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Climate of the Past

Precipitation changes in the South American Altiplano since 1300 AD reconstructed by tree-rings

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Abstract. Throughout the second half of the 20th century, the Central Andes has experienced significant climatic and environmental changes characterized by a persistent warming trend, an increase in elevation of the 0 °C isotherm, and sustained glacier shrinkage. These changes have occurred in conjunction with a steadily growing demand for water resources. Given the short span of instrumental hydroclimatic records in this region, longer time span records are needed to understand the nature of climate variability and to improve the predictability of precipitation, a key factor modulating the socio-economic development in the South American Altiplano and adjacent arid lowlands. In this study we present the first quasi-millennial, tree-ring based precipitation reconstruction for the South American Altiplano. This annual (November–October) precipitation reconstruction is based on the *Polylepis tarapacana* tree-ring width series and represents the closest dendroclimatological record to the Equator in South America. This high-resolution reconstruction covers the past 707 yr and provides a unique record characterizing the occurrence of extreme events and consistent oscillations in precipitation. It also allows an assessment of the spatial and temporal stabilities of the teleconnections between rainfall in the Altiplano and hemispheric forcings such as El Niño-Southern Oscillation. Since the 1930s to present, a persistent negative trend in precipitation has been recorded in the reconstruction, with the three driest years since 1300 AD occurring in the last 70 yr. Throughout the 707 yr, the reconstruction contains a clear ENSO-like pattern at interannual to multidecadal time scales, which determines inter-hemispheric linkages between our reconstruction and other precipitation sensitive records modulated by ENSO in North America. Our reconstruction points out that century-scale dry periods are a recurrent feature in the Altiplano climate, and that the future potential coupling of natural and anthropogenic-induced droughts may have a severe impact on socio-economic activities in the region. Water resource managers must anticipate these changes in order to adapt to future climate change, reduce vulnerability and provide water equitably to all users.

1 Introduction

Water availability is the main limitation for the socio-economic development of many regions in the world. In addition, fluctuations in water supply have large impacts on natural ecosystem productivity (Viviroli et al., 2003; Messerli et al., 2004). These affirmations are certainly valid for high-altitude regions in the tropics, such as the South American Altiplano (Messerli et al., 1997). This semi-arid plateau, with a mean elevation of 4000 m in the Central Andes (15–24° S), has been the physical environment for many native communities who have inhabited the region for thousands of years. Historically, human activities in the Altiplano have been strongly influenced by variations in climate, particularly water availability (Tandeter, 1991; Binford et al., 1997; Núñez et al., 2002). Agriculture in the Altiplano region is extremely susceptible to drought conditions, with consequent yield reductions (García et al., 2003, 2007). Episodic summer rainfall represents the major source of water for human consumption, agriculture, streamflow, and the recharge of the underground aquifers in the central and southern Altiplano, as well as adjacent arid lowlands of southern Bolivia, northern Chile and northwestern Argentina (Garreaud et al., 2009).

Major droughts across this region have severe economic and social impacts, larger than any other type of natural disaster threatening rural livelihood (Gil Montero and Villalba, 2005). Common crops yield, such as potato and quinoa (*Chenopodium quinoa*), is strongly affected by precipitation, indicating that persistent droughts are the main cause of this region's economic stress (García et al., 2003, 2007). For instance, the severe drought of 1998 provided a comprehensive view of the adverse impacts of dry events on the socioeconomic activities, when 60 % of the camelid livestock (llamas) and other domestic animals died in the Puna of Jujuy (Argentinean Altiplano). Small streams disappeared and people competed with animals for water resources (Gil Montero and Villalba, 2005).

Across the southern Altiplano, summer rainfall represents more than 80 % of the total annual precipitation (Garreaud et al., 2003; Vuille and Keimig, 2004). Recent studies, based on instrumental records, have documented important variations in the Altiplano's climate, together with a positive warming trend since the second half of the 20th century (Vuille and Bradley, 2000; Vuille et al., 2003; Trenberth et al., 2007). This regional increase in temperature has been related to an increase in elevation of the 0 °C isotherm (Vuille et al., 2008; Carrasco et al., 2008), a rapid and likely unprecedented melting of ice caps (Thompson et al., 2003), and sustained shrinking of small glaciers (Francou et al., 2003; Coudrian et al., 2005; Jomelli et al., 2011). All these environmental changes have occurred in conjunction with a growing demand for water resources as a result of the population increase and the rapid expansion of the mining industry in the Andean region (Messerli et al., 1997; COCHILCO, 2007). In addition, recent model simulations have projected a reduction of precipitation in the Central Andes, curtailing water resource availability (Bradley et al., 2006; Urrutia and Vuille, 2009; Minvielle and Garreaud, 2011).

Our knowledge of climate variability in the last 1000 yr in the Altiplano is severely limited by the low number of high-resolution palaeoclimatic records in the tropical Andes, a research topic of high priority in paleoclimatology in South America (Jansen et al., 2007; Villalba et al., 2009). The lack of information on past climate variations constrains the possibility of validating climate models used to predict future precipitation trends (Randall et al., 2007; Lohmann, 2008). This is a key issue for developing mitigation and/or adaptation strategies for future climate change scenarios in the region. Instrumental precipitation records for the Altiplano are generally short, fragmentary and nonhomogeneous, making them inadequate for the development of a baseline-understanding of long-term trends (Vuille et al., 2003). Therefore, we need longer precipitation records to complement the limited nature of the current instrumental registries in order to properly understand how interannual modes of climate variability have evolved under changes in long-term background conditions.

In contrast to the extratropical Andes, where tree-ring studies have yielded more than a hundred chronologies and over 30 climate reconstructions (Boninsegna et al., 2009), in the South American Altiplano suitable extremely moisture sensitive tree-ring chronologies of *Polylepis tarapacana* (*Queñoa*) have only just begun to be developed in the past few years (Morales et al., 2004; Solíz et al., 2009). Developing an annually resolved tree-ring precipitation reconstruction for the Altiplano represents a great opportunity to enhance our knowledge about past and present climate variability in the tropical Andes region. This record would help to fill a significant geographic gap in the present coverage of dendroclimatological reconstructions within the Andes.

The main goal of our study was to develop an exactly-dated, annually-resolved precipitation reconstruction for the South American Altiplano during the past 707 yr from recently-developed *P. tarapacana* tree-ring chronologies. We analyzed this quasi-millennial paleoclimatic record to describe its temporal evolution, the recurrence of extreme events, the presence of persistent cycles and the relationships with hemispheric climate forcings such as El Niño-Southern Oscillation (ENSO). Our contribution expands the tree-ring based precipitation reconstructions in South America to the tropical Andes and provides the first annual resolution paleoclimatic reconstruction for rainfall in the Altiplano.

2 Setting and climate of the South American Altiplano

The tropical Central Andes represents a formidable obstacle for atmospheric circulation over South America, generating two contrasting regions: the tropical humid lowlands to the east and the Pacific coastal deserts to the west (Garreaud et al., 2003). A particular physiographic feature in the Central Andes is the Altiplano, a high-elevation, inter-mountain plateau extending from 15 to 24° S (Fig. 1a). Precipitation across the Altiplano decreases from ∼500 mm in the northeast transition and the Amazon Basin to <200 mm in the southwest sector adjacent to the Atacama Desert. More than 80 % of total annual rainfall occurs during the austral summer (December–February) (Vuille and Keimig, 2004). The

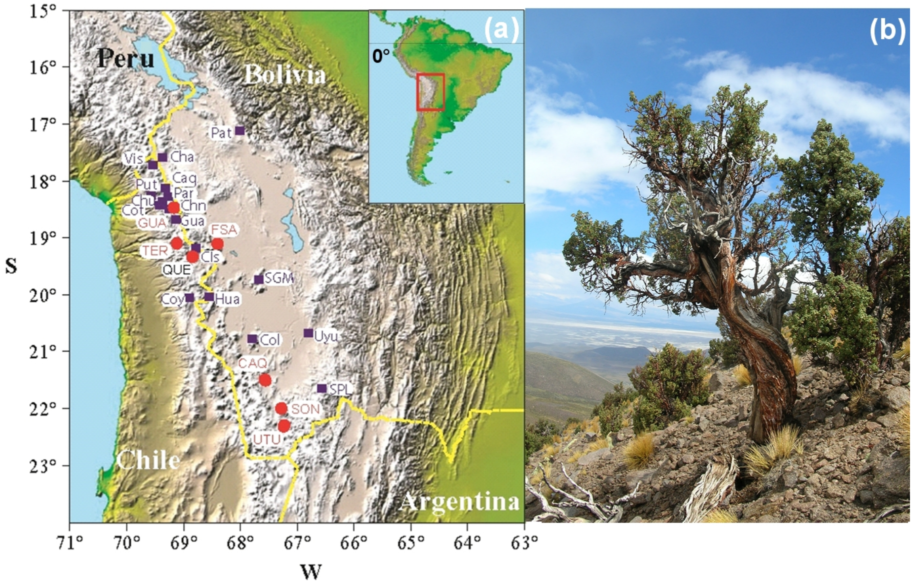

Fig. 1. Location of tree-ring sites (red dots) and precipitation stations (blue squares) in the Altiplano, Central Andes. See Tables 1 and 2 for code identifications **(a)**. A 500 yr old *Polylepis tarapacana* (*Queñoa*) individual growing on the slope of the Tata Sabaya volcano in Bolivia at 4750 m a.s.l. In the background, the Coipasa salt lake on the Bolivian-Chilean border **(b)**.

episodic precipitation has a convective nature relating to the upper-air circulation with an easterly (westerly) zonal flow, favoring the occurrence of wet (dry) events (Garreaud et al., 2003). This precipitation's extreme seasonality is associated with the onset and decay of the Bolivian High, an upper-level high-pressure cell that develops over the Central Andes in response to the latent heat released by the summer's deep convection over the Amazon Basin (Lenters and Cook, 1997). Wet intervals are related to a pronounced southward-displaced Bolivian High, which allows for the expansion of the upper-air easterly flow and the ingression over the Altiplano of the moisture influx from the Amazon Basin (Lenters and Cook, 1997; Garreaud et al., 2009).

Year-to-year variability in precipitation is mainly related to changes in the mean zonal wind over the Altiplano, largely modulated by sea surface temperature (SST) across the tropical Pacific Ocean (Vuille et al., 2000; Garreaud and Aceituno, 2001; Bradley et al., 2003). During the warm (cold) phase of the El Niño-Southern Oscillation (ENSO), the Altiplano climate is dry (wet) (Aceituno, 1988; Lenters and Cook, 1999; Vuille, 1999; Vuille et al., 2000). Wet summers are related to a cooling of the central and eastern sectors of the tropical Pacific (La Niña event). Weaker upper-elevation Westerlies during wet episodes facilitate the ingression of the wet easterly flow, transporting humid air masses from the Amazon Basin. In contrast, dry summers associated with El Niño events in the tropical Pacific, are characterized by the dominance of westerly flows and the concurrent blocking of the humid air penetration from the east (Vuille, 1999; Garreaud et al., 2003).

3 Data and methods

3.1 Precipitation and tree-ring data

Monthly precipitation records for the Altiplano were obtained from the **SE**rvicio **NA**cional de **M**eteorología e **HI**drología in Bolivia (SENAMHI) and the **D**irección **G**eneral de **A**guas in Chile (DGA). The 17 precipitation stations used in this study are located from 17 to 22° S and range in elevation from 3545 to 4600 m (Fig. 1a, Table 1). We developed a regional monthly precipitation record based on these 17 individual records. Few instrumental records exist prior to 1950 and they are not evenly distributed across the Altiplano. In consequence, a robust and spatially representative record of regional precipitation was built starting in 1961. Total annual precipitation across the Altiplano decreases in a northeast-southwest direction; however, the interannual variability in rainfall shows a uniform pattern across the region (Garreaud et al., 2003). To minimize the influences of weather stations with higher rainfall on the regional mean, our regional precipitation record was developed by averaging the precipitation anomalies (expressed as percentages) with respect to the common interval 1982–2000.

The world's highest elevation woodlands of *Polylepis tarapacana* (Rosaceae) in the Altiplano represents a remarkable resource to develop reliable high-resolution paleoclimate reconstructions in the tropical Andes (Argollo et al., 2004; Morales et al., 2004; Boninsegna et al., 2009; Christie et al., 2009; Solíz et al., 2009). *P. tarapacana* is a unique tree species that reaches over 700 yr old and grows along the South American Altiplano from 16 to 23° S between 4000

Table 1. Precipitation stations used to developed a regional series of November–October rainfall variations in the Altiplano.

Station, code	Lat S, long W	Elevation (m)	Country	Period	Mean mm*
Patacamaya, Pat	17°15′/67°57′	3789	Bolivia	1948–2003	390
Charaña, Cha	17°35′/69°26′	4059	Bolivia	1948–2004	263
Visviri, Vis	17°37′/69°28′	4080	Chile	1968–2007	293
Caquena, Caq	18°03′/69°12′	4400	Chile	1970–2007	411
Putre, Put	18°11′/69°33′	3545	Chile	1970–2007	191
Cotakotani, Cot	18°11′/69°13′	4550	Chile	1963–2007	448
Chucuyo, Chu	18°12′/69°17′	4400	Chile	1961–2006	345
Parinacota, Par	18°12′/69°16′	4420	Chile	1933–2007	324
Chungará, Chn	18°16′/69°06′	4600	Chile	1962–2008	374
Guallatiri, Gua	18°29′/69°09′	4240	Chile	1969–2007	270
Colchane, Cls	19°16′/68°38′	3700	Chile	1978–2007	138
Huaytini, Hua	19°33′/68°37′	3720	Chile	1982–2008	157
Salinas G.M., Sgm	19°38′/67°40′	3737	Bolivia	1948–2001	211
Coyacagua, Coy	20°03′/68°50′	3990	Chile	1961–2008	131
Uyuni, Uyu	20°28′/66°48′	3660	Bolivia	1975–2003	185
Colcha, Col	20°47′/67°47′	3700	Bolivia	1980–2000	207
S. Pablo Lípez, Spl	21°41′/66°37′	4165	Bolivia	1979–2003	289

* Mean annual (November–October) precipitation (mm) for the common period 1982–2000.

Table 2. Characteristics of *Polylepis tarapacana* tree-ring sites and the regional chronology from the Altiplano, Central Andes.

Site name, code	Lat S, long W	Elev (m a.s.l.)	Country	No. series	Period	*r* PC1*
Volcán Guallatiri, GUA	18°28′, 69°04′	4450	Chile	82	1377–2007	0.77
Salar de Surire, TER	18°56′, 69°00′	4517	Chile	11	1278–1901	0.77
Frente Sabaya, FSA	19°06′, 68°27′	4430	Bolivia	30	1352–2008	0.73
Queñiza, QUE	19°22′, 68°55′	4303	Chile	51	1444–2007	0.78
Volcán Caquella, CAQ	21°30′, 67°34′	4520	Bolivia	63	1226–2009	0.82
Soniqueira, SON	22°00′, 67°17′	4543	Bolivia	35	1431–2003	0.72
Volcán Uturuncu, UTU	22°32′, 66°35′	4457	Bolivia	81	1242–2006	0.84
REGIONAL Chronology statistics: MTR 0.47/MS 0.3/EPS 0.95/				353	1242–2009	0.98

* Correlation coefficients between individual chronologies and the first Principal Component (PC1) from the standard chronologies over the common period 1668–1776. The PC1 explains 60 % of the total variance. All correlation coefficients are significant at $P < 0.001$ level. MS: Mean Sensitivity, MTR: Mean Tree-Ring Width (mm), EPS: Expressed Population Signal.

to 5200 m (Fig. 1b; Braun, 1997). Previous studies show that the radial growth of the *P. tarapacana* is strongly related to interannual variations in summer precipitation. At the regional scale, tree growth patterns resemble the spatio-temporal variations of precipitation across the Altiplano, highlighting the great potential of this species to provide precipitation reconstructions with highly significant hindcast skills (Solíz et al., 2009).

In this study, seven regional chronologies from *P. tarapacana* were developed by merging previous single-site records, incorporating new chronologies, as well as updating and extending previous records back in time (Argollo et al., 2004; Christie et al., 2009; Solíz et al., 2009). New tree-ring sites were sampled on steep, rocky and xeric environments in the western flank of the Andean Western Cordillera (Fig. 1; Table 2). Due to the twisted stems and the eccentric radial growth patterns of *P. tarapacana*, cross-sections were collected from branches of living trees and subfossil wood that have remained on the ground surface for several centuries due to the cold, dry climate. Wood samples were mounted and sanded following standard dendrochronological techniques (Stokes and Smiley, 1968). For dating purposes, we followed Schulman's convention (1956) for the Southern Hemisphere, which assigns to each tree-ring the date in the year in which radial growth started. Tree-rings were visually cross-dated and measured with a binocular stereoscope with a 0.001 mm precision. Precise dating for the floating TER chronology (composed of subfossil woods) was established by cross-dating the individual samples with nearby (GUA, QUE and FSA) chronologies. To assess the quality of the cross-dating and identify measurement errors, we utilized the computer program COFECHA (Holmes, 1983).

