Centennial-scale precipitation anomalies in the southern Altiplano (18° S) suggest an extra-tropical driver for the South American Summer Monsoon during the late Holocene

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Abstract

Modern precipitation anomalies in the Altiplano region of South America are closely linked to the strength of the South American Summer Monsoon (SASM) which is influenced by large-scales climate features sourced in the tropics such as latitudinal shifts of the Intertropical Convergence Zone (ITCZ) and El Niño-Southern Oscillation (ENSO). However, the timing, direction and spatial extent of precipitation changes prior to the instrumental period are still largely unknown, preventing a better understanding of the long-term drivers of the SASM and their effects over the Altiplano. Here we present a detailed pollen reconstruction from a sedimentary sequence covering the period between 4500-1000 cal yr BP in Lago Chungará (18° S; 4570 masl), a high elevation lake in the southwestern margin of the Altiplano where precipitation is delivered almost exclusively during the mature phase of the SASM in the austral summer. We distinguish three well-defined centennial-scale anomalies, with dry conditions between 4100-3300 and 1600-1000 cal yr BP, and a conspicuous humid interval between 2400-1600 cal yr BP; which resulted from weakening and strengthening of the SASM respectively. Comparisons with other climate reconstructions from the Altiplano, the Atacama Desert, the Tropical Andes and the southwestern Atlantic coast reveal that - unlike the modern climatological controls - past precipitation anomalies at Lago Chungará were largely decoupled from north-south shifts in the ITCZ and ENSO. A regionally coherent pattern of centennial-scale SASM variations and a significant latitudinal gradient in precipitation responses suggest the contribution of an extra-tropical moisture source for the SASM, with significant effects over precipitation variability in the Southern Altiplano.

1 Introduction

Detailed paleoclimate records are not only necessary to document past climate anomalies, but also to decipher regional drivers of atmospheric variability and to explore teleconnections that extend beyond the period of instrumental climate measurements (Wanner et al., 2008; Loisel et al., 2017). Unfortunately, the number of reliable climate reconstructions is still small in many regions of the world which hinders a contextualization of modern climate trends into longer-term natural variability. This long-term perspective is necessary considering the brief period of meteorological measurements, the current scenario of unprecedented climate change, and the uncertainties about future trends (Deser et al., 2012; Neukom et al., 2015).

In the tropical Andes (5-13° S) and the Altiplano (13-22° S) regions of South America, a set of well-grounded reconstructions have revealed that significant precipitation changes occurred during the most recent millennia (Seltzer et al., 2000; Baker et al., 2005; Giralt et al., 2008; Bird et al., 2011a; Novello et al., 2016), reflecting decadal, centennial and millennial changes in the mean strength of the South American Summer Monsoon (SASM). In addition, a composite tree ring chronology from the Altiplano showed that decadal anomalies in SASM-derived precipitation have been strongly modulated by variability of El Niño-Southern Oscillation (ENSO) over the last 700 year (Morales et al., 2012). This control

is consistent with instrumental measurements which show a significant relationship between modern ENSO variability and summer precipitation at interannual timescales (Vuille et al., 2000; Knüsel et al., 2005; Garreaud, 2009). However, it is still unknown if this close relationship extends at timescales longer than decadal. Evidence from precipitation records covering the last two millennia in the Altiplano are at odds with the modern ENSO-precipitation relationship (Vuille et al., 2012), providing evidence that this instrumental relationship has not remained stationary in time. These discrepancies have prompted discussions regarding the existence of different drivers of past SASM-derived precipitation in the Altiplano, such as the austral summer insolation (Bustamante et al., 2016), Northern Hemisphere temperatures (Vuille et al., 2012), the latitude of the Intertropical Convergence Zone (ITCZ) (Bird et al., 2011a; Bird et al., 2011b), solar variability (Novello et al., 2016) and moisture levels in the extra-tropical Atlantic region (Baker et al., 2005; Apaéstegui et al., 2018).

Here we present a new pollen-based precipitation record for the Altiplano that covers the interval between 4500-1000 cal yr BP. The timing and direction (positive/negative) of precipitation anomalies inferred from the pollen data is evaluated with the primary aim of exploring past drivers of precipitation change and assessing the evolution of teleconnections between the Altiplano and other regions in South America, the Pacific and Atlantic Ocean. Our pollen data were therefore compared with proxy-base records from the Altiplano and the tropical Andes, along with reconstructions of past ITCZ variability and ENSO-like changes.

