# Recent trends in precipitation and streamflow in the Aconcagua River Basin, central Chile

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**Abstract**. In this paper, trends in streamflow and precipitation at the annual, seasonal and monthly timescales for different periods of records are analysed for the Aconcagua River Basin in central Chile. In this mountainous basin in the dry Andes water resources originate mainly from glaciers and seasonal snowcovers. The Mann-Kendall nonparametric test is used, and statistically significant trends are identified for each station on an annual, seasonal and monthly basis. Trends in streamflow are examined together with changes in precipitation and temperature. Analysis of correlation of the hydroclimatic variables with large-scale atmospheric circulation patterns such as the Southern Oscillation is also carried out. The main identified trend is a decrease in streamflow in the upper section of the basin, which is consistent at both the annual and seasonal scale. Changes in precipitation are not sufficient to explain the observed trend in runoff. Precipitation patterns, however, seem to have changed in the last 30 years, and results of seasonal trend analysis seem to indicate that there has been a shift in precipitation seasonality. Temperature at one station in the basin shows increasing trends at all temporal resolution. We argue that the decreasing trend in runoff might be explained by a decrease in glaciers and snowcover contribution to the total streamflow in the upper basin. Analysis of correlation reveals that both streamflow and precipitation are affected by ENSO events, and in particular that warm ENSO events are associated with an increase in winter and autumn precipitation, and an increase in summer streamflow.

**Key words**. Trend analysis; Hydroclimatic variability; Mann-Kendall test; Aconcagua river basin; ENSO; El Niño events; SOI.

## 1. INTRODUCTION

Mountainous catchments are the origin of many of the largest rivers in the world and represent a major source of water availability for many countries. They represent a local resource (local freshwater supply, hydropower generation), but also considerably influence the runoff regime of the downstream rivers. A change of climatic regimes due to the increase of the greenhouse effect as predicted by many studies is expected to affect the river systems originating in mountainous areas (Huber *et al*., 2005).

The debate on climate variability and climate change relies heavily on the detection of trends (or lack thereof) in instrumental records of hydroclimatic variables such as air temperature, precipitation and streamflow. In many parts of the world, and in particular in the United States, Canada and Europe, numerous large-scale analyses of hydroclimatic trends have recently been conducted on precipitation and streamflow data at different time scales (e.g. Lettenmaier *et al*., 1994; Karl & Plummer, 1995; Lins & Slack, 1999; Groisman *et al*., 2001; Zhang *et al*., 2001; Molnár & Ramírez, 2001; Burn & Hag Elnur, 2002; Kahya & Kalayci, 2004; Birsan *et al*, 2005). This is not the case for the South American continent, where analyses of trends in instrumental records of streamflow and precipitation are scarce (e.g. Rosenblüth *et al*, 1997). In this paper, we present a watershed-based analysis of streamflow and precipitation trends in a mountainous watershed in central Chile, the Aconcagua River Basin, with emphasis placed on the connection between observed changes in the precipitation and streamflow regimes and possible variations of glaciers in the area. This study is part of a larger investigation aimed to assess past and future variations in water resources in the basin, with special focus on the role played by glaciers and snowcovers. The Aconcagua Basin, located in the dry Andes and one of the major Chilean basins, depends heavily on glaciers and seasonal snow covers for its water supply. Precipitation is characterised by a typical annual pattern with very limited rainfall totals during summer and high precipitation during winter. In summer, almost all water supply to the basin, which is used for agriculture, domestic uses and industry, comes from the snow and ice melt in the upper basin. The basin is experiencing increasing pressure on its water resources and competition among different users for water allocation, because of the growing industrialisation, the large intensive agricultural production in the lower watershed and growing population. In this context, it is crucial to evaluate both future and past changes in the water resources in the basin. The study presented in this paper is a first step in this direction. We conduct a thorough examination of hydroclimatic data from different periods in order to identify seasonality, variability, trends and other properties of precipitation and streamflow at different time scales. Statistically significant trends are identified for each station on an annual, seasonal and monthly basis. Connections to large-scale climate anomalies which are relevant in the region, such as the Southern Oscillation (SO), are also established, and their effect on hydroclimatic variability is examined through correlation analysis.

The goals of this study are: 1) to identify significant trends in observed streamflow data and their occurrence in time and space in the Aconcagua river basin, with particular attention to its upper section; 2) to analyse the connection between observed changes in streamflow, precipitation and air temperature; 3) to analyse the correlation between hydroclimatic variables and global climatic indices representative of large-scale circulation patterns that are active in the region. Results of aims 1 to 3 will be used to attempt a preliminary investigation of the correlation between streamflow trends and watershed properties, in particular glacier coverage. This work complements a couple of previous studies on the Aconcagua Basin (e.g. Waylen & Caviedes, 1990; Montecinos & Aceituno, 2003), all of which however have focused on the impact of the El Niño – Southern Oscillation (ENSO) phenomenon on the interannual variability of precipitation and streamflow and not on trends analysis.

The methods used in this study are standard. Monthly, seasonal and annual precipitation, temperature and streamflow data were analysed for trends using the Mann-Kendall nonparametric trend test. A limitation of this study is that higher (i.e. daily) resolution data were not available. In order to discriminate trends from stochastic fluctuations and from the influence of serial correlation in time series, the series presenting a positive lag-1 serial correlation after detrending were prewhitened by applying a first order autoregressive filter to the data prior to the trend analysis. The data used in this study are described in Section 2 together with the main characteristics of the Aconcagua Basin, and the methods are discussed in Section 3. Section 4 lists the main results according to the goals of this study: first observed streamflow trends are presented, at the different time scales; then precipitation and temperature trends are shown and linked to the changes in streamflow. In Section 5 the results are discussed, and further analysis is suggested that should be conducted to complete this first step of the investigation. The main conclusions are listed in Section 7.

## 2. ACONCAGUA CASE STUDY AND DATA DESCRIPTION

The Aconcagua River is the largest mid-latitude river of Chile, and its characteristics are typical of the temperate latitudes of western South America. Located at the boundary between semi-arid and central Chile, it drains both the ice- and snow-fields of the Andes and Coastal Plain (Figure 1). The river basin is located about 50 km north of the national capital Santiago, and has a total area of 7.550 km$^2$. The river has a total length of about 214 km, flowing from East to West from the spring of Juncal to the mouth at Concón bay. Tributaries join along the main stream, maintaining baseflow, and flooding results from intense winter precipitation and summer snowmelt. The upper watershed has several peaks above 5000 m a.s.l. and vegetation is sparse. The Aconcagua upper section is essentially underdeveloped, and uses of economic significance in the upper watershed are limited to mining. In the lower watershed, on the contrary, intensive agricultural production depending almost entirely on irrigation takes place.

There are no dams in the basin, but water is used for agriculture and mining. All drinking water in the Aconcagua basin comes from melt water, which also sustains the rich irrigated agriculture in the lower basin. There is also increasing competition for water use and allocation, as water demands from mining and industry are rising. The basin was divided in an upper and lower section, the divide being the meteorological station of San Felipe (DGA station 25), which is considered as part of the upper watershed.

Hydro-climatic records for the basin were obtained from the Chilean Dirección General de Aguas (DGA). Monthly streamflow data from five stations in the upper basin were obtained. Selection of streamflow data was based on two criteria: 1) no substantial influence by water withdrawals for hydropower or other water-use purposes; 2) at least 30 years of continuous and complete observations. In this way, four stations were identified that were in operation in 2002 and had sufficiently long record. The stations are: Rio Aconcagua at Chacabuquito (14), Rio Juncal at Juncal (16), Rio Aconcagua at Blanco (17), and Rio Blanco at Blanco (18). In brackets is the DGA station number, which will be used throughout this paper to indicate the streamflow gauging stations. Of these stations, two were located directly on the Aconcagua course, and two on the two upper watershed tributaries of Rio Juncal and Rio Blanco. Location of the streamflow stations is shown in Figure 1 and basic information is given in Table 1. Trend analysis was conducted for two study periods: 1952-2002 for one site (station 14), and 1970-2002 for four sites (station 14, 16, 17 and 18).

Precipitation and temperature records were also analysed. Of the 15 meteorological stations provided by the DGA, nine stations were selected that had sufficiently long records (at least 30 years) (Figure 1 and Table 2). In contrast to the streamflow stations, which are located in the upper basin (Figure 1), the precipitation stations are situated both in the upper and lower section of the watershed. Throughout this paper, the meteorological stations will be referred to by their DGA station identification number. The analysis on the precipitation records was conducted for five periods: 1929-2004 (one station: 34); 1940-2004 (two stations: 34 and 18);

1954-2004 (three stations: 34, 18 and 26); 1965-2004 (seven stations: 34, 18, 26, 25, 28, 29 and 30); and 1974-2004 (all nine stations).

Temperature data were available from four DGA meteorological stations (stations 29, 33, 37 and 45). Of these, only station 29 (Vilcuya), had a number of years of records sufficient for the hydrological investigation (more than 30 years), and was therefore used in this study. The station is located in the upper section of the basin, between streamflow stations 14 and 15.

