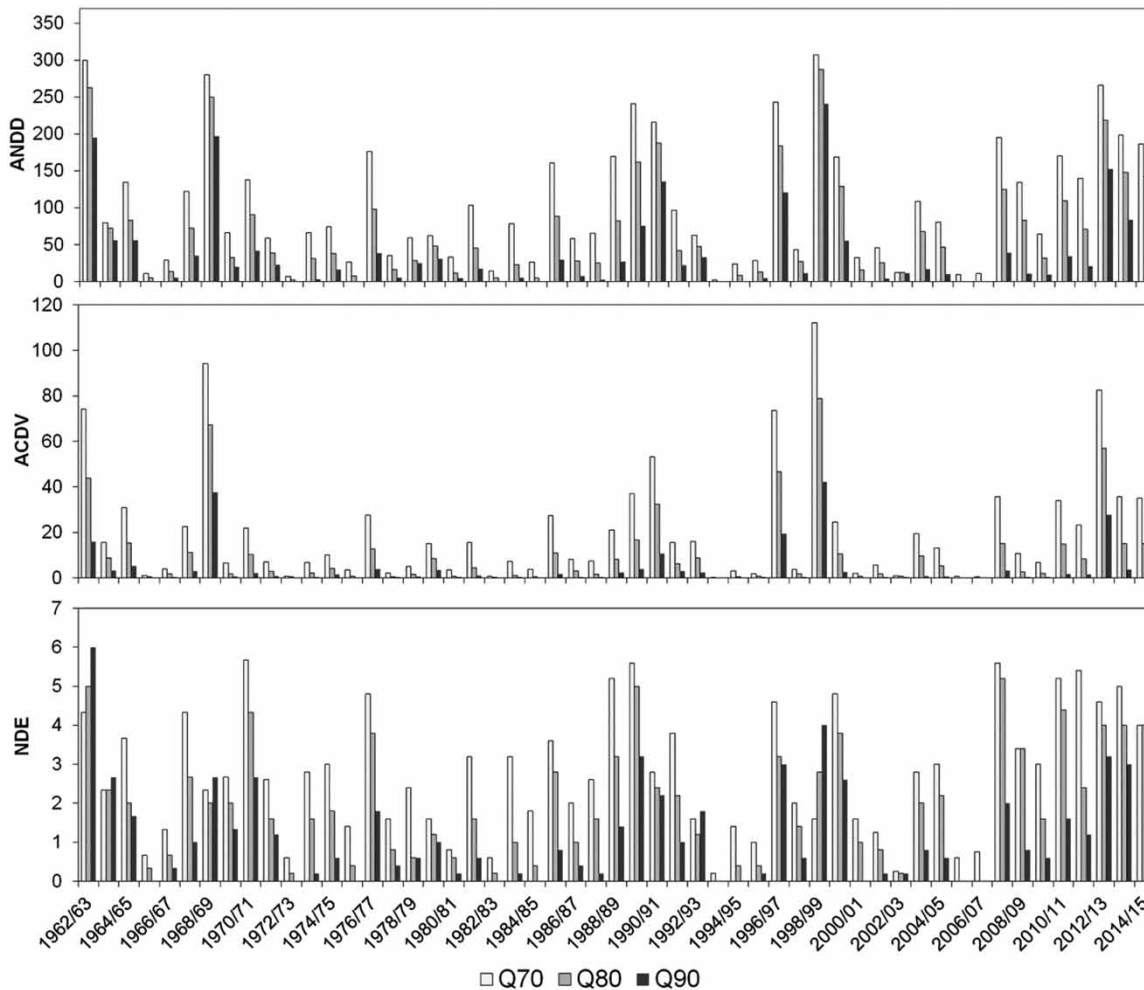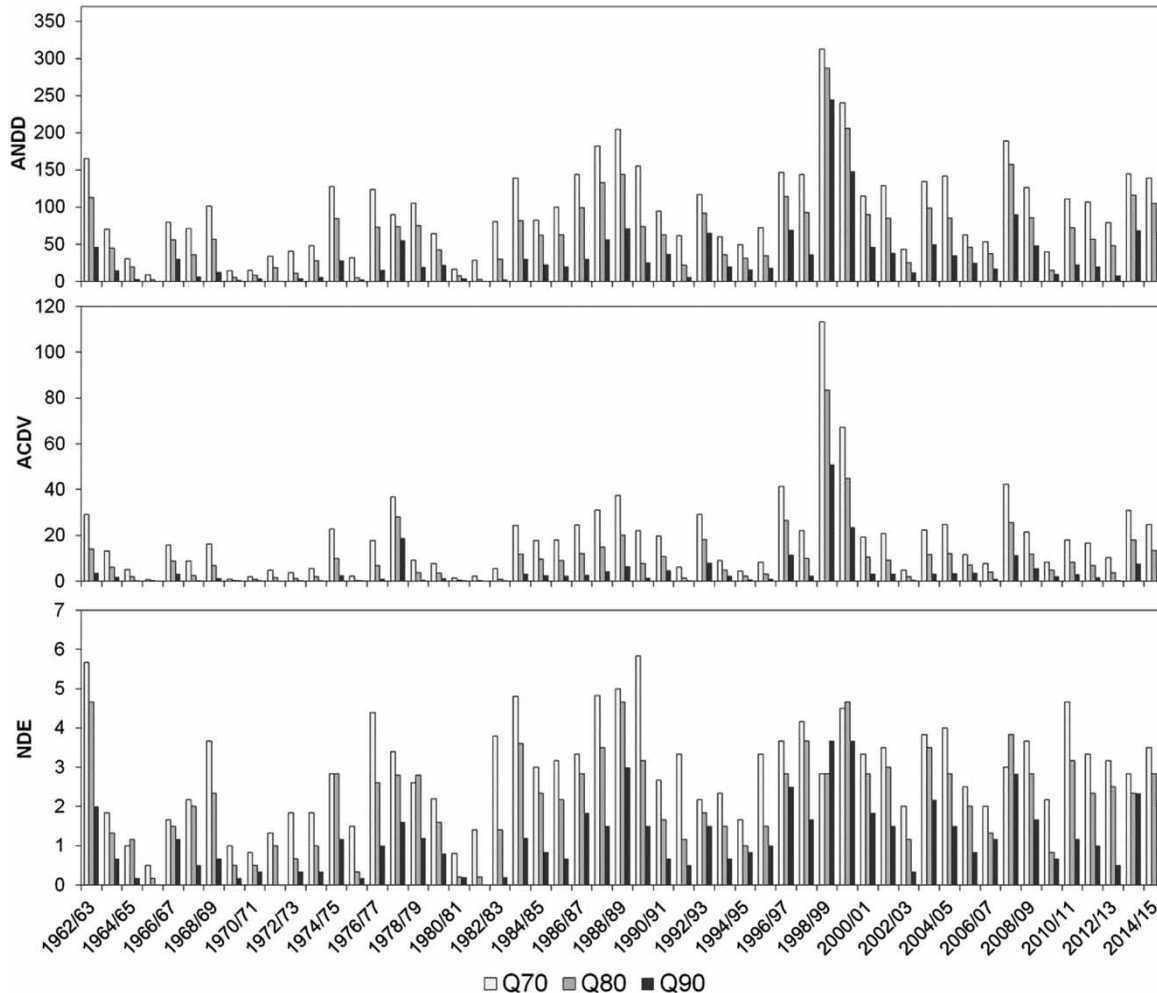
Figure 3 | North Patagonia regional time series of the ANDD, ACDV, and NDE for the three different threshold levels.

Based on the close relationship between the time series of ANDD and ACDV (r = 0.923, $p < 0.001$ for North Patagonia; r = 0.903, $p < 0.001$ for Central Patagonia), we applied the CEEMDAN only to the time series of ANDD. We selected the Q70 threshold given the continuity of the time series (i.e., lack of long periods with zero values) in comparison with the time series based on the Q80 and Q90 thresholds (see Figures 3 and 4). The results of the empirical decomposition are shown in Figure 5. The original time series were decomposed into four IMF and a residual non-linear trend. The first two modes of variability accounts for the interannual variations in the ANDD, while the remaining IMFs and the residual can be associated with the interdecadal variability. Comparing the amplitude of

IMF1 of North and Central Patagonia, a larger contribution of this mode to the ANDD signal is observed in the case of North Patagonia, with several years explaining more than 100 dry days. The average oscillation of IMF1 is between two and three years for North Patagonia (2–5.8 years in South Patagonia). Both IMF2 and IMF3 contribute to the dry periods observed in the last part of the 1980s and during the extreme years of 1998/99–1999/00 over the whole study area. The increase in the ANDD after 2010 over North Patagonia can be associated with IMF2-3-4 and the residual. In the 2010/11–2014/15 period, IMF3 (average oscillation of 10–13 years) contributes with more than 50 dry days. This dry period is not clearly defined in the ANDD of Central Patagonia, which is also in line with

Figure 4 │ Central Patagonia regional time series of the ANDD, ACDV, and NDE for the three different threshold levels.

the different behavior observed in IMF2-3-4 in comparison to North Patagonia. IMF4 is characterized by a low frequency oscillation of approximately 26 years over North Patagonia and around 40 years over South Patagonia. The non-linear trends also exhibit different regional patterns: a monotonic positive trend since the second half of the 1970 decade ranging from 85 to 112 dry days per year over North Patagonia and a positive trend until the first half of the 2000 decade, from 70 to 125 dry days per year, which has a reversion after 2002/03 over Central Patagonia. In this sense, the behavior of the low frequency oscillatory modes over the study area is different in the North and Central Patagonian basins and can be connected to different large-scale climatic oscillations.

## Links with large-scale climate oscillations

In order to analyze the signal of the large-scale climate oscillations (El Niño and La Niña events, the PDO and SAM index) in the ANDD over North and Central Patagonia, we decided to separate the interannual and interdecadal variations of the regional time series. This was performed by considering the sum of the IMFs 1 and 2 as the interannual component of the signals and the sum of the IMFs 3, 4 and the residual as the decadal component. The interannual ANDD time series were compared to the occurrences of El Niño and La Niña events, while the decadal component of the ANDD was compared to both the decadal components of the PDO and the SAM. This assessment is shown in
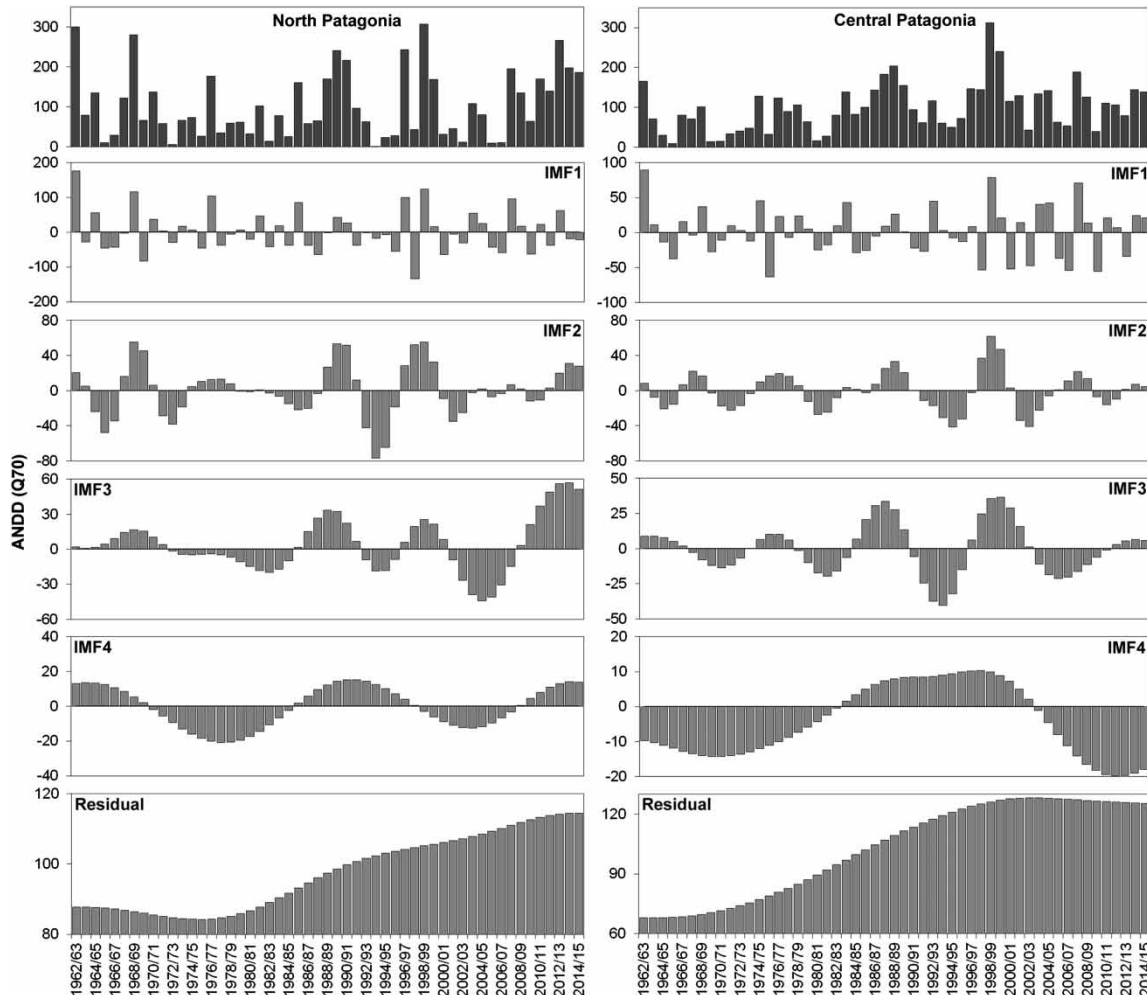
Figure 5 | Main modes of variability according to the CEEMDAN applied to the regional ANDD for the Q70 threshold over North Patagonia (left) and Central Patagonia (right). The top panel shows the original signal, while the rest of the panels show the IMFs and the residual of the decomposition. Notice that the scale of the y-axis changes depending on the amplitude of the IMF considered.

