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Multi-century lake area changes in the Andean high-elevation ecosystems of the Southern Altiplano

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Abstract

High-elevation endorreic lakes in the Southern Altiplano of South America represent a major source of local biodiversity. Size and depth of wetlands in Northwest Argentine (NWA) and Southwest Bolivia (SWB) have shown to be very sensitive to basin hidrological balances, and consequently, very vulnerable to deleterious effects from climate changes. The management of these water resources requires a comprehensive knowledge of their natural variability over multiple time scales. In this study we present a multi-century reconstruction of past lake-area fluctuations in the NWA and SWB, inferred from *Polylepis tarapacana* tree-ring records. Between 1975 and 2009 interannual lake area fluctuations from nine lakes were quantified based on Landsat satellite images. A composite *P. tarapacana* tree-ring chronology was developed. Correlations analyses were performed to screen potential predictor tree-ring chronologies for reconstruction models. Inter-annual lake area fluctuations were positively correlated with inter-annual variations of the radial growth of *P. tarapacana*. A tree-ring chronology (601 years long) was use as predictor, in a regression model, to reconstruct the annual (January–December) mean lake area from nine endorreic lakes. The chronology captures 60 % of the total variance in lake-area fluctuations and shows adequate levels of cross-validation. The twentieth century was unusual in the long-term context provided by the reconstruction; a persistent negative trend in lake area is clear in the reconstruction during the past century and is consistent with glacier retreat and other climate proxies from the Altiplano and tropical Andes. These results provide a baseline for the historical range of variability in lake fluctuations, and thus should be considered for the management of biodiversity and water resources in the region, particularly in relation to future XXI century climate scenarios.

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1 Introduction

The southern Altiplano or dry Puna, is located in the southern subtropical Andes. A prominent feature of the landscape between 21.5 and 24° S is the shallow salty lakes in the bottom of endorreic watersheds at very high elevation (above 4400 m a.s.l.).

Productivity in the dry Puna is low and mainly concentrated in the wetlands (lakes and peat bogs), which in consequence plays a critical role in sustaining a unique diversity of rare and endemic biota (Squeo et al., 2006). Large vertebrate species depend upon the wetlands for grazing, nesting and water. The extreme environmental conditions that characterize this lacustrine zone, including a prolonged dry season, strong winds, high daily temperature amplitude with frequent frosts, intense solar radiation, and hypoxia, prevent agriculture development and permanent grazing, resulting in the absence of human settlement above 4000 m. During summer, however, the zone is used as grazing area for livestock, which is an important component of the local indigenous economy (Nielsen, 2003). The ecological dynamics of these wetlands is sensitive to the watershed's hydrological balance, related mainly to precipitation and temperature (Carilla et al., 2013); and lake ecosystems act as direct and indirect indicators of climate variability.

During the twentieth century, the tropical and subtropical Andes have experienced a persistent warming trend (Vuille and Bradley, 2000). Climate scenarios for the twenty first century predict a decrease in precipitation and an increase in temperature (Urrutia and Vuille, 2009), posing a major threat for water resources in this arid region. Changes in lake area, reflecting hydrological dynamic and vegetation productivity (Carilla et al., 2013), allow the assessment of climate change effects in areas and periods with poor or non-existing instrumental records. Lake hydrological dynamics are usually measured as fluctuations in lake levels and most of these data are recorded at gauging stations. Our study region is characterized by a lack of such instrumental data. However, interannual changes in lake area between 1975 and 2009 were quantified based on Landsat

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satellite images and their association with tree-ring and instrumental climatic records (adjacent to our study area) assessed (Carilla et al., 2013).

Polylepis tarapacana treelets grow between 4200 and 5200 m a.s.l. in the slopes of the volcanoes nearby the study lacustrine zone. This extremely moisture sensitive woody species has allowed the development of a network of multi-century tree-ring width chronologies along the South American Altiplano from 16 to 23° S (Morales et al., 2012). As the yearly growth of Polylepis trees varies depending on hydrological balance (Soliz et al., 2009; Christie et al., 2009), annual rings of this species may therefore be used to reconstruct past lake area fluctuations.

Based on *P. tarapacana* tree ring records and Landsat satellite images, the main goal of our study was to develop a high-resolution multi-century reconstruction of past fluctuations in lake area from the Vilama-Coruto region in Northwest Argentina (NWA) and Southwest Bolivia (SWB). We described its temporal fluctuations and put recent changes and trends in the context of the past six centuries. We compare this reconstruction with palaeo-hydroclimatic records from subtropical and tropical Andes. In addition, we analyzed the recurrence of extreme drought events, the presence of persistent periodicities and dominant oscillation modes of variation at different time scales. Finally, in order to identify the major climatic forcing influencing lake area, we compared the Vilama-Coruto lake reconstruction with El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) indexes.

2 Methods

2.1 Study system

The study area is located on the border between Argentina (Rinconada, Jujuy) and Bolivia (Sud Lipez, Potosí) from 22°10′ to 22°45′ S and from 66°25′ to 67°13′ W (Fig. 1). This area shows the influence of a prolonged volcanic activity during the Upper Cenozoic (Polo, 2008) with the presence of a large concentration of shallow lakes that form an interrupted chain of endorreic watersheds above 4400 m. The study area belongs to a broader ecological region called dry Puna, located in the high-elevation plateaus of the southern subtropical Andes (Cabrera et al., 1976). Vegetation cover does not exceed the 20 % and is dominated by Poaceae (*Festuca, Deyeuxia*), several small shrubby species (*Parastrephia, Adesmia, Acantholipia*), and cushion plants (Azorella), (Cabrera et al., 1976). Being a c. 2–3 m tall treelet, *P. tarapacana* is the largest woody species that grows on the slope of the high volcanoes between 4200–5200 m. The extreme aridity (< 150 mm annual rainfall) and low temperatures (mean annual < 5 °C) characterize this region (http://www.worldclim.org). Precipitation is mostly concentrated during summer and more than 80 % of the total annual rainfall falls between November and March (Vuille et al., 2003; Vuille and Keimig, 2004).

2.2 Lake area records

Between 1975 and 2009, fluctuations in inter-annual lake area from nine lakes were quantified using Landsat images. The nine lakes are located between 4400 and 4600 m in the Vilama-Coruto region from NWA-SWB (Fig. 1). Lake area variations were derived from Landsat MSS (60 m pixel resolution, path 249 row 076) for the period 1975–1982, and Landsat TM images (30 m pixel resolution path 232 and row 076) for the period 1984–2009. The area of the lakes in each particular image was determined using the non-parametric method Support Vector Machine (SVM; Hsu et al., 2007). The annual (January–December) lake areas for each of the nine lakes were estimated by averaging every available images (from one to ten) for a particular year. Based on the nine individual records, we developed a regional record of annual lake area fluctuations. To minimize the influences of lakes with different sizes on the regional mean, annual lake area records were standardized as a Z score. Finally, the standardized lake area records from the nine lakes were averaged on a regional mean covering the interval 1975–2009. There was no image available in the entire region for the year 1983. The model used for the calibration and verification of the past lake area reconstruction, requires continuous time series without missing years. Therefore, a linear regression model between the regional lake area and a regional precipitation index from the Altiplano was applied to estimate the 1983 lake area value. Dates of images and a list of the meteorological stations used for this analysis are reported in Supplement.

2.3 Tree-ring data collection and standardization

Our study area encompasses the southern latitudinal limit of *P. tarapacana* distribution, and tree stands are mostly scattered on north-east wetter slopes of high volcanoes but not in the south and west slopes. Sample sites include the *P. tarapacana* populations located in relatively close proximity to the study lakes. Cross-sections and wedges were obtained from dead and living trees. From a total of seven sampled sites, we selected those that were highly replicated (> 60 tree-ring series), expand at least three centuries in the past, and recorded high correlation with lake area fluctuations ($r > 0.5$; Table 1). Two sites met these criteria: the tree-ring records from the Granada and Uturunco volcanoes (Table 1). The Schulman's convention (1956) for the Southern Hemisphere was used to assign to each ring the date of the calendar year in which radial growth starts. We measured total ring width to ±0.001 mm and cross-dated samples using standard procedures (Stokes and Smiley, 1968; Fritts, 1976). The program COFECHA (Holmes et al., 1983) was used to detect measurement and cross-dating errors. The ring-width chronologies from Granada and Uturunco shared large percentage of common signal in tree-ring variations ($r > 0.62$), therefore, 155 tree-ring series were merged in a regional chronology. Ring-width measurements were standardized to remove the age-related growth trends and minimize the growth variations not related to climate (Fritts, 1976). A negative exponential curve or straight line was used to fit ring-width series. When this fitted growth trend is removed, some of the variance related to climatic forcing signal can also be removed, leading to a trend distortion in resulting index series (Melvin, 2004). To prevent trend distortion a "signal free" detrending procedure (Melvin, 2004; Melvin and Briffa, 2008) was applied to the tree-ring measurements. The regional tree-ring chronology was

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produced with the RCSigFree program (Tree Ring Lab-LDEO, Columbia University http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software).

The quality of the tree-ring chronology was tested based on standard chronology diagnostics such as the RBar (Briffa, 1995) and the Expressed Population Signal (EPS; Wigley et al., 1984). The RBar is the mean correlation coefficient from all possible pairings among individual cores in the chronology (Briffa, 1995). EPS is a measurement of the strength of the common signal in the chronology used to identify the most reliable interval in the chronology valid for climate reconstructions. To calculate the RBar and EPS, we use a 50 year window with an overlap of 25 year between adjacent windows.

2.4 Lake area reconstruction

First, we identified the best relationship between variations on regional lake area and inter-annual tree growth. For that purpose, we computed correlation coefficients between the regional standard *P. tarapacana* chronology and annual mean lake area records. The highest correlation coefficient with tree-ring variations was founded using for comparison the regional mean annual (January–December) lake area ($r = 0.69$; $p < 0.0001$). We reconstructed, using a linear regression, the mean January–December lake area from the Vilama-Coruto lacustrine region over the period 1407–2007. To capture possible climate-related persistence in the tree-ring series and enhance the common climate signal, we included as predictors in the regression the regional chronology in the temporal lags significantly correlated ($p < 0.05$) to annual lake area during the calibration period 1975–2007. Two lags (t, t-1) were considered as candidate predictors of annual lake area in a stepwise multiple regression (Weisberg, 1985). To validate the model, we used the "leave-one-out" cross-validation procedure (Michaelsen, 1987; Meko and Baisan, 2001). This method allowed the use of all available data to calibrate and validate the model, and it is very useful when observed records are short temporal series, such us our lake area records. In this approach, the reconstruction model is calibrated using the full available overlap period. Then, the method sequentially withheld one observation and calibrates additional models with the remaining observations.

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Each model is used to estimate the withheld observation. Finally, all these estimated values are assembled in a time series used as the validation data set. The quality of the model during the calibration period was measured by the proportion of variance explained by the regression (R^2_{adj}). The model accuracy was evaluated using the reduction of error (RE) statistic, which measures the model skill in estimating values of the predictand in the cross-validation process (Wilkes, 1995; Fritts, 1976). We also computed the root-mean-square error (RMSE) statistic as a measure of inherent uncertainties in the reconstruction (Weisberg, 1985).

2.5 Identification of extreme high/low events in the lake area reconstruction

Significant shifts in the mean state conditions of the lake area reconstruction were identified using a simple regime shift detection technique (Rodionov, 2004) with a cut-off segment length $l = 25$ years, a target probability level $p = 0.1$ and a Hubert's weight parameter $h = 1$ (Fig. 2). In order to determine the intensity and duration of drought (pluvial) events in the lake area from the Vilama-Coruto region, we computed the lowest (highest) reconstructed n year running means for $n = 1$, 5, 25 and 50 yr. In addition, we analyzed the occurrence rate of extreme reduction in lake area along the reconstruction. For that purpose, we employed a kernel estimation technique (Mudelsee et al., 2004; Girardin et al., 2006). This method allows the detection of non-monotonic trends and imposes no parametric restrictions. A Gaussian kernel function was applied to weigh reconstructed years of extreme decrease in lake area and calculate the occurrence rate (probability per time unit). A Kernel bandwidth of 50 years was used and pseudo-data generation rule “reflection” to reduce boundary bias (Mudelsee et al., 2004). Confidence bands at the 90 % level were obtained by using 2000 bootstrap simulations (Cowling et al., 1996; Mudelsee et al., 2004). The extreme events dates were define by a percentile threshold of 20 %.

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2.6 Spatial and spectral analyses of the reconstructed lake area and climate forcing

In order to identify the Pacific influence on lake fluctuations from Vilama-Coruto region, we estimated the spatial correlation coefficient pattern between the reconstructed annual (January–December) lake area and the annual averaged (January–December; 2.5×2.5 gridded cell) from the NCEP reanalysis global dataset (Kistler et al., 2001: http://www.cpc.ncep.noaa.gov/data/indices/). Additionally, power-spectral and cross-spectral analyses (Jenkins and Watts, 1968) were used to determine the frequency domains of the reconstructed lake area variations in the Vilama-Coruto region and the annual averaged Pacific N3.4-SST.

The Blackman–Tukey (BT) spectral analysis (Jenkins and Watts, 1968) was computed for the periods 1407–2007 and 1872–2007 for the reconstruction and the Pacific N3.4-SST, respectively. The number of lags used for the auto- and cross-covariance functions was equal to 30 % of the series length. Spectra functions were smoothed with the Hamming filter. The 95 % confidence level of the spectrum was estimated from a "red noise" first-order Markov null continuum based on the lag-1 autocorrelation of the time series (Mitchell et al., 1966). A coherency spectrum analysis was computed over the common period 1872–2007 between the reconstructed lake area and N3.4-SST records. The coherency spectrum measures the variance in common between reconstructed lake area and N3.4-SST as a function of frequency. Both, BT and coherency analysis were performed using the AnClim program (Štěpánek, 2008).

To detect the dominant, non-stationary oscillatory modes of variability in the 601 yr series of reconstructed lake area we used Singular Spectral Analysis (SSA; Vautard and Ghil, 1989). SSA is a non-parametric method related to empirical orthogonal function analysis that samples lagged copies of time series at equal time intervals and calculates eigenvalues and eigenvectors of the auto-covariance matrix (Vautard and Ghil, 1989; Vautard, 1995). SSA enables the user to evaluate the changing periodic behaviour in a single time series by extracting "reconstructed components" or "wave-

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forms", which represent the dominant periodic modes of the time series. This method detects changes in amplitude and phasing of the dominant cycles over time because waveforms retain the temporal periodic behaviour (Vautard and Ghil, 1989; Vautard, 1995; Speer et al., 2001). In addition, SSA was computed for the N3.4-SST and PDO indexes to assess the relationship in the time frequency domain between the reconstructed lake area and Pacific climate forcing. The SSA analysis was performed by using SSA program (Boninsegna and Holmes, unpublished operating manual (on file at Laboratory of Tree-Ring Research, University of Arizona)).

3 Results

3.1 Tree-ring chronology and reconstruction model

In this study, 155 tree-ring samples from dead and living trees of *P. tarapacana* were combined to develop a robust composite tree-ring chronology for the Vilama-Coruto region in NWA and SWB. The chronology covers the period AD 1242–2008, but is best replicated since AD 1407 ($N > 10$ tree ring width series). As it was demonstrated in previous studies (Morales et al., 2004, 2012; Carilla et al., 2013), *P. tarapacana* trees are drought sensitive and show relative-high variability in tree-ring widths (mean sensitivity = 0.30). The RBar and EPS statistics indicate that the chronology is of good quality with a strong common signal in ring width between individuals (Table 1). The chronology statistics are similar to those previously documented for *P. tarapacana* tree-ring records from the Bolivian Altiplano and the Argentine Puna (Morales et al., 2004, 2012; Solíz et al., 2009; Christie et al., 2009; Carilla et al., 2013). The EPS remains above the threshold of 0.85 over the period 1399–2008. The mean EPS for the period 1407–2008 is 0.96 (Table 1). The "signal free" standardization method, using negative exponential curves, allows to the *P. tarapacana* composite chronology capturing appreciable amounts of both low- (multi-decadal) and high-frequency (inter-annual) variability in lake area fluctuations.

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We present here a 601 yr high-resolution tree-ring reconstruction of annual area fluctuations from nine lakes in the Vilama-Coruto region. Our reconstruction, calibrated and validated on satellite image January–December lake area (1975–2007; Fig. 2), accounts for 60 % of the total variability in lake area changes (R^2_{adj} adjusted for loss of degrees-of-freedom; Draper and Smith, 1981). The consistence between the observed and estimated lake area indicates good quality in the calibration model for reproducing past lake area fluctuations. The high predictive power of the calibration model is consistent with a highly significant F value ($F = 25.4$; $P < 0.001$) and a largely positive Reduction of Error (RE = 0.54). Analyses of regression residuals indicated no violations of regression assumptions. The residuals of the regression models are normally distributed, not significantly autocorrelated and without a significant trend according to Durbin–Watson tests (Fig. 2b).

3.2 Temporal evolution of the lake area reconstruction

The lake area reconstruction for the Vilama-Coruto region is characterized by inter-annual variations embedded within decadal to multi-decadal fluctuations (Fig. 3). Significant persistent changes in the mean state of the reconstruction were detected with the Rodionov analysis (Rodionov, 2004; Fig. 3). This analysis shows that lake-area conditions around the long-term mean for the period 1407–1440 were followed by a lake area increase lasting to the beginning of the sixteenth century (1503). This fifteenth century was characterized by high inter-annual variance, with extreme high- and low-lake area years. The longest period of comparatively low-lake area spans for almost a century covering the interval 1504–1595. This long-term dry period was interrupted by two decade-scale periods showing contrasting high and low lake areas centered on the years 1600 and 1620, respectively. After that, significant high-area conditions prevailed for more than 160 yr (1627–1790). Two of the five years with the largest lake areas were recorded during this period (1734 and 1744; Table 2). The 35 yr smoothing spline shows a period of gradual reduction in lake area between 1750 and 1790. However, no significant shifts in mean lake-area extent were detected over this inter-

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val. For the period 1797–1818 low lake area conditions was identified. A marked shift from low- to high-lake areas was identified around 1820. The period 1820–1859 encompass the highest lake areas reconstructed during the past 601 years. After this long-term increase in lake area, a gradual decrease in lake areas was reconstructed to the first decades of the twentieth century. After that, a steady negative trend in lake area starts in 1930s and persists to the present. The most pronounced negative decline for the entire reconstruction is recorded for the period 1976 to 2007. Over this 30 year interval, the lake area during the year 1987 slightly surpassed the long-term historical mean. Three of the five years with the lowest lake areas occurred during the last three decades (Table 2).

An alternative picture of the long-term history of increase-decrease lake area periods is given by averaging non-overlapping intervals of 5, 25, and 50 years (Table 2). Based on a 5 year moving average, three of the five lowest lake-area periods occurred since 1930 (i.e. 1938–1942, 1998–2002, 2003–2007), whereas the highest lake-area periods in the reconstruction were centered around 1740s and 1840s (Table 2). In terms of 25 year moving averages, the period from 1983 to 2007 ranks at the top among the five lowest events. The standardized anomalies of lake area during this interval were substantially lower than during 1608–1632, which ranks second among the 25 year long lowest periods (Table 2). The marked lake area increase from 1833 to 1857 is also a prominent feature revealed by the 25 year moving averages. Similar patterns emerge when the analysis is extended to 50 year periods. The intervals 1958–2007 and 1808–1857 respectively, rank first of the five lowest and highest periods over the past six centuries, respectively (Table 2). The above results indicate that lake-area fluctuations in Vilama-Coruto region during the second half of twentieth century have been comparatively the lowest whereas those during the nineteenth century have been the largest in the context of the past 601 years.