2 Geographic setting

2.1 The Altiplano

The Altiplano (13-22° S) is a high-Andean tectonic plateau that covers an area of ~190,000 km^2 encompassing the central Andes Cordillera of southern Perú, western Bolivia, and northern Chile and Argentina (Fig. 1). Sitting in a north-south axis over Cenozoic ignimbrites that overlay Cretaceous marine deposits, this high-Andean plateau has widths ranging from 200 to 300 km and mean elevations between 3000-5000 masl (meter above sea level) (De Silva, 1989; Garzione et al., 2006). Multiple phases of tectonic uplifting and crustal shortening during the last 30 Ma account for the unusual high elevations of this continental plateau (Isacks, 1988), although more recent investigation suggest a slow and steady uplift over the last 40 Ma (Barnes and Ehlers, 2009)In any case, it has been estimated that the present-day Altiplano altitude was attained around 6-5 Ma (Garzione et al., 2017). Since that time, continuous internal drainage and erosional processes have produced a general flattening of the elevated surface resulting in several large-scale plane fluvio-lacustrine basins (Garzione et al., 2006). Although the Altiplano has been volcanically active since its initial formation, present magmatism is expressed exclusively in its western margin in the form of a prominent Cretaceous-Neogene magmatic arc featuring several 5000-6000 masl stratovolcanoes (Allmendinger et al., 1997).

The climate of the Altiplano is cold and semiarid with mean annual temperature and precipitation ranging between 4 and 17° C and 20 to 800 mm, respectively. The pronounced climate gradients observed in stations across this region result from its

large latitudinal extension including subtropical and extra-tropical regions, and altitudinal differences between the central plateau and its eastern and western flanks. Summer (DJFM) precipitation, both as rain or snow, represents around 70-90 % of the total annual amount (Fig. 2a), and comes in the form of convective storms associated with the development of the SASM in the interior of the continent (Garreaud et al., 2003) (Fig. 2b). Seasonal and interannual precipitation variability in the Altiplano is directly associated with the strength of the SASM, which is in turn controlled both by the latitudinal position of the ITCZ at the lower atmospheric level (>850 hPa), and by the Bolivian high pressure cell at the upper-level (<300 hPa; Garreaud et al., 2003). In general, above-mean summer precipitation is associated with a southward extension of the ITCZ and a southward position of the Bolivian high pressure cell, which results in an easterly wind anomaly and an strengthening of the SASM (Vuille, 1999; Aceituno and Montecinos, 1993; Garreaud et al., 2009). Easterly SASM moisture comes in two distinctive modes: a northerly mode originating in the Amazon basin; and a southerly mode sourced in the Gran Chaco basin and the South Atlantic Ocean (Chaves and Nobre, 2004; Vuille and Keimig, 2004). In addition, there is a general consensus that a significant amount of interannual variability in summer precipitation over the Altiplano is influenced by El Niño Southern Oscillation (Garreaud and Aceituno, 2001; Garreaud et al., 2003; Vuille et al., 2000; Sulca et al., 2018). During la Niña phases, the Bolivian high pressure cells sits over the Altiplano, weakening the prevailing westerly flow and promoting the incursion of convective storms associated with the SASM from the northeast. As a result, above-mean precipitation occurs more often during La Niña years, whereas opposite anomalies tend to occurs during El Niño phases (Fig. 2c).

The vegetation of the Altiplano is rich and diverse, presenting a great number of shrubland, grassland, peatland and forest communities. The distribution of these communities varies locally according to elevation, soil, erosion, water availability and drainage; and regionally by the gradients in precipitation and temperature described above (Brush, 1982). For the sake of the pollen-climate interpretations of this study, and considering the outstanding diversity of the Altiplano vegetation, we restricted our characterization to the vegetation belts established across the western Andean slopes and the southern Altiplano around our study site. Our brief and simplified description of the regional vegetation communities is based on the much more comprehensive work of Villagrán et al. (1983), Arroyo et al. (1988), Rundel and Palma (2000), and Orellana et al. (2013). We followed the taxonomic nomenclature adopted by Rodriguez et al. (2018).

The Prepuna vegetation belt established above the upper margin of the absolute desert from ~2000 to 3200 masl, and it is a low density vegetation community (coverage >40%) composed by a floristically diverse assemble of shrubs and herbs. It is dominated by shrubs such as *Ambrosia artemisioides* (Asteraceae), *Atriplex imbricata* (Chenopodiaceae), and *Aloysia deserticola* (Verbenaceae), with several herbs such as *Descurainia pimpinellifolia* (Brassicaceae), *Balbisia microphylla* (Francoaceae) and *Bryantiella glutinosa* (Polemoniaceae), and scattered cacti such as *Browningia candelaris* and *Corryocactus brevistylus*.

The Puna belt sits above the aforementioned vegetation formation, roughly between 3000 and 4000 masl. It is a floristically more diverse and a more densely vegetated shrubland-grassland community. The Puna belt is dominated by *Fabiana densa* (Solanaceae), *Baccharis boliviensis* (Asteraceae), *Diplostephium meyenii* (Asteraceae), *Lophopappus tarapacanus* (Asteraceae) and *Ephedra americana* (Ephedraceae). Other plants natural to the Puna belt are annual herbs such as *Chersodoma jodopappa* (Asteraceae), *Junellia seriphioides* (Verbenaceae), the cactus *Cumulopuntia echinacea* (Cactaceae) and the fern *Cheilanthes pruinata* (Pteridophyta). Grasses representative of the Poaceae family are *Nassella pubiflor*, *Eragrostis kuschelii*.

A gradual transition from a shrubland- to a grassland-dominated community occurs at the upper limit of the Puna belt. Above 4000 masl, high-Andean steppe tends to replace Puna scrubs, forming a grassland belt characterized by several species of Poaceae family such as *Festuca arundinacea*, *F. chrysophylla*, *Deyeuxia breviaristata*, *Poa lepidula* and several species of the *Anatherostipa* genus. This high elevation steppe also features scattered shrubs such as *Parastrephia lucida* (Asteraceae) and *P. quadrangularis*. Woodlands of the tree *Polylepis tarapacana* (Rosaceae) occur preferably on the north-facing slopes at elevation above 4100 masl, usually accompanied by species such as *Azorella compacta* (Apiaceae), *Parastrephia teretiuscula* (Asteraceae) and *Baccharis tola* (Asteraceae). The altitudinal limit of vegetation, which sometimes surpasses 5000 masl (Orellana et al., 2013), is occupied by a low shrubland community mostly made of cushion-plants such as *Pycnophyllum molle* (Caryophyllaceae), the cactus *Cumulopuntia ignescens*, and several species of the genera *Werneria* (Asteraceae) and *Nototriche* (Malvaceae), with this latter plant genus usually found on the characteristic rocky substrates of the mountain slopes.

2.2 Lago Chungará

Lago Chungará (18.24° S; 69.15° W; 4570 masl; 23 km^2; 40 m maximum depth) is located at the base of Volcán Parinacota on the western border of the southern Altiplano plateau (Fig. 1). The lake sits over Miocene and Pleistocene alluvial, fluvial, lacustrine and volcanic sediments of the Lauca Basin (Gaupp et al., 1999). To the west, the western Andean flanks connect the basin with the lowlands of the Atacama Desert through a series of river basins and dried canyons (Fig. 1). Lago Chungará was formed by the damming of the Lauca River caused by a debris avalanche during a partial collapse of the ancient Volcán Parinacota caldera, previously dated between 17,000-15,000 cal yr BP (Hora et al., 2007). A recent study using ^{10}Be surface exposure dates indicate that the collapse of the old cone of Volcán Parinacota led to a major lake expansion at about 8800 cal yr BP (Jicha et al., 2015). The main inlet of the lake is the Río Lauca to the south and the ephemeral streams Ajata and Sopocalane to the west. Lago Chungará has no surface outlets, although groundwater outflow has been reported (Herrera et al., 2006). The absence of lacustrine deposits above the lake suggests that its present-day water levels are the highest in their history (Herrera et al., 2006). The Lago Chungará area receives between 50-670 mm of precipitation annually (mean 1961-2016 =353 mm), with 88% of this the total amount being received during summer months

(DJFM). Mean annual temperature is 4.5° C. The precipitation at the Lago Chungará heavily contrasts with the Andean slopes and the lowlands of the Atacama Desert to the west, where precipitation plummets to zero below 2500 masl. The close link between ENSO and summer rainfall in the Altiplano mentioned above is clearly seen at Lago Chungará, where instrumental time series shows that around 35-40% of summer rainfall variability (1961-2016) results from variations in the tropical Pacific climatological state, with significant correlation between instrumental rainfall and ENSO (El Niño 3.4 index; Pearson correlation coefficient r = -0.46; p-value <0.01). The vegetation around the lake is dominated by high-Andean tussock grasses with scattered *Polylepis* woodland.

2.3 Previous investigations in Lago Chungará

Lago Chungará has been the focus of several paleolimnological and paleoclimatological studies over the last 20 years. An initial detailed seismic profile of the sediments was presented by Valero-Garcés et al. (2000). A 500-yr reconstruction of hydrological variability around Lago Chungará was developed a few year later based on sedimentological, geochemical and stable isotopes analyses from a 57cm-long sediment core (Valero-Garcés et al., 2003). In 2002, a field campaign retrieved 15 new sediment cores from different areas of the lake and several publications have emerged from analysis on those sediment sequences. Such studies included a detailed lithological correlation of all cores (Sáez et al., 2007); analysis of the physical properties of the sediments such as magnetic susceptibility, mineral composition, total organic carbon and grey-colour values (Moreno et al., 2007); a climate reconstruction based on the statistical analysis of mineralogical and chemical parameters (Total Organic Carbon, XRF Scanner, gray-colour values, Total Biogenic Silica among others) and a detailed chronological framework (Giralt et al., 2008); oxygen and carbon isotope composition of diatom silica and their relationship with the hydrological evolution of the lake, as well as solar and ENSO forcings (Hernández et al., 2008, 2010, 2011, 2013); and petrology and isotopic composition of carbonate fraction (Pueyo et al., 2011). More recently, Bao et al (2015) presented a long-term productivity reconstruction based on fossil diatoms composition and geochemical data, assessing the interplay between regional precipitation, lake levels and organic activity in Lago Chungará. Overall, these studies have provided a detailed paleolimnological and paleoenvironmental history of Lago Chungará that extend for at least 12,800 years, showing a sedimentation regime marked by diatom-rich deposits, interbedded with multiple tephra and carbonate-rich layers (Pueyo et al., 2011). Volcanic input, more frequently recorded after 7800 cal yr BP, was most likely composed by tephra deposits erupted from Volcán Parinacota (Sáez et al., 2007). Relative high lake levels are recorded before 10,000 cal yr BP, in overall agreement with a pluvial interval documented elsewhere in the Altiplano (Giralt et al., 2008). Dry conditions seem to have prevailed between 8000-3500 cal yr BP (Pueyo et al., 2011), with peak aridity probably occurring between 8000-6000 cal yr BP (Moreno et al., 2007; Giralt et al., 2008; Pueyo et al., 2011). Relative high lake levels prevailed over the last 5000 years (Sáez et al., 2007), superimposed on several high-amplitude lake stand oscillations after 4000 cal yr BP (Sáez et al., 2007; Giralt et al., 2008). Humid and high lake stands have been recognized between 12,400-10,000 and 9600-7400 cal yr BP, while dry intervals prevailed between 10,000-9600 and 7400-3500 cal yr BP (Bao et al., 2015). The last 200 years are

marked by overall dry conditions (Valero-Garcés et al., 2003). Despite all this information, the climate history around Lago Chungará and its regional drivers over the most recent millennia has not yet been addressed in detail yet (Hernández et al., 2010; Bao et al., 2015).

3 Methods

In November 2002, fifteen sediment cores up to 8 m long were obtained from different parts of the lake using a raft equipped with a Kullenberg corer (Sáez et al., 2007). The fossil pollen sequence presented here was developed from Core 7, which was obtained from the northwestern border of the lake at 18 m of water depth (Sáez et al., 2007). In addition, we obtained pollen data from 26 surface samples collected along west-east transect on the western Andes slope at 18° S with the aim to determine the pollen signals associated with modern vegetation belts. Surface pollen samples were obtained from exposed soils located at regular intervals of ~100 m, from 2100 to 4400 masl. Thus, a surface pollen transect was formed crossing all vegetation belts established across the western Andean slopes up to the base of Lago Chungará (Fig. 1). Furthermore, we obtained annual temperature and summer precipitation data for each surface sample point from the WorldClim2 dataset (Fick and Hijmans, 2017), with the aim of documenting the climate gradients associated with the pollen transect. All pollen and climate data was used as supporting our paleoclimate inferences.

The 26 surface samples plus 49 fossil pollen samples from Core 7 were prepared following standard procedures for palynological analysis (Faegri and Iversen, 1989) in the Laboratory of Paleoecology and Paleoclimatology of CEAZA, La Serena, Chile. Pollen data is expressed as relative percentage, which was calculated from the sum of a minimum of 300 terrestrial pollen grains. The percentage of aquatic pollen was calculated from a sum that included all terrestrial pollen and aquatic pollen. Pollen accumulation rate (PAR; particles yr^{-1} cm^{-2}) was calculated for terrestrial and aquatic pollen using the data from the age-depth model published by Giralt et al., (2008). Statistical analysis on pollen data included a Stratigraphically Constrained Cluster Analysis (CONISS) for the identification of major pollen changes (Grimm, 1987).

4 Results

4.1 Stratigraphy and Chronology

Core 7 comprises sections 7A-1K-1 (146 cm), 7A-2K-1 (151 cm) and 7A-3K-1 (51 cm) with a total length of 348 cm. These core sections correspond to Subunit 2b described in Sáez et al. (2007), composed of dark grey diatomite with abundant macrophyte and four black tephra layers. These layers are made of andesitic and rhyolitic material with presence of amphibole (Moreno et al., 2007). The chronological framework used in this study is based on the one presented in Giralt et al. (2008). The chronology of Core 7 is constrained by 3 AMS radiocarbon dates obtained from Subunit 2b in cores 11 and 14, which were translated into Core 7 after detailed correlation based on seismic profiles and tephra keybeds identified as peaks in magnetic susceptibility (Sáez et al., 2007). This chronology uses a modern reservoir effect of ^{14}C 3260 years which

is assumed to be constant throughout the whole Subunit 2b. A constant reservoir effect for this unit is supported by multiple lines of evidence, and suggests that the average characteristics of the lake -such as depth or water volume- did not experience significant changes during the time represented by this Subunit 2b (Giralt et al., 2008). The chronological framework indicates that Core 7 encompasses the period between 4500-1000 cal yr BP, with depositional rates ranging from 0.26 to 1.31 mm/yr. Unfortunately, the last 1000 years of sediment history were not recovered during the field campaign.

4.2 Modern pollen transect

Our modern surface pollen transect reveals important changes in the abundance of pollen type across Prepuna, Puna and High Andean Steppe vegetation belts (Fig. 3). Between ~2000 and 3200 masl Prepuna pollen samples are largely dominated by Chenopodiaceae, Asteraceae (Ast.) *Ambrosia*-type, Brassicaceae *Sisymbrium*-type, B. *Draba*-type and Ast. Ophryosporus-type. Other pollen types with minor abundances are Portulacaceae *Cistanthe*-type, Juncaceae and Malvaceae. Between ~3200 and 4000 masl Puna dominant taxa include Ast. *Parastrephia*-type and Ast. *Baccharis*-type along with *Ephedra* spp., Fabaceae *Prosopis*-type, Solanaceae, Ledocarpaceae *Balbisia*-type and Ast. *Chuquiraga*-type. Above 4000 masl, surface pollen samples at the high-Andean steppe are less diverse and overwhelmingly dominated by Poaceae with minor contribution of Apiaceae *Mulinum*-type. Mean annual temperatures associated with the transect show a sustained decreases from 14° C at 2100 masl to less than 3° C at 4400 masl; summer precipitation, on the other hand, exhibits a continuous increase from less than 40 mm/yr at 2100 masl to more than 280 mm/yr at the upper limit of our transect.

4.3 Pollen record

Five general zones are recognized based on the major changes in pollen percentages (Fig. 4) and PAR (Fig. 5), assisted by a CONISS ordination. Overall, the record is largely dominated by Poaceae (mean value 55%), followed by Ast. *Parastrephia*-type (13%), Chenopodiaceae (8%), Ast. *Baccharis*-type (7%), Apiaceae (6%), Ast. *Ambrosia*-type (4%) and *Polylepis* spp. (3%). The record mean abundances of *Botryococcus* spp. and *Potamogeton* spp., the two most abundant aquatic taxa, correspond to 72% and 2% of the total terrestrial sum respectively.

The basal portion of the record (Zone CHU1; 4500-4100 cal yr BP) features above-mean percentage of Poaceae (67%) and relative low abundances of all other major taxa, especially *Polylepis* spp. which shows minimal presence in this zone (1%). The PAR record indicates overall very low pollen accumulation for all taxa during this zone.

The following interval (Zone CHU2; 4100-3300 cal yr BP) exhibits a downturn of Poaceae (52%), a rapid and sustained decline in *Botryococcus* spp. (56%), and a significant increase in Ast. *Baccharis*-type (19%) and Ast. *Ophryosporus*-type (2%). These latter two increments are also displayed in the PAR diagram which reveal otherwise relatively low value for all the remaining taxa.

Zone CHU3 (3300-2300 cal yr BP) is characterized by a recovery of Poaceae (59%) and a notable decline in Ast. *Baccharis*-type (3%). Other significant changes in this zone include a rise in *Polylepis* spp. (4%) and sustained increments of Ast. *Parastrephia*-type (17%) and *Botryococcus* spp. (67%). The PAR diagram shows very low values of all terrestrial and aquatic taxa during this entire zone.

Zone CHU4 (2300-1600 cal yr BP) features below-mean abundances of Poaceae (49%) and Ast. *Parastrephia*-type (11%) and marked increments of Apiacea (9%) and *Botryococcus* spp. (81%). This zone also features the appearance of Poaceae *Stipa*-type and P. *Bromus*-type; along with minor peaks in Solanaceae and Fabaceae at the base and the top of this zone respectively. The PAR diagram exhibits a notable increase in all terrestrial taxa and *Botryococcus* spp.

Finally, Zone CHU5 (1600-1000 cal yr BP) exhibits a sustained recovery of Poaceae (56%), a rapid decline in Apiaceae (3%) and a drastic drop of about 50% in *Botryococcus* spp. (72%) in the upper part of the zone. Other notable signatures of this zone are the minor presence of Brassicaceae, above-mean abundance of Ast. *Ambrosia*-type (5%), below-mean Ast. *Baccharis*-type (3%), and rapid increases of Ast. *Ophryosporus*-type and the aquatic *Potamogeton* spp. (3%). The PAR of all terrestrial taxa (excepting Brassicaceae) and *Botryococcus* spp. plummet to near-zero values whereas *Potamogeton* spp. PAR shows noticeable increases.

5 Discussion

5.1 Pollen-climate relationship

At present, Lago Chungará is situated within the high-Andean steppe vegetation belt and, consistent with this position, pollen assemblages are primarily composed of high-Andean pollen types. This composition suggests that high-elevation steppe vegetation dominated the surroundings of Lago Chungará between 4500-1000 cal yr BP. Nonetheless, the fossil pollen sequence shows a significant representation of pollen types of vegetation belts situated at lower elevations on the western Andes slopes (i.e. Prepuna and Puna belts). For instance, high Andean pollen types (e.g. *Polylepis* spp. [record mean = 3%]) are sometimes presented in lower abundances than Puna or Prepuna elements (e.g. Chenopodiaceae [8%]), although this might also be related to differences in specific pollen production and long distance transport. A considerable altitudinal thermal gradient of up to 10° C is observed in our surface transect which corresponds to a lapse rate of -4.9° C per 1000 m (Fig. 3), a value within the ranges calculated from the Andes of northern Chile and the Altiplano (e.g. Kull et al., 2002; Gonfiantini et al., 2001). Nonetheless, low latitude (30° N to 30° S) Holocene temperature reconstructions estimate thermal oscillations of less than 0.8° C in magnitude for the 4500-1000 cal yr BP period (Marcott et al., 2013). Climate-glacier models in the Tropical Andes (16° S) provides a more regional constrain on past temperature variations, suggesting that temperatures during the Little Ice Age (~600-100 cal yr BP) were between 2.2° to 1.1° C cooler compared with modern conditions (Jomelli et al., 2011; Rabatel et al., 2008). Although the Chungará record did not cover the Little Ice Age, we consider those values as a benchmark for the potential magnitude of temperature variations during timespan of the Chungará

record, which is clearly insufficient to explain the changes in vegetation observed in our reconstruction. Hence, we assume that precipitation is the largely responsible for the vegetation shifts recorded at Lago Chungará. Our surface pollen transect indicates a continuous increase in summer precipitation in the western Andean slopes from 2100 to 4400 masl (Fig. 3), a trend that is well supported by the instrumental record and the previous literature (Villagrán et al., 1981; Latorre et al., 2006). Based on this information, we infer above-mean abundances of high-Andean taxa as humid conditions, and above-mean abundances of Puna and Prepuna pollen as suggestive of dry periods (Latorre et al., 2006; Maldonado et al., 2005; De Porras et al., 2017). Terrestrial pollen accumulation reflects plant productivity and vegetation cover, both increasing significantly from the Prepuna belt to the high-Andean steppe. Therefore, terrestrial PAR is used as a proxy for regional humidity. In other words, we interpret pollen variations at Lago Chungará as expansions/contractions of Andean vegetation belts and plant productivity in response to changes in regional summer precipitation. On the other hand, aquatic taxa exhibit notable variations at multiple parts of the sequence rather than a unique monotonic trend (Fig. 4). These multiple variations suggest a response to underlying climate variations rather than sustained changes in the lake surface area or water depth due to the continuous sediment infilling of the base (Hernandez et al., 2008; Bao et al., 2015). Thus, we interpret variations in aquatic taxa as changes in lake levels driven by regional precipitation (Jankovská and Komárek, 2000). More precisely, below-mean abundances of the freshwater algae *Botryococcus* spp. are interpreted as reduced water levels (Grosjean et al., 2001; Sáez et al., 2007); whereas above-mean abundances of the macrophyte *Potamogeton* spp., which is currently presented in shallow waters in the periphery of the lake (Mühlhauser et al., 1995), are interpreted as responding to centripetal expansions of palustral environments due to shallower lake levels (Graf, 1994). Finally, considering that 80-90% of modern precipitation at the Lago Chungará area fall during summer months associated with the development of the SASM (Vuille, 1999; Fig. 2a), we interpret our precipitation changes as responding to long-term variations in the strength of the SASM.

5.2 Past precipitation trends

Relative humid conditions are inferred prior to 4100 cal yr BP based on the dominance of Poaceae along with below-mean abundances of all Puna and Prepuna taxa. Above-mean abundances of *Botryococcus* spp. are coherent with this interpretation, suggesting relative low variability in water table and overall increased lake stands. Although Poaceae PAR values are relatively high, total terrestrial PAR is below the long-term mean during this interval, suggesting sparse vegetation cover. This early period of relative high moisture and stable lake levels occurred during an interval of regional aridity and reduced water levels at Lago Chungará between 9000-4000 cal yr BP (Giralt et al., 2008; Bao et al., 2015), although these studies have shown that this interval was not homogenous, including significant wet/dry variability at sub-millennial timescales.

Between 4100-3300 cal yr BP, the record exhibits lower than mean Poaceae and *Botryococcus* spp.; and above-mean Ast. *Baccharis*-type and *Ophryosporus*-type. Corresponding PAR increases reveals that the observed changes in the percentage

diagram reflect genuine increments in the abundance of the aforementioned pollen types. Our modern pollen transect shows that comparable percentages of Ast. *Baccharis* are found below 4000 masl, and therefore their expansion at Chungará points to a decrease in effective precipitation not lower than 60 mm/year relative to modern values. This evidence and the very low terrestrial PAR observed during this zone suggest that those few Puna and Prepuna pollen grains deposited on the lake were most likely windblown from far-distant shrubland communities downslope. Consistent with a relative dry climate, a drastic drop of *Botryococcus* spp. suggests an overall reduction in lake levels during this interval.

These changes are followed by a decline in Ast. *Baccharis*-type by 3600 cal yr BP and a sustained expansion of Ast. *Parastrephia*-type between 3400-2400 cal yr BP; and culminates with a period of persistent above-mean percentages of Apiaceae between 2400-1600 cal yr BP. The modern distribution of vegetation on the western Andes slopes and our modern pollen transect shows that Apiaceae is one of the only families which distribution occurred above 4000 a masl (Fig. 3). In fact, the species *Azorella compacta* is one of the dominant members above 4600 masl, in the altitudinal limit of vegetation in the Chungará area (Orellana et al., 2013). Hence, the rapid increase of Apiaceae between 2400-1600 cal yr BP represents a downward expansion of high-Andean and Subnival vegetation. Interestingly, the PAR diagram shows a rapid expansion of representatives of all vegetation belts between 2400-1800 cal yr BP, expressed as an abrupt increment in the total terrestrial PAR (Fig. 5). These trends indicate a conspicuous increase of terrestrial plant productivity that was not restricted to the high-Andean vegetation as suggested by the percentage diagram, but rather to all vegetation belts downwards. Alternatively, the expansion of cold-tolerant Apiaceae species could have resulted from a cooling event. However, such a thermal excursion should have been associated with a decrease in plant productivity around the lake and downwards. Thus, the observed sequence of pollen changes points to a significant increase in terrestrