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Water availability reconstructions using tree-rings in the Valdivian rainforest ecoregion, Chile

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Abstract. Water availability can be considered as one of the main restrictions for future development in South-Central Chile, due to the reported decreasing trends in precipitation in the last decades and the increasing demand for this resource. This issue makes the study of past water availability fundamental for the understanding of present and future variations. This paper presents a comparison of two water availability reconstructions within the Valdivian rainforest ecoregion (35º-48ºS), one corresponding to a precipitation (37º-39.5º S) and the other to a streamflow reconstruction (41º S). This study shows that there are fundamental differences between them especially in the long term variability. However, there are also coincidences, mainly at higher frequency variations, such as at a bidecadal, decadal and annual scale. Another important finding is that these reconstructions show significant correlations with different climatic forcings in this area. The northern reconstruction presents a significant relationship with ENSO (El Niño Southern Oscillation), while the southern does the same with the AAO (Antarctic Oscillation Index).

1. Introduction

Water availability has been acquiring an increasing importance in South-Central Chile, especially considering the reported decreasing trends observed in the instrumental precipitation records during the last century (between 40% and 60% of decrease in the period 1901-2005, Trenberth et al., 2007), the unprecedented increment of extreme drought events during the last century in the context of the previous six (Christie et al. 2009), the regional glacier retreat (Masiokas et al. 2009), and the continuing decreasing rainfall projected for this area (Fuenzalida et al., 2007). This scenario imposes a restriction for future development even in areas with a relatively high amount of precipitation, such as the Valdivian rainforest ecoregion (35º-48º S, Lara et al., 2008). This region has been declared among the most threatened areas of the world by the Global Initiative 200 (WWF, World Bank), due to the high degree of plants and animals endemisms, as well as to the threats to different ecosystems and critical conservation status.

Given these circumstances and the development of important activities that require water within this region (agriculture, forestry, hydropower production), it is essential to understand changes in water availability in a long term perspective in this area.

Tree-rings provide annual records, being one of the proxies most commonly used to reconstruct past climate variability. Long streamflow and precipitation reconstructions can be developed by correlating tree-growth series with natural discharge and rainfall, respectively. Several streamflow reconstructions have been developed in North America (e.g., Stockton and Jacoby 1976; Meko et

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al. 1995; Hidalgo et al. 2000; Woodhouse 2001; Brito-Castillo et al. 2003; Woodhouse and Lukas, 2006; Meko et al., 2007) and a smaller number in South America, two of them in Argentina (Holmes et al. 1979 ; Cobos and Boninsegna 1983). In addition, a number of precipitation reconstructions have been developed in South America, especially in Chile and Argentina (Boninsegna, 1998, Villalba et al, 1998, Le Quesne et al., 2006).

As the number of studies reconstructing water availability is reduced in South America and two of them have already been developed in the Valdivian rainforest ecoregion in Chile, the objective of this study is to compare both reconstructions in order to assess differences in the past variability of water availability at these two distinct locations. One of them refers to a streamflow reconstruction (Lara et al., 2008) and the other to a precipitation reconstruction (Peña et al., not published), both covering the last 400 and 335 years, respectively.

2. Study area

The study area corresponds to the Valdivian rainforest ecoregion in South-Central Chile (35º-48º S). Climate in this area varies from Mediterranean in the north, where rainfall is concentrated in austral fall and winter (April-August, Miller, 1976) to Oceanic wet temperate in the south, with two dry months in summer (January-February). The precipitation reconstruction was developed for the Temperate-Mediterranean Transition zone in the Andes (TMTAN, approx. 37° - 39.5° S), corresponding to a transitional situation between southern temperate and northern Mediterranean influences. The streamflow reconstruction, on the other hand, was developed in a watershed characterized by an oceanic wet temperate climate with mild Mediterranean influence (41º S, Lara et al., 2008).

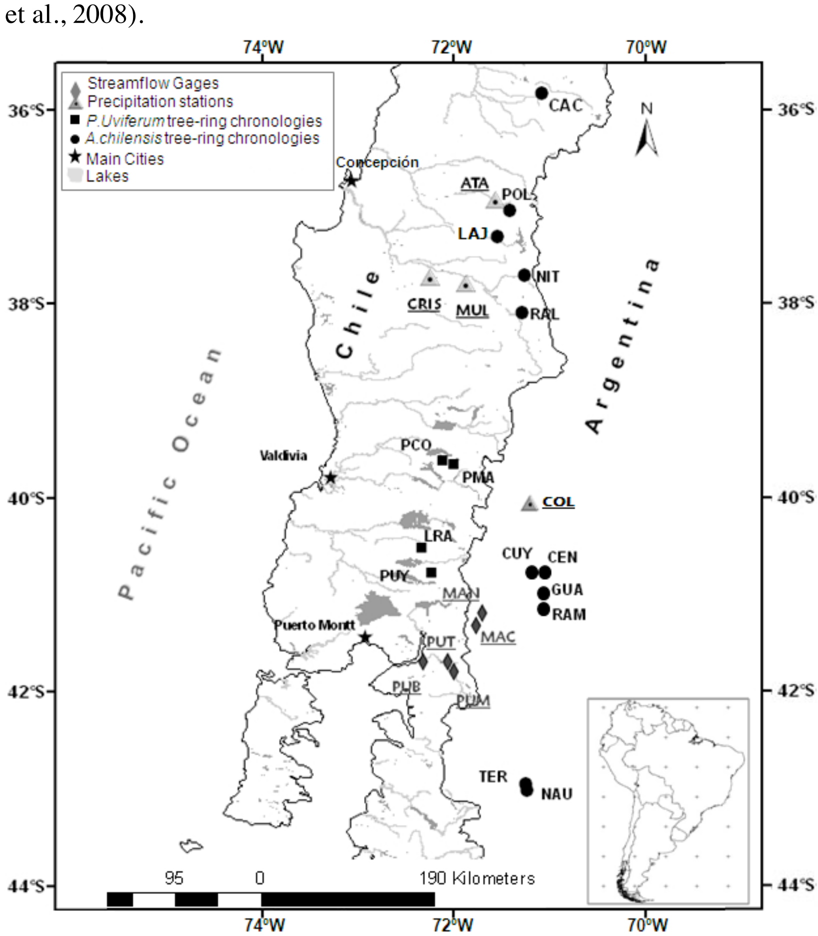

Figure 1. Regional map showing the location of the tree-ring chronologies, precipitation stations and streamflow gages that were used in the TMTAN precipitation reconstruction and the Puelo river streamflow reconstruction.

Climate variability in the ecoregion is driven by both low- and high latitude climatic forcings. Toward the northern portion (~35°-38°S), El Niño events are characterized by positive rainfall anomalies during late-spring (Montecinos & Aceituno, 2003). Conversely, toward the southern portion (40°-42°S), El Niño events are characterized by negative rainfall anomalies during summer (Montecinos & Aceituno, 2003).

The Antarctic Oscillation Index (AAO) also influences climate across the Valdivian rainforest ecoregion. The AAO corresponds to the leading principal component of 850hPa anomalies south of 20°S (Thompson and Wallace, 2000). Positive values in this index are associated with low geopotential height over Antarctica and increased values, and consequently dry conditions, over mid-latitudes and thus, over the study area.

3. Water availability reconstructions

A late spring-early summer precipitation reconstruction was developed for the Temperate-Mediterranean Transition zone of the Andes using five *Austrocedrus chilensis* tree-ring chronologies (CAC, POL, LAJ, NIT, RAL, Peña et al., not published, Figure 1). In order to preserve a large percentage of the low-frequency variance (decadal-multidecadal variability), the standardization process was done by fitting each ring width to a negative exponential or linear regression curve, using the TURBO ARSTAN program (Cook, 1985). This 335-year reconstruction was developed by regressing the November-December precipitation on principal components (PCs) of standard chronologies' selected lags (t-1, t, t+1, predictors) using a stepwise multiple regression. The reconstruction explained 41% of the total variance in the late spring-early summer precipitation for the whole calibration period (1937-2002, Figure 2). The selected reconstruction period represents 7.5% of the annual rainfall, representing a portion of the precipitation falling during the dry season.