Following these results, the reconstruction suggests an increase in the occurrence of extreme events in lake-area reduction during the twentieth century (Fig. 4). To assess the occurrence rate of extreme lake-area decrease along the reconstruction, we

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employed the recurrence analysis by Mudelsee et al. (2004). The results indicate that the occurrence rate of extreme events of lake area reduction (i.e. lake area values under percentile 20) in the Vilama-Coruto region, ranges between 4–7 years since the fifteenth to eighteenth centuries. In the nineteenth century, the occurrence of lake area reduction was every 7 to 15 years and steadily increased since 1930s to present with a recurrence period of small lake area from 6 to 2 years.

3.3 Spectral properties and Pacific influence on lake area reconstruction

The spatial correlation pattern between the reconstructed lake area and the global gridded sea surface temperatures (SSTs) were determined for the interval 1948–2006 (Fig. 5). The annual lake area is negative and significantly correlated with SSTs from the tropics to the mid-latitude Pacific coasts of the Americas, resembling an El Niño–Southern Oscillation (ENSO) – Pacific Decadal Oscillation (PDO) like pattern (Fig. 5).

Figure 6 shows the BT spectra for the annual lake-area reconstruction over the Vilama-Coruto region and the N3.4 SSTs. Peaks that exceed the 95 % confidence limit in the lake area reconstruction are prominent at 12.9, 5.9–6.3, 3.2 and 3 years. Except for the decadal peak of 12.9, all significant peaks coincided with the N3.4 SSTs peaks recorded in Fig. 6b (5.9, 3.6–3.7). At inter-annual time scale, the lake reconstruction contained similar periodicities to N3.4 SSTs, falling within the preferred frequency band of ENSO (2–7 years).

The coherency spectrum was significant at 2.8, 3.4–3.9 year cycles, revealing that the lake area reconstruction captures the inter-annual variability in SST records (Fig. 6c). These results suggest that part of the variance in the lake-area reconstruction from the Vilama-Coruto region reproduces the timing and duration of high frequency SST anomalies.

We used singular spectral analysis (SSA), to isolate the main oscillatory modes of the lake area reconstruction variability (Fig. 7). Several important waveforms were recorded at multi-decadal (26–33 yr), decadal (11–15 yr) and inter-annual (5–8 and 2–4 yr) time scales (Fig. 7). The multi-decadal waveform amplitudes around 1600s were

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the largest in the series at times when two severe decade-scale reductions in lake area (1583–1595; 1614–1627) were interrupted by a decade of increased lake area (1596–1613). The decadal oscillation mode show high amplitude variability during the fifteenth, eighteenth and the beginning of nineteenth centuries, and was reduced during the sixteenth and the second half of nineteenth centuries. The reconstruction contains an important 5–8 years cycle waveform that explains a high percentage (27 %) of the lake-area reconstruction variability. The amplitude of this oscillatory mode was relatively large along the entire reconstruction but decreased from around the 1920s to present. The inter-annnual oscillation mode (2–4 yr) shows high amplitudes during the fifteenth, first half of sixteenth, second half of nineteenth and in particular during the second half of twentieth centuries.

A comparative analysis between the dominant oscillatory modes in the reconstruction with those in the Pacific Decadal Oscillation index (PDO) and in the N3.4 SSTs, highlighted the occurrence of common waveforms between them at different frequencies (Fig. 8). The lake-area reconstruction shares similar oscillations with PDO at multi-decadal modes of variability, while at decadal and inter-annual modes, the reconstruction waveforms are closely related to those recorded at N3.4 SSTs. High correspondence in the inter-annual modes are evident in the amplitudes of the lake reconstruction and N3.4 SSTs waveforms showing both records large and small amplitudes during 1870–1890/1960–2008 and 1930–1960, respectively; (Fig. 8c).

4 Discussion and concluding remarks

Our study represents the first high-resolution tree-ring based reconstruction of variations in lake area over the past six centuries in the Andes. Through the analysis of 601 years of water balances of the dry Puna lakes, this study provides a novel insight into the climate variability of the subtropical Andes. The evidence used to develop and validate this reconstruction includes satellite images and century-long tree-ring series of *P. tarapacana*, a climate-sensitive species from the Altiplano. The use of satellite-derived

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lake area records as a measured of water balance, resulted a useful approach to explore hydrological trends in this region devoid of local meteorological records (Carilla et al., 2013).

The regression model used to develop the reconstruction explains 60 % of the total variance in the January–December lake area over the 1975–2007 calibration period. This value is comparatively higher to that previously reported for a tree-ring based precipitation reconstruction of the Southern Altiplano ($R^2_{adj} = 0.54$; Morales et al., 2012). Since tree rings and lake areas in arid environments, simultaneously integrate precipitation and evaporation, a closer association is expected between tree rings and lake extents than between tree rings and precipitation.

Extended periods of small lake areas in our reconstruction, such those recorded in 1504–1595, 1614–1626, 1790–1818 and 1976–2007, highlight the occurrence of decadal to multi-decadal droughts in the region. Similar, relatively long-term humid conditions were reconstructed during the intervals 1596–1613, 1627–1770, 1820–1859. Concurrent dry and wet periods to those registered in our reconstruction have been documented in a tree-ring based precipitation reconstruction for the South American Altiplano (Morales et al., 2012) and in a gridded multiproxy PDSI (Palmer Drought Severity Index) for the South American subtropics (Boucher et al., 2011).

Wet and cold conditions in NWA-SWB, associated with large areas of the lakes during the period 1627–1796, have also been documented for other climate proxies from northern locations in tropical Andes such as the δ^{18}O isotopes in the ice core from the Quelccaya (Thomson et al., 2006) and in the sediment core from Pumacocha (Bird et al., 2011). However, wet and cold conditions in these records occurred during almost 300 years (1500–1800), whereas in our tree-ring reconstruction, wet and cold conditions last 169 years from 1627 to 1796. In addition, small lake areas were recorded in this time interval for the years 1661–1662, 1724, 1740, and 1753–1755. In contrast to the Quelccaya and Pumacocha records, our reconstruction shows persistent low lake areas in the sixteenth century. Differences between these records may reflect distinct climate conditions between sites separate for more than 1000 km in north–south di-

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rection along the Andes. Discrepancies between proxies are also related to the own nature of records (tree-rings, ice cores and lake sediments) capturing environmental changes at different frequency and time lags.

Analyses of satellite-derived lake area and vegetation index in the Vilama-Coruto region revealed sustained negative trends in water balance and ecosystem productivity for the periods 1985–2009 and 2000–2010, respectively. These environmental changes have been associated with recent climate variability in NWA-SWB (Carilla et al., 2013). Our lake-area reconstruction places the recorded dry conditions of the late twentieth century in the context of the past six centuries. The late twentieth century decrease in lake areas is exceptional over the period 1407–2007. Three of the five 5 yr periods with smallest lake areas occurred from 1930 to present. Similarly, the top ranks for the 25 and 50 yr periods indicate that the longest interval with reduced lake areas occurred during the second half of twentieth century.

Recurrence of extremely small lake-area events has been a common feature in the Vilama-Coruto region over the past six centuries. However, the twentieth century shows the highest rate of extreme events, that shifts from a period of 15 yr in the second half of nineteenth century to every 2 yr in the late twentieth century.

Since the mid 1970s, the Vilama-Coruto lake system recorded an accelerated decrease in area consistent with the driest conditions of the past six centuries. This shift to arid conditions has also been recorded in oxygen isotopic rate $\delta^{18}O$ from Quelccaya (Thompson et al., 2006) and Pumacocha (Bird et al., 2011). In both records, this pervasive dry period was also unprecedented in the context of the last 600 yr. The dry conditions seems to be a regional pattern affecting the southern tropical Andes, and a major cause of the steady shrinking of glaciers from 1930 to 2005 in southern Perú and Bolivia (Ramirez et al., 2001; Francou et al., 2003; Vuille et al., 2008). Glacier retreat is also related to the increasing trend in temperature during the last decades across the region (Vuille and Bradley, 2000; Urrutia and Vuille, 2009). Annual temperature deviations averaged over the tropical Andes (1° N–23° S) indicate a significant warming trend for the period 1939–1998. However, this trend has intensified since the

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mid 1970s (Vuille and Bradley, 2000) and was highly consistent with the faster rate of global temperatures increases (Jones et al., 1999).

Significant changes in precipitation patterns in tropical and subtropical South America have been identified in instrumental records during the twentieth century. A trend analysis (1950–1998) of atmospheric vertical motion and winds across a north–south transect at 65° W in tropical-subtropical South America shows a significant increase in precipitation and cloudiness in the inner tropics whereas the southern tropics and subtropics become drier and less cloudy (Vuille et al., 2008). These changes in precipitation and cloudiness have been associated with an intensification of the regional Hadley circulation, with a more vigorous vertical ascent, favorable for convective activity, in the tropics, balanced by enhanced subsidence and less cloudiness in the subtropics (see Fig. 6, in Vuille et al., 2008).

Spectral analyzes reveal periodicities and dominant waveforms in the lake-area reconstruction at multi-decadal (26–33 yr), decadal (11–15 yr) and inter-annual (5–8 and 2–4 yr) modes of variability. All these oscillations were consistent with the spectral properties from the N3.4 SSTs and PDO indexes. The amplitudes of the different modes change along the reconstruction. A dominant multi-decadal mode shows large-amplitude oscillations around 1600, whereas the decadal mode was more important in the 1500s and from 1700s to the beginning of 1800s. The inter-annual 5–8 yr bandwidth was dominant for almost the entire analyzed period, except after 1950, where amplitudes decreased. Inter-annual 2–4 yr bandwidth was strong at the second half of nineteenth and twentieth centuries. The shift from a dominant decadal to an inter-annual mode was also recorded in a PDO index reconstruction based on western North America and southern Central Andes tree-ring chronologies (D'Arrigo et al., 2001; Villalba et al., 2001). These authors reveal evidences for a shift to a less pronounce decadal variability since 1700 to 1830, after which the interannual mode was more pronounced (D'Arrigo et al., 2001; Villalba et al., 2001).

When we compared the main oscillation modes of variability between the lake-area reconstruction and the instrumental PDO and N3.4 SSTs indexes over the common

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period, negative relationships were evident at multi-decadal, decadal and inter-annual mode of variability, highlighting the Pacific influence over most modes of variability in Coruto-Vilama lake areas. Decrease in reconstructed lake areas and Pacific-SSTs amplitudes at inter-annual modes was recorded from 1930 to 1960, which was coherent with a reported low ENSO activity during the same interval (Aceituno and Montecinos, 1993; Torrence and Webster, 1999; Sutton and Hodson, 2003).

The BT spectral density analysis suggests that the lake-area reconstruction and N3.4 SSTs contain similar inter-annual periodicities within the preferred frequency band of ENSO (2–7 years). In particular, the strong spectral coherency between both series within the 2–4 yr bandwidth indicates that the timing and magnitude of high-frequency anomalies in Pacific SSTs modulate the interannual lake-area variability in the Vilama-Coruto system. During the past 600 years, 16 % of the variance in lake area is associated with the 2–4 yr bandwidth (Fig. 8d); however, the largest contribution to the total variance (27 %) arises from cycles at the 5–8 yr bandwidths (Fig. 8c). The amplitude of the 5–8 yr waveforms decreased from the 1930s to present. In contrast, an increase in amplitudes of the 2–4 yr oscillation is recorded over the same interval.

In contrast to high-frequency oscillations associated with ENSO, decadal to multi-decadal modes of variability in the lake-area reconstruction appears to be associated with changes in the PDO index. Previous studies have documented a long-lived pattern of Pacific climate variability in palaeoclimate records from Western North America and the Central Andes (D'Arrigo et al., 2001; Villalba et al., 2001; Masiokas et al., 2010). The persistent trend to arid conditions recorded from mid 1970s to present in the Vilama-Coruto lake-area reconstruction was coincident with a documented shift from the negative to the positive phase of the PDO in 1976 (Mantua et al., 1997). This PDO positive phase, which lasted to the end of the twentieth century, coincided with a marked increases in global mean surface temperatures (Trenberth et al., 2013, 2014) and have significantly impacted climate and ecosystems along the western coasts of North and South America (D'Arrigo et al., 2001; Villalba et al., 2001; Masiokas et al.,

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2010). During this interval of positive PDO phase, an increased in ENSO was recorded in both instrumental and reconstructed data (Li et al., 2013).

Interactions between PDO and ENSO have documented for both North and South America (Andreoli and Kayano, 2005). More intense El Niño (La Niña) rainfall anomalies occur when both ENSO and PDO share positive (negative) phases. In contrast weaken anomalies occur when they are in opposite phases. It has been suggested that PDO switched to a negative phase (La Niña-like pattern) around 1999, coincident with a pause in the sustained increase in global mean surface temperatures (Trenberth et al., 2014). However, we note that the downward trend in Coruto-Vilama lake areas have persisted since the year 1999. This suggests that, in addition to PDO, different forcings may have contributed to the persistence of dry conditions in our study region for the past decade.

The lake-area reconstruction presented in this study provides valuable information about ENSO and PDO evolution during the past 600 years and should be considered as a key input in further high-resolution reconstructions of PDO and ENSO. Given that ENSO and PDO variability represent major factors affecting hydrological patterns in the high-elevation lake systems from NWA-SWB, the longer time frames provide here may also complement those studies discussing the regional manifestations and long-term variability of these large-scale ocean–atmosphere features (Stahle et al., 1998, 2005; Evans et al., 2001; D'Arrigo et al., 2001, 2005; Villalba et al., 2001; Cobb et al., 2003; Gergis and Fowler, 2009; Li et al., 2013).