## 3. METHODS

### 3.1 Trend analysis

Trend analyses were conducted using the nonparametric Mann-Kendall (MK) test (Helsel & Hirsch, 1992). This test has been widely used for hydrological data analysis (e.g. Lettenmaier *et al.*, 1994; Molnár & Ramírez, 2001; Zhang *et al.*, 2001; Birsan *et al.*, 2005). It is a rank-based procedure especially suitable for non-normally distributed data, censored data, and nonlinear trends. Its advantages are that it is distribution free, robust against outliers, and has a higher power than many other commonly used tests (e.g. Hess *et al.*, 2001). The null hypothesis of randomness $H_0$ states that the data ($x_1, \ldots x_n$) are a sample of $n$ independent and identically distributed random variables. The alternative hypothesis $H_A$ is that the distributions of $x_k$ and $x_j$ are not identical for all $k, j \leq n$ with $k \neq j$. The null hypothesis is rejected at a significant level $\alpha$ if $|Z_s| > Z_{crit}$, where $Z_{crit}$ is the value of the standard normal distribution with an exceedance probability of $\alpha / 2$. A positive value of $Z$ indicates an upward trend, whereas a negative value indicates a downward trend in the tested time series. Statistically significant trends are generally reported at the 10% significance level (α = 0.1, two-tailed test), or confidence level β = 1 - α = 0.90, in this paper. The trend test statistic $Z$ is used as a measure of trend magnitude, or of its significance. It is not a direct quantification of trend magnitude.

The MK test should be applied to uncorrelated data (Helsel & Hirsch, 1992). It has been demonstrated that the presence of serial correlation decreases the power of the MK test and leads to an erroneous rejection of the null hypothesis (Type II error) (e.g. Kulkarni and von Storch, 1995; Yue *et al.*, 2002; Yue & Wang, 2002; Yue & Pilon, 2003). One of the most common corrections applied in previous studies has been to remove the serial correlation in the data by *prewhitening*, i.e. by applying the MK test to the series $x^*$: $x_i^* = x_i - r_1 x_{i-1}$, where $r_1$ is the lag-1 serial correlation coefficient of the detrended series (e.g. Yue *et al.*, 2002; Yue *et al.*, 2003; Yue & Pilon, 2003). In this paper, detrending was done by removing a linear trend in the data with slope $b$ estimated using the nonparametric Theil-Sen method. This method is suitable for nearly linear trend in the variable $x$ and is less affected by non-normal data and outliers (Helsel & Hirsch, 1992). The slope is computed between all pairs $i$ of the variable $x$ as:

$$\beta_i = \frac{x_j - x_k}{j - k} \quad \text{with} \quad j > k \left( j = 2,...,n; k = 1,...,n-1 \right) \qquad (1)$$

where $i = 1 \ldots N$. For $n$ values in the time series $x$, this will result in $N = n\,(n\text{-}1)/2$ values of $\beta$. The slope estimate $b$ is the median of $\beta_i$, $i = 1 \ldots N$. Prewhitening was applied only to time series with $r_1 > 0$. To check for the effect of the pre-whitening on the results, we analysed both original data as well as prewhitened data. Because serial correlation coefficients were generally low for the annual and seasonal time series, the differences between the two approaches were not large.

The method was applied to annual, seasonal and monthly data. Four climatological seasons were identified in the region, and analysed separately: Winter (June, July and August), Spring (September, October and November), Summer (December, January and February) and Autumn (March, April and May) (see e.g. Waylen and Caviedes, 1990; Montecinos and Aceituno, 2003). The analysis was conducted for streamflow, precipitation and temperature data, and it is reported separately for the three variables.

### 3.2 Correlation analysis with large-scale circulation patterns

In order to investigate the influence of global atmospheric circulation patterns on the hydroclimatic variables, correlation with indices of the general circulation of the atmosphere was carried out. The main natural interannual climatic fluctuation affecting the region under study is the El Niño – Southern Oscillation (ENSO) phenomenon (e.g. Aceituno, 1988; Waylen & Caviedes, 1990; Montecinos *et al.*, 2000; Montecinos & Aceituno, 2003; Waylen & Poveda, 2002; Schneider & Gies, 2004). Using established definitions, El Niño is the warm ocean current frequently observed in the eastern equatorial Pacific off the cost of Ecuador. In contrast to the El Niño, La Niña refers to an anomaly of unusually cold sea surface temperatures found in the eastern tropical Pacific. The large scale fluctuations in air pressure that are associated with the El Niño and La Niña ocean temperature changes are referred to as the Southern Oscillation (SO). The SO phase is negative during El Niño and positive during La Niña episodes. A detail explanation of the generation mechanisms of ENSO and its relation with Sea Surface Temperature (SST) and the thermocline can be found in Waylen & Poveda (2002).

The main effect of ENSO in central Chile is an increase in annual precipitation during El Niño events, which results mainly from an increase in winter precipitation (e.g. Waylen & Caviedes, 1990; Montecinos *et al.*, 2000; Montecinos & Aceituno, 2003). A decrease in rainfall during La Niña events, due to the strengthening of the anticyclone, has also been reported (Rubin, 1955; Aceituno, 1988; Rutllant & Fuenzalida, 1991). Several indices of the ENSO phenomenon exist (e.g. Waylen & Poveda, 2002). In this study, we employed the Southern Oscillation Index (SOI), defined as the difference of monthly atmospheric pressure anomaly between Tahiti (18 S, 150 W) and Darwin (12S, 131 W), Australia. Prolonged periods of negative SOI values correspond with abnormally warm ocean waters in the eastern tropical Pacific, which is typical of an El Niño event. Conversely, the prolonged positive SOI correspond with abnormally cold ocean waters in the eastern tropical Pacific, which is typical of a La Niña event (e.g. Schneider and Gies, 2004).

The standardised SOI was obtained from the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, and was downloaded at http://www.cpc.ncep.noaa.gov. For the details of the calculation the reader is referred to the NOAA website. The SOI has been used in several studies of climatic variation in Chile (e.g. Pittock, 1980; Aceituno, 1988) and in South America in general (e.g. Waylen & Poveda, 2002; Schneider & Gies, 2004). It was selected because of its definition on a monthly basis, its easy updating, and its close relationship to other SO indices (Wright, 1984; Aceituno, 1988).

In this work, we first compared monthly anomaly of streamflow and precipitation with the standardised monthly SOI. Second, we computed the correlation between SOI and monthly, seasonal and annual data. Time lag between time series were incorporated by allowing a lag up to 12 months.

## 4. RESULTS

The main results are reported in three sections. First, trends in streamflow are analysed for different time scales, and their spatial distribution in the upper Aconcagua basin is studied. Second, trends in precipitation and temperature are analysed and their connections with streamflow trends are explored. Third, results of the correlation analysis of streamflow and precipitation with the SOI index are reported.

It is clear that the study period has an impact on trend identification. It has been noted that runoff records may contain large-scale periodic behaviour, and that trend analysis should be conducted on periods that span one or multiple full cycles of this process if it exists (e.g. Pekarova *et al*., 2003). Figure 2 shows annual streamflow anomalies for station 14. It is clear from this figure that all the two study periods contain both high and low flow phases. We can therefore assume that the trend reported here for even the shortest study period are not due to low-frequency large-scale behaviour of the data and are representative of changes in the runoff regime.

### 4.1 Streamflow

#### Seasonality

Figure 3 shows the distribution of mean monthly streamflow at the five gauging stations. Runoff peaks in December, at the beginning of the austral summer, and it is very high in November (end of spring) and during summer (DJF). Runoff during summer is almost entirely due to snow- and ice-melt, as precipitation in the basin is very low during DJF (see Section below). During winter (JJA), streamflow is very low, varying between 5.6 % (at station 15) and 12% (at station 14) of the annual total. There are differences in the streamflow magnitude at the stations, with streamflow being the highest at the most downstream station 14, and decreasing at the upstream stations with higher elevation (Figure 3). Mean monthly streamflow in the peak month of December ranged from 13 $m^3 s^{-1}$ at station 16 to 78 $m^3 s^{-1}$ at station 14 (Figure 3). Differences in streamflow magnitude can be observed between station 17 and 18, which are situated in close proximity at the Blanco village. As an example, the mean monthly December streamflow (which is the maximum streamflow at both stations) is 42 $m^3 s^{-1}$ at station 17 and nearly half of this value at station 18 (22 $m^3 s^{-1}$). This is due to the fact that, although the two sites are very close to each other, station 17 is situated on Rio Aconcagua, while station 18 on the tributary Rio Blanco, which carries much less water. Seasonality, however, is coherent at all stations (Figure 3). Nevertheless, while the annual maximum is always in December at all stations, apart from station 16 (maximum in January, but with a minimum difference with respect to the December value), the timing of the annual minimum varies from station to station within the summer months. At the most downstream station (14) the minimum annual is in May, at station 15 is in June and at the three uppermost stations is in July.

There are also differences in the ratio of the minimum to the annual total from station to station, with station 14, the most downvalley one, having the lowest summer contribution of the five station (45.5 % of the annual total), and the highest winter contribution (11.8 % of annual total). This is a clear indication of the fact that the stations higher up in the upper basin, being fed almost solely by snow and glacier fields, have a more pronounced glacio-nival regime.

### Trends

Results of trend analysis on annual streamflow data for complete records show a decreasing trend at all stations, although the trend is significant only at station 17 and 18 (Figure 4). The $Z$ statistic for the analysis of trend conducted on the longer period of observations at station 14 is much smaller than the $Z$ obtained when analysing the common period of record (1970-2002). This is in agreement with findings of recent research on hydroclimatic trends, which suggest that longer periods of data exhibit fewer and less significant trends than shorter data periods (e.g. Birsan *et al*., 2005). Results of trend analyses on seasonal streamflow data for the four gauging stations are shown in Figure 5 for the common period of record. There is no common behaviour at the four stations in term of trends in the monthly and seasonal streamflow. While station 14 and 16 show both increasing and decreasing trends, none of them statistically significant, and with predominance of decreasing trends, station 17 and 18 exhibit consistently negative trends for all months, and statistically significant for all months but May at station 17. The observed decreases in annual streamflow have different explanations at station 14 and 16, and 17 and 18 respectively. At both stations 14 and 16, the observed annual decrease in streamflow comes primarily from a decrease in the high-flow months from December to February. Stations 17 and 18, on the contrary, exhibit a significant decrease all throughout the year, with the strongest decreasing trends in spring (SON) (Figure 5).

## 4.2 Precipitation and temperature

### Seasonality of precipitation

The monthly distribution of mean precipitation at the main gauges in the Aconcagua Basin is shown in Figure 6. On the average, most precipitation occurs between May and August, with 62 % of total during the winter months (JJA) at station 34. June and July are commonly the months with the highest observed precipitation. There is hardly any precipitation in the summer months of December, January and February (Figure 6), with summer precipitation being less than 2% of annual total at station 34.

### Trends

Results of trend analyses on *annual* precipitation data show no statistically significant trend at any of the stations and for any of the period of record considered (Figure 7). There is, however, an influence of the period of record on the results of the trend analysis. Trends at highest elevation station 34 are positive, although not statistically significant, in the three periods 1940-2004, 1954-2004 and 1965-2004 (Figure 7a, b and c). For the period of record 1929-2004, the trend in the annual data at this station is slightly negative and statistically not significant ($Z = -0.1$). Results for the common period of record 1965-2004 (seven stations) show consistently positive trends, although not statistically significant at any of the stations (Figure 7c). Analysis of trends for the common period of record 1974-2004 (all stations), however, reveals that there is no longer a coherent behaviour at the nine stations examined, with both positive and negative trends (Figure 7d). None of the trends in individual stations is statistically significant (Figure 7d). Figure 7d shows both increasing and decreasing trends, with a slight predominance of decreasing trends. Most noteworthy, the increasing trend at station 34 observed in the periods of record 1940-2004, 1954-2004 and 1965-2004 has been reverted into a decreasing trend. The same inversion can be observed at station 28 and 30.

Trend analyses were conducted also on *monthly* and *seasonal* precipitation data for the five periods of records. Results show no statistically significant trend at any station, but few after 1954 (Figure 8). The increase in annual precipitation observed at station 34 in the period 1940-2004 is caused by an increase in winter (JJA) and spring (SON) precipitation totals, which compensate the decrease in summer precipitation (Figure 8a). It has to be kept in mind, however, that summer has a much smaller contribution to total precipitation than both the winter and spring totals.

Seasonal trends at individual stations in the period 1954-2004, although not statistically significant, are consistently positive, in agreement with the results of annual data trend analysis (Figure 8b). Analysis of trend results in the period of record 1965-2004 shows that the annual increase in precipitation, which was observed at all stations, comes primarily from an increase in autumn (MAM) precipitation, which is consistent at all stations and significant at stations 18 and 29 (Figure 8c). On the other side, results of analysis of trends on seasonal precipitation totals in the period of record 1974-2004 clearly indicate that there has been a consistent decrease in the spring (SON) precipitation amount at all stations (Figure 8d), this effect being stronger at stations 28, 30, 25 and 26. No major changes have occurred in the periods 1965-2004 (seven stations) and 1974-2004 (nine stations) to the winter precipitation total (Figure 8c and d), which represents the main contribution to the annual total at all stations in the basin (see Figure 6).

Air temperature plays a crucial role in the water cycle of the upper Aconcagua, because of the impact it has on the occurrence of snowfalls and snowmelt in this highly mountainous basin. Analysis of trends in annual, seasonal and monthly temperature data conducted at meteorological station 29 for the period of record 1965-2004 showed a statistically significant increase in temperature at annual, monthly and seasonal scale (Table 3 and Figure 9). At the annual scale, the increasing trend is significant at 1% significance level. Trends in monthly temperature data are consistently positive in all months, and statistically significant in summer (December to February), in March, June, August and October-November (Figure 9).

### 4.3 Correlation with global climatic signals

Comparison of the time series of monthly mean streamflow anomalies at station 14 and standardised monthly SOI is shown in Figure 10. It is evident from Figure 10 that there is a strong inverse correlation between SOI and standardised streamflow during ENSO events. Maxima in the monthly streamflow record coincide with warm phase ENSO years (negative SOI) at all stations in the Aconcagua Basin (see for instance the event of 1977-78, of 1982-83 and of 1987-88 in Figure 10). In some years, runoff peaks can be observed in both the ENSO and ENSO-plus-one year, such as in the warm phase events of 1977-78 and 1982-83 (Figure 10). This might be explained by the increase in winter precipitation associated with warmphase ENSO events, which has been both documented by previous research (e.g. Waylen & Caviedes, 1990; Rutllant & Fuenzalida, 1991; Montecinos and Aceituno, 2003) and revealed by the analysis conducted in this study (see below in this section). Increased winter precipitation at high elevations leads to increased winter accumulation, which results in turn in an increase in summer melt and therefore runoff in the following summer. This mechanism has been reported by, among others, Cerveny *et al.*, 1987; Waylen & Caviedes, 1990 and Schneider & Gies, 2004.

Correlation coefficients at time lag 0, $\rho$, were computed between the time series of annual, seasonal and monthly streamflow at the five gauging stations and the SOI, and are listed in Table 4 for the seasonal time scale. Correlation coefficients are in general negative, in agreement with results of previous studies (e.g. Pittock, 1980; Schneider & Gies, 2004). At the monthly time scale, correlation coefficients vary from $\rho = -0.18$ at station 16 to $\rho = -0.28$ at station 14. Correlation analyses conducted on a seasonal basis between streamflow and SOI reveals a number of characteristics. First, correlation is always negative in all seasons and at all stations (Table 4), which is also in agreement with findings of the current literature that have shown that SOI is inversely correlated to streamflow. Second, in summer (DJF), when runoff is high and the contribution to annual total runoff is the highest, correlation coefficients are also high, varying between $\rho$ = -0.47 at station 18 and $\rho$ = -0.63 at station 15 (Table 4). This can be explained by increased temperature associated with the ENSO warm phase events (see below), and might also indicate that ENSO phenomena cause an increase in summer precipitation. Third, winter (JJA) correlation coefficients are also high, revealing the well documented increase in winter precipitation reported by several studies (see Waylen & Caviedes, 1990; Montecinos & Aceituno, 2003), which results in turns into an increase of winter runoff. Values of winter correlation coefficients are very high at station 14 ($\rho$ = -0.58) and 15 ($\rho$ = -0.52), which are situated in the lower part of the upper basin. Stations 17, 18 and 16, however, show smaller correlation coefficients (Table 4). At these sites, winter precipitation falls mainly as snow, and has therefore a limited effect on the winter runoff. It creates, however, a storage of water in the form of winter accumulation which will melt in the following summer season. This effect is particular evident at the highest station 16, which has the lowest correlation coefficient of all stations ($\rho$ = -0.17, Table 4).

Time series of mean annual, seasonal and monthly precipitation records were also correlated to the SOI. The results reveal that correlation coefficients are negative at both the annual and seasonal scale at almost all stations (Table 5). Annual correlation coefficients vary between $\rho$ = -0.40 (station 37) and $\rho$ = -0.55 (station 27), indicating that a stronger connection between precipitation and SOI at the annual scale exists than between streamflow and SOI. This was to expect, given that runoff is an integrated variable that is affected by the transformation of rainfall into runoff operated by the watershed. The three highest $\rho$ are found at station 34, 29 and 27, which are located in the upper section of the Aconcagua basin. At the annual scale, results seem to suggest that the effect of ENSO is more marked at the stations located in the upper section of the basin. Seasonal correlation coefficients also reveal a couple of interesting features. First, very strong correlation between precipitation and SOI can be observed in winter (JJA) at all stations (Table 5). As mentioned above, this funding agrees with the evidence produced by a number of other studies that looked at the effect of ENSO events on the hydroclimatic variability of the region. The order of magnitude of the correlation coefficient is very similar to that found by Aceituno (1988). Second, correlation coefficients in autumn (MAM) are also consistently negative and important. Less conclusive is the evidence about the summer (DJF) and spring (SON) seasons, which show both negative and positive $\rho$ of different, but always limited, magnitude.

Analyses of lags correlations for both streamflow and precipitation did not bring any insight into the relation of streamflow and precipitation with the SOI.

Mean monthly, annual and seasonal temperature was also correlated to the SOI, and results of the correlation analysis show a consistent negative correlation at all time scale. On a seasonal basis, the stronger negative correlation was found in autumn (MAM).

## 5. DISCUSSION

The analyses of recent trends in streamflow, precipitation and temperature in the Aconcagua Basin has revealed several interesting features of this mountainous basin originating in the dry Andes. Analysis of annual, seasonal and monthly trends in streamflow has revealed the existence of significant decreasing trends in the period 1970-2002 at stations 17 and 18 in the upper section of the basin. Decreasing trends, although not significant, were observed at all time scale at the remaining streamflow stations. This decrease in runoff observed in the uppermost stations suggests that progressively lower annual runoff is produced in the basin, especially in its upper section. In contrast to streamflow, annual and seasonal precipitation records do not show the same significant decreasing trends in recent decades. For the 40 years common period from 1965 none of the studied gauges in Table 2 exhibited a statistically significant trend in annual precipitation. We did not find significant trends in seasonal precipitation but in the spring (SON) precipitation at station 34 for the period of record 1954-2004 (positive); and in autumn (MAM) total at station 18 and 29 for the period of record 1965-2004 (positive) (Figure 8c). Most notable is that there are no significant trends in the precipitation amount in recent winter seasons, which represent the highest contribution to the annual precipitation totals (see Section 4.2 above). Analyses of seasonal precipitation in the shortest and most recent period of record (1974-2004) showed however an inversion in trend tendency at some stations, with stations 34, 28 and 30 seeing negative trends in both annual (Figure 7d) and spring mean runoff time series (Figure 8d). None of these trends is however statistically significant. The results of this analysis show that trends in precipitation and streamflow in the Aconcagua Basin in recent periods are not well correlated, and that changes in spring (and to a less degree winter) precipitation measured at some rain gauges can only partly explain the trends in streamflow observed in the upper basin since 1972.