Interannual variations of *P. tarapacana* growth show consistent spatial similarities across the Altiplano. Previous studies have associated the similarity among records with the occurrence of a common precipitation pattern in the region (Solíz et al., 2009). Based on these observations, a regional, well replicated tree-ring chronology was developed by assembling, in a single record, the 353 tree-ring width series from the seven sites listed in Table 2. An indication of the common signal between the seven site chronologies is the highly significant mean correlation coefficient of all possible pairings among them (21) computed over the well-replicated common period 1668–1776 (>8 samples in all sites) ($r = 0.54 \pm 0.02$ standard error, $n = 109$, $P < 0.001$). A principal component analysis of the seven site chronologies over the period 1668–1776 provides similar loadings (0.72 to 0.84) from the seven records to the first principal component (Table 2).

Ring-width measurements were standardized to remove variability in the time series not related to climate, such as tree aging or forest disturbances (Cook et al., 1990). To conserve the low-frequency signal in tree growth, we used a conservative method of standardization, fitting negative exponential or linear curves with zero or negative slope to each individual series. The regional tree-ring chronology was calculated by averaging the detrended *P. tarapacana* tree-ring width series with a biweight robust mean estimation using the ARSTAN program (Cook, 1985). The quality of the tree-ring chronology was tested by the Expressed Population Signal statistic (EPS), which measures the strength of the common signal in a chronology over time and quantifies the degree to which a particular chronology portrays the hypothetically perfect chronology (Cook et al., 1990). To calculate the EPS, we used a 50-yr window with an overlap of 25-yr between adjacent windows. While there is no level of significance for EPS, values above 0.85 are generally accepted as a good level of common signal fidelity between trees, so we used only the portion of the chronology with EPS > 0.85 as a predictor of the precipitation in the reconstruction (Wigley et al., 1984).

3.2 Reconstruction method

Correlation coefficients between the regional standard *P. tarapacana* chronology and monthly variations in regional precipitation were used to define the seasonal precipitation best related to radial growth (Blasing et al., 1984). Total annual precipitation (November to October) was the period best correlated with annual growth. We developed the annual precipitation reconstruction by regressing the regional standard chronology against total November–October precipitation utilizing a principal component regression approach (Cook et al., 2007). Predictors for the reconstruction included the regional chronology in all temporal lags significantly correlated ($\alpha = 0.05$) to annual precipitation during the 1961–2009 calibration period. While the chronology was not significantly correlated at year t, statistically significant correlations with annual precipitation were recorded at lags $t+1$, $t+2$, and $t+3$ ($r = 0.71$, 0.37 and 0.31, respectively; $n = 45$; $P < 0.05$). These three lags were considered candidate predictors of annual precipitation and entered in a principal component analysis to reduce the number of predictors and enhance the common precipitation signal. Thus, the intercorrelated set of predictors was converted to orthogonal variables, reducing the dimension of the regression problem by eliminating the higher-order eigenvectors that explain a small proportion of the variance (Cooley and Lohnes, 1971). The selection criterion for choosing the best reconstruction model was based on maximizing the adjusted R^2 in a stepwise multiple regression procedure (Weisberg, 1985). Given the relatively short precipitation record for calibration, the reconstruction model was developed using the "leave-one-out" cross-validation procedure (Michaelsen, 1987; Meko, 1997). In this approach each observation is successively withheld; a model is estimated on the remaining observations, and a prediction is made for the omitted observation. At the end of this procedure, the time series of predicted values assembled from the deleted observations is compared with the observed predictors to compute the validation statistics of model accuracy and error. The goodness of fit between observed and predicted precipitation values was tested based on the proportion of variance explained by the regression (R^2_{adj}), the F-value of the regression, the linear trend and the normality of the regression residuals, and the autocorrelation in the residuals measured by the significance of the linear trend and the Durbin-Watson test (Draper and Smith, 1981). As additional measures of regression accuracy, we also computed the Reduction of Error (RE) statistic over the verification period (Gordon, 1982), as well as the root-mean-square error (RMSE) statistic as a measure of inherent uncertainties in the reconstruction (Weisberg, 1985).

3.3 ENSO, spectral properties and temporal evolution of the reconstructed precipitation

It is widely accepted that ENSO plays a strong role in modulating precipitation variability in the South American Altiplano (Vuille et al., 2000; Garreaud et al., 2009). Therefore, we expect that our reconstruction will show a strong ENSO signal. To determine the relationship between our reconstruction and ENSO, we estimated the spatial correlation pattern between the reconstructed annual (November–October) precipitation and the mean annual SST (November–October; $2.5 \times 2.5°$ gridded cell) from the NCEP reanalysis global dataset (Kistler et al., 2001). In addition, the relationship to the time frequency space between the reconstructed precipitation and ENSO was assessed using two cross-spectral techniques. Similarities in the temporal evolution of the reconstructed precipitation and the mean November–October Niño 3.4 SST (N3.4) were estimated using cross-singular spectral analysis (SSA; Vautard and Ghil, 1989) and wavelet coherence analyses (WTC; Grinstead et al., 2004). The SSA detects and extracts the main oscillatory modes of a time series over time, whereas the WTC analysis identifies regions in the time frequency space where the two series covary. The WTC detects phase relationships between series and assesses the statistical significance against a red noise background using the Monte Carlo methods. After assessing the spectral relationships between the precipitation reconstruction and instrumental ENSO, we determined the dominant oscillatory modes of the precipitation reconstruction along the reconstructed 1300–2006 period by performing a continuous wavelet transform analysis (WT; Torrence and Compo, 1998). To assess the temporal relationship between the spectral oscillations of our precipitation reconstruction and ENSO across its full length, we used a cross-wavelet transform analysis (XWT) between the Altiplano precipitation and a well-known independent ENSO proxy represented by the first principal component time series of the North American Drought Atlas (NADA) during the 1300–2002 period (Cook et al., 2004; Li et al., 2011). Finally, to examine the relationship between the significant regime shifts and the interannual and low-frequency variability of the precipitation reconstruction, we compared the regime shifts in the mean detected over the entire 1300–2006 period using the Rodionov (2004) method with a window length of 25 yr, the variance in moving windows of 25-yr, and a cubic smoothing spline that reduces 50 % of the variance in a sine wave of 35 yr.

4 Results and discussion

4.1 Tree-ring chronology and calibration of the precipitation reconstruction model

Here, we report on the development of an annually-resolved, moisture-sensitive chronology from tree-ring widths in the South American Altiplano (Table 2). The record, covering the past 707 yr, starts in 1226 AD, but is well replicated for the period 1300–2009 (> than 10 series and EPS > 0.85). The chronology is based on ∼87 896 annual ring measurements from more than 350 tree-ring width series (Table 2). Chronology statistics show high series intercorrelation ($r = 0.54$), a clear indication of the strong internal coherence in the regional record. Additionally, the mean expressed population signal (EPS = 0.95) also indicates a good level of common signal fidelity between trees.

Due to the highest significant correlation between tree growth and November to October precipitation, we used this period as our target instrumental series (1961–2006) to be modeled back in time using the *P. tarapacana* regional chronology. Although at a lag $t = 0$ the correlation coefficient is not significant, correlations with annual precipitation are statistically significant at lags $t+1$, $t+2$, and $t+3$ ($r = 0.71$, 0.37 and 0.31, respectively; $P < 0.05$), corroborating previous studies that have shown a persistent influence of the previous year's precipitation on *P. tarapacana* radial growth (Argollo et al., 2004; Morales et al., 2004; Solíz et al., 2009). The amplitudes from the first and second principal component were included as predictors of the annual precipitation using a multiple regression. Over the 1961–2006 calibration period, tree-ring indices explain 55 % of the total observed variance in the Altiplano annual precipitation. The statistics used to assess the quality of the regression model indicate that it has highly significant hindcast skills. The strength in the relationship between the observed and estimated precipitation (adj $R^2 = 0.55$) suggests that the tree-ring reconstruction is quite accurate in representing the instrumental precipitation changes, highlighting the predictive ability of the calibration model as indicated by $F = 26.32$ ($P < 0.001$), a positive RE (0.5), and non-significant autocorrelation and residuals trend (DW = 2.4; Fig. 2).