At local and regional scales, the lake-area reconstruction should be used as input in water system models to refine the reliability of water-balance assessments and ecosystem productivity in this arid region with persistent hydrological deficits. This study is especially useful in understanding the temporal variability of water availability in the Vilama-Coruto lake system, where water resource is fundamental for biodiversity conservation and socio-economic activities such as grazing, mining and tourism. Global and regional climate models for the Altiplano and Puna (Urrutia and Vuille, 2009; Minvielle and Garreaud, 2011; IPCC, 2013) projected a marked reduction in precipitation to

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the end of the 21st century, exacerbating actually dry conditions. If the negative trend in precipitation documented in recent decades continues, it is likely that the ranges of natural variability of these high altitude ecosystems will be exceeded. Therefore, quantitative information on past hydrological changes is required to provide reliable information to better adaptation to future drier conditions in the Altiplano. Further improvements in the existing lake area and precipitation reconstructions could be achieved by expanding the temporal and spatial coverage of the tree-ring network in the Puna and Altiplano from Argentina, Bolivia, Chile and Peru. Similar reconstruction exercises could be performed for neighboring high altitude lake systems from the Altiplano and northernmost tropical Andes.

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Table 1. Geographical location and statistics of the *Polylepis tarapacana* ring width chronologies. Mean RBar and mean EPS were averaged over chronology periods including > 10 tree-ring series.

Chronology	Location (° S/° W)	Period (years)	No. of series	Mean Inter-correlation	Mean sensitivity	Mean RBar	Mean EPS	*r* with regional lakes
Uturunco	22 16/67 10	1242–2006	81	0.59	0.28	0.39	0.95	0.59
Granadas	22 35/66 33	1620–2008	74	0.63	0.31	0.40	0.95	0.58
Regional		1407–2008	155	0.58	0.30	0.37	0.96	0.69

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Table 2. Lowest and highest non-overlapping moving averages of the reconstructed (1407–2007) lake area fluctuations for the Vilama-Coruto lake system. Annual lake area expressed as anomalies (Z score) of the 1975–2007 lake area mean. Ranks 1–5 correspond the most extreme lake-area reconstructed years.

Rank	Minimum Lake Area			
	1 yr	5 yr	25 yr	50 yr
1	−0.803 (2007)	−0.425 (2003–2007)	0.040 (1983–2007)	0.398 (1958–2007)
2	−0.727 (1998)	−0.225 (1618–1622)	0.661 (1608–1632)	0.775 (1508–1557)
3	−0.661 (1505)	−0.148 (1998–2002)	0.741 (1533–1557)	0.915 (1608–1657)
4	−0.610 (1621)	−0.091 (1753–1757)	0.754 (1783–1807)	0.924 (1758–1807)
5	−0.553 (1983)	−0.127 (1938–1942)	0.757 (1958–1982)	0.926 (1558–1607)
Rank	**Maximum Lake Area**			
	1 yr	5 yr	25 yr	50 yr
1	3.277 (1456)	2.352 (1838–1842)	1.727 (1833–1857)	1.399 (1808–1857)
2	2.941 (1734)	2.216 (1733–1737)	1.358 (1858–1882)	1.345 (1858–1908)
3	2.844 (1840)	1.962 (1743–1747)	1.335 (1883–1907)	1.196 (1458–1507)
4	2.826 (1744)	1.936 (1453–1457)	1.295 (1458–1482)	1.188 (1658–1708)
5	2.802 (1431)	1.912 (1843–1847)	1.281 (1908–1933)	1.164 (1908–1957)

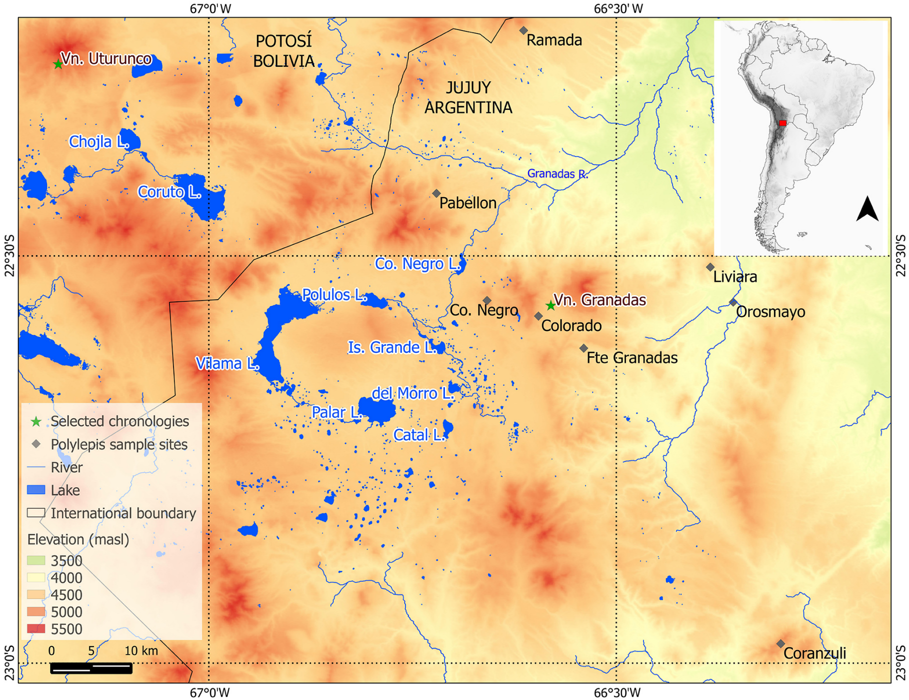

Figure 1. Map showing the Vilama-Coruto lake system in the Northwest Argentina and South-west Bolivia. Green stars represent the selected tree-ring chronologies used in this study.