A factor that needs to be considered when studying the relationship between driving climatic factors such as temperature and precipitation and their effect on the integrated catchment variable streamflow are the characteristics of the watershed. In this case, a predominant characteristic of the basin is the presence of glaciers and extensive snow covers. The decrease in streamflow observed in the upper basin could be explained by a progressive change in glaciers area and volume in the basin, corresponding to the retreat of the glaciers. This would explain the decrease in runoff observed at the two gauging stations that are closest to the glacier-covered area of the basin (statistically significant decreasing trends), which is reflected to a lesser extent in the time series records at the stations downvalley (15 and 14, statistically not significant decreasing trends). Evidence of glacier retreat and thinning in central Chile during the 20$^{th}$ century has been provided by Casassa (1995) and Rivera *et al.* (2002). Rivera *et al.* (2002) examined glacier surface and thickness variations for 95 Chilean glaciers, and concluded that a general glacier recession has occurred in central Chile, with an average estimate of 12.8% of area loss in the last 51 years from 1945-96. The hypothesis that glaciers have been retreating in the recent past in the Aconcagua upper section and are therefore contributing less to the downvalley streamflow is corroborated by the results of temperature trends, which showed a statistically significant increase in monthly, seasonal and annual temperature in the common period of record 1965-2004. This result is in agreement with findings of previous studies on temperature trends (Rosenblüth *et al.*, 1997, Carrasco *et al.*, 2005), which have indicated statistically significant warming since the end of 19$^{th}$ century to the end of the 20$^{th}$ century in central Chile. Carrasco *et al.* (2005) obtained an overall warming of 1.3-2.1 °C in minimum near-surface air temperature in central Chile during the period from 1961 to 2001, and a warming of 0.2-1.5 °C in maximum temperature. A sustained positive change in air temperature will likely affect both the summer snowmelt, by enhancing it, and the phase of the winter precipitation, by increasing the amount of precipitation that falls as liquid precipitation, thus decreasing glacier storage. This seems to be confirmed by the fact that the negative temperature trend reported is due to changes in minimum temperature rather than in maximum (Rosenblüth *et al.*,1997; Carrasco *et al.*, 2005). For the same reasons, it is likely that also the extension and depth of the seasonal snow covers in the area have been decreasing, as it might be inferred also from the results of Carrasco *et al.*, 2005, which have shown an increase of the snow line elevation in central Chile in the last quarter of the 20$^{th}$ century by 127 m. Glacier changes in the Aconcagua Basin, however, are difficult to document because of limited data (e.g. Rivera *et al.*, 2002). A current new mapping of the glacier extension in the area is been undertaken by the authors in cooperation with Centro de Estudios Cientificos, Chile, using images of ASTER satellite. They will allow comparison of the actual glacier extent with that derived from the older maps of the Instituto Geografico Militar of the Chilean Army that were made during the 1970s, and therefore assessment of changes intervened in the last 30 years. It is evident from the analysis in this paper that this is a key step to be carried out to interpret the observed hydroclimatic trends in the context of recent glacier cover changes in the basin.

Analysis of hydroclimatic variability has often been conducted at the monthly and annual time scale for the South American region (e.g. Pittock, 1980; Aceituno, 1988; Montecinos *et al.*, 2000; Schneider & Gies, 2004). This is partly due to the fact that data are often available only at this time resolution. In this respect, our study is standard. In order to completely understand the observed variability in hydroclimatic factors in the basin, however, it will be crucial to perform the analysis of trends at higher time resolution. Several recent studies have shown that analysing trends in annual or monthly streamflow totals cannot provide the complete picture of runoff behaviour (e.g. Chiew & McMahon, 1996; Molnár & Ramírez, 2001; Birsan *et al.*, 2005). Comprehensive trends analysis conducted in the United States (e.g. Lettenmaier *et al.*, 1994; Lins & Slack, 1999; Groisman *et al.* 2001) and Canada (e.g. Zhang *et al.*, 2001; Burn & Hag Elnur, 2002) have shown that both precipitation and streamflow records exhibit a complex behaviour in which trends significance depends on flow magnitude and season. Shifts in the distribution were observed, with high and low frequency exhibiting different behaviour in different seasons. The results of these and other studies have demonstrated that in many cases only detailed examination of high resolution (i.e. daily) streamflow data can identify the complex changes that may have occurred in the instrumental record (e.g. Chiew & McMahon, 1996). The analysis conducted in this paper has already highlighted differences in trend behaviour between seasons (see Section 4.2). This need to be complemented by analyses of trends in event frequency, event intensity, in different quantiles and in particular in precipitation and streamflow maxima, in wetness (number of wet days), etc., as it has been done in recent contributions for watersheds in Europe or North America (e.g. Molnár & Ramírez, 2001, Birsan *et al.*, 2005).

There is a lack of trends analysis conducted in the South-American region and in particular in central Chile (Rosenblüth et al., 1997), and this paper intended to contribute to explore this issue in the region. Most of the studies conducted in the region have focused on the impact of the ENSO on hydroclimatic variability (e.g. Waylen & Caviedes, 1990; Montecinos &

Aceituno, 2003). The results of our analysis of SOI correlation with streamflow, precipitation and temperature records are in agreement with previous findings. Winter precipitation has been shown to increase during El Niño years (e.g. Montecinos & Aceituno, 2003).This was confirmed by our analysis, which has shown that winter (JJA) precipitation correlates very well with SOI (high negative correlation coefficients at all stations). Correlation coefficients between mean seasonal runoff and SOI were also high in winter at the stations at the lower elevation in the upper basin, reflecting the increase in precipitation that causes an increase in runoff at lower elevation. At higher elevation, precipitation falls as snow and does not affect the runoff in that season (while it will in the following summer). Summer streamflow also correlates well with SOI, probably because of increase in temperature associated with El Niño events. In addition to confirming previous findings, our study has provided evidence for correlation between SOI and autumn (MAM) precipitation (Table 5), suggesting that warmphase ENSO years cause an increase not only in winter, but also in autumn precipitation.

Results of trend analysis on seasonal precipitation data in the period of records 1965-2004 and 1974-2004 reveal an interesting feature of the precipitation pattern in the recent decades. Figure 8d shows that in the most recent period of record (1974-2004), autumn (MAM) precipitation totals have consistently increased and spring (SON) totals have consistently decreased at all stations, while no major changes have occurred in winter precipitation totals (no trends at all or small negative trends, such as at station 34, 28 and 27, see Figure 8d). This might suggest that from 1974 a shift in precipitation seasonality has occurred in the Aconcagua Basin, with more precipitation falling in autumn and less in spring. This is likely going to impact the glaciers mass balance, in that precipitation falling as snow at the onset of the melt season covers the glacier with a highly reflecting layer with high albedo that slows down the melt process by reducing absorption of shortwave incoming radiation. The effect of fresh snowfalls on the glacier albedo and melt at the onset of the ablation season has been demonstrated by Brock *et al.* (2000). Less precipitation falling as snow in the upper basin in spring, together with increased temperature (see Section 4.2), might have contributed to shift the onset of the melt season. This might suggest an earlier start of the melt season in the last thirty years. Such a precipitation pattern was observed for the period of record 1974-2004, which corresponds to the period analysed for streamflow trends in which statistically significant decreasing trends in mean runoff at the two stations 17 and 18 in the upper basin were observed.

A contribution of this paper has been to highlight a decrease in streamflow in the recent decades in the upper section of the Aconcagua Basin. Recent literature suggests that increasing runoff trends are found in many parts of the world (e.g. Birsan *et al.*, 2004), associated with increasing precipitation and/or temperature. The preliminary results presented here, however, seem to suggest that no increase in runoff took place in the upper section of the Aconcagua Basin from 1972. This is to connect with the hydrological character of the basin, which has a glacio-nival regime dominated by snow- and ice-melt, and in which therefore glaciers and snow cover play a crucial role in determining the streamflow regime. Decrease in glacier and snow cover extension, which has been documented for this region by a recent study (Rivera *et al*., 2002), could counteract the effect of increased precipitation and determine an overall decrease in streamflow. The finding of this paper should be supported by further analysis with more complete data sets.

In order to interpret the observed hydroclimatic trends in the context of recent glacier cover changes, therefore, this investigation needs to be complemented by two further steps of analysis: 1) analysis of high resolution (i.e. daily) data; 2) a more complete analysis of changes in the glacier volume and area and in the snowcover extension. Both steps have been already undertaken by the authors, and results will be published in a follow-up paper.

## 6. CONCLUSIONS AND OUTLOOK

This paper has provided a first assessment of the hydroclimatic variability in the Aconcagua River Basin, and in particular in its upper section, as it was reconstructed from monthly means of streamflow, precipitation and temperature records. Two types of analysis were conducted. First, the impact of global climatic signals on the interannual variability of streamflow was investigated through correlation analysis in order to gain a complete picture of the factors affecting the variability of streamflow. Second, analysis of trends was conducted to detect changes in the hydroclimatic variables on the long term.