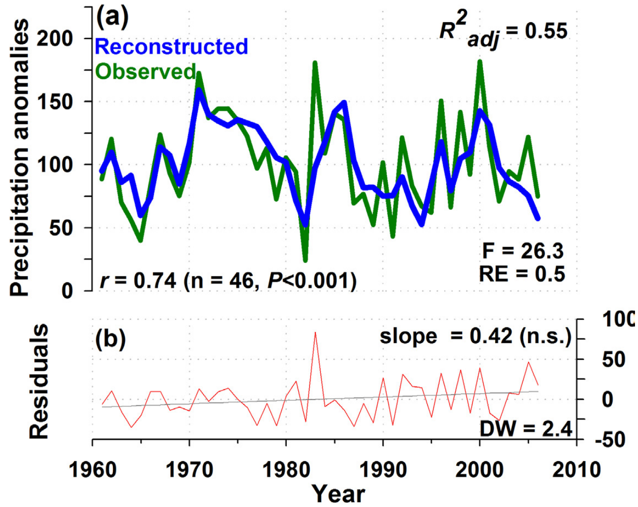

Fig. 2. Observed and tree-ring predicted annual precipitation (November–October) variations across the South American Altiplano (annual precipitation expressed as percentages (%) of the 1982–2000 instrumental precipitation mean). Calibration and verification statistics: explained variance (R^2_{adj}) over the calibration period, the Pearson correlation coefficient (r) between observed and reconstructed values, F-value of the regression, and the reduction of error (RE) **(a)**. Regression residuals (red line) with trend slope (black line). The Durbin-Watson (D-W) statistic and the slope value are indicated **(b)**.

4.2 Precipitation variations in the Altiplano throughout the last 700 yr

4.2.1 Spatial representation and temporal evolution

To evaluate the spatial representation of the reconstructed annual precipitation, we determined the spatial correlation maps across tropical-subtropical South America between the Altiplano precipitation (both observed and reconstructed)

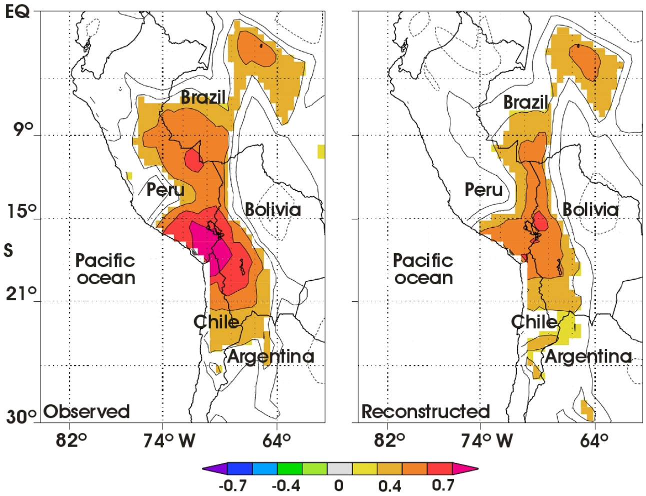

Fig. 3. Spatial correlation field between the CRU 3.1 $0.5 \times 0.5°$ gridded November–October precipitation and our regional instrumental precipitation series for the Central Andes (see Table 1) **(a)**, and the Altiplano reconstructed November–October precipitation **(b)** for the 1961–2006 period (only significant correlations are shown).

with $0.5 \times 0.5°$ gridded November–October precipitation from the CRU TS 3.1 dataset (Mitchell and Jones, 2005). The two spatial correlation fields (Fig. 3), estimated over the 1961–2006 common period, show significant correlations across the entire Altiplano, a clear indication of the wide spatial representation of both observed and reconstructed precipitation records. The spatial correlation fields show that the highest correlation coefficients are concentrated in the north-central section of the Altiplano with decreasing values towards the southern Altiplano. Although the correlation coefficient between the estimated and observed values is pretty high in our reconstruction ($r = 0.74$; Fig. 2), correlations between the CRU gridded data and the reconstruction are comparatively lower. This observation is consistent with relatively low correlations between our regional instrumental series and the CRU data. Our findings support previous studies that indicate the poor representation of climatic variability by gridded products based on few or no high-altitude stations in remote areas with complex topographies, such as the Central Andes (Garreaud et al., 2009; Tencer et al., 2011).

The annual tree-ring based reconstruction covers the past 707 yr and portrays interannual to multidecadal variations in precipitation across the South American Altiplano since AD 1300 (Fig. 4). Several multidecadal persistent droughts are observed during the 14th, 16th, 17th, 18th and 20th centuries. Almost the entire 14th century was characterized by below average precipitation with a single subdecadal humid period between 1300 and 1307. This severe centennial drought persisted until the beginning of the 15th century (around the 1410s). It has been proposed that the negative impact of this persistent centennial drought on local agricultural-based societies triggered social conflicts and a period of wars in the Altiplano during the 14th and 15th centuries (Nielsen et al., 2002). A persistent drought has also been recorded during the 14th century in the Palmer Drought Severity Index (PDSI) field reconstruction, mainly based on the Quelccaya, Huascarán and Sajama ice-cores for the Altiplano region (Boucher et al., 2011). Our reconstruction presents milder to wet conditions prevailing from the 1410s to the 1520s with a particularly humid interval at the end of the 15th century. This relatively wet interval was interrupted by a remarkably dry event in the 1450s. Indeed, the year 1451 appears as one of the ten driest years in the reconstruction. Although the 16th century was characterized by persistently dry conditions, extreme dry events were rare. Just the year 1593 recorded precipitation 60 % below the long-term mean. In contrast to our record, wet conditions during the 16th century have been inferred from the Quelccaya ice core (Thompson et al., 1985, 1986). The persistent dry conditions prevailing during the 16th century were interrupted by a remarkably pluvial period during the first decade of the 17th century, which in turn was followed by a pronounced drought in the 1620s. After that, sustained wet conditions prevailed until the mid 18th century. Cold and wet conditions for the region during the first half of the 18th century have also been proposed by Liu et al. (2005) and Thompson et al. (2006). Lichenometry dating of glacier moraines at Cerro Charquini in the Cordillera Real, Bolivia (5392 m; Rabatel et al., 2006) suggest that the Little Ice Age maximum occurred during the second half of the 17th century. These observations are consistent with the persistent wet conditions recorded in our reconstruction during the second half of 17th century, lasting until the middle of the 18th century. However, it is important to note that cold/wet conditions during this period were not so pronounced as those recorded in the Quelccaya ice core (Thompson et al., 2006) and the Pumacocha sediments (Birds et al., 2011) from northernmost tropical Andes. Moreover, within this long-term wet period, two severe decade-long droughts 1615–1637 and 1684–1696 were recorded in our reconstruction. The years 1620–1621 and 1694 appeared as the extreme dry years associated with these droughts, respectively.

The long-term drought registered in our reconstruction during the second half of 18th century (1750–1818) was characterized, as the long-term drought recorded during the 16th century, by low interannual precipitation variability. Drier conditions from 1780 to 1820 were also recorded in the PDSI reconstruction for the South American subtropical region (Boucher et al., 2011). Based on historical documents, Gioda and Prieto (1999) recorded severe droughts in Potosí (southern Bolivia) during this period, with two extreme dry events lasting consecutively 10- (1777–1786) and 5-yr (1801–1805). After the persistent dry conditions from around 1750 to 1818, a steady increase in precipitation occurred. This long-term persistently wet period, lasting from around 1818 to 1887, represents the wettest interval during

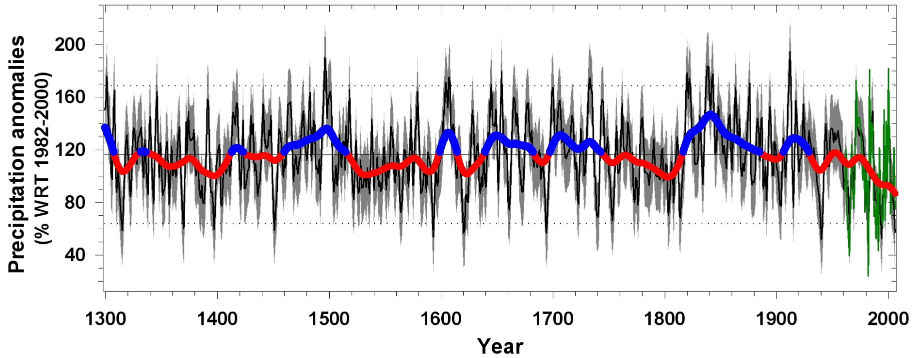

Fig. 4. The tree-ring reconstruction of annual (November–October) precipitation in the Altiplano region, Central Andes, for the period 1300–2006 (annual precipitation expressed as percentages (%) of the 1982–2000 instrumental precipitation mean). The shaded area denotes the 1 ± root-mean-square error bars and the green line represents the instrumental record. To emphasize the low-frequency variations a 35-yr smoothing cubic spline designed to reduce 50 % of the variance is shown in blue and red indicating wet and dry periods, respectively, with respect to the 1300–2006 mean. The dotted horizontal lines indicate ± 2 standard deviations.

the past seven centuries, showing four extreme wet events occurring in 1820–1822, 1837–1839, 1842–1843, and 1876. In the dated moraine chronology from Cerro Charquini, Rabatel et al. (2006) showed the 19th century to be a dry period with no advances of glaciers. However, in our reconstruction this long-term pluvial event is coincident (∼1830–1850) with the highest peak in the *Polylepis* pollen concentrations recorded in a 600-yr long ice core registry from the Sajama volcano (Liu et al., 2005). Persistent wet conditions may have favored *Polylepis* forest productivity and expansion, and consequently, contributed to the increase in pollen across the Altiplano (see Gosling et al., 2009). Another important peak in *Polylepis* pollen concentrations also occurred during the wet 1700–1720 reconstructed period (Liu et al., 2005).