Figures 6(a) and 7(a). The decadal components of the PDO and SAM were obtained by also applying the CEEMDAN to the original time series and grouping the modes that account for interdecadal variabilities. A total of 18 (16) El Niño (La Niña) events were identified between 1962/63 and 2014/15 hydrological years. Over the North Patagonian basins (Figure 6(a)), we found a consistent relationship between El Niño events and negative values of the interannual component of the ANDD (14 of 18 El Niño episodes). The consistency of the signal, expressed as the ratio between the number of years in the time series that confirms the El Niño/La Niña signal in sign to the total episode number, is 0.78, a value close to the threshold used to identify core

regions according to Kahya & Karabork (2001). The contribution of La Niña events is not defined in terms of sign, with nine of 16 episodes with positive ANDD. The El Niño (La Niña) event of 1968/69 (1998/99) contributes with more than 150 days with streamflow drought conditions (Figure 6(a)). The regional interannual component of the ANDD over Central Patagonia exhibits a poor consistency regarding El Niño and La Niña signals (Figure 7(a)). Ten of 18 El Niño episodes contribute to negative streamflow drought days, while nine of 16 La Niña episodes contribute to positive streamflow drought days. The higher positive contributions are observed during La Niña years of 1998/99, 1999/00, and 2007/08, with more than 50 dry days.
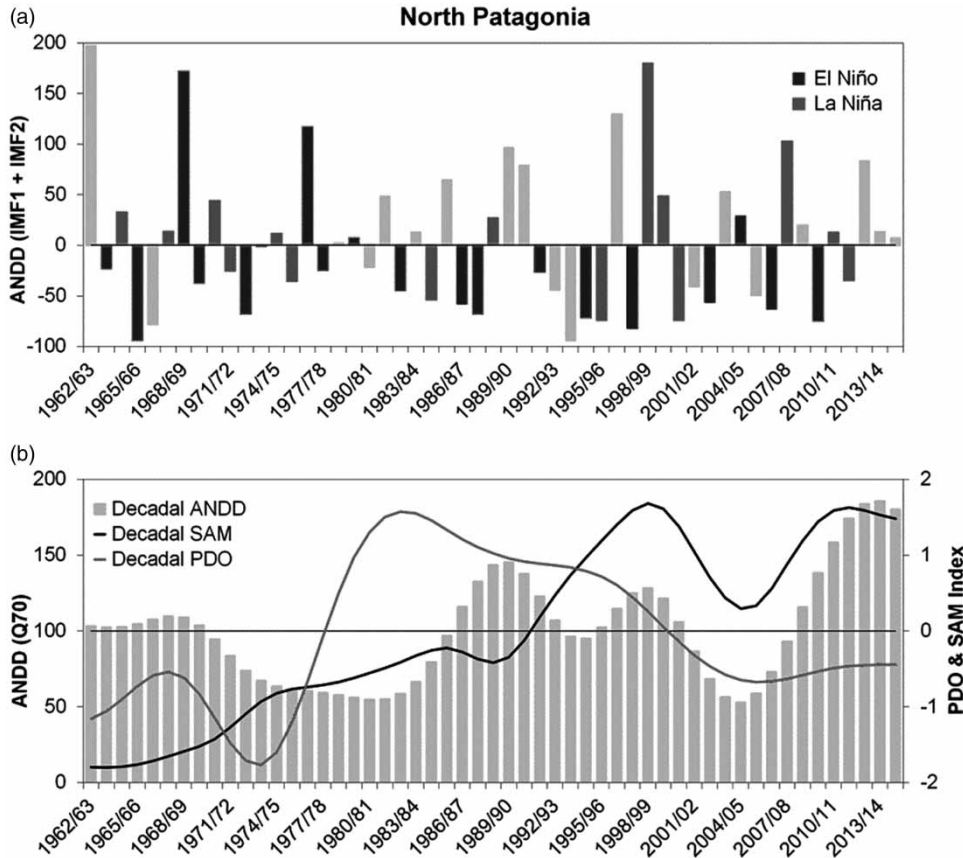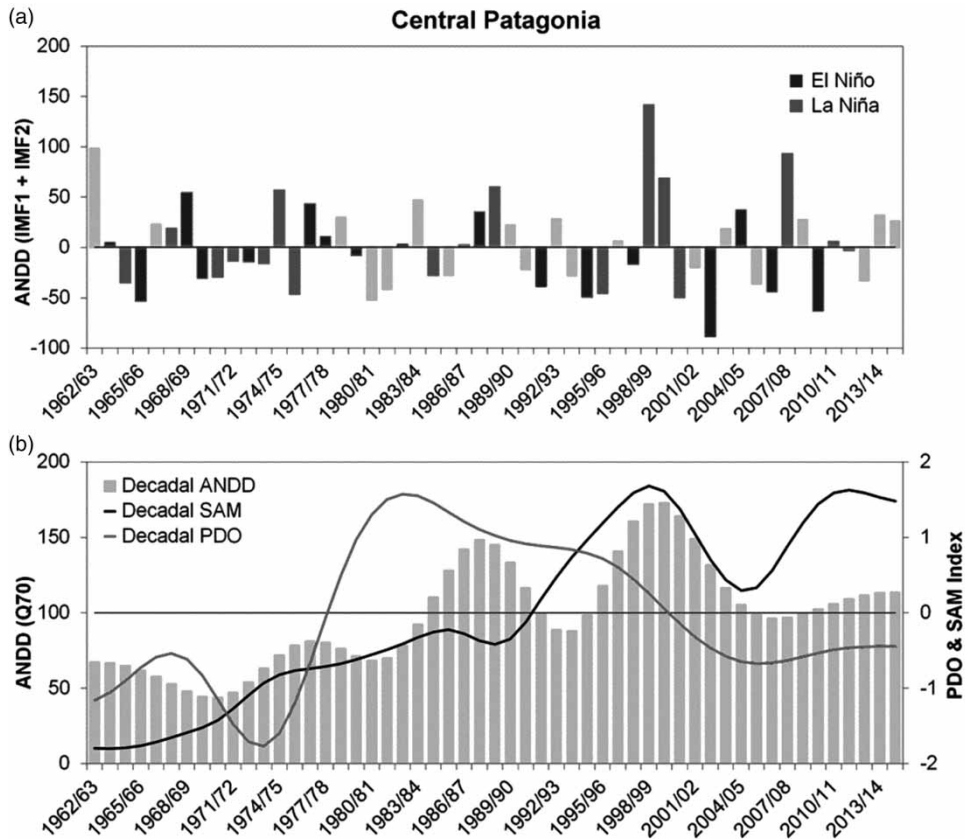
Figure 6 │ Temporal evolution of (a) the interannual and (b) decadal modes of variability of the ANDD over North Patagonia. El Niño/La Niña years are shown in the time series of the interannual modes of the ANDD. The decadal components of the PDO (grey line) and the SAM (black line) are shown with the decadal modes of the ANDD (in bars).

The decadal modes of the ANDD, PDO, and SAM are shown in Figures 6(b) and 7(b). Over the North Patagonia region, the decadal modes of the ANDD are significantly correlated to the decadal variations in the SAM (r = 0.437, $p <$ 0.01), but show non-significant relationship with the decadal modes of the PDO (r = 0.026, p = 0.428) (Figure 6(b)). The best agreement between the ANDD and SAM signals is found in the last 20 years, between 1994/95 and 2014/15. This decadal behavior results as a combination of variabilities between 10 and 26 years (Figure 5). In the case of Central Patagonia, we found significant contributions of both the SAM (r = 0.737, $p <$ 0.001) and the PDO (r = 0.407, p = 0.002) (Figure 7(b)). Over both regions, the association of positive SAM/PDO decadal components with increased streamflow drought conditions – both in duration and severity – is evident. However, the contribution of the PDO is more relevant over Central Patagonia, a fact that could explain the observed differences in the IMF4 of both regions (Figure 5).

DISCUSSION

A streamflow drought climatology involving 11 representative basins of Argentinian Patagonia was performed for three different severity levels: Q70 (moderate), Q80 (severe), and Q90 (extreme). Considering that: (1) a daily streamflow value is the result of the average of three daily measurements; (2) data were quality controlled to remove suspicious values; and (3) a moving average filter of 7 days was applied to the streamflow time series to define an independent sequence of deficits, we can neglect the impact of streamflow instrument errors in the definition of streamflow drought conditions. Moreover, even when the threshold levels were selected arbitrarily, recent studies have shown that thresholds between the 70th and 90th percentile are frequently used for streamflow drought assessment considering perennial rivers (Beyene *et al.* 2014; Van Loon & Laaha 2015; Rangecroft *et al.* 2016). The

Figure 7 | Temporal evolution of (a) the interannual and (b) decadal modes of variability of the ANDD over Central Patagonia. El Niño/La Niña years are shown in the time series of the interannual modes of the ANDD. The decadal components of the PDO (grey line) and the SAM (black line) are shown with the decadal modes of the ANDD (in bars). Same as Figure 6 for Central Patagonia.

appearance of multi-year droughts (i.e., droughts lasting longer than 365 days) and zero-drought years (the flow never falls below the threshold level in a year) are important features when choosing a consistent threshold level (Tallaksen & Hisdal 1997). In this research, these features are absent, supporting our threshold level choices for a proper streamflow drought assessment. It is worthwhile to mention that, even when some regions in Patagonia are characterized by a semi-arid climate, none of the analyzed rivers are intermittent or ephemeral, which guarantees a proper definition of drought events based on the selected thresholds.

Based on the streamflow drought climatology, we found that the basins with more (less) numbers of streamflow drought events have short (large) mean duration, and as longer (shorter) the mean duration, the larger (shorter) the cumulative deficit volume (Figure 2). There has been relatively limited research on the spatial aspects of

hydrological drought (Van Loon 2015). Our results show that the spatial pattern of streamflow drought characteristics is not homogeneous (see Figure 2) and is also related to the selected threshold. This may be associated with the role of catchment characteristics in the modulation of the drought signal from the meteorological to the hydrological deficits, a topic that deserves further research.

In order to summarize the temporal variabilities of streamflow droughts over the study area, we applied rotated principal component analysis to the annual indices linked to drought duration (ANDD) and drought severity (ACDV). Previous research used the same methodology for adequate regional drought monitoring considering meteorological (Portela *et al.* 2015; Penalba & Rivera 2016) and hydrological (Arabzadeh *et al.* 2016) drought assessment. Two geographically consistent regions were used: North Patagonia, comprising the Neuquén, Agrio, Quilquihue, and Cuyín Manzano river basins; and Central Patagonia, encompassing