With respect to the first part of the analysis, this study has confirmed the findings of previous studies conducted in the region suggesting that ENSO has an effect on the streamflow and precipitation regimes during both its warm and cold phase, and that increased winter precipitation is associated with warm phase ENSO events. In addition to previous findings, our work has also shown that the increase in winter precipitation associated with warm phase ENSO years is accompanied also by an increase in autumn (MAM) precipitation. On a longer time scale, this work has provided initial evidence of a consistent decrease in annual, seasonal and monthly streamflow at the stations in the upper basin in the most recent period of record 1970-2004, which might be attributed to a change in glacier streamflow contribution. Seasonal snowcovers, on the other side, might also have been decreasing in the last decades, as it might be inferred by the decrease (although statistically not significant) in precipitation observed in the same period at some stations and the consistent increase in temperature exhibited by station 29 and observed at other stations in central Chile (Rosenblüth *et al*., 1997; Carrasco *et al*., 2005).

This evidence will have to be confirmed by further research including both analysis of longer and higher resolution data records and analysis of changes in glacier runoff. This study is part of an ongoing extensive investigation aimed at assessing the past and future variations of water resources in the upper Aconcagua Basin with emphasis put on the role played by glaciers and snow cover. The analysis conducted in this paper is a first step towards the identification of the causes of the recent hydro-climatic variations. The two next steps that need to be taken are: 1) analysis of trend of daily data and quantiles of the distribution at all stations in the basin (these data have been very recently made available by DGA to the authors); 2) connection of observed changes in streamflow with recent changes in glacier cover and extension in the basin. Evidence of glacier shrinkage in central Chile has been provided by Casassa (1995) and Rivera *et al*. (2002). These studies have shown that from 1945 on glaciers in the area have been thinning and retreating, with an average rate of surface loss higher than in the other regions of Chile. In this context, it would be appropriate to investigate when the glacier shrinkage and consequent contribution to runoff have taken place most intensely, in association with the increase in minimum and maximum temperature suggested by some authors (Rosenblüth et al., 1997; Carrasco et al., 2005). The results of this investigation seem to suggest that the increase in the melt water production from the glaciers in the upper section of the Aconcagua Basin took place earlier, and that the glaciers are actually in a phase of lesser contribution to the basin streamflow than before. Accordingly, a new mapping of glacier extension is being currently undertaken by the authors, which could be used in the future to relate the observed trends, or lack thereof, in streamflow to the basins attributes and in particular to the presence of glaciers and their extension. Analysis of daily data and in particular of the quantiles distribution is currently under investigation, and will be published in a following paper.

**Acknowledgements**

The Chilean Dirección General de Aguas (DGA) is gratefully acknowledged for providing the hydroclimatic data for this analysis. We would like to thank Marius Birsan for his help with trend analysis, and Peter Molnar for useful discussions about this article. We thank Lars Ribbe for providing the original Figure 1. FP would like to thank José Araos for support when

FP was in Chile. We gratefully acknowledge the comments of two anonymous reviewers that considerably improved the final manuscript.

**REFERENCES**

Aceituno, P. (1988) On the functioning of the Southern Oscillation in the South America Sector. Part I: Surface Climate. *Monthly Weather Rev.*, **116**, 505-524.

Birsan, M. V., Molnár, P., Burlando, P. & Pfaundler, M. (2005) Streamflow trends in Switzerland. *J. Hydrol.*, **314 (1-4)**, 312-329.

Brock, B. W., Willis, I.C., Sharp, M. J. & Arnold, N. S. (2000) Modelling seasonal and spatial variations in the surface energy balance of Haut Glacier d'Arolla, Switzerland. *Ann. Glaciol.*, **31**, 53-62.

Burn, D. H. & Hag Elnur, M. A. (2002) Detection of hydrologic trends and variability. *J. Hydrol.*, **255**, 107-122.

Carrasco, J. F., Casassa, G. & Quintana J. (2005) Changes of the 0 C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century. *Hydrol. Sci. J.*, **50 (6)**, 933-948.

Casassa, G. (1995) Glacier inventory in Chile: current status and recent glacier variations. *Ann. Glaciol.*, **21**, 317-322.

Cerveny, R. S., Skeeter, B. R. &Dewey, K. F. (1987) A preliminary investigation of a relationship between South American snow cover and the southern oscillation. *Monthly Weather Rev.*, **115**, 620-623.

Chiew, F.H.S. & McMahon, T.A. (1996) *Trends in historical streamflow records. Regional Hydrological Response to Climate Change*, J.A.A. Jones (editor), Kluwer, 63-68.

Groisman, P. Y., Knight, R. W. & Karl, T. R. (2001) Heavy precipitation and high streamflow in the contiguous United States: trends in the twentieth century. *Bull. Amer. Met. Soc.*, **82 (2)**, 219-246.

Helsel, D.R. & Hirsch, R. M. (1992) *Statistical Methods in Water Resources*, Elsevier, 522 pp.

Hess, A., Iyer, H. & Malm, W. (2001) Linear trend analysis: a comparison of methods. *Atmos. Environment* **35**, 5211-5222.

Huber, U. M, H. K. M. Bugmann & A.M. Reasoner (Eds.), (2005) *Global Change and Mountain Regions: An Overview of Current Knowledge*, “Advances in Global Change Research” series, Vol. 23, Springer, 650 p.

Kahya, E. & Kalayci, S. (2004) Trend analysis of streamflow in Turkey. *J. Hydrol.*, **289**, 128-144.

Karl, T. R. & Plummer, N. (1995) Trends in high-frequency climate variability in the twentieth century. *Nature*, **377**, 217-220.

Kulkarni, A. & von Storch, H. (1995) Monte Carlo experiments on the effect of serial correlation on the Mann-Kendall test of trend. *Meteorol. Z.*, **4 (2)**, 82-85.

Lettenmaier, D. P., Wood, E. F. & Wallis, J. R. (1994) Hydro-climatological trends in the continental United States, 1948-88. *J. Climate*, **7**, 586-606.

Lins, H. F. & Slack, J. R. (1999) Streamflow trends in the United States. *Geophys. Res. Lett.*, **26 (2)**, 227-230.

Molnár, P. & Ramírez, J, G. (2001) Recent trends in precipitation and streamflow in the Rio Puerco basin. *J. Climate*, **14**, 2317-2328. Montecinos, A., Díaz, A. & Aceituno, P. (2000) Seasonal diagnostic and predictability of rainfall in subtropical South America based on tropical Pacific SST. *J. Climate*, **13**, 746-758.

Montecinos, A., Díaz, A. & Aceituno, P (2000) Seasonal diagnostic and predictability of rainfall in subtropical South America based on tropical pacific SST. *J. Climate*, **13**, 746-758.

Montecinos, A. & Aceituno, P. (2003) Seasonality of the ENSO-related rainfall variability in central Chile and associated circulation anomalies. *J. Climate*, **16**, 281-296.

Pekarova, P., Miklanek, P. & Pekar, J. (2003) Spatial and temporal runoff oscillation analysis of the main rivers of the world during the 19$^{th}$-20$^{th}$ centuries. *J. Hydrol*. **274**, 62-79.

Pittock, A.B. (1980) Patterns of climatic variations in Argentina and Chile. Part I: Precipitation, 1931-1960. *Monthly Weather Rev*., **108**, 1347-1361.

Rivera, A., Acuña, C., Casassa, G. and Bown F. (2002) Use of remote sensing and field data to estimate the contribution of Chilean glaciers to the sea level rise. *Ann. Glaciol*., **34**, 367-372.

Rosenblüth, B., Fuenzalida, H. A. & Aceituno, P. (1997) Recent temperature variations in Southern South America. *Int. J. Climatol.*, **17**, 67-85.

Rubin, M. J. (1955) An analysis of pressure anomalies in the Southern Emisphere. *Notos*, **4**, 11-16.

Rutllant, J. & Fuenzalida, H. (1991) Synoptic aspects of the central Chile rainfall variability associated with the Southern Oscillation. *Int. J. Climatol*., **11**, 63-76.

Schneider, C. & D. Gies (2004) Effects of El Niño-Southern Oscillation on Southernmost South America precipitation at 53 S revealed from NCEP_NCAR reanalyses and weather station data. *Int. J. Climatol*., **24**, 1057-1076.

Waylen, P. R. & Caviedes, C. N. (1990) Annual and seasonal streamflow fluctuations of precipitation and streamflow in the Aconcagua River basin, Chile. *J. Hydrol*., **120**, 79-102.

Waylen, P. R. & Poveda, G. (2002) El Nino – Southern Oscillation and aspects of western South American hydro-climatology. *Hydrol. Processes,* **16**, 1247-1260.

Wright, P. B. (1984) Relationships between the indices of the Southern Oscillation. *Monthly Weather Rev*., **112**,1913-1919.

Yue, S., Pilon, P. & Cavadias, G. (2002) Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J. Hydrol.*, **259**, 254-271.

Yue, S. & Pilon, P. (2003) Interaction between deterministic trend and autoregressive process. *Water Resour. Res*., **39 (4)**, doi:10.1029/2001WR001210.

Yue, S., Pilon, P. & Phinney, B. (2003) Canadian streamflow trend detection: impacts of serial and cross-correlation. *Hydrol. Sci. J*., **48 (1)**, 51-63.

Yue, S. & Wang, C. Y. (2002) Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. *Water Resour. Res.*, **38 (6)**, doi:10.1029/2001WR000861.

Zhang, X., Harvey, K.D., Hogg, W.D. & Yuzyk, T. R. (2001) Trends in Canadian streamflow. *Water Resour. Res.*, **37 (4)**, 987-998.