The wet conditions of the 19th century continued until the beginning of the 20th century (1906–1929). Since the 1930s, a persistent negative trend in precipitation has been recorded up until present day. Two severe decadal and multidecadal drought events were registered during 1930–1948 and 1956–2006, respectively. Four of the seven most extreme dry years for the past 707 yr in the Altiplano occurred during the 1940–2006 period (1940, 1982, 1994 and 2006, respectively). Our results are consistent with the drier conditions shown by the PDSI record for the region (Boucher et al., 2011), and the rapid retreat of the tropical Andes glaciers during the second half of the 20th century (Ramirez et al., 2001; Francou et al., 2003; Vuille et al., 2008; Jomelli et al., 2009). The two driest years recorded in the past 700 yr (1940 and 1982) have been associated with very strong El Niño events.

4.2.2 Spectral properties, ENSO and temporal regimes

The spatial correlation field between SSTs and the precipitation reconstruction for the interval 1948–2006 shows a clear ENSO-like pattern across the Pacific Ocean (Fig. 5). Wet years in the Altiplano reconstruction are significantly related

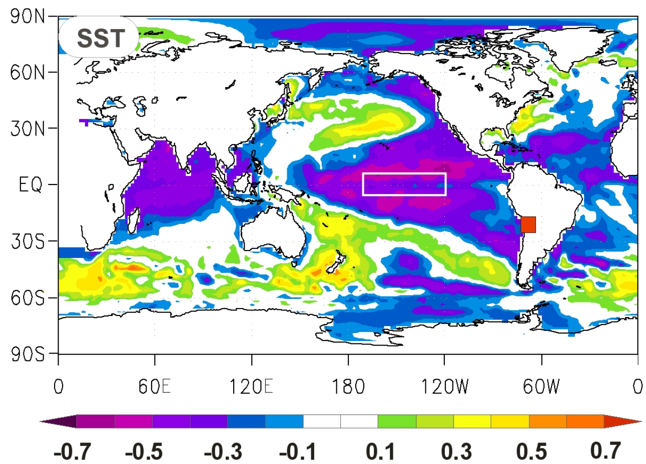

Fig. 5. Spatial correlation field between the annual (November–October) precipitation reconstruction and 2.5 × 2.5° gridded monthly averaged November–October sea surface temperature (SST) for the interval 1948–2006 (NCEP-NCAR reanalysis). The white box indicates the Niño 3.4 region in the tropical Pacific. The reconstructed precipitation region is indicated by the red square.

to negative anomalies in N3.4 SST (La Niña-like), while dry years correspond to positive tropical Pacific temperatures (El Niño-like; Vuille et al., 2000; Garreaud et al., 2009).

Figure 6a shows a comparison to the main dominant oscillatory modes of the precipitation reconstruction and the instrumental N3.4 SST record over the interval 1872–2006. Major oscillatory waveforms at 8.5–13, 5–6.7 and 3–4.7 years were identified in both the reconstructed precipitation and the N3.4 SST records. These oscillatory modes explain 28 (19), 13 (29) and 9 (26) % of the total variance in past precipitation (N3.4 SST records). For these cycles, the SSA-reconstructed precipitation periodicities follow the dominant

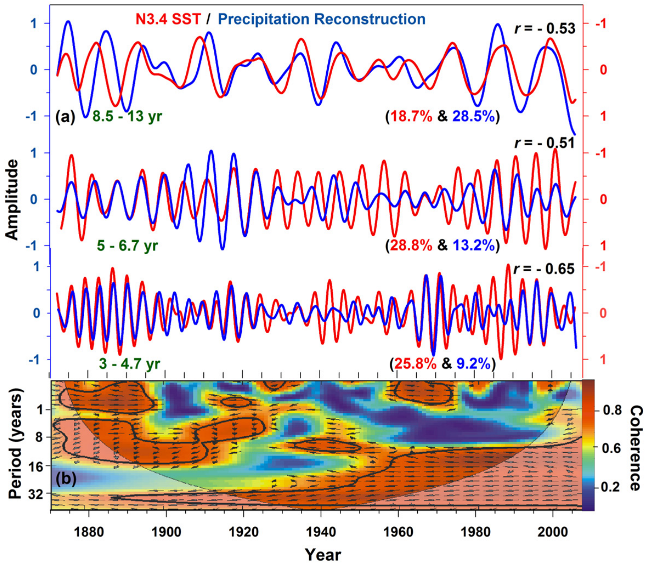

Fig. 6. Comparisons between the spectral properties of the Altiplano precipitation reconstruction and the N3.4 SST record during the common period. Waveforms extracted by Singular Spectrum Analysis (SSA). The frequencies for each SSA are indicated in years with green numbers, the correlation between the two series at the right corner, and the percentage of variance explained by each frequency indicated in parentheses. The N3.4 SST waveforms are shown inverse to facilitate the comparison between records **(a)**. wavelet coherency (WTC) and phase spectrum between the Altiplano precipitation reconstruction and the N3.4 SST. The vectors indicate the phase difference between the two records (arrows pointing right and left correspond to in-phase and antiphase relationships, respectively). Thick black contours encircle the periods where both series were related at a significance level (95 % c.l.). The cone of influence is shown at the bottom in a lighter shaded **(b)**.

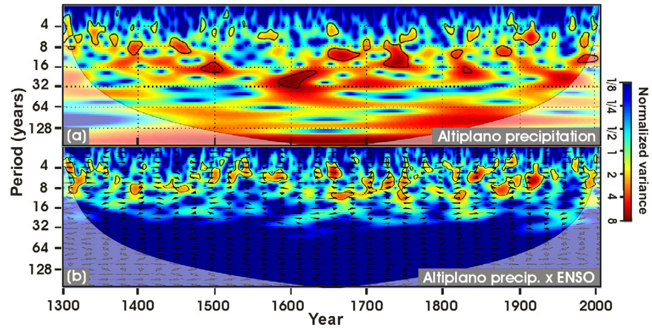

Fig. 7. The wavelet (WT) power spectrum (Morlet) of the annual (November–October) precipitation reconstruction in the Altiplano region **(a)**, and the cross-wavelet transform (XWT) between the precipitation reconstruction in the Altiplano and the first principal component of the North American Drought Atlas (NADA) as an ENSO proxy during the period 1300–2006 (Cook et al., 2004; Li et al., 2011) **(b)**. Thick black contours indicate the 95 % significance based on the red noise model, and the cone of influence is shown as a lighter shade at the bottom of both figures. Vectors indicate the relative phase relationship between the Altiplano precipitation and NADA PC1. Horizontal arrows pointing right and left correspond to in-phase and antiphase relationships between records, respectively.

oscillation modes in the instrumental N3.4 record in an antiphase relationship (Fig. 6a). However, there are some noncoherent changes in the amplitudes of the SSA waveforms for the reconstruction and N3.4. For instance, the amplitudes of the oscillatory modes at 3.1–4.7 yr were quite similar during the 1872–1925 period, reduced around 1930–1960 and were in antiphase around 1945–1950 and 1975–1985. This observation is consistent with previous studies indicating low ENSO activity during the 1930–1960 period (Aceituno and Montecinos, 1993; Torrence and Webster, 1999; Sutton and Hodson, 2003).

A particularly remarkable feature in the spectral comparison between the precipitation reconstruction and the ENSO3.4 records is the positive agreement, both in amplitude and phase relation at decadal (8.5–13 yr) scales. During the common period (1872–2006), the WTC shows a consistently stable antiphase relationship between both records (Fig. 6b). A marked shift in the relative importance of the coherence relation from interannual and decadal band to multidecadal cycles is observed at around 1930. In the decadal bands of the WTC, we identified a significant spectral coherence between both records around 1940, suggesting that the 1940–1941 El Niño event was part of the extreme decadal variability in ENSO. This particular feature is clearly observed in the 8.5–13 yr SSA band (Fig. 6a). This particular El Niño event is associated with the second driest year of the past 707 yr in the Altiplano. Shifts in ENSO strength, together with changes in the ENSO Altiplano teleconnection pattern may be related to the lack of spectral coherence between records throughout all the years studied. Therefore, changes in the coherency and phase between the N3.4 SST and Altiplano precipitation records could be related to ENSO's non-stationary behavior and the spatial variability of this ocean-atmospheric phenomenon.

