

ENSO and solar activity signals from oxygen isotopes in diatom silica during Late Glacial-Holocene transition in Central Andes (18°S)

Armand Hernández^{1*}, Santiago Giralt¹, Roberto Bao², Alberto Sáez³, Melanie J. Leng^{4,5}, Philip
A. Barker⁶

¹Institute of Earth Sciences Jaume Almera-CSIC, C/Lluís Solé i Sabarís s/n, 08028 Barcelona,
Spain

²Faculty of Sciences, University of A Coruña, Campus da Zapateira s/n, 15701 A Coruña, Spain

³Faculty of Geology, University of Barcelona, C/ Martí Franquès s/n, 08028 Barcelona, Spain

⁴NERC Isotope Geosciences Laboratory, British Geological Survey, Nottingham NG12 5GG, UK

⁵School of Geography, University of Nottingham, Nottingham NG7 2RD, UK

⁶ Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK

***Correspondence to:** Armand Hernández;

Institute of Earth Sciences 'Jaume Almera' (CSIC). C/Lluís Solé i Sabarís s/n. E-08028
Barcelona (Spain).

Phone: +34.934.095.410

Fax: +34.934.110.012

E-mail: ahernandez@ija.csic.es

Abstract

The Late Glacial-Holocene transition from the Lago Chungará sedimentary record in northern Chilean Altiplano (18°S) is made up of laminated sediments composed of light and dark pluriannual couplets of diatomaceous ooze. Light sediment laminae accumulated during short-term extraordinary diatom blooms whereas dark sediment laminae represent the baseline limnological conditions during several years of deposition. Diatom oxygen isotope data ($\delta^{18}\text{O}_{\text{diatom}}$) analyzed in 40 successive (lamina by lamina) dark laminae, from 11,990 to 11,450 cal years BP, suggest that there occurred a series of decadal-to-centennial dry-wet oscillations. Dry periods are marked by relatively high isotope values whereas wet episodes are indicated by lower values. This interpretation agrees with the reconstructions on allochthonous inputs and regional effective moisture availability carried out in the lake. The $\delta^{18}\text{O}_{\text{diatom}}$ record documents repeated effective moisture changes at a centennial-scale. Three major cycles have been established (11,990 to 11,800, 11,800 to 11,550 and 11,550 to 11,450 cal years BP). Each cycle is defined by an increasing isotope trend followed by a sudden depletion of the isotope values. In addition, several wet and dry events at a decadal scale are superimposed onto these major cycles. The spectral analyses of the $\delta^{18}\text{O}_{\text{diatom}}$ values suggest that cycles and events could be triggered by both the El Niño-Southern Oscillation (ENSO) and the solar activity. Significant ENSO frequencies of 7-9 years and 15-17 years, and periodicities of the solar activity cycles such as 11 yr (Schwabe), 23 yr (Hale) and 35 yr (Brückner) have been recognized in the oxygen isotope time series. Time-frequency analysis shows that the activity of these two forces, although was also present in the onset of the Holocene, it was more intense during the Late Glacial period. The early Holocene could be mainly governed by La Niña-like conditions that correspond to wet conditions over the Andean Altiplano.

Keywords: Lake, Oxygen isotopes, Late Glacial, Holocene, Andean Altiplano, ENSO, Solar activity, Diatoms

Introduction

The study of the Andean Altiplano lacustrine records plays a prominent role for interpreting the Quaternary palaeoclimatic history of the South American tropics and therefore for understanding the role of the tropics in the Earth's climate system (Grosjean et al. 2001; Valero-Garcés et al. 2003; Placzek et al. 2006) (Fig. 1). For this reason, studies on the sedimentary records from this area have increased in the last few decades. Most of these studies have focussed on the reconstruction of the climatic events at millennial time scales, mainly since the Last Glacial Maximum (Baker et al. 2001a). There is a general consensus that orbital forces are the main factor triggering the climatic conditions at a millennial-scale (Rowe et al. 2002; Placzek et al. 2006), and are therefore responsible for those climatic events. Superimposed onto this long term variability, changes in the hydrologic balance at a sub-millennial scale in the Andean Altiplano, have been attributed to the variability of the Pacific Sea Surface Temperatures (SSTs) and the strength of the zonal winds (Rowe et al. 2002; Garreaud et al. 2003). Both factors are controlled by El Niño-Southern Oscillation (ENSO) and changes in the solar activity (Theissen et al. 2008). A number of studies have detected multidecadal- to centennial-scale hydrological balance shifts, suggesting that these relationships have been active since, at least, the mid-Holocene (Valero-Garcés et al. 2003; Theissen et al. 2008).

Diatom oxygen isotopes ($\delta^{18}\text{O}_{\text{diatom}}$) are increasingly being used for palaeoenvironmental reconstructions in lacustrine sedimentary records (Rietti-Shati et al. 1998; Barker et al. 2001). However, application of this proxy to high-resolution centennial to millennial lacustrine records is still in its infancy (Barker et al. 2007). $\delta^{18}\text{O}_{\text{diatom}}$ in decadal-to-centennial resolution palaeoclimatic reconstructions has not been utilised, mainly due to the difficulty in obtaining large enough variation in $\delta^{18}\text{O}_{\text{diatom}}$ that can be easily characterised at this temporal scale. Additional difficulties in using $\delta^{18}\text{O}_{\text{diatom}}$ as a high-resolution palaeoclimate proxy are related to the difficulty in obtaining monospecific diatom sample in order to eliminate any species-specific effect variability, to acquire the necessary amount of sample for these short periods of time to ensure reliable isotopic data, and to have pure diatom samples, since significant contaminants can produce excursions in $\delta^{18}\text{O}_{\text{diatom}}$ that are similar magnitude to those produced by climate variation (Brewer et al. 2008).

The well laminated diatomaceous oozes and continuous record of Lago Chungará have previously been the subject of a preliminary diatom oxygen isotope study on non successive laminae record with less resolution paleoclimatic study purposes ([Hernández et al. 2008](#)). Nevertheless, for the present study we can select and separate to analyze until 40 successive dark-green laminae of these sediments (see sedimentary model in chapter ...), which represent a continuous record of the lake deposition under background limnological conditions ([Hernández et al. 2008](#)). The study of these rigorously continuous record can be more suitable for reconstruct changes in the regional moisture balance than those do it on a discontinuous record. The exceptional good quality (mejor ser más preciso Pureza?) of the sedimentary record of Lago Chungará allowed a detailed study of the dark-baseline conditions laminae in order to reconstruct the regional moisture balance at a decadal and centennial timescale.

In this study, we present the decadal to centennial time scale moisture balance reconstruction for the Andean Altiplano during the Late Glacial-Holocene transition (11,990-11,450 cal years BP) by means of the application of $\delta^{18}\text{O}_{\text{diatom}}$ analysis performed on successive and continuous 40 dark laminae of lacustrine sediments present in a core located in the offshore zone of Lago Chungará. In order to support the interpretation, isotope data are compared with the reconstructions of the allochthonous inputs and inferred regional effective moisture in the Lago Chungará performed in the same core by [Giralt et al. \(2008\)](#).

Lago Chungará setting

Geology and hydrology

Lago Chungará (18°15'S, 69°10'W, 4520 m a.s.l.) is located in the Chilean Altiplano (Central Andes) lying in a highly active tectonic and volcanic context ([Hora et al. 2007](#)). The lake sits in the small hydrologically closed Chungará sub-Basin which was formed as a result of a debris avalanche during the partial collapse of the Parinacota Volcano, damming the former Lauca River (Fig. 2). Lago Chungará and Lagunas Cotacotani were formed almost immediately. However, the age of this collapse is not well constrained, with estimates ranging from 13,000 to 20,000 years BP ([Hora et al. 2007](#)).