## Tables

**Table 1**. Streamflow stations used in this study. In bold are the yearly period for stations that are used in this paper for trend analysis. Station 15 is used for analysis of seasonality only.

| Name of station | DGA n. | Lat. | Long. | Elevation (m) | Drainage area ($km^2$) | Observation period |
|---|---|---|---|---|---|---|
| Rio Aconcagua at Chacabuquito | 14 | 32 50 | 70 34 | 1030 | 2400 | 1950 – 2002 (**53**) |
| Rio Colorado en Colorado | 15 | 32 52 | 70 25 | 1062 | 743 | 1976 – 2002 (27) |
| Rio Juncal en Juncal | 16 | 32 53 | 70 09 | 1800 | 233 | 1970 – 2002 (**33**) |
| Rio Aconcagua en Rio Blanco | 17 | 32 54 | 70 19 | 1420 | 875 | 1970 – 2002 (**33**) |
| Rio Blanco en Rio Blanco | 18 | 32 55 | 70 19 | 1420 | 382 | 1970 – 2002 (**33**) |

**Table 2**. Precipitation stations. In bold are those where long term temperatures were used for trend analysis.

| Name of station | Lat. | Long. | Elevation (m) | DGA n. | Observation period |
|---|---|---|---|---|---|
| Resguardo Los Patos | 32 30 | 70 36 | 1220 | 18 | 1940-2004 |
| San Felipe | 32 45 | 70 43 | 640 | 25 | 1962-2004 |
| Catemu | 32 44 | 70 56 | 440 | 26 | 1954-2004 |
| Los Andes | 32 50 | 70 36 | 820 | 27 | 1972-2004 |
| Lo Rochas | 32 47 | 71 17 | 175 | 28 | 1964-2004 |
| **Vilcuya** | **32 52** | **70 28** | **1100** | **29** | **1965-2004** |
| Rabucco Estero | 32 51 | 71 07 | 300 | 30 | 1965-2004 |
| Riecillos | 32 56 | 70 21 | 1290 | 34 | 1929-2004 |
| Los Aromos | 32 57 | 71 22 | 100 | 37 | 1974-2004 |

**Table 3**. Trend statistic Z for seasonal and annual temperature data at station 29, for the period of record 1965-2004. In bold are statistically significant trends. All significant trends are at 1% significance level.

| DJF | MAM | JJA | SON | Annual |
|---|---|---|---|---|
| **2.74** | 1.54 | **3.16** | **3.03** | **2.94** |

**Table 4**. Correlation coefficients between mean seasonal streamflow and mean seasonal standardised SOI at the five streamflow stations.

| Station | DJF | MAM | JJA | SON |
|---|---|---|---|---|
| **14** | *-0.49* | -0.30 | -0.58 | -0.37 |
| **15** | *-0.63* | -0.22 | -0.52 | -0.41 |
| **16** | *-0.52* | -0.16 | -0.17 | -0.12 |
| **17** | *-0.54* | -0.09 | -0.30 | -0.28 |
| **18** | *-0.47* | -0.13 | -0.24 | -0.28 |

**Table 5**. Correlation coefficients between mean seasonal precipitation and mean seasonal standardised SOI at the meteorological stations. In bold the seasonal correlation coefficients higher than 0.5.

| Station | Annual | DJF | MAM | JJA | SON |
|---|---|---|---|---|---|
| **18** | -0.48 | -0.13 | -0.36 | **-0.60** | -0.03 |
| **25** | -0.47 | -0.17 | -0.43 | **-0.60** | -0.06 |
| **26** | -0.49 | -0.21 | -0.33 | **-0.62** | -0.05 |
| **27** | -0.55 | -0.23 | -0.42 | **-0.65** | -0.23 |
| **28** | -0.45 | 0.02 | -0.36 | **-0.55** | -0.01 |
| **29** | -0.54 | -0.09 | -0.41 | **-0.62** | -0.23 |
| **30** | -0.41 | 0.26 | -0.36 | **-0.55** | -0.02 |
| **34** | -0.51 | -0.15 | -0.38 | **-0.57** | -0.31 |
| **37** | -0.40 | 0.06 | -0.38 | **-0.54** | -0.21 |

## Figure captions

**Figure 1.** Aconcagua River Basin with the location of the meteorological and streamflow stations. Stations are identified by the numbers of the Dirección General de Aguas (DGA).

**Figure 2**. Standardised annual streamflow $Q$ from station 14 in the period 1950-2002. $Q$ is computed by subtracting to the annual streamflow its long-term mean.

**Figure 3**. Mean monthly streamflow distribution over the period of record at the Aconcagua gauges from Table 1. Stations are identified by their DGA number.

**Figure 4**. Trend statistic $Z$ for annual streamflow data for the four stations analysed for trends. The sign of $Z$ indicates trend direction. Results are shown for the pre-whitened data. Analyses are both for the common period of record (1970-2002) and at station 14 also for the period 1950-2002. In grey are the statistically significant trends, in black the not statistically significant ones.

**Figure 5**. Trend test statistics for seasonal streamflow totals at the four gauging stations analysed for trends. The sign of $Z$ indicates trend direction. In grey are the statistically significant trends, in black the statistically not significant trends. Analyses are for the common period of record (1970-2002).

**Figure 6.** Distribution of mean monthly precipitation totals over the period of record at five of the nine Aconcagua gauges from Table 2. Stations are indicated by their DGA number.

**Figure 7**. Trend test statistic $Z$ for annual precipitation total at individual stations for the period of records: a) 1940-2004 (stations 34 and 18); b) 1954-2004 (stations 34, 18 and 26); c) 1965-2004 (stations 34, 18, 26, 25, 28, 29 and 30); and d) 1974-2004 (all stations). The sign of $Z$ indicates trend direction. Grey indicates statistically significant trends, black indicates no statistically significant trends.

**Figure 8.** Trend test statistic $Z$ for seasonal precipitation totals at individual stations for the period of records: a) 1940-2004 (stations 34 and 18); b) 1954-2004 (stations 34, 18 and 26);

c) 1965-2004 (stations 34, 18, 26, 25, 28, 29 and 30); and d) 1974-2004 (all stations). Statistically significant trends are indicated by an arrow.

**Figure 9.** Trend test statistic $Z$ for monthly mean temperature at station 29. The sign of $Z$ indicates trend direction. Grey indicates statistically significant trends; black indicates no statistically significant trends.

**Figure 10**. Time series of the standardised monthly South Oscillation Index (SOI) and of standardised monthly mean streamflow $Q$ at station 14, for the period 1951-2002. Positive values of SOI indicate cold phase ENSO events (La Niña) and negative values warm phase ENSO events (El Niño). The grey boxes indicate warm ENSO events.