The WT spectrum shows non-stationary periodicities across the precipitation reconstruction with most significant oscillatory modes concentrated in oscillations <16 and a single period of multidecadal oscillation centered around 1600 and related to the extremely dry events of 1592–1593 and 1621–1622, separated by approximately 30 yr (Fig. 7a). The WT spectrum shows a large percentage of the variance explained by the classical ENSO band (2 to 8 yr; Deser et al., 2010), with significant increases in the precipitation variability during the 14th century, a period of relatively reduced oscillations between 1450 and 1750 and a small increase in the spectral activity since the mid 18th century (Fig. 7a). These spectral characteristics, observed since the mid 15th century, have also been described for tree-ring hydroclimatic reconstructions from others region of the Southern Andes, where ENSO plays an active role in modulating the local climate

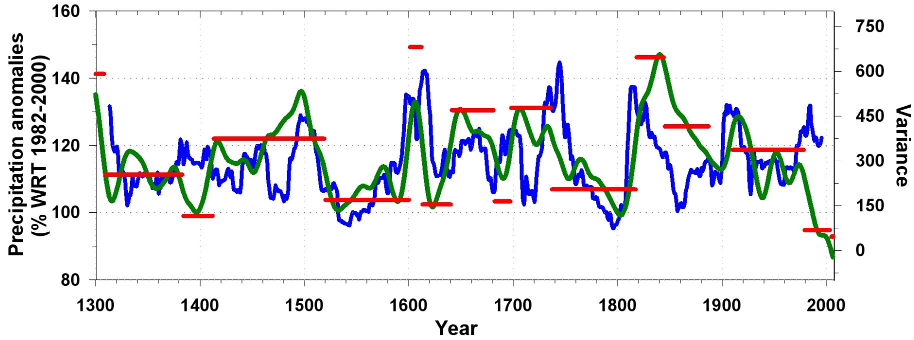

Fig. 8. Comparison between periods of reduced vs. abundant precipitation and interannual variability in the Altiplano precipitation reconstruction. Significant (95 % c.l.) regime shifts (red line) detected by the Rodionov (2004) method (window length = 25 yr), smooth spline (35 yr) of the precipitation reconstruction (green line) shown in Fig. 3, and changes in variance (×10) calculated for 25-yr intervals plotted on the centroid + 1 for each interval (blue line).

(LeQuesne et al., 2009; Christie et al., 2011). Decadal to multidecadal frequencies in our reconstruction have been relatively high since the 17th century.

Finally, we compared the spectral oscillations from the Altiplano precipitation reconstruction with those from the NADA for the past 700 yr. According to the XWT analysis, both records share a large proportion of common spectral power within the ENSO bandwidth, suggesting interhemispheric linkages between paleoclimatic reconstructions from regions influenced by ENSO (Fig. 7b). Vector directions in the XWT analysis revealed antiphase relationships between both records, consistent with the well-known negative (positive) relationship between warm conditions in the tropical Pacific SST and precipitation in the Altiplano (southwest North America) (Vuille et al., 2000; Smith et al., 2008). These results are also consistent with previous spatial correlation fields between the precipitation reconstruction and global SSTs shown in Fig. 5, and the spectral analyses included in Fig. 6. This ENSO precipitation teleconnection across the western Americas has also been described as the cause of the covariability between precipitation sensitive records from Central Chile (32–35° S) and southwestern North America during the last 350 yr (Villalba et al., 2011). However, the relationship between ENSO and precipitation in both regions is similar (wet years during the ENSO events) and contrary to the documented relationship between ENSO and precipitation in the Altiplano.

Applying regimen shift detection to the precipitation reconstruction shows the occurrence of six long-term periods with significantly reduced precipitation: a 40-yr interval centered around 1400, almost the entire 16th century connected to a decade-long drought during the first half of the 17th century, the second half of the 18th century, and an unprecedented dry period in the last 20 yr of the reconstruction. Interestingly, the most extended and severe droughts during the 16th and 18th centuries also showed a strong reduction in the variance of the reconstruction. In contrast, pluvial periods showed high levels of interannual precipitation variability (Fig. 8). As droughts in the South American Altiplano are trigged by El Niño-like conditions (Garreaud et al., 2009), it is likely that extended dry periods occurred in conjunction with a reduction of the interannual precipitation variability modulated by persistent El Niño-like conditions. However, the relationship between relative high variance and humid conditions break during the last 20 yr of the reconstruction, where interannual variability increased in a long-term interval with reduced precipitation.

5 Concluding remarks

In this study we present the first quasi-millennial, tree-ring based annual precipitation reconstruction (November–October) for the South American Altiplano. This high-resolution precipitation reconstruction covers the past 707 yr in a region devoid of such environmental proxy records. Our reconstruction extends dendroclimatological studies to the tropical Andes and represents the closest tree-ring based reconstruction to the Equator in South America. Our study provides insight into the Altiplano climate through the identification of long-term wet or dry periods and the temporal evolution of extremes in annual precipitation during the past seven centuries. In addition, interannual and decadal scale variations in precipitation and ENSO variability are identified, showing common cycles and periodicities between precipitation in the Altiplano and this hemispheric forcing. This reconstruction improves our knowledge on interannual, decadal and multicentury-scale precipitation variability in the Altiplano and will serve as a resource for research on the past, present and future climate variability in South America.

Some of the persistent drought/wet periods in the past 707 yr are highly consistent with evidence from the few proxy records available in the region, for example, the droughts during the 14th century (Boucher et al., 2011) and second half of the 20th century (Boucher et al., 2011; Jomelli et al., 2011), and the humid period during the 17th century (Rabatel et al., 2006). However, other extreme precipitation anomalies, such as the drought of 1520–1597 or the long pluvial extreme from 1820 to 1880, have not been previously reported. A high concentration of extreme dry events has occurred during the last 70 yr with four of the twelve driest years since AD 1300. The three most severe droughts in the past 707 yr have occurred in 1940, 1982 and 1994. The instrumental analysis of precipitation patterns in the Altiplano region can be addressed only for the last 50 yr, which preclude detecting any robust long-term trend in rainfall (Vuille et al., 2003). Our 707-yr rainfall perspective allows the 20th century and the period of instrumental records to be considered within a long-term context. A persistent negative trend in the precipitation reconstruction since the early 20th century suggests that the 50-yr interval of instrumental records is concurrent with the last, long-term dry event in the Altiplano, and consequently is not entirely representative of the precipitation regime in the region.

Results from global and regional climate models indicate that increased greenhouse gas emissions will exacerbate dry conditions in the Altiplano until the end of the 21st century. Most climate models predict an increase in the westerly flow over the Altiplano, which will induce a decrease in the transport of humid air masses from the east. Climate models estimate a precipitation reduction in the Altiplano from 10 to 30 % throughout the 21st century (Urrutia and Vuille, 2009; Minvielle and Garreaud, 2011). As ENSO variability is a key factor affecting precipitation patterns in the Altiplano, high resolution precipitation reconstructions from the Central Andes can provide valuable information about how ENSO teleconnections affect the Altiplano under different global climate conditions. On the other hand, our reconstruction, together with ENSO sensitive records around the world, will help to understand the spatial dynamics of ENSO teleconnections worldwide, and consequently, improve ENSO predictability.

Our reconstruction points out that century-scale dry periods are a recurrent feature in the Altiplano. The potential coupling of natural and anthropogenic-induced droughts in the near future will have a severe impact on present socioeconomic activities in the region. In the western, drier sector of the Altiplano, water resources are under severe growing pressure. Human and fast expanding mining activities obtain water from the scarce streams that originate in the Altiplano and from overexploited aquifers that depend on groundwater recharge from the Central Andes (Messerli et al., 1997; Houston, 2002). The frequency and intensity of future dry and wet episodes must be anticipated to properly establish strategies for the water demands of agriculture, industry and the population. Water resource managers must anticipate these changes to adapt to future climate change, reduce vulnerability and provide water equitably to all users.

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References

Aceituno, P. and Montecinos, A.: Circulation anomalies associated with dry and wet periods in the South American Altiplano, in: Preprints 4th Int. Conf. on Southern Hemisphere Meteorology and Oceanography, Hobart, Australia, 29 March–2 April, 330–331, 1993.

Argollo, M., Solíz, C., and Villalba, R.: Potencialidad dendrocronológica de *Polylepis tarapacana* en los Andes centrales de Bolivia, Ecología en Bolivia, 39, 5–24, 2004.