The lake has an irregular shape with a maximum length of 8.75 km, maximum water depth of 40 m, a surface area of 21.5 km² and a volume of 400 x 10⁶ m³ (Mühlhauser et al. 1995; Herrera et al. 2006) (Fig. 2A). At present, the main inlet to the lake is the Chungará River (300-460 l s⁻¹) although secondary streams enter to the lake in the south-western margin. The evaporation is the main water loss (3.10⁷ m³ yr⁻¹), and groundwater outflow from Lago Chungará to Lagunas Cotacotani (6-7.10⁶ m³yr⁻¹, Dorador et al. 2003) represents about 20% of the total outflow. The calculated residence time for the lakewater is approximately 15 years (Herrera et al. 2006). Water inputs to the lake have, on average, the following composition: 42 ppm HCO₃⁻, 3 ppm Cl⁻, 17 ppm SO₄²⁻, 7 ppm Na⁺, 4 ppm Mg²⁺, 8 ppm Ca²⁺, 3 ppm K⁺ and 22 ppm Si. The Mg/Ca ratio of water inputs ranges from 0.22 to 0.71, depending on the local lithology of the catchment (Herrera et al. 2006; Sáez et al., 2007). Data on isotope analyses, temperature, pH, O₂ and conductivity profiles of the lake water and the water inputs to the lake are shown in Table 1. The lake can be considered as polymictic and oligo- to meso-eutrophic (Mühlhauser et al. 1995). The δ¹⁸O and δD composition of the lake water revealed that it diverges from the Global Meteoric Water Line (GMWL) and the Regional Meteoric Line (RML). This divergence can be attributed to the enrichment of the lake water by evaporation with regard to rainfall and springwater (Fig. 3a and Herrera et al. 2006). The mean lake water values of δ¹⁸O and δD are –1.4‰ SMOW and –43.4‰ SMOW, respectively (Table 1).

Climate

Climate in the Chungará-Cotacotani lake district is dominated by arid conditions due to the influence of the South Pacific Anticyclone (Fig. 1). Modern mean annual temperature at Lago Chungará is +4.2°C. Annual rainfall ranges from 100 to 750 mm yr⁻¹ (mean 411 mm yr⁻¹), losing 1200 mm yr⁻¹ via evaporation, which exceeds precipitation (Fig. 3b and Valero-Garcés et al. 2000). The lake region shows pronounced seasonal contrasts due to the dominance of the tropical summer moisture (Garreaud et al. 2003), known as the South American Summer Monsoon (SASM) (Vuille and Werner 2005). Regional moisture is originated from the tropical Atlantic Ocean and is transported to the Altiplano throughout the Amazonia during the summer months (DJFM). During these months weak easterly flow prevails over the Altiplano as a

consequence of the southward migration of the subtropical jet stream and the establishment of the Bolivian high-pressure system (Garreaud et al. 2003). This climatic situation defines this time window as the wet season in the Altiplano accounting for more than 70% of the annual precipitation (Fig. 3b). The SASM is a major component of the climate system over tropical and subtropical South America during the austral summer and is remotely forced by tropical Pacific SSTs (Vuille and Werner 2005). Thus, the inter-annual to decadal climate variability is currently related to ENSO-like variations over the Pacific basin (Valero-Garcés et al. 2003). Instrumental data from the Chungará area show a reduction of the precipitation during moderate to intense El Niño years (Fig. 3c). However, there is no direct relationship between the relative El Niño strength and the amount of rainfall reduction (Valero-Garcés et al. 2003). Furthermore, on longer timescales, it is speculated that changes in tropical-Atlantic meridional SST gradients also force precipitation variability on the Altiplano (Baker et al. 2001b).

Rainfall isotope composition in Central Andes (Fig. 3d) is characterised by a large variability in $\delta^{18}\text{O}$ (between +1.2 and -21.1‰ SMOW) and of δD (between +22.5 and -160.1‰ SMOW). The origin of the lightest isotope oxygen values is the strong fractionation in the air masses from the Amazon and is directly related to higher rainfall intensity ('amount effect') (Herrera et al. 2006). However, the rainfall isotope composition in the Chungará-Cotacotani lake district only oscillates of 6‰ SMOW, between -14‰ and -20‰ SMOW, with a mean value of -14.3‰ SMOW (Fig. 3a and 3d).

Sedimentary sequence and rhythmite type

The sedimentary infill of Lago Chungará was characterized by the lithological description of fifteen lake cores obtained in 2002 (Sáez et al. 2007) and by seismic imagery obtained in 1993 (Valero-Garcés et al. 2000; Sáez et al. 2007). A composite core recording the upper 10 meters of the lake sedimentary infill from the offshore zone was constructed from the detailed description and correlation of cores 10 and 11 (Fig. 2). Hereafter, all core depths are referred to this composite core. From the bottom to the top of the core, two sedimentary units (units 1 and 2) were identified and correlated over the offshore zone of the lake mainly using tephra keybeds. Unit 1 is made up of diatomaceous ooze with variable types (calcite, aragonite) and

quantities of carbonates and amorphous organic matter. It is continuous across the lake, although thickest in the NW sector of the central plain and thins towards the south and west, probably onlapping the Miocene substrate. Unit 1 occurs in the central plain and the rise of the lake (Fig. 2B) and is divided in two subunits. Subunit 1a is composed by light and dark-green diatomaceous ooze couplets and a rhythmite type was defined (Hernández et al. 2008). Light-white laminae are formed by a quasi-monospecific assemblage of *Cyclostephanos andinus*. Dark-green laminae, with higher organic matter content, are made up by a mixture of diatoms, including the euplanktonic *Cyclostephanos andinus*, although diatoms of the *Cyclotella stelligera* complex are co-dominant taxa. Subdominant groups are some tycho planktonic (*Fragilaria* spp.) and benthic taxa (*Cocconeis* spp., *Achnanthes* spp., *Navicula* spp., *Nitzschia* spp.). Subunit 1b is composed of centimetre- to decimetre-thick laminated brown diatomaceous ooze and endogenic carbonates that occur in low concentrations. Unit 2 is about 6 meters-thick and grades laterally to the west and south into alluvial and deltaic deposits, and towards the east into macrophyte, organic-rich facies (Fig. 2B). It is mainly composed of massive to slightly banded diatomaceous ooze interbedding until 15 tephra layers. Unit 2 is also divided in two subunits. Subunit 2a is composed of brownish-red massive to slightly banded sapropelic diatomaceous ooze with common calcitic crystals (silt grain-sized) and carbonate-rich layers. Subunit 2b consists of dark-grey diatomaceous ooze with frequent macrophyte remains alternating with massive black tephra layers, mainly composed of plagioclase, glass and mafic minerals (Sáez et al. 2007; Moreno et al. 2007).

The chronological model for the sedimentary sequence of Lago Chungará is based on 17 AMS ^{14}C dates obtained from bulk organic matter from the central plain cores and aquatic organic microfossils picked from littoral cores, and one $^{238}\text{U}/^{230}\text{Th}$ date from carbonates. Details on the construction of the chronological framework are discussed elsewhere (Giralt et al. 2008). According to this chronological model, the studied interval records the late glacial-Holocene transition (11,990-11,450 cal years BP) and each couplet was deposited during time intervals ranging from 4 to 24 years. Light-white sediment laminae accumulated during short term diatom blooms (occurring from days to week) whereas dark-green sediment laminae represent the baseline limnological conditions during several years of deposition (Hernández et al. 2008).

Previous work has characterised the surface and underground waters from the Chungará and Cotacotani lake district ([Herrera et al. 2006](#)), as well as the sediments of Lago Chungará. X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), Total Carbon and Total Organic Carbon (TC and TOC), Total Biogenic Silica (TBSi), pollen and diatom analyses were performed. These multiproxy studies have allowed us to establish the sedimentary, hydrological and environmental evolution of the Lago Chungará at different time scales ([Sáez et al. 2007](#); [Moreno et al. 2007](#); [Giralt et al. 2008](#)).

Methods

An interval of 46.5 cm from the laminated dark and light sediments of Subunit 1a (deposited between 11,990 and 11,450 cal years BP) was selected and sampled lamina by lamina from core #11 (Fig. 2). All the dark laminae (40 samples) of this interval were selected for $\delta^{18}\text{O}_{\text{diatom}}$ analyses to carry out a very high-resolution (sampling ranging from 4.1 to 36.4 yr; average temporal resolution is ca. 12 yr) study of the baseline environmental evolution of Lago Chungará during the late glacial and early Holocene transition period. From these, 22 of these samples were also previously used in a lower resolution study ([Hernández et al. 2008](#)). The thickness of the dark laminae sampled ranges between 2 mm and 9 mm.

Analysis of the oxygen isotope composition of diatom silica requires the material to be almost pure diatomite ([Juillet-Leclerc 1986](#)). Our samples were treated following the method proposed by [Morley et al. \(2004\)](#) with some variations ([Hernández et al. 2008](#)). The samples were first sieved at 125 μm to eliminate resistant charcoal and terrigenous particles. The 63 μm and 38 μm sieves were used to obtain a diatom concentrate made up almost exclusively by the large valves of centric diatom *Cyclostephanos andinus*, eliminating in most of the samples any species-specific effect variability on the oxygen isotope fractionation (Fig 4). Gravity settling in a water column during the sieving process also helped to remove any remaining glass and clay particles. The Gravitational Split-flow Thin Fractionation (SPLITT) was then applied to the most problematic samples, at Lancaster University (UK), as an alternative approach to heavy liquid separation ([Rings et al. 2004](#); [Leng and Barker 2006](#)). Finally, the purified diatom samples were dried at 40°C between 24h and 48h. After the cleaning process, all the samples were checked

under the light microscope and some of them also with XRD and scanning electron microscope (SEM), as well as analysed for total carbon content (TC) to verify that they did not contain any significant amount of terrigenous matter (Fig 4).

For the oxygen isotope analysis, a stepwise fluorination method was applied to 5-10 mg of the purified diatoms in order to strip the frustule hydrous layer before a full reaction with BrF_5 (Leng and Barker 2006). The oxygen liberated was then converted to CO_2 using the method of Clayton and Mayeda (1963), measured by IRMS and normalised against NBS standards. A random selection of 7 samples were analysed in duplicate or triplicate giving a mean reproducibility value of $<0.2\text{‰}$ (1σ), only one sample gave a reproducibility value of 0.4‰ (1σ). The fluorination process and the $^{18}\text{O}/^{16}\text{O}$ ratios measured were carried out at the NERC Isotope Geosciences Laboratory, British Geological Survey (UK).

We employed two methods of spectral analyses to examine any periodic components in the $\delta^{18}\text{O}$ values: Multi-Taper Method (MTM) and Time-Frequency analysis. These two spectral analyses allowed us to examine statistically significant signals in the time series in both the frequency and time domains. MTM provided both a mean of spectral estimation and signal reconstruction for time series with spectra that contain both singular and continuous components (Theissen et al. 2008). Time-Frequency (TF) analysis is a hybrid tool between the Fourier Transform and wavelets that intends to use a localized spectrum. For that, this analysis does not use a fixed-size Gaussian window but a Gaussian window that adapts to the spectrum (Stockwell et al. 1996)

All the statistical treatments of the datasets were performed using the R software package (R Development Core Team 2008).

Results

Oxygen isotopes

The $\delta^{18}\text{O}_{\text{diatom}}$ record (Fig. 5E) shows both short-term (decadal) and long-term oscillations (centennial time scales) ranging from $+35\text{‰}$ to $+39.2\text{‰}$ (mean= $+37.4 \pm 0.8\text{‰}$). From the bottom to the top, the studied record can be subdivided into three intervals. These intervals correspond

to three enrichment/depletion cycles (Fig. 5D). Each cycle starts with a continuous centennial isotope enrichment which abruptly ends with sharp depletion:

Cycle 1. Lower interval (11,990 to 11,800 cal yr BP). It shows the maximum and minimum $\delta^{18}\text{O}_{\text{diatom}}$ values (+39.2‰ and +35.1‰ respectively, with a mean value of $+37.7 \pm 1\%$) throughout the whole record. It starts with an increasing trend of $\sim 3.3\%/100$ years which finishes at 11,860 cal yr BP. This trend is followed by a shift to lighter values of $\sim 8.1\%/100$ years with a sharp final decrease in the $\delta^{18}\text{O}_{\text{diatom}}$ values of 3.5‰ in less than 10 years, acquiring the minimum value for the whole record at ca. 11,800 cal yr BP. Both trends are interrupted by ca. 5 to 20 yr depletion/enrichment excursions ranging between ± 0.9 and $\pm 1.7\%$.

Cycle 2. Middle interval (11,800 to 11,550 cal yr BP). This section (mean values $+37.3 \pm 0.7\%$) starts with an enrichment trend showing an upwards gradient of $\sim 1.3\%/100$ years which finishes at 11,570 cal yr BP with a +38.3‰ $\delta^{18}\text{O}_{\text{diatom}}$ value. This trend is however punctuated by one sudden rise (+2.3‰) and up to four minor depletions (ranging from -0.6 to -1.3‰) of the $\delta^{18}\text{O}_{\text{diatom}}$ values on a 40 to 55 yr basis. The enrichment trend is followed by a shift of $\sim 9.1\%/100$ years to lighter values reaching a minimum value of +36.2‰.

Cycle 3. Upper interval (11,550 to 11,450 cal years BP). This interval (mean values $+37.2 \pm 0.7\%$) also starts with an enrichment trend but, because the section only comprises three samples, this enrichment has not been estimated. This trend is also followed by depletion of 1.3‰ in 10 yr.

Spectral analyses of the diatom oxygen isotope record

Multi-taper analysis (MTM) performed on the $\delta^{18}\text{O}_{\text{diatom}}$ values shows a number of clear periodicities (Fig. 6a). Almost all identified periodicities (7.16, 8.90, 11.13, 12.97, 18.62, 22.27 and 39.37 yr) exceed the 99% confidence interval whereas only two (3.73 and 8 yr) lie between 95-99% confidence interval (Fig. 6a). Most of the sub-decadal identified frequencies are close to the minimum temporal resolution of the sampling (4.1 yr), which explains in great part the weaker intensity of the short periodicities between 3 and 8 yrs. Therefore, only the most significant frequencies and above the minimum temporal sampling resolution have been taken into account in the discussion.

Time-Frequency (TF) analysis reveals the strongest energy for the lower values of frequency, mainly focussed on the 35 years- cycles, whereas it decreases towards higher frequency values, i. e., the higher periodicities (Fig. 6b). This fact can mostly be explained by the decadal sampling resolution, making periodicities lower-than-ten-years less significant. Additionally, TF analysis indicates that the highest energies of the significant frequencies are located in the Late Glacial period between ca. 11,950 and 11,700 cal years BP, decreasing just from the onset of the Holocene until, at least, approximately 11,550 cal years BP (Fig. 6b). The TF diagram also highlights that the identified frequencies correspond to a not active force during all the studied period. For instance, the shortest significant periodicity observed in the MTM (7.16 yr) was mainly active during the first 150 yr of the record, whereas it was only active during three short time windows in the following 500 yr. A similar pattern is also observed for the rest of the significant periodicities (8.9, 12.97, 11.13, 18.62, 22.27 and 39.37 years). The maximum energy areas correspond to depletions in the $\delta^{18}\text{O}_{\text{diatom}}$ values, i.e. 11,800 and 11,550 cal yr BP (Fig. 6b).