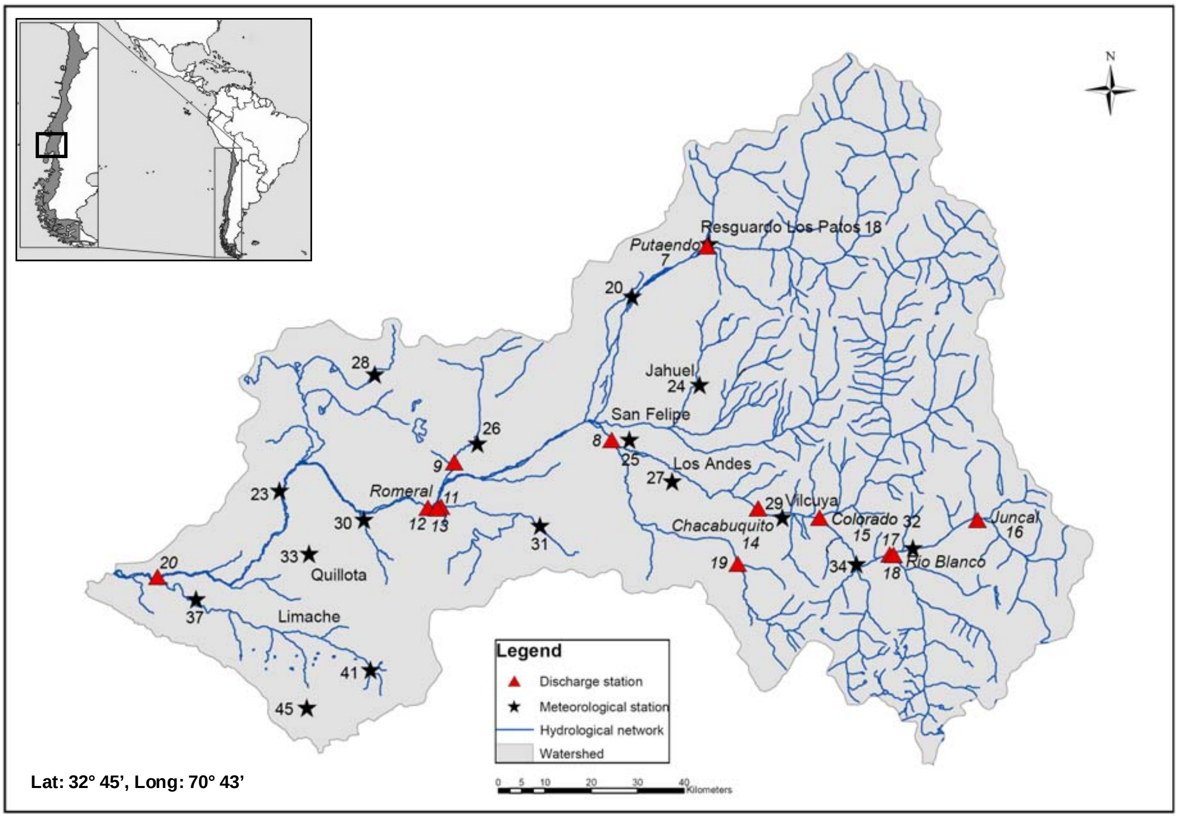


**Figure 1**

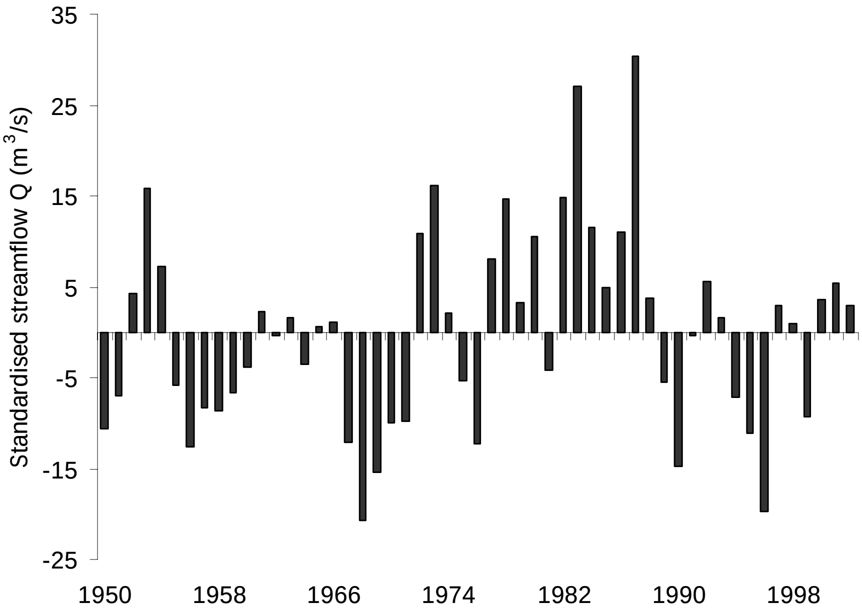


**Figure 2**

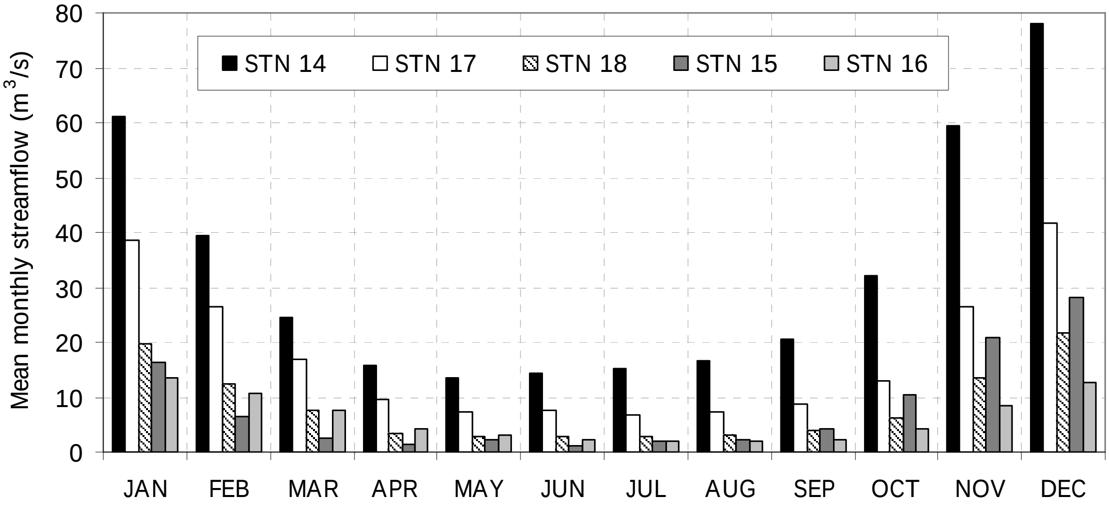


**Figure 3**

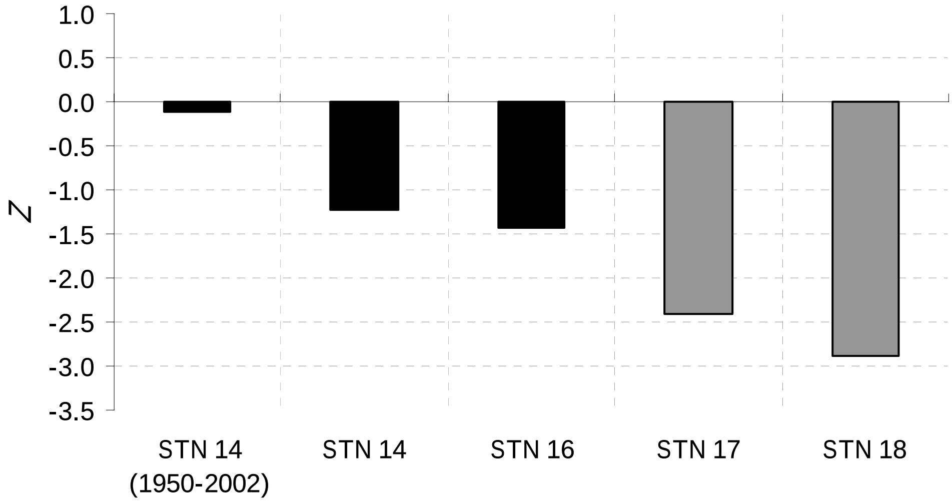


**Figure 4**

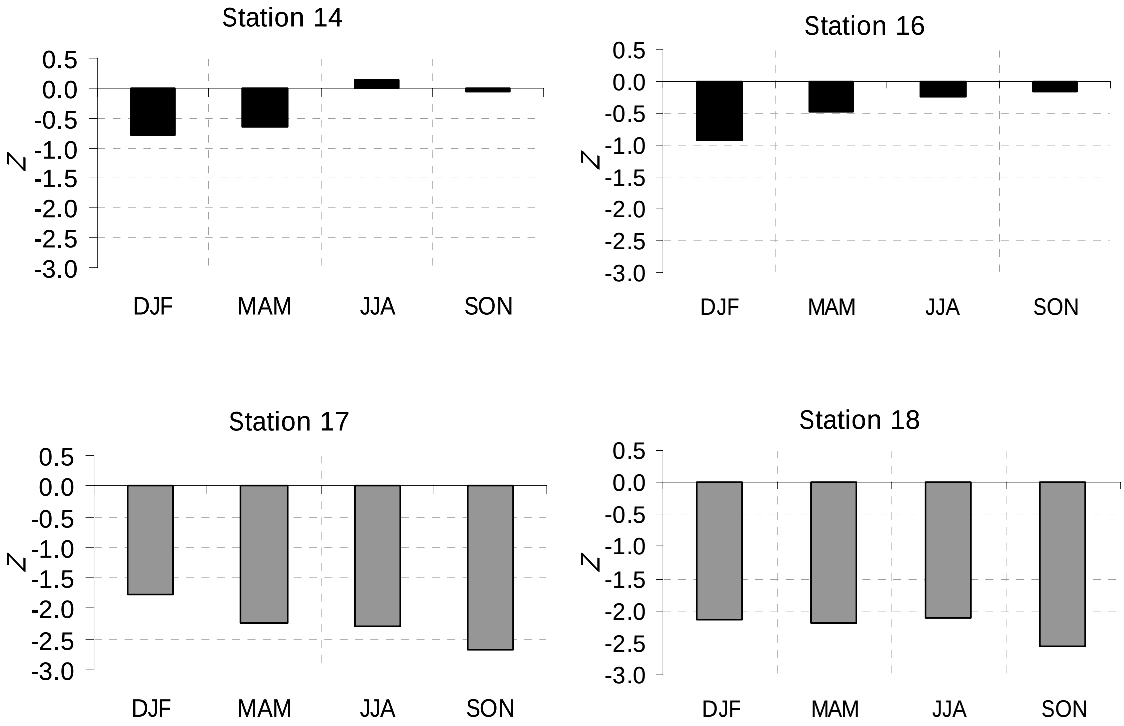