the Manso, Quemquemtreu, Chubut, Carrileufú, Carren-leufú, and Senguerr River basins. Even when the study area has been considered as a homogeneous region in terms of monthly variations of streamflow (Compagnucci & Araneo 2005), our results show that the streamflow drought variability has two dominant modes. The limits of the North Patagonia region seem to be related to the hom-ogeneity observed in winter precipitation totals over central Chile and Argentina (Compagnucci & Vargas 1998). Therefore, the interannual variations in the stream-flow drought duration and severity over the North Patagonia basins can be linked to the variations in winter precipitation over the central Andes. In order to identify the main modes of variability over the homogeneous regions, we used the CEEMDAN to separate the interannual and decadal oscillations. This methodology allowed four modes of variability and a non-linear trend to be identifies. When we grouped the modes that account for the interann-ual variations in the ANDD, a consistent El Niño signal was identified, with 14 of a total of 18 El Niño episodes contri-buting to negative ANDD values over North Patagonia. In the case of La Niña episodes, the contribution was mainly to positive ANDD, although with a less consistent signal (nine of 16 episodes). The last results are in line with the observed influence of El Niño and La Niña events in snow-pack variations over the central Andes (Masiokas *et al.* 2006) and streamflow over Cuyo rivers (Compagnucci & Vargas 1998), just to mention two examples of the ENSO influence over the region. The El Niño signal in the inter-annual modes of ANDD over the Central Patagonia is less consistent, with 10 of 18 events contributing to negative ANDD, while the La Niña years contribute to positive ANDD in the same proportion as in North Patagonia. We can conclude that the El Niño signal on streamflow drought characteristics is less pronounced south of Cuyín Manzano basin, a result that is in line with the non-significant corre-lations obtained between the tropical SST anomalies and the mean seasonal streamflow in Chubut river (Compag-nucci & Araneo 2007). The same conclusions can be extended to the ACDV, given the strong relationship between streamflow drought duration and severity.

Regarding the low frequency variations, the leading pat-tern of circulation variability in the southern Hemisphere, i.e., the SAM, has a significant correlation with the decadal

component of the ANDD over the study area, although the strongest relationship is found in higher latitudes (i.e., Cen-tral Patagonia basins). Based on 42 sites distributed over Patagonia, Holz & Veblen (2011) found an association of positive SAM with increased fire activity due to drought con-ditions. The positive trends in the ANDD observed over the study area (see Figure 5, residual component) can be linked with the trend towards a positive phase of the SAM. This pattern led to an increase in the pressure in mid-latitudes (around 40°S) and a decrease in the pressure at high lati-tudes (around 65°S). The trend in the SAM is associated with a southward shift in the storm tracks, which led to a decrease in the number of cyclones over the southern hemi-sphere and a rainfall decrease, i.e., leading to more frequent streamflow drought conditions. This pattern can lead to a decrease in precipitation – both rainfall and snowfall – that partially explains the increase in the streamflow drought duration and severity during the last 50 years. Moreover, the SAM trend can be responsible for the observed shrinkage of Patagonian glaciers (Davies & Glasser 2012) and the recently documented forest decline across northern Patagonia (Rodríguez-Catón *et al.* 2016).

CONCLUSIONS

This work analyzed the statistical properties of the stream-flows over Argentinean Patagonia in terms of the occurrences of streamflow droughts. Based on the variable threshold level method applied to the daily hydrographs of the main Patagonian rivers, we obtained the characteristics of streamflow droughts – frequency, mean duration, and mean severity – over the 1962/63–2014/15 period. We found that drought frequency is related to its duration and severity, although the spatial pattern of streamflow drought characteristics is not homogeneous. The streamflow drought variability in terms of drought duration and deficit has two dominant modes: the rivers of North Patagonia (36°S–41°S), with large interannual variability and a consistent El Niño signal accounting for wet conditions, together with a contribution from the decadal variations of the SAM to dry conditions; and the rivers of Central Patagonia (41°S–46°S), with a relevant contribution of the decadal modes of the PDO and the SAM to dry conditions. Long-term

trends in the ANDD and ACDV are in line with the observed positive trend in the SAM index, especially after the 1970s and over Central Patagonia. Future projections indicate that, depending on the time horizon and scenario considered, the SAM trend is likely to continue during the 21st century, in agreement with expected changes in meteorological drought over Patagonia and – according to the findings of this study – with important implications for the decadal behavior of streamflow droughts. Given that the Andean rivers of Patagonia generate a large proportion of the total hydroelectric power of Argentina, the results obtained regarding streamflow drought characteristics and the different temporal variabilities have direct application for water resources management throughout the region.

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