Discussion

Controlling factors of $\delta^{18}\text{O}_{\text{diatom}}$ in Lago Chungará

$\delta^{18}\text{O}_{\text{diatom}}$ of lake sediments is controlled by oxygen isotope composition of the lake water ($\delta^{18}\text{O}_{\text{lakewater}}$), temperature, and the possible disequilibrium by vital effects or diagenesis (Leng and Barker 2006). We discount vital effects and diagenesis as analyses were made on near-monospecific diatom samples and preservation is excellent (Fig. 4).

$\delta^{18}\text{O}_{\text{lakewater}}$ depends on the balance between the isotope composition of water inputs (including the source and amount of precipitation, surface runoff and groundwater inflow) and outputs (evaporation and groundwater loss) in the lake. The measured $\delta^{18}\text{O}$ of the inputs (springs, Río Chungará and rainfall) in the Lago Chungará is homogeneous, being values close to the isotope composition of precipitation ($\delta^{18}\text{O}_{\text{precipitation}}$) (Fig. 3a). $\delta^{18}\text{O}_{\text{precipitation}}$ is a function of the isotope composition of the moisture source and air-mass trajectory, but in the Lago Chungará there are not changes in the moisture source composition since the air masses

always come from the Atlantic Ocean throughout the Amazon basin (Grosjean et al. 1997). During the moisture transport from the Atlantic to the lake area, three processes are directly responsible of the low and variable values of the present $\delta^{18}\text{O}_{\text{precipitation}}$ throughout the Andean Altiplano (Aravena et al. 1999). These processes include interaction of the air masses within the Amazon basin, an altitude effect due to the ascent of the air masses along the eastern slope of the Andes, and the convective nature of the storms in the Altiplano region. Nevertheless, in the Lago Chungará region the values obtained for the measured $\delta^{18}\text{O}_{\text{precipitation}}$ are relatively stable with almost all values around -14 and -20‰ SMOW (Fig. 3a, 3d and Herrera et al. 2006), whereas $\delta^{18}\text{O}_{\text{lakewater}}$ is much higher (Fig. 3A). This result is in accordance with a $\delta^{18}\text{O}_{\text{lakewater}}$ enrichment via evaporation. Thus, any isotopic variation of $\delta^{18}\text{O}_{\text{lakewater}}$ will be more related to changes in the amount of precipitation (“amount effect”) and evaporation rather than on the variability of $\delta^{18}\text{O}_{\text{precipitation}}$. As indicated in the setting, this lake can be considered a hydrologically closed system, with a water residence time of about 15 years (Herrera et al. 2006), where the main inlet is the Chungará River and the main outlet is the evaporation. Evaporation enriches $\delta^{18}\text{O}$ of lake water by 14‰ relative to the inlets (precipitation, springs and river) in the present day (Fig. 3a and 3b, Table 1). However, during the late glacial and early Holocene the water residence time in the lake was shorter than the 15 years averaging at the present, and, because of the different palaeohydrological context of the lake at that time, it can also be considered closed for that period (Hernández et al. 2008). Thereby the variations in the $\delta^{18}\text{O}_{\text{diatom}}$ must be mainly derived from changes in the $\delta^{18}\text{O}_{\text{lakewater}}$ resulted from shifts in the balance between the precipitation and the evaporation (P-E). Another factor controlling $\delta^{18}\text{O}_{\text{diatom}}$ is temperature, as stated above.

Two different factors should be considered in the interpretation of the $\delta^{18}\text{O}_{\text{diatom}}$ values in terms of water lake temperature oscillations. The first factor is related to $\delta^{18}\text{O}_{\text{precipitation}}$ that correlates directly with changes in the air temperature. The global relationship between changes in $\delta^{18}\text{O}_{\text{precipitation}}$ with the water lake temperature is commonly referred to as the ‘Dansgaard relationship’, and it implies changes between +0.2 and +0.7‰/°C (Dansgaard 1964). The second factor that should be considered is the water lake temperature dependence of oxygen isotope fractionation between diatom silica and the lake water (Brandriss et al. 1998). Nevertheless, the fractionation factor value of this temperature dependence is still controversial.

Published fractionation factors range from -0.2‰ and $-0.5\text{‰}/^{\circ}\text{C}$ (Brandriss et al. 1998; Moschen et al. 2005). The two temperature factors have opposing effects on $\delta^{18}\text{O}_{\text{diatom}}$, but owing to its larger variability the effects of the first factor usually dominate over the second. Thereby, even in the case of the largest change due to the Dansgaard relationship, its magnitude will be greatly damped by the effect of the isotope fractionation between diatom silica and lake water. Moreover, it is known that most of the tropical rainfall isotope datasets exhibit a far stronger correlation with total precipitation than with air temperature (Leng et al. 2005), indicating in the Lago Chungará case a magnification of the precipitation-evaporation (P-E) balance in wetter periods.

Hence, we can assume that in the Lago Chungará the effects of precipitation variability and temperature oscillations in the $\delta^{18}\text{O}_{\text{diatom}}$ values will be small in comparison to evaporative concentration, as pointed by other authors for closed lakes in general (Gat 1980; Gasse and Fontes 1992).

Variations of the Precipitation/Evaporation balance in the lake

Oxygen isotopes have been widely used to carry out lake level reconstructions and to establish consequent palaeoclimatic interpretations (Barker et al. 2001; Valero-Garcés et al. 2003). There is a relationship between lake level change and the P-E balance for Lago Chungará during the late glacial and early Holocene, but this fact is hampered by local palaeohydrological factors such as changes in the groundwater outflow and shifts in the lake surface/volume ratio (Hernández et al. 2008). This effect is however negligible when considering isotopic changes at a decadal to centennial time scale. Both present (Fig. 3) and past (Thompson et al. 1998) rainfall isotope values in the Lago Chungará region are much lighter than those measured for the lakewater, and the magnitude of the long-term enrichment trend is very small compared to them. This background enrichment trend is related to the evolution of local hydrological factors as changes in the groundwater outflow as well as shifts in the surface/volume ratio of Lago Chungará during the late glacial and early Holocene (Hernández et al. 2008). Therefore, depletions of $\delta^{18}\text{O}_{\text{diatom}}$ would directly be related to wet episodes in the Andean Altiplano,

whereas exceptionally high values, which stand out over the general enrichment trend, would indicate arid episodes.

The observed $\delta^{18}\text{O}_{\text{diatom}}$ enrichment trends agree with periods where light laminae are more common, whereas depletion episodes coincide with poorly developed and less abundant light laminae (compare C and F in Fig. 5). These light laminae are most likely the result of exceptional periods of mixing of the shallow water column during lowstands, which recycle nutrients from the hypolimnion and therefore trigger extraordinary diatom blooms. Conversely deeper water conditions are more favourable for the development of dark laminae (Hernández et al. 2007). This interpretation is also supported by allochthonous input and regional effective moisture reconstructions previously performed on the Lago Chungará sedimentary record (Giralt et al. 2008) (Fig. 5, G and H). These reconstructions were carried out by applying multivariate statistical analyses (Redundancy Analyses (RDA), Principal Component Analysis (PCA), and cluster) to magnetic susceptibility, XRF, XRD, TC, TOC, TBSi and grey-colour curve data. The allochthonous input was derived from the first eigenvector of the PCA, whereas the regional effective moisture reconstruction was obtained from the second eigenvector. For the lower part of Chungara sequence, the more positive values of the terrigenous inputs were interpreted, as increasing erosion rate of catchment volcanic rocks, suggesting humid conditions. Similarly, the effective moisture availability proxy depends on the evaporation/precipitation balance, with positive values corresponding to drier conditions (Giralt et al. 2008). The comparison of the three proxies (Fig. 5F, G and H) shows that the hydrological response of the diatom silica oxygen isotopes (biological proxy) and of the other two reconstructions to the environmental variations is not the same.

The main trends of the three curves (Fig. 5F, G and H) are similar but there is a systematic temporal disagreement (ranging between ca. 5 and 50 cal years BP) between the terrigenous inputs and the regional effective moisture availability (which both react first) and the $\delta^{18}\text{O}_{\text{diatom}}$ (reacting afterwards). This time lag between the two proxies highlights the complex and non-linear and immediate response of the lacustrine ecosystem to environmental forcings (Fritz 2008). After rainfall the increased runoff and input of terrigenous is almost immediate. On the contrary, the lakewater oxygen isotope homogenization which later will be incorporated on the diatom frustule, has a delayed time of response. This depends of the epilimnion water

residence time and furthermore whether the lake is hydrologically closed or not. Hence, the observed time lag can be showing these different responses of the system to the same forcing. However, we cannot discount the poorly understood concept of silica maturation, where pores in the silica matrix close through early diagenesis creating differences in the $\delta^{18}\text{O}$ between living diatoms and sediment assemblages (Schmidt 2001) and therefore a lag in the $\delta^{18}\text{O}_{\text{diatom}}$ record.

At centennial-scale, the Lago Chungará isotopic values shows a general pattern of increasing $\delta^{18}\text{O}_{\text{diatom}}$ (Fig. 5B), with an enhanced enrichment period at the bottom, but interrupted by three major depletion events. The depletion events, accentuated by the “amount effect”, correspond to heavy rainfall conditions, whereas enriched values would indicate exceptional dry circumstances favouring the evaporation. This interpretation is reinforced by the allochthonous input and effective regional moisture availability independent reconstructions.

Besides this centennial-scale evolution, tree decadal wet/dry cycles can be identified in the $\delta^{18}\text{O}_{\text{diatom}}$ record (Fig. 5D and E). The cycle 1I (11,990 – 11,800 cal years BP) shows a significantly increased gradient in $\delta^{18}\text{O}_{\text{diatom}}$ suggesting that dominant dry palaeoclimate conditions played a key role triggering this isotope enrichment. Because of this drier situation the lake level would be lower, as also indicated by the important development and major presence of light laminae in this part of the interval. Three low-intensity and short-term wet episodes punctuate the established late glacial arid period (Fig. 5E). These episodes can also be recognized and correlated with events of increased allochthonous inputs and effective moisture availability (compare Fig. 5E, F and G).

The much weaker isotope enrichment for the cycle 2 (11,800 and 11,550 cal years BP) can be mainly ascribed to the general low magnitude palaeohydrological background trend towards heavier isotope conditions of the late glacial-early Holocene transition (Hernández et al. 2008). This fact, together with the poorer development and minor presence of the light laminae with respect to the previous interval, suggests that the enrichment via evaporation was much less important than during the sedimentation of cycle 1, corresponding to a more humid period. Furthermore, the terrigenous inputs and effective regional moisture availability curves show relatively wetter conditions for this period (Fig. 5F and G). This trend is also punctuated by a sudden rise in the lowest part of the interval indicating a short dry event and slight depletions in $\delta^{18}\text{O}_{\text{diatom}}$ indicating wet decadal-scale events (Fig. 5E).

In the cycle 3 any clear trend is difficult to identify (Fig. 5E). Although the $\delta^{18}\text{O}_{\text{diatom}}$ record seems to show a new trend towards drier conditions after the sudden wet event dated at 11,550 cal years BP, the lack of enough samples hampered any possible conclusion.

Long-term, centennial- to millennial-scale palaeoclimatic implications

There are many Late Quaternary palaeoclimatic reconstructions from the Andean Altiplano region (Sylvestre et al. 1999; Rigsby et al. 2005) but the climatic context for the late glacial-Holocene transition still remains unclear. Some authors have defined a cold period (12,600-11,500 cal years BP) coincident with the Northern hemisphere's Younger Dryas event (Baker et al. 2001b). The wet ("Coipasa phase", Thompson et al. 1998; Placzek et al. 2006) or dry (Maslin and Burns 2000; Weng et al. 2006) character of this event remains controversial. On the contrary, other authors consider this period just the final part of the deglaciation towards the present interglacial ("Ticaña phase", Sylvestre et al. 1999), as part of a long-term dry pattern (Rowe et al. 2002; Abbott et al. 2003).

The previous lake level reconstruction, mainly based on the abundance of planktonic diatoms, shows a shallowing followed by a long term rising trend for the interval presented here (Sáez et al. 2007). Additionally, recent data on the Lago Chungará record, mainly based on XRF core scanner analysis, has established the late glacial to Holocene transition as a relatively wet period (Giralt et al. 2008). The centennial scale $\delta^{18}\text{O}_{\text{diatom}}$ record is congruent with the lake level reconstruction performed by Saéz et al (2007) and it represents the lower frequency palaeoclimatic evolution, related with major lake level variations, of the Lago Chungará than this do it in this study (Fig. 5A). For the late glacial-early Holocene transition, the non continuous isotopic data (Fig. 5B) also displays a persistent, but minor, background isotope enrichment trend related to shifts in the surface/volume ratio and therefore in the lake morphology as well as changes in the groundwater outflow during its ontogeny (Hernández et al. 2008). In any case, $\delta^{18}\text{O}_{\text{diatom}}$ new data exposed here highlights that the glacial-interglacial transition in the central Andean Altiplano was punctuated by abrupt and high-frequency centennial climatic variability. The high-resolution sampling, carried out in this study, prevents us of making direct comparisons with other published reconstructions made at lower resolution.

Short-term, decadal- to centennial-scale palaeoclimatic implications

Millennial-scale shifts in the Atlantic-Amazon-Altiplano hydrologic system have been attributed to orbitally induced changes in solar insolation, coupled with long-term changes in the ENSO variability (Rowe et al. 2002; Abbott et al. 2003; Servant and Servant-Vildary 2003). However, higher-resolution changes are not directly related to orbitally induced insolation forcing (Abbott et al. 2003). The interannual climate variability in the Andean Altiplano is most likely related to changes in the Pacific Tropical SSTs, and the sign and strength of the zonal winds above the Altiplano (Garreaud et al. 2003). Both factors would affect the strength and position of the Bolivian high and, hence, the moisture distribution over the region. The main force controlling the SSTs is the ENSO variability, involving dry or wet situations in the Altiplano during El Niño- or La Niña-like conditions respectively (Garreaud et al. 2003; Vuille et al. 2005). This is consistent with instrumental data from the Chungará area where precipitation is reduced during moderate to intense El Niño years (1965, 1972, 1983, and 1992) (Fig. 3c). Additionally, the sign and strength of the zonal winds above the Altiplano would be modulated by decadal and multidecadal variations in solar activity, being or not independent of the state of the ENSO system (Theissen et al. 2008). Although an ENSO modulation by solar activity has been suggested (Velasco and Mendoza 2008), no clear relationship has been demonstrated between both forcings. Nevertheless, there is broad agreement that ENSO events are the main control governing the moisture distribution in the Altiplano (Servant and Servant-Vildary 2003), and that decadal-scale changes in the effective moisture could be related to the solar activity during the mid-Holocene (Theissen et al. 2008).