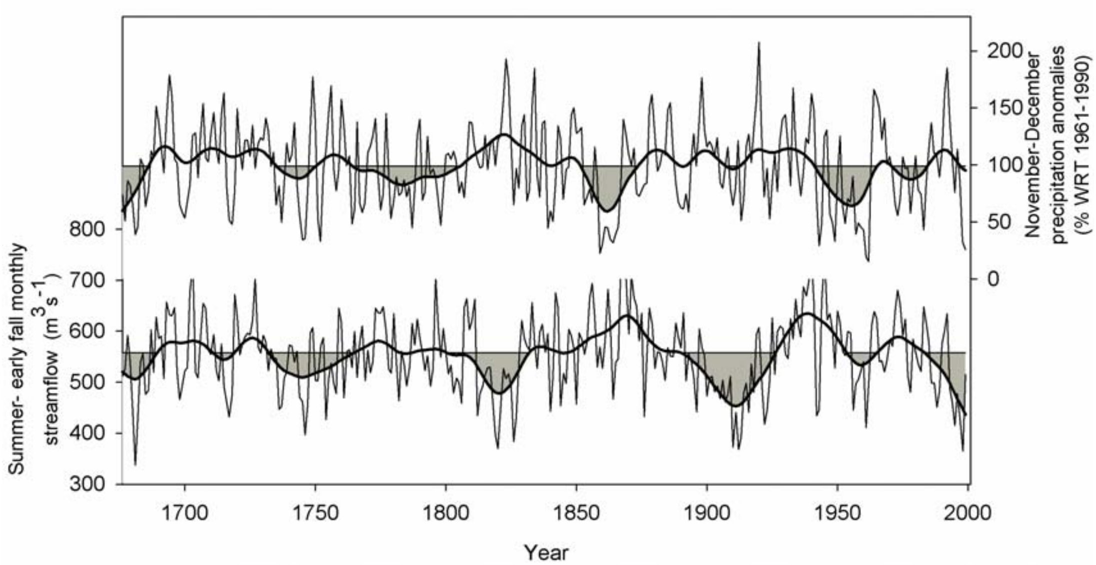

Figure 2. November-December precipitation reconstruction for the TMT of the Andes (top). December-May streamflow reconstruction for the Puelo river (bottom). Both reconstructions cover the period 1676-1999. To emphasize the long-term variations, a cubic spline version designed to reduce 50% of the variance in a sine wave with a periodicity of 25 years is also shown for both reconstructions (Cook and Peters, 1981).

Additionally, a summer-early fall streamflow reconstruction was developed for the Puelo river (Lara et al., 2008), a watershed shared with Argentina, that has its mouth at approximately 41° 35' S in the Reloncaví estuary (Figure 1). The 400-year streamflow reconstruction used three composite *Austrocedrus chilensis* and one composite *Pilgerodendrum uviferum* tree-ring chronologies which were also standardized using the method mentioned above. The reconstruction equation was estimated by regressing the summer-early fall streamflow on principal components of the four composite tree-ring chronologies. This reconstruction also accounted for low frequency variability, explaining 42% of the total variance in the December-May streamflow for the entire calibration period (1943-1999, Figure 2). The summer-early fall reconstruction period is the season when water availability becomes critical for different uses (salmon farming and sport fishing, among others) and represents 21% of the annual streamflow.

It is important to mention that the conifers used in this reconstruction are endemic of Chile and Argentina, andhave clear annual growth rings that are sensitive to moisture supply.

4. Comparison of both water availability reconstructions

Comparing both reconstructions (Figure 2), it is possible to see that they mostly present a different behaviour. The pronounced decreasing trend in the last decades in the streamflow reconstruction (also present in the instrumental record) is not observed in the precipitation reconstruction toward the north. Additionally, most of the multi-year periods of low and high water availability do not match between them, except for a few cases where there is a partial coincidence (e.g. around 1680, 1740, 1960). Despite this differential behaviour at a multi-year scale, there is a significant correlation between them ($r=0.24$, $p<0.05$).

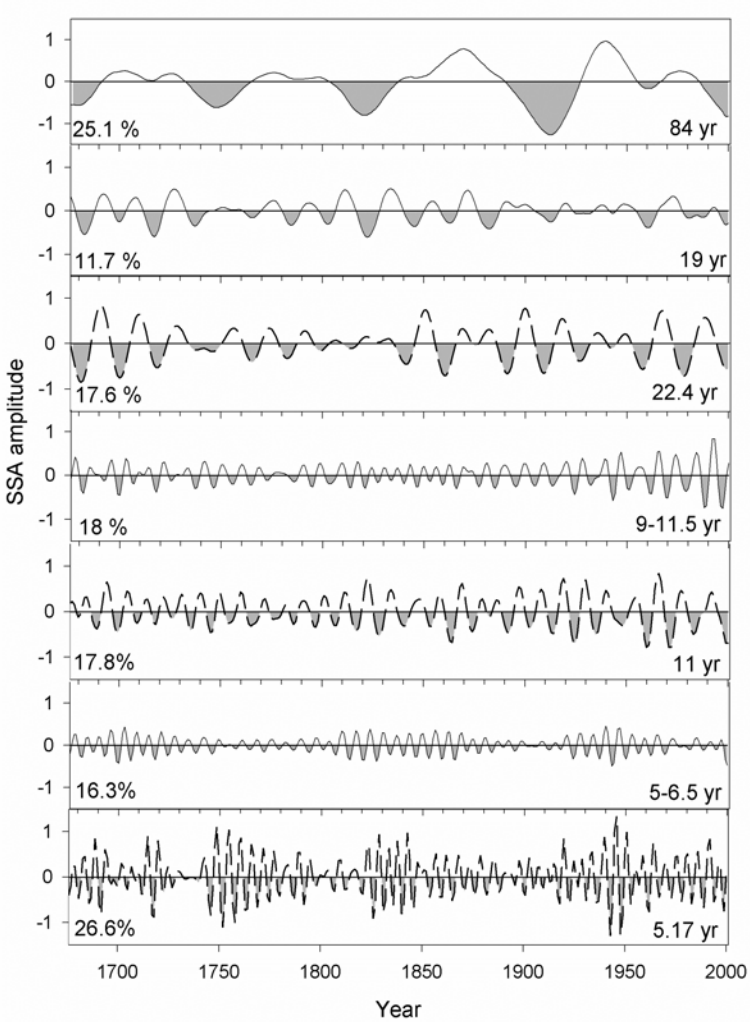

Figure 3. The most significant oscillation modes estimated using Singular Spectrum Analysis (units are dimensionless) for both reconstructions (solid lines for the Puelo river streamflow reconstruction and dashed lines for the TMTAN precipitation reconstruction). Periods in years and the percentage of variance associated with each waveform are shown in the lower right and left corners of the streamflow waveforms, respectively.

The major differences between both reconstructions might be explained by looking at the main oscillation modes, obtained through singular spectral analyses using a lag of 12% of the series length (31 years,Vautard and Ghil, 1989, Figure 3). The main difference is that the southern reconstruction shows a prominent multidecadal cycle of 84 years that explains the largest percent of the variance (25%), and that is not observed in the precipitation reconstruction toward the north. It has been stated that the decreasing trend of the Puelo river in the last six decades forms part of this cycle that has been increasing its negative amplitude through time (Lara et al., 2008). In the case of the precipitation reconstruction the largest percent of the variance is explained by a much shorter-term mode, the 5.17 year cycle. However, it is possible to observe that there are coincidences in the bidecadal cycles of 19 and 22 years in the precipitation and streamflow reconstructions, respectively, and also in the decadal cycle of around 11 years presented in both cases. Correlations among them are r= 0.4 (n=325) for the bidecadal cycle and r=0.27 (n=325), for the decadal cycle. These correlations do not account for autocorrelation in the series, therefore the level of significance is not provided.

The bidecadal and decadal oscillation modes may be explained by the 22-year Hale cycle and the 11-year sunspot cycles, respectively, both invoked to explain these modes, not only in the Puelo river streamflow reconstruction, but also in two millenial temperature reconstructions using *Fitzroya cupressoides* (Villalba et al., 1996, Lara et al., 2008).

Finally, both reconstructions present the oscillation mode close to 5 years, although the amplitude is much larger in the case of the precipitation reconstruction. This cycle might be attributed to the ENSO activity that is more conspicuous to the north.

5. Water availability reconstructions and climatic forcings

As mentioned before, ENSO and the AAO have a strong influence on climatic variability in this area. Figure 4 shows the best correlations found between water availability reconstructions and these forcings. In this figure it is possible to see that the northern late spring-early summer precipitation reconstruction is significantly and negatively correlated with the spring-early summer Southern Oscillation Index (SOI, http://www.cru.uea.ac.uk/cru/data/soi.htm). This means that high (low) SOI values or La Niña (El Niño) events are related with low (high) precipitation anomalies in this area. Conversely, the summer-early fall streamflow reconstruction is mostly related to the Antarctic Oscillation Index (http://jisao.washington.edu/data/aao/slp/) in summer, relationship also found for the observed streamflow record (Lara et al., 2008). Although the northern reconstruction includes part of the summer, no significant correlation was found between this one and the AAO and between the southern reconstruction and the SOI. These correlations demonstrate the influence of climatic forcings at different seasons of the year on the variability of water availability in this area. Toward the south the recorded positive trend of the AAO (Marshall, 2003) could be influencing the pronounced decreasing trend in the streamflow in this area, however its influence is not observed toward the north, at least during the late spring-early summer season.