Binford, M. W., Kolata, A. L., Brenner, M., Janusek, J. W., Seddon, M. T., Abbott, M. B., and Jason, H.: Climate variation and the rise and fall of an Andean civilization, Quaternary Res., 47, 235–248, 1997.

Bird, W. B., Abbott, M. B., Vuille M., Rodbell, D. T., Stansella, N. D., and Rosenmeier, M. F.: A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes, P. Natl. Acad. Sci. USA, 108, 8583–8588, doi:10.1073/pnas.1003719108, 2011.

Blasing, T. J., Solomon, A. M., and Duvick, D. N.: Response Functions Revisited, Tree Ring Bull., 44, 1–15, 1984.

Boninsegna, J. A., Argollo, J., Aravena, J. C., Barichivich, J., Christie, D. A., Ferrero, M. E., Lara, A., Le Quesne, C., Luckman, B. H., Masiokas, M., Morales, M. S., Oliveira, J. M., Roig, F., Srur, A., and Villalba, R.: Dendroclimatological Reconstructions in South America: A review. Palaeogeogr. Palaeocl., 281, 210–228, 2009.

Boucher, É., Guiot, J., and Chapron, E.: A millennial multi-proxy reconstruction of summer PDSI for Southern South America, Clim. Past, 7, 957–974, doi:10.5194/cp-7-957-2011, 2011.

Bradley, R. S., Vuille, M., Hardy, D., and Thompson, L. G.: Low latitude ice cores record Pacific sea surface temperatures. Geophys. Res. Lett., 30, 1174, doi:10.1029/2002GL016546, 2003.
Bradley, R. S., Vuille, M., Diaz, H. F., and Vergara, W.: Threats to water supplies in the tropical Andes, Science, 312, 1755–1756, 2006.
Braun, G.: The use of digital methods in assessing forest patterns in an Andean environment: the *Polylepis* example, Mt. Res. Dev., 17, 253–262, 1997.
Carrasco, J. F., Osorio R., and Casassa, G.: Secular trend of the equilibrium-line altitude on the western side of the southern Andes, derived from radiosonde and surface observations, J. Glaciol., 54, 538–550, 2008.
Christie, D. A., Lara, A., Barichivich, J., Villalba, R., Morales, M. S., and Cuq, E.: El Niño-Southern Oscillation signal in the world's high-elevation tree-ring chronologies from the Altiplano, Central Andes, Palaeogeogr. Palaeocl., 281, 309–319, 2009.
Christie, D. A., Boninsegna, J. A., Cleaveland, M. K., Lara, A., LeQuesne, C., Morales, M. S., Mudelsee, M., Stahle, D., and Villalba, R.: Aridity changes in the Temperate-Mediterranean transition of the Andes since AD 1346 reconstructed from tree-rings, Clim. Dynam., 36, 1505–1521, 2011.
COCHILCO.: Copper and other mineral statistics 1987–2006. Comisión Chilena del Cobre, Gobierno de Chile, Santiago, Chile, 2007.
Cook, E. R.: A time series analysis approach to tree-ring standardization, Ph.D. thesis, The University of Arizona, Tucson, Arizona, 171 pp., 1985.
Cook, E. R., Briffa, K. R., Shiyatov, S., and Mazepa, V.: Tree Ring Standardization and Growth-Trend Estimation, in: Methods of Dendrochronology: Applications in the Environmental Sciences, edited by: Cook, E. R. and Kairiukstis, L. A., Kluwer Academic Publishers, Dordrecht, 104–123, 1990.
Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., and Stahle, D. W.: Long-term aridity changes in the western United States, Science, 306, 1015–1018, 2004.
Cook, E. R., Seager, R., Cane, M., and Stahle, D. W.: North American drought: Reconstructions, causes, and consequences, Earth-Sci. Rev., 81, 93–134, 2007.
Cooley, W. W. and Lohnes, P. R.: Multivariate data analysis, John Wiley & Son, New York, 1971.
Coudrain, A., Francou, B., and Kundzewicz, Z. W.: Glacier shrinkage in the Andes and consequences for water resources, Hydrol. Sci. J., 50, 925–932, 2005.
Deser, C., Alexander, M. A., Xie, S-P., and Phillips, A. S.: Sea surface temperature variability: Patterns and mechanisms, Annu. Rev. Mar. Sci., 2, 115–143, 2010.
Draper, N. R. and Smith, H.: Applied Regression Analysis, John Wiley & Son, New York, 1981.
Francou, B., Vuille, M., Wagnon, P., Mendoza, J., and Sicart, J. E.: Tropical climate change recorded by glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16° S, J. Geophys. Res., 108, 4154, doi:10.1029/2002JD002959, 2003.
Fritts, H. C.: Tree rings and climate, Academic Presss, London, 1976.
Garcia, M., Raes, D., and Jacobsen, S. E.: Reference evapotranspiration and crop coefficient of quinoa (*Chenopodium quinoa* Willd) in the Bolivian Altiplano, Agr. Water Manage., 60, 119–134, 2003.
Garcia, M., Raes, D., Jacobsen, S. E., and Michel, T.: Agroclimatic constraints for rainfed agriculture in the Bolivian Altiplano, J. Arid. Environ., 71, 109–121, 2007.
Garreaud, R. and Aceituno, P.: Interannual rainfall variability over the South American Altiplano, J. Climate, 14, 2779–2789, 2001.
Garreaud, R., Vuille, M., and Clement, C.: The climate of the Altiplano: Observed current conditions and mechanisms of past changes, Palaeogeogr. Palaeocl., 194, 5–22, 2003.
Garreaud, R. D., Vuille, M., Compagnucci, R., and Marengo, J.: Present day South American climate, Palaeogeogr. Palaeocl., 281, 180–195, 2009.
Gil Montero, R. and Villalba, R.: Tree rings as a surrogate for economic stress – an example from the Puna of Jujuy, Argentina in the 19th century, Dendrochronologia, 22, 141–147, 2005.
Gioda, A. and Prieto, R.: Histoire des sécheresses andines: Potosí, El Niño et le Petit Age Glaciaire, La Météorologie, 8, 33–42, 1999.
Gordon, G.: Verification of dendroclimatic reconstructions, in: Climate from Tree Rings, edited by: Hughes, M. K., Kelly, P. M., Pilcher, J. R., and LaMarche Jr., V. C., Cambridge University Press, 58–61, 1982.
Gosling, W. D., Hanselman, J. A., Knox, C., Valencia, B. G., and Bush, M. B.: Long-term drivers of change in *Polylepis* woodland distribution in the central Andes, J. Veg. Sci., 20, 1041–1052, 2009.
Grinsted, A., Moore, J. C., and Jevrejeva, S.: Application of the cross wavelet transform and wavelet coherence to geophysical time series, Nonlin. Processes Geophys., 11, 561–566, doi:10.5194/npg-11-561-2004, 2004.
Holmes, R. L.: Computer-assisted quality control in tree-ring dating and measurements, Tree Ring Bull., 43, 69–75, 1983.
Houston, J.: Groundwater recharge through an alluvial fan in the Atacama Desert, northern Chile: mechanisms, magnitudes and causes, Hydrol. Process., 16, 3019–3035, 2002.
Jansen, E., Overpeck, J., Briffa, K. R., Duplessy, J. C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W. R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba R., and Zhang, D.: Palaeoclimate, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, United States, 433–497, 2007.
Jomelli, V., Favier, V., Rabatel, A., Brunstein, D., Hoffmann, G., and Francou, B.: Fluctuations of glaciers in the tropical Andes over the last millennium and palaeoclimatic implications: A review, Palaeogeogr. Palaeocl., 281, 269–282, 2009.
Jomelli, V., Khodri, M., Favier, V., Brunstein, D., Ledru, M.-P., Wagnon, P., Blard, P.-H., Sicart, J.-E., Braucher, R., Grancher, D., Bourlès, D. L., Braconnot, P., and Vuille, M.: Irregular tropical glacier retreat over the Holocene epoch driven by progressive warming, Nature, 474, 196–199, 2011.
Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., Van den Dool, H., Jenne, R., and Fiorino, M.: The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation, B. Am. Meteorol. Soc., 82, 247–267, 2001.

Le Quesne, C., Acuña, C., Boninsegna, J. A., Rivera, A., and Barichivich, J.: Long-term glacier variations in the Central Andes of Argentina and Chile, inferred from historical records and tree-ring reconstructed precipitation, Palaeogeogr. Palaeocl., 281, 334–344, 2009.

Lenters, J. D. and Cook, K. H.: On the origin of the Bolivian High and related circulation features of the South American climate, J. Atmos. Sci., 54, 656–677, 1997.