The results presented here would suggest a similar pattern during the late glacial-Holocene transition over the Andean Altiplano (Fig. 6b). The identified frequencies can be attributed to different periodicities of the solar activity cycles such as Schwabe 11 years (identified as 11.13 yr), Hale 23 years (22.27 yr) and Brückner 35 years (39.37 yr), and of the ENSO frequency (main frequency at 7-9 years (7.16 and 8.90 yr) and its decadal frequency 15-17 (18.62 yr) years). The influence of solar activity and ENSO variability on the isotope record is supported by the fact that several periodicities concordant with both forces were identified. The

time-frequency analysis suggests that the driest period (11,950 - 11,800 cal years BP) was ruled by high solar activity, mainly represented by a Brückner cycle, and strong ENSO-like conditions.

The ENSO and solar activity signals remain present for the early Holocene period (between 11,750 until 11,500 cal yr BP), although they show a weakening pattern through this period (Fig. 5b). This fact is congruent with the progressive weakening of the ENSO suggested by other authors for the late glacial-Holocene transition (Rodbell et al. 1999; Moy et al. 2002; Rodó and Rodríguez-Arias 2004). In Lago Chungará, the onset of the Holocene was characterized by minor $\delta^{18}\text{O}_{\text{diatom}}$ enrichment by evaporation and by the occurrence of multi-decadal weak depletions that would be governed by the more humid La Niña-like conditions. This would agree with previous observations that suggest a reduction in the El Niño intensity within the region during the early-Holocene in favour of long-term La Niña-like conditions in the tropical Pacific (Betancourt et al. 2000; Koutavas et al. 2002).

Conclusions

The late glacial to Holocene transition from the Lago Chungará record is made up of laminated diatom-rich sediments which provide excellent material for the application of oxygen isotope analysis in biogenic silica. $\delta^{18}\text{O}_{\text{diatom}}$ data have successfully provided palaeoclimatic reconstruction at decadal-to-centennial resolution. The laminated nature of these sediments and its continuous sampling, lamina by lamina, have enabled one of the highest resolution records available of $\delta^{18}\text{O}_{\text{diatom}}$ and has revealed important insights into the usefulness of this method, as well as provided decisive palaeoenvironmental information of this critical period.

$\delta^{18}\text{O}_{\text{diatom}}$ from dark diatom laminae represent the baseline environmental evolution of Lago Chungará, and show decadal to centennial variability in the moisture conditions of the Andean Altiplano. The isotopic record displays a persistent background isotope enrichment trend related to changes in the lake morphology and groundwater outflow during the late glacial and early Holocene. Overprinted onto this long-term (centennial to millennial) trend there are cyclically short-term (decadal to centennial) shifts which are not related to changes in

temperature or isotopic composition of the source of precipitation, but to the P-E balance variability in the Altiplano.

The record shows two major isotope depletions, accentuated by the well-known 'amount effect', occurring at a centennial time scale (11,800 and 11,550 cal yr BP) indicating a long-term increase in moisture conditions, and one major isotope enrichment above the background levels that occurred between 11,990 and 11,800 cal yr BP indicating a short dry phase during the late glacial. Minor depletions at a decadal time scale are associated with weaker rainfall short-term events. The comparison with allochthonous input and effective moisture availability reconstructions previously performed for Lago Chungará reflects an agreement but includes a systematic lag time between these proxies and $\delta^{18}\text{O}_{\text{diatom}}$, due to the time necessary to change the $\delta^{18}\text{O}_{\text{lakewater}}$ values and its subsequent incorporation into the diatom frustules. This time lag highlights the fact that not all the proxies react at the same time to environmental forcings.

Sub-millennial shifts in the hydrological balance of Lago Chungará are hypothesised to be the result of changes in the strength and position of the Bolivian High. Spectral analyses of $\delta^{18}\text{O}_{\text{diatom}}$ suggest that these changes in the atmospheric conditions over the Altiplano during the wet events were triggered by both ENSO and solar activity. The change from the late glacial dry period to a wetter early Holocene period confirms a weakening of El Niño intensity in the Andean Altiplano region in favour of La Niña-like conditions found elsewhere. Nested upon the underlying climate dynamics are the different cyclicities of solar activity (Schwabe, Hale and Brückner) that were active during different time windows. There is undoubtedly an interaction between these and ENSO at the decadal and greater scales and it is likely that apparent solar forcing of the Lago Chungará record is transmitted via ENSO modulation of the South American monsoon. The complex Andean Altiplano palaeoenvironmental interlinks, and the absence of other high resolution studies for this time interval, did not allow us to establish any conclusion on the existence of any significant climatic event synchronous to the Younger Dryas in the northern hemisphere. While many studies have demonstrated ENSO-like forcing during the glacial-interglacial transition, this highly resolved record preserves key ENSO frequencies.

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Figure Captions

Figure 1: Location of Lago Chungará on a South America map of rainfall rate map (mm/month) simplified from [Negri et al. \(2004\)](#). Main atmospheric systems are indicated. ICTZ Intertropical Convergence Zone, SPCZ South Pacific Convergence Zone.

Figure 2: A. Location of the cores (dots) and modern water sampling sites (stars with roman numerals) in the Lago Chungará (Image modified from Google Earth). B. Cross section of sediments infilling Lago Chungará. Position of the studied core #11 is shown. Arrows indicate major hydrological inputs and sedimentary contributions to the lake (simplified from [Sáez et al. 2007](#)).

Figure 3: A. Isotope values ($\delta^{18}\text{O}/\delta\text{D}$) from rainfall, Lago Chungará, Río Chungará and studied area springs. GMWL: Global Meteoric Water Line; LML: Local Meteoric Line; EL: Evaporation Line. Note the isotopic enrichment of the lake water by evaporation with regard to rainfall and springwater. B. Mean monthly rainfall (mm) and temperature ($^{\circ}\text{C}$) at Chungará meteorological station (18.17S, 69.08W, 4500 m a.s.l.). Note the stationality of both parameters. C. Annual rainfall in the Chungará region from 1962 to 1994. The arrows indicate strong El Niño years. Modified from [Valero-Garcés et al. \(2003\)](#). D. Isotope composition ($\delta^{18}\text{O}$ y δD) of rainfall samples from La Paz (Bolivia) obtained by the International Atomic Energy Agency (IAEA) since 1995 until 1998 (blue and black circles), and the samples of Lago Chungará and the very close Lagunas de Cotacotani obtained from [Herrera et al. \(2006\)](#) (red circles). LML: Local Meteoric Line ($\delta\text{D} = 7,9\delta^{18}\text{O} + 14$). Note the large variability in $\delta^{18}\text{O}$ and of δD values.

Figure 4: Diatom-rich sediment from Lago Chungará after the cleaning process. Large *Cyclostephanos andinus* valves are the unique component.

Figure 5: Oxygen isotope data for a period between 11,990 and 10,475 cal years BP from Lago Chungará record studied here, compared with other paleoenvironmental records from Lago Chungará. A. Percentage of planktonic diatoms and the lake level evolution curve for whole

Lago Chungará sequence (Sáez et al. 2007). B. Oxygen isotope from diatom silica analysed in three intervals including non-successive dark laminae (Hernández et al. 2008). C. Oxygen isotope data for the period studied in the present work and its interpretation in terms of wet and dry conditions. The values correspond to successive 40 dark-green laminae and the selected period is divided in three different intervals defined by three enrichment/depletion isotope cycles (lower, middle and upper). D. Photography of laminated sediments corresponding to the sampled interval of subunit 1a in core # 11. E. Interpreted tree oxygen isotope enrichment/depletion cycles in the studied interval. F. Terrigenous inputs variations from main eigenvector of Principal Component Analysis (Giralt et al. 2008). G. Effective moisture availability variations from second eigenvector of Principal Component Analysis (Giralt et al. 2008). Correlation lines correspond to main oxygen isotopes depletion peaks. Note that the main trends of the three curves are similar but there is a systematic temporal disagreement between them.

Figure 6: A. Multi-taper analysis of the $\delta^{18}\text{O}_{\text{diatom}}$ values. The 90%, 95% and 99% confidence levels are indicated and significant periodicities are shown. Note that periodicities with more than 99% of significance are shown in black and those with more than 95% significance in blue. B. Time-Frequency analysis of the $\delta^{18}\text{O}_{\text{diatom}}$ values. Pink indicates high energy whereas blue displays low energy areas. Energies below 0.03 were clipped in order to facilitate understanding of the graph. Red and blue horizontal bands mark different frequency bands of the ENSO and solar activity forcings. Yellow vertical bands show zones with $\delta^{18}\text{O}_{\text{diatom}}$ shifts and their corresponding power values for each frequency. A weakening pattern in ENSO and solar activity energies can be observed through the late glacial-early Holocene transition.

Table 1: Isotopic and other chemical and physical data analysed from water samples collected in the Lago Chungará (Modified from Herrera et al. 2006). See Figure 1 for location of sites. na = not available data.

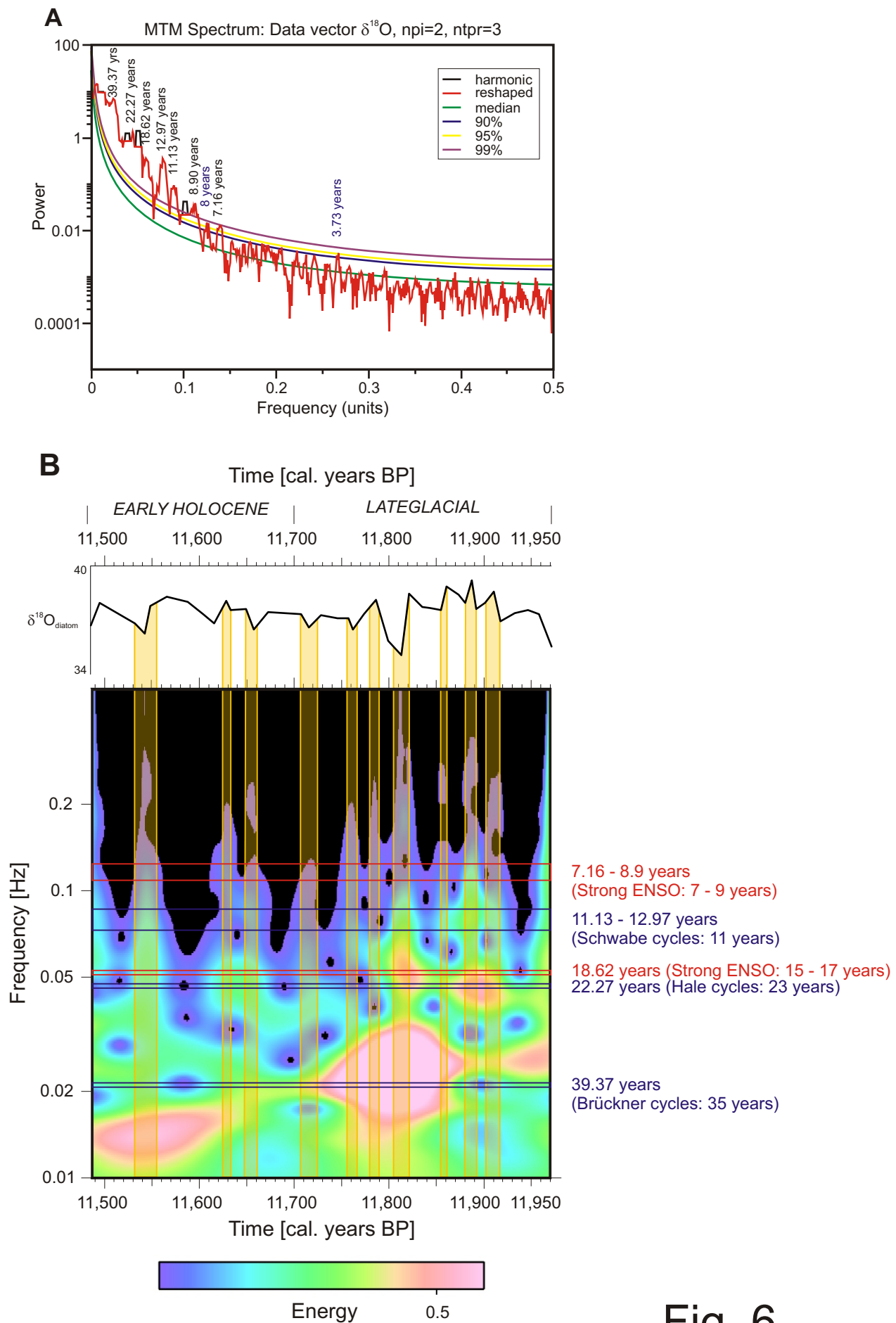


Fig. 6

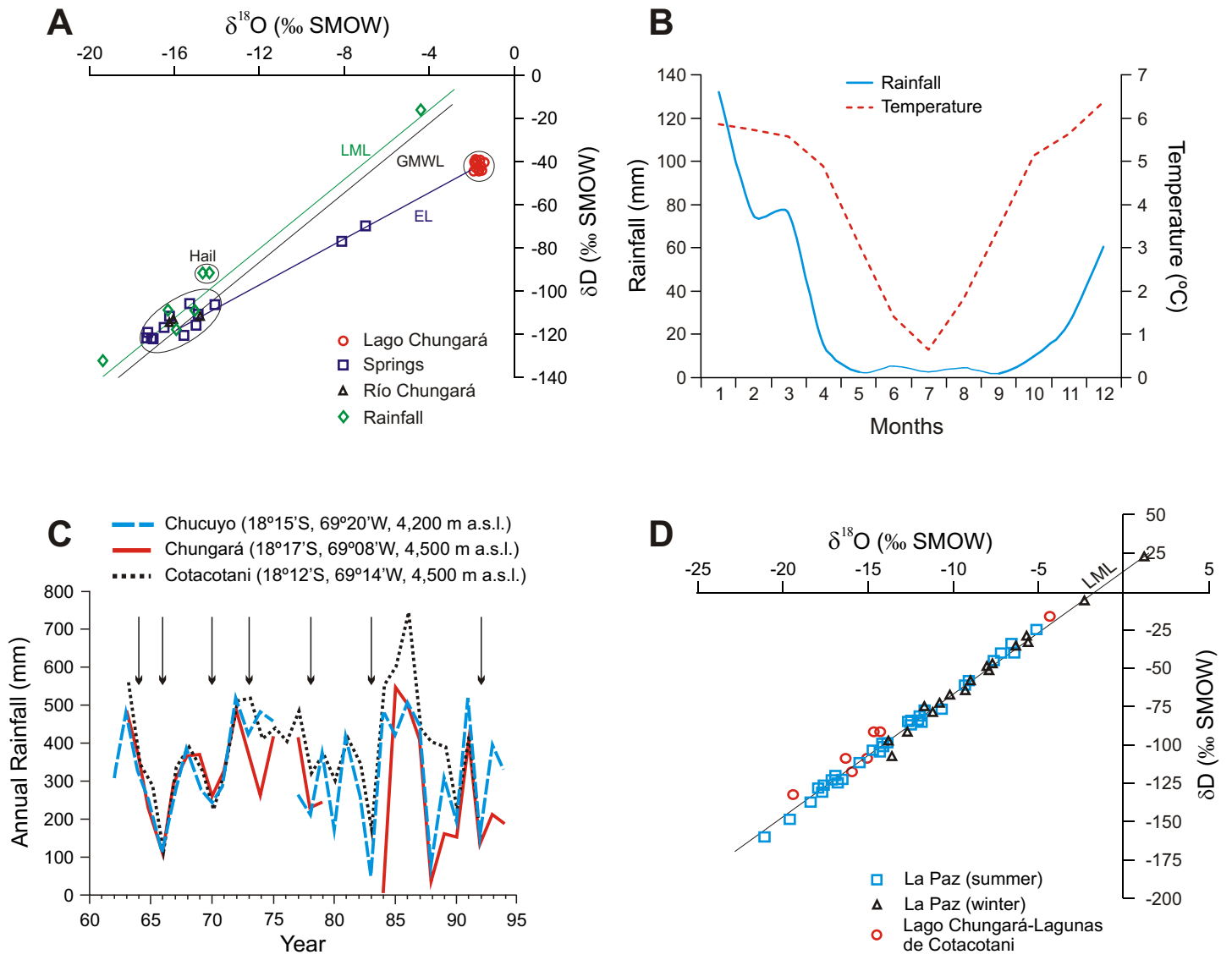


Fig. 3

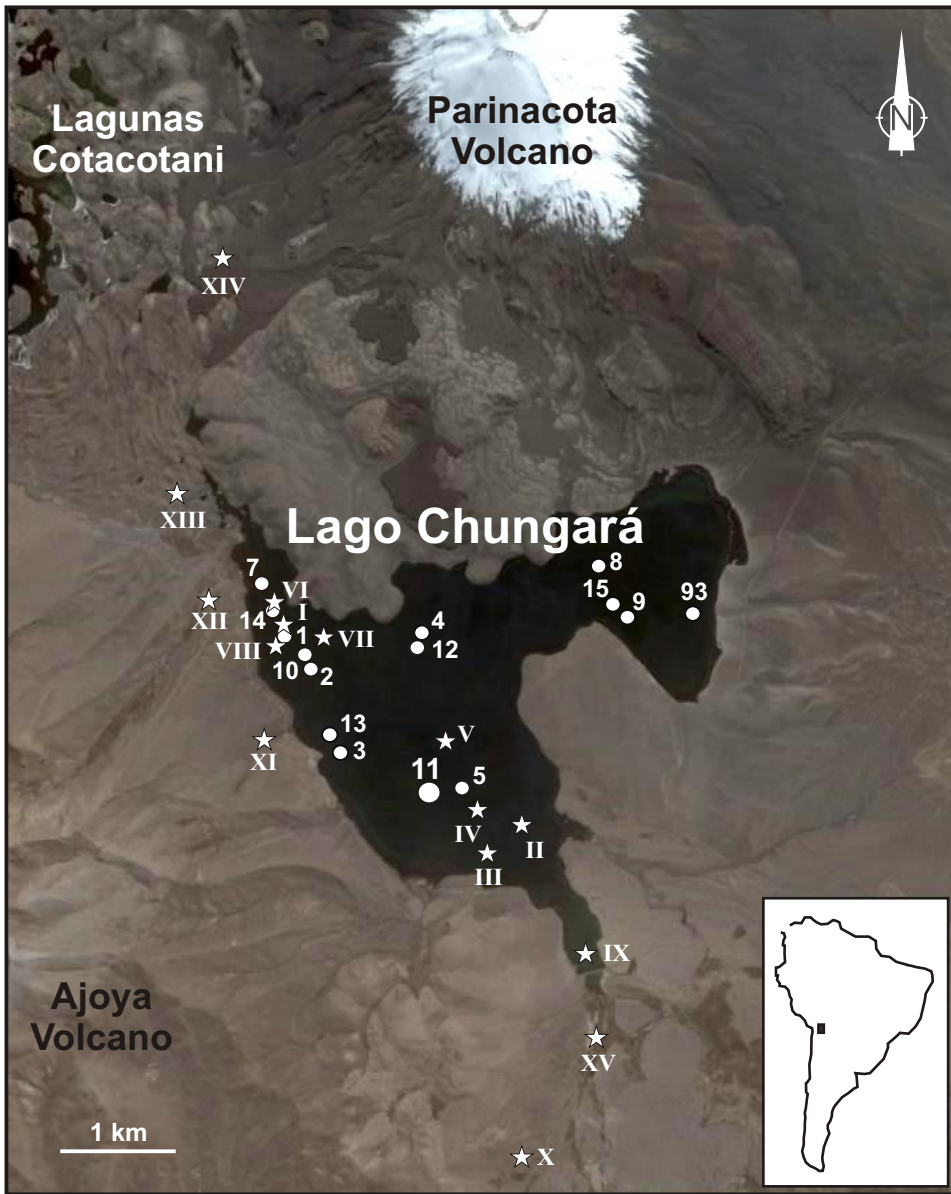


Fig. 2

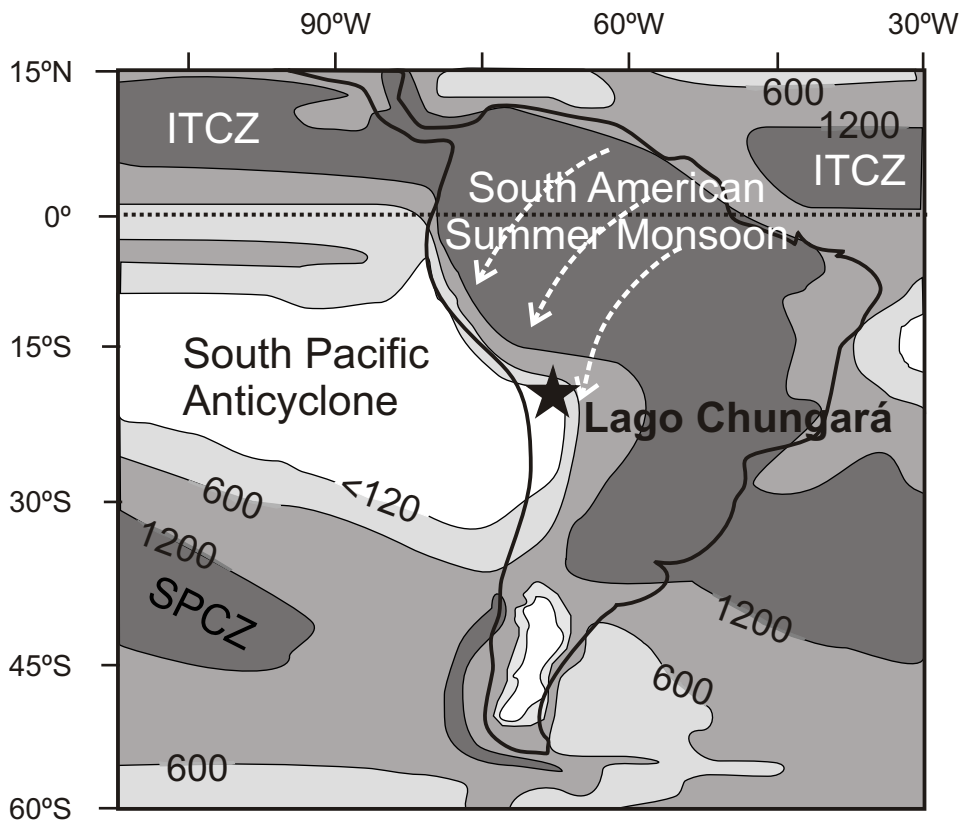


Figure 1