6. Conclusions

Reconstructing past water availability using tree-rings in south-central Chile is essential to understand the last decades' changes in a long term perspective and to improve the future water resources allocation in the Valdivian rainforest ecoregion in Chile. This region is especially important due to its conservation status and the different activities that develop and compete within this area. In this study, two existing water availability reconstructions were compared, providing a broad characterization of the low frequency water availability changes that have affected this ecoregion in the last 325 years. Their comparison also contributes to the understanding of the main differences in variability at two locations within the area (approx. 37º-39.5º and 41º S).

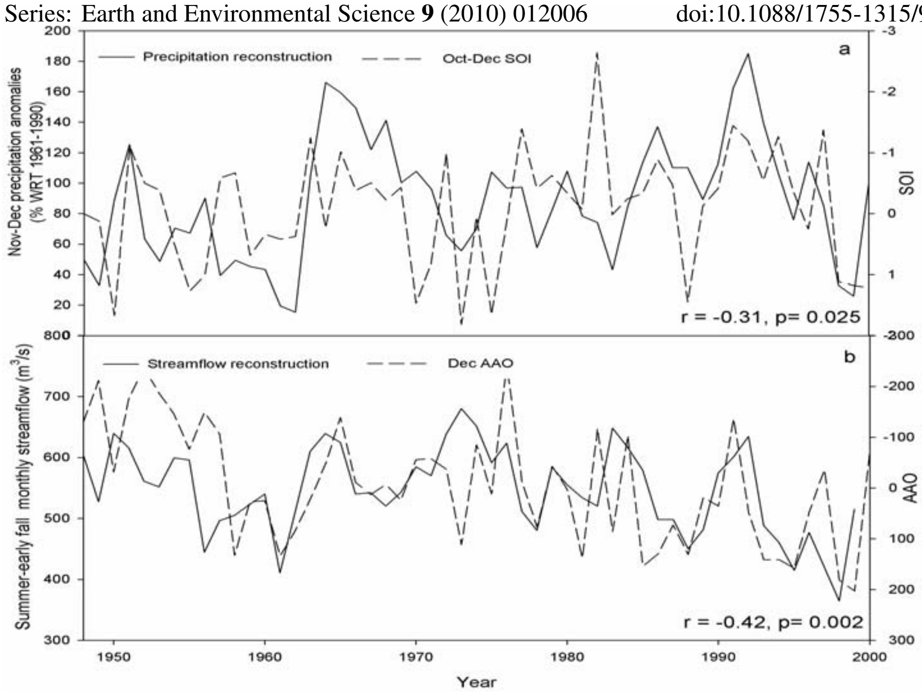

Figure 4. a) Late spring-early summer (November-December) precipitation reconstruction for the TMTAN zone and its relation with the October-December Southern Oscillation Index (SOI) for the 1948-1999 period. This index is inverted to clearly appreciate wet (El Niño) and dry (La Niña) periods. Correlation between both is shown. b) Summer-early fall (December-May) Puelo streamflow reconstruction and its relation with the December Antarctic Oscillation Index for the same period. This index has been inverted to facilitate the comparison with the streamflow data. Correlation between both is also shown.

Both the precipitation reconstruction in the northern site and the streamflow reconstruction in the southern area present major differences in the multidecadal low-frequency variability that characterize them, but not in the decadal-bidecadal variability that is more closely related. This could be partially attributed to the differential and contrasting effects of ENSO events between both locations and to the stronger modulation of AAO over the local hydroclimate toward the southern portion of the study area (Garreaud et al. 2009). However, it is important to be careful in the comparison, since streamflows may carry the effects of other factors besides precipitation, and since hydrological events are usually out of phase with or lag the occurrence of meteorological episodes.

Both reconstructions appear to be affected by climatic forcings in this area, ENSO especially influencing late spring-early summer precipitation behavior toward the north and the AAO affecting summer-early fall water availability toward the south. The current and projected increasing trend in the AAO, could be a real threat for water availability in the ecoregion, enhancing the actual decreasing trend in streamflow in the southern area, although its influence might be less prominent toward the north. More studies are needed to comprehend latitudinal variations in past water availability in South-Central Chile, as well as the forcings that are responsible for these changes.

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