Lenters, J. D. and Cook, K. H.: Summertime Precipitation Variability over South America: Role of the Large-Scale Circulation, Mon. Weather Rev., 127, 409–431, 1999.

Li, J., Xie, S. P., Cook, E. R., Huang, G., D'Arrigo, R., Liu, F., Ma, J., and Zheng, X. T.: Interdecadal modulation of El Niño amplitude during the past millennium, Nature Climate Change, 1, 114–118, doi:10.1038/nclimate1086, 2011.

Liu, K. B., Reese, C. A., and Thompson, L. G.: Ice-core pollen record of climatic changes in the central Andes during the last 400 yr, Quaternary Res., 64, 272–278, 2005.

Lohmann, G.: Linking data and models, Past Global Changes PAGES, 16, 4–5, 2008.

Meko, D. M.: Dendroclimatic reconstruction with time varying subsets of tree indices, J. Climate, 10, 687–696, 1997.

Messerli, B., Grosjean, M., and Vuille, M.: Water availability, protected areas, and natural resources in the Andean desert Altiplano, Mt. Res. Dev., 17, 229–238, 1997.

Messerli, B., Viviroli, D., and Weingartner, R.: Mountains of the world: Vulnerable water towers for the 21st century, Ambio, 13, 29–34, 2004.

Michaelsen, J.: Cross-validation in statistical climate forecast models, J. Clim. Appl. Meteorol., 26, 1589–1600, 1987.

Minvielle, M. and Garreaud, R.: Projecting rainfall changes over the South American Altiplano, J. Climate, 24, 4577–4583, 2011.

Mitchell, T. D. and Jones, P. D.: An improved method of constructing a database of monthly climatological observations and associated high-resolution grids, Int. J. Climatol., 25, 693–712, 2005.

Morales, M. S., Villalba, R., Grau, H. R., and Paolini, L.: Rainfall controlled tree growth in high elevation subtropical treelines, Ecology, 85, 3080–3089, 2004.

Nielsen, A. E.: Asentamientos, conflicto y cambio social en el Altiplano de Lípez (Potosí, Bolivia), Rev. Esp. Antropol. Am., 32, 179–205, 2002.

Núñez, L., Grosjean, M., and Cartagena, I.: Human occupations and climate change in the Puna de Atacama, Chile, Science, 298, 821–824, 2002.

Rabatel, A., Machaca, A., Francou, B., and Jomelli, V.: Glacier recession on Cerro Charquini (16°), Bolivia, since the maximum of the Little Ice Age (17th. century), J. Glaciol., 52, 110–118, 2006.

Ramirez, E., Francou, B., Ribstein, P., Descloîtres, M., Guérin, R., Mendoza, J., Gallaire, R., Pouyaud, B., and Jordan, E.: Small glaciers disappearing in the tropical Andes. A case study in Bolivia: Glacier Chacaltaya (16° S), J. Glaciol., 47, 187–194, 2001.

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R. J., Sumi, A., and Taylor, K. E.: Climate Models and Their Evaluation, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, United States, 489–662, 2007.

Rodionov, S. N.: A sequential algorithm for testing climate regime shifts, Geophys. Res. Lett., 31, L09204, doi:10.1029/2004GL019448, 2004.

Schulman, E.: Dendroclimatic changes in semiarid America, Tucson, University of Arizona Press, 1956.

Solíz, C., Villalba, R., Argollo, J., Morales, M. S., Christie, D. A., Moya, J., and Pacajes, J.: Spatio-temporal variations in Polylepis tarapacana radial growth across the Bolivian Altiplano during the 20th century, Palaeogeogr. Palaeocl., 281, 296–330, 2009.

Smith, T., Reynolds, R., Peterson, T. C., and Lawrimore, J.: Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature analysis (1880–2006), J. Climate, 21, 2283–2296, 2008.

Stokes, M. A. and Smiley, T. L.: An introduction to tree-ring dating, University of Chicago Press, Chicago, 1968.

Sutton, R. T. and Hodson, D. L. R.: Influence of the ocean on North Atlantic climate variability 1871–1999, J. Climate, 16, 3296–3313, 2003.

Tandeter, E.: Crisis in Upper Peru, 1800–1805, HAHR-Hisp. Am. Hist. R., 71, 35–71, 1991.

Tencer, B., Rusticucci, M., Jones P., and Lister, D.: A Southeastern South American Daily Gridded Dataset of Observed Surface Minimum and Maximum Temperature for 1961–2000, B. Am. Meteorol. Soc., 92, 1339–1346, doi:10.1175/2011BAMS3148.1, 2011.

Thompson, L., Mosley-Thompson, E., Bolzan., J. F. and Koci, B. R.: A 1500-Year Record of Tropical Precipitation in Ice Cores from the Quelccaya Ice Cap, Peru, Science, 229, 971–973, 1985.

Thompson, L., Mosley-Thompson, E., Dansgaard, W., and Grootes, P. M.: The Little Ice Age as Recorded in the Stratigraphy of the Tropical Quelccaya Ice Cap, Science, 234, 361–364, doi:10.1126/science.234.4774.361, 1986.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P. N., Henderson, K., and Mashiotta, T. A.: Tropical glacier and ice core evidence of climate change on annual to millennial time scales, Climatic Change, 59, 137–155, 2003.

Thompson, L. G., Mosley-Thompson, E., Brecher, H., Davis, M., León, B., Les, D., Lin, P. N., Mashiotta, T., and Mountain, K.: Abrupt tropical climate change: Past and present, P. Natl. Acad. Sci., 103, 10536–10543, 2006.

Torrence, C. and Compo, G.P.: A practical guide to wavelet analysis, B. Am. Meteorol. Soc., 79, 61–78, 1998.

Torrence, C. and Webster, P.: Interdecadal changes in the ENSO-Monsoon system, J. Climate, 12, 2679–2690, 1999.

Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J. A., Rusticucci, M., Soden, B., and Zhai, P.: Observations: Surface and Atmospheric Climate Change, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, United States, 235–336, 2007.

Urrutia, R. and Vuille, M.: Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century, J. Geophys. Res., 114, D02108, doi:10.1029/2008JD011021, 2009.

Vautard, R. and Ghil, M.: Singular spectrum analysis in nonlinear dynamics, with applications to paleoclimatic time series, Physica D, 35, 395–424, 1989.

Villalba, R., Grosjean, M., and Kiefer, T.: Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives, Palaeogeogr. Palaeocl., 281, 309–319, 2009.

Villalba, R., Luckman, B. H., Boninsegna, J., D'Arrigo, R. D., Lara, A., Villanueva-Diaz J., Masiokas, M., Argollo, J., Solíz, C., LeQuesne, C., Stahle, D., Roig, F., Aravena, J. C., Wiles, G., Jacoby, G., Hartsough, P., Wilson, R. J. S., Watson, E., Cook, E. R., Cerano-Paredes, J., Therrell, M., Cleaveland, M., Morales, M. S., Moya, J., Pacajes, J., Massacchesi, G., Biondi, F., Urrutia, R., and Martinez Pastur, G.: Dendroclimatology from regional to continental scales: Understanding regional processes to reconstruct large-scale climatic variations across the Western Americas, in: Dendroclimatology: Progress and Prospects, edited by: Hughes, M., Swetnam, T., and Diaz, H., Springer, Dordrecht, Heidelberg, London, New York, 175–227, 2011.

Viviroli, D., Weingartner, R., and Messerli, B.: Assessing the hydrological significance of the world's mountains, Mt. Res. Dev., 23, 32–40, 2003.

Vuille, M.: Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation, Int. J. Climatol., 19, 1579–1600, 1999.

Vuille, M. and Bradley, R.: Mean annual temperature trends and their vertical structure in the tropical Andes, Geophys. Res. Lett., 27, 3885–3888, 2000.

Vuille, M. and Keimig, F.: Interannual variability of summertime convective cloudiness and precipitation in the central Andes derived from ISCCP-B3 data, J. Climate, 17, 3334–3348, 2004.

Vuille, M., Bradley, R. S., and Keimig, F.: Interannual climate variability in the Central Andes and its relation to tropical Pacific and Atlantic forcing, J. Geophys. Res., 105, 12447–12460, 2000.

Vuille, M., Bradley, R., Werner, M., and Keimig, F.: 20th century climate change in the tropical Andes: observations and model results, Climatic Change, 59, 75–99, 2003.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B., and Bradley, R.: Climate change and tropical Andean glaciers: Past, present and future, Earth-Sci Rev., 89, 79–96, 2008.

Weisberg, S.: Applied Linear Regression, John Wiley & Son, New York, 1985.

Wigley, T. M. L., Briffa, K. R., and Jones, P. D.: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, J. Clim. Appl. Meterol., 23, 201–213, 1984.