**Figure 5**

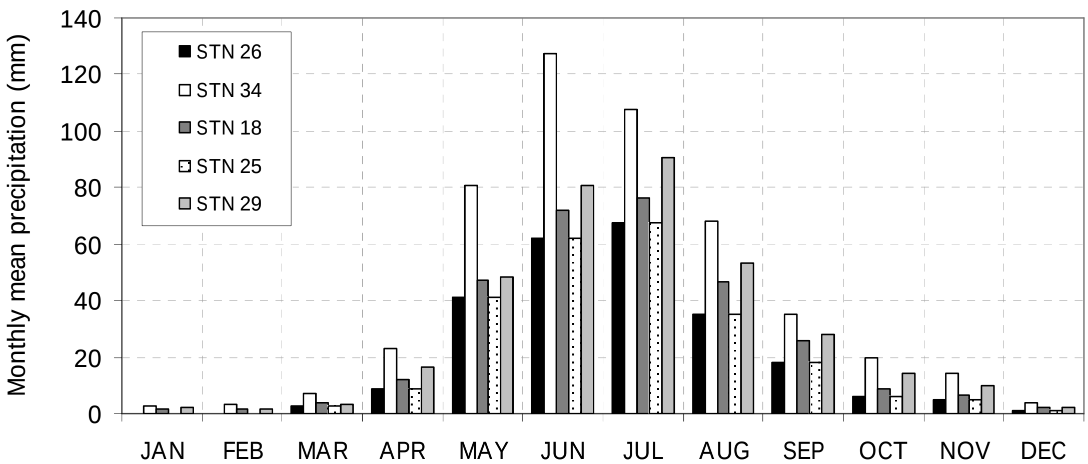


**Figure 6**

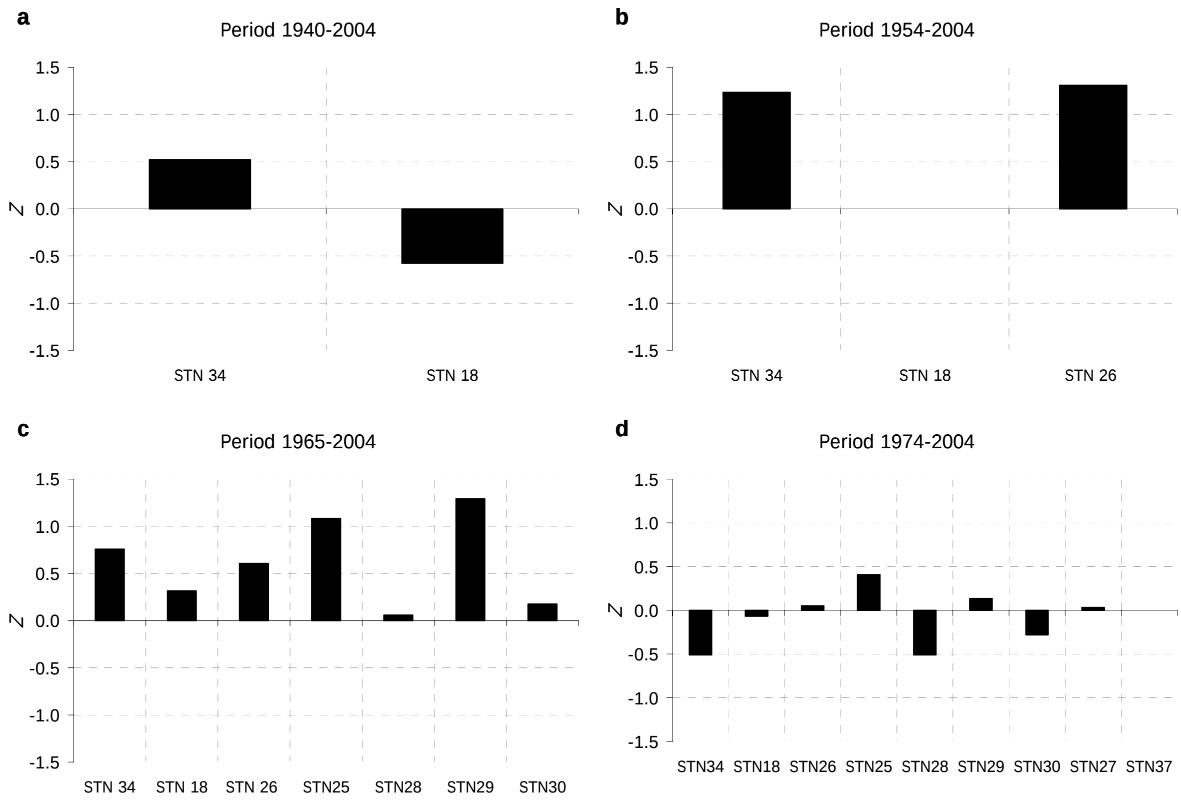


**Figure 7**

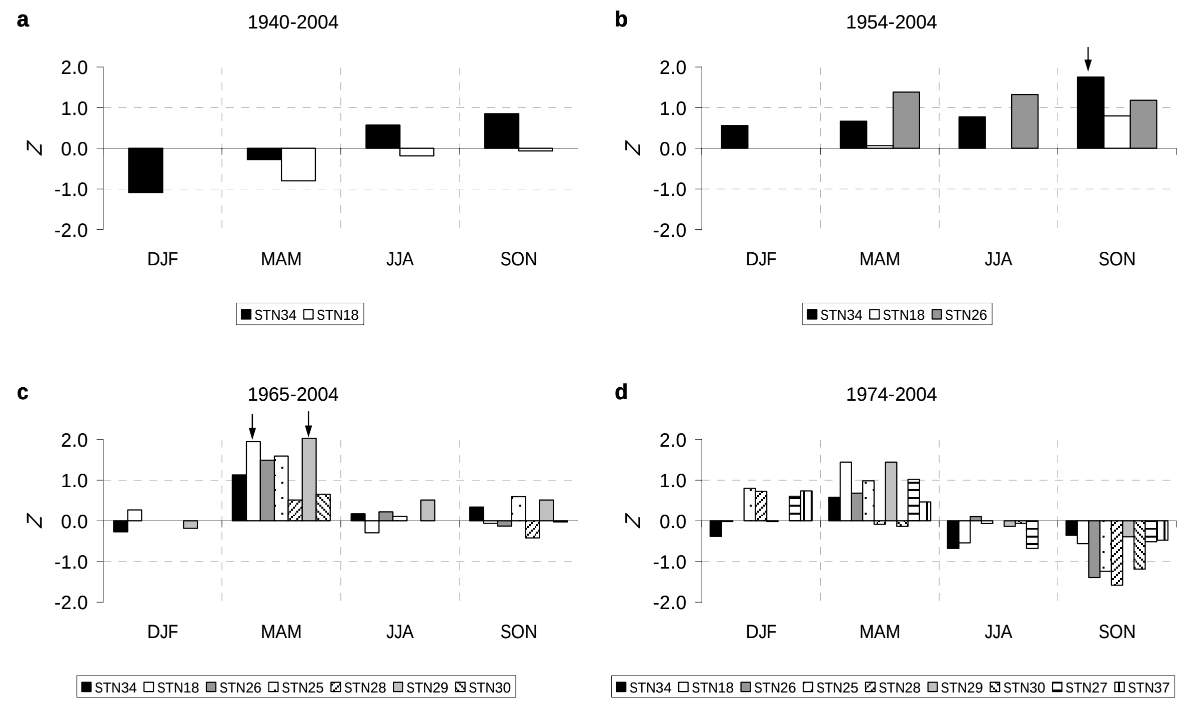


**Figure 8**

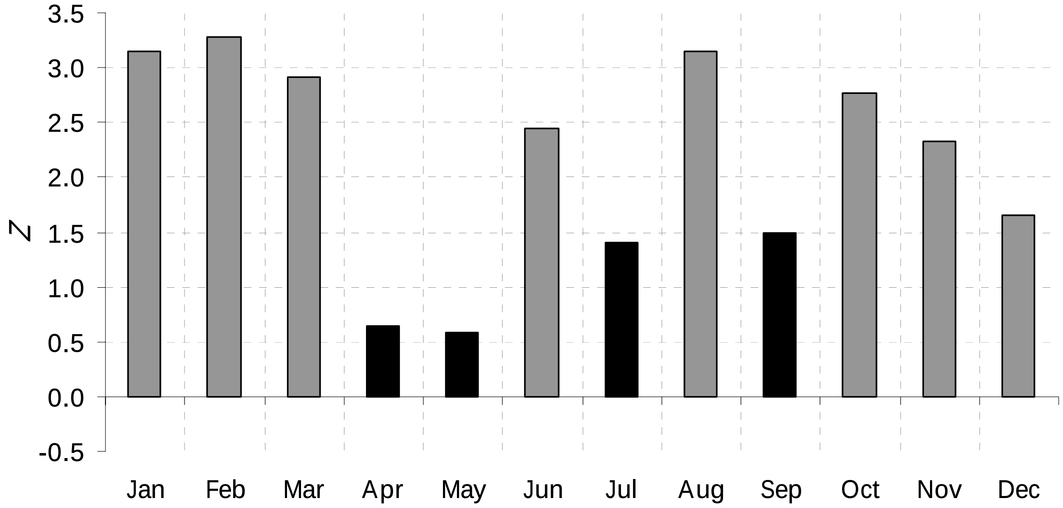


**Figure 9**

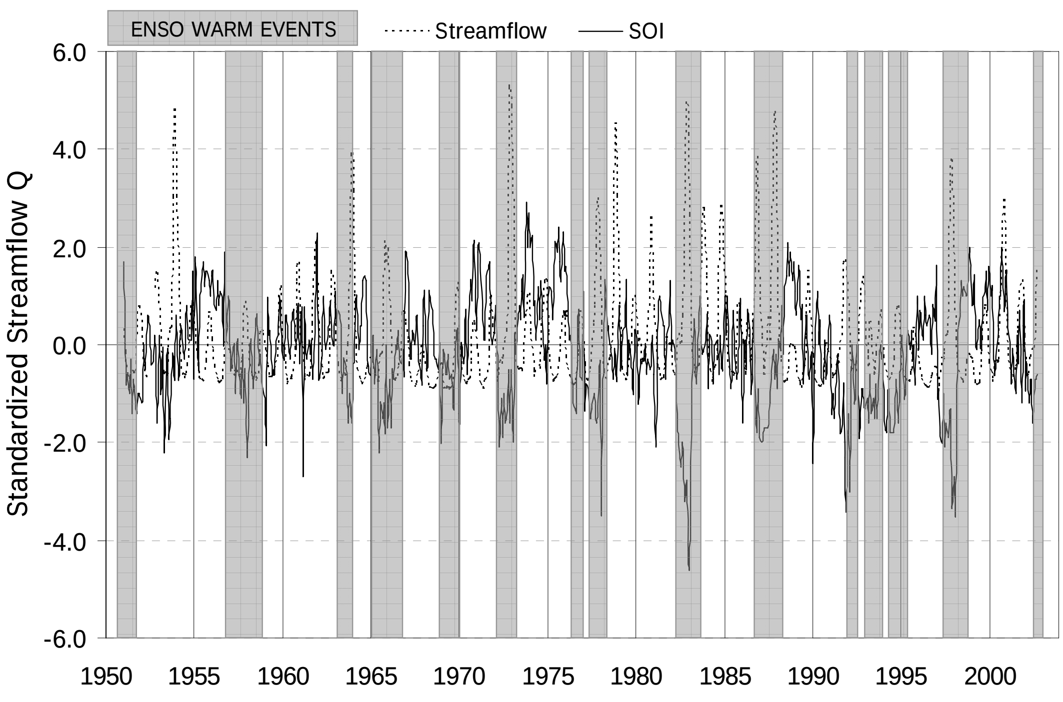


**Figure 10**