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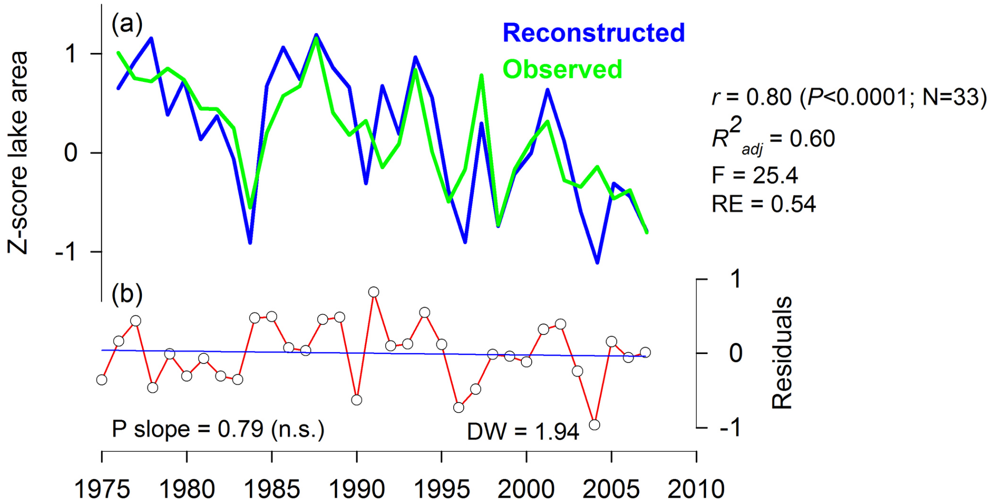

Figure 2. Observed (green line) and tree-ring predicted (blue line) annual lake area (January–December) variations in the NWA-SWB. Annual lake area expressed as a *Z* score of the satellite-derived 1975–2007 lake area mean. Calibration and verification statistics: the Pearson correlation coefficient (r) between observed and reconstructed values, the coefficient of determination adjusted for the degrees of freedom in the model (R^2_{adj}) over the calibration period, the *F* value of regression (the ratio between the explained and the unexplained variability in the model), and the reduction of error (RE) **(a)**. The linear trend of regression residuals (slope: blue line) and the Durbin–Watson (D-W) statistics used to test for first-order autocorrelation of the regression residuals are shown in **(b)**.

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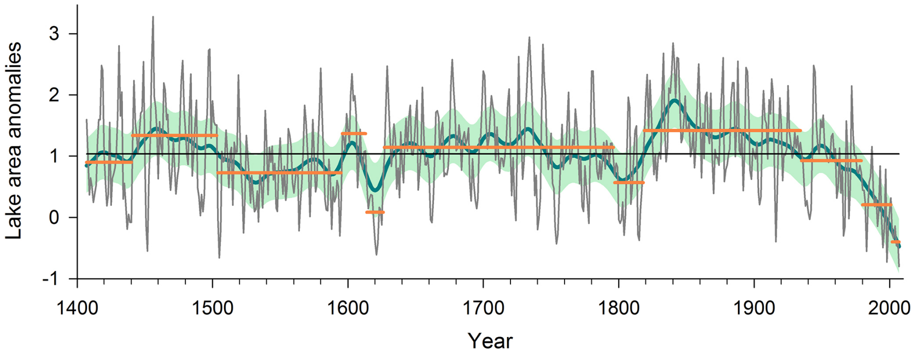

Figure 3. Annual (January–December) Vilama-Coruto lake area reconstruction for the period AD 1407–2007. Annual lake area expressed as anomalies (*Z* score) of the 1975–2007 lake area mean. The 35 yr smoothing-spline curve highlights the multi-decadal variability. Significant (95 % c.l.) regime shifts (orange horizontal line) detected by the Rodionov (2004) method (window length = 25 yr). Uncertainties of the reconstruction are shown by the light green band (±1 RMSE).

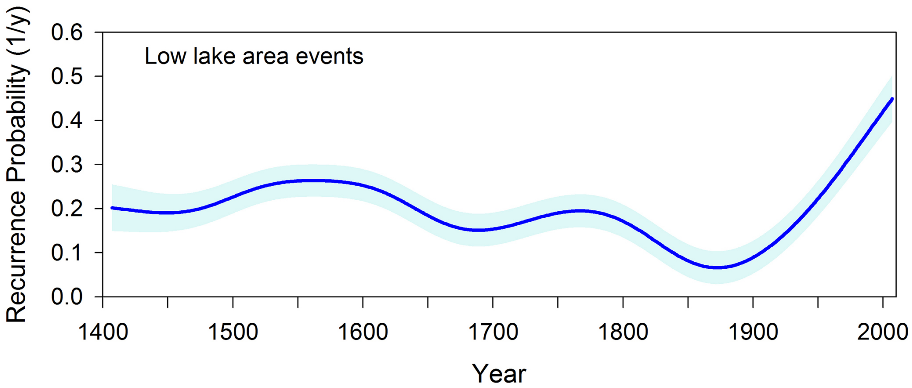

Figure 4. Occurrence rate of extreme lake area decrease (lake area values under percentile 20) along the reconstruction time span (1407–2007) in the Vilama-Coruto region.

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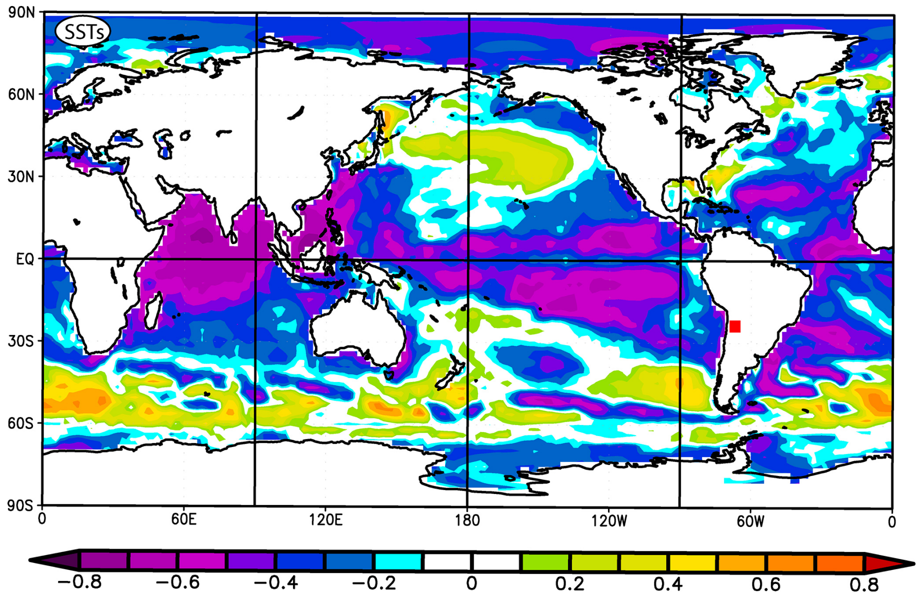

Figure 5. Spatial correlation patterns over the interval 1948–2006 between the 2.5×2.5 gridded monthly averaged January–December sea surface temperatures (SSTs) and the reconstructed January–December lake area for the Vilama-Coruto region. Spatial correlations were obtained from the National Oceanic and Atmopheric Administration website (http://www.esrl.noaa.gov/psd/data/correlation/). The reconstructed lake area region is indicated by the red square.

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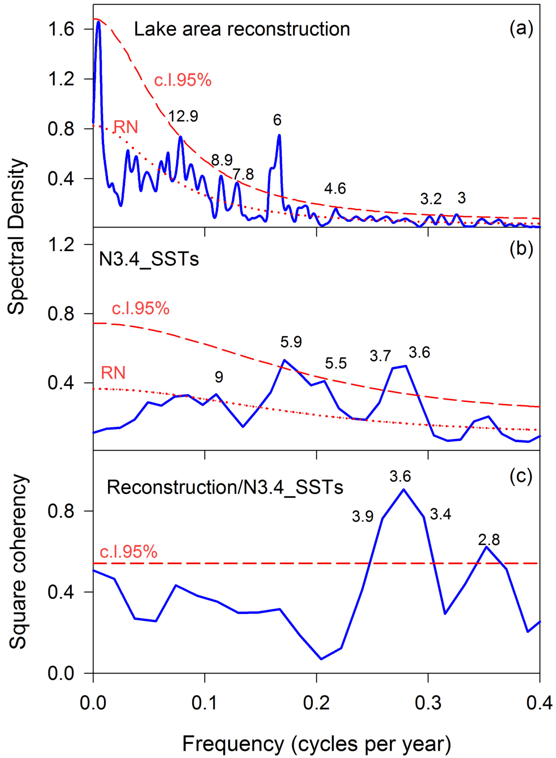

Figure 6. Blackman–Tukey power spectra analysis of the reconstructed lake area (1407–2007) **(a)** and the sea surface temperatures from the N3.4 Pacific sector (N3.4 SST; 1872–2007) **(b)**. Coherency spectrum of N3.4 SST and reconstructed lake area in the Vilama-Coruto region, estimated over the common period 1872–2007 **(c)**. Short dashed and dotted lines represent the 0.05 probability levels and the red noise band, respectively. Dominant periodicities are indicated in each panels.

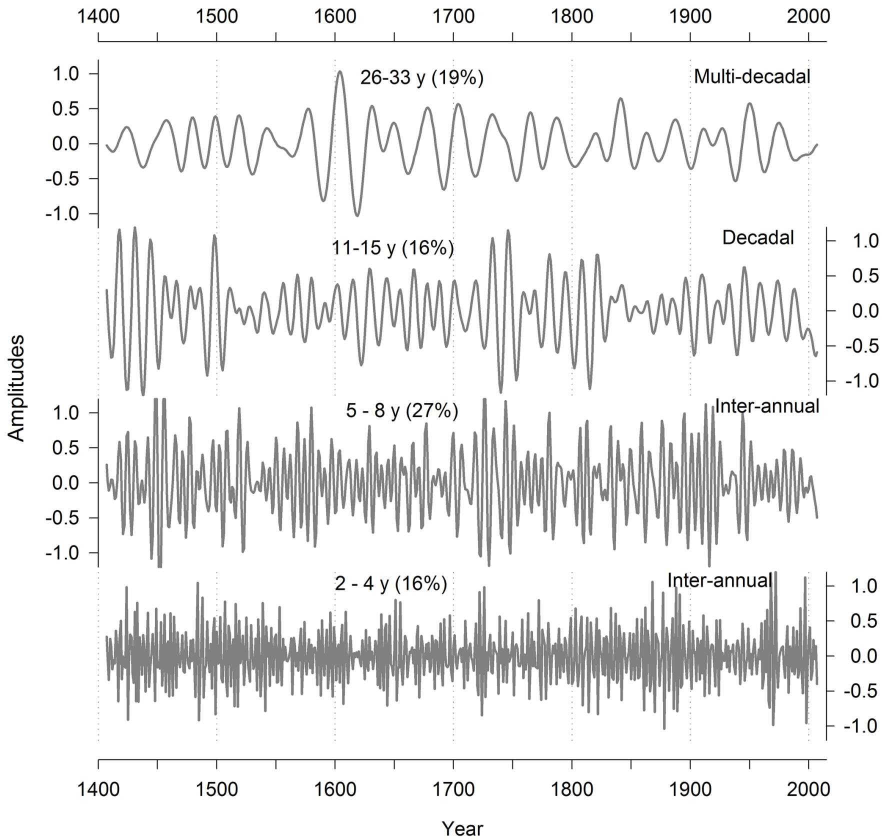

Figure 7. Multi-decadal, decadal and inter-annual main oscillation modes of variability extracted by Singular Spectral Analysis (SSA). The frequencies for each SSA are indicated in years with the corresponding explained variance in percentage (%).

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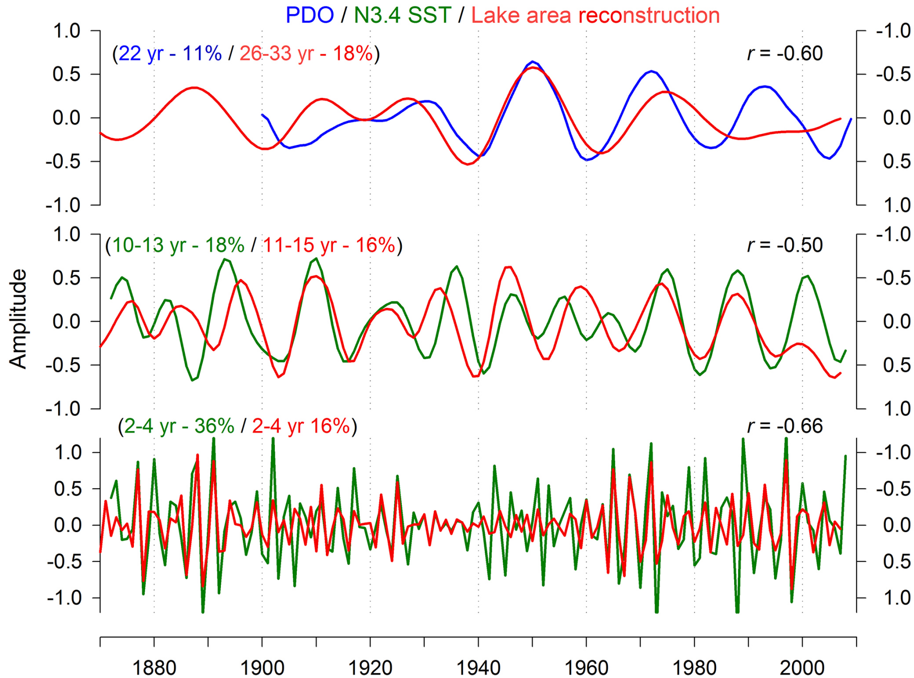

Figure 8. Comparisons between the waveforms of the lake area reconstruction (red line), PDO (blue line) and the N3.4 SST (green line) extracted by Singular Spectrum Analysis (SSA). The frequencies and percentage of variance explained by each frequency are indicated in parentheses. The correlation coefficients between the two series are shown at the right corner. The PDO and N3.4 SST waveforms are shown inverse to facilitate the comparison between records (right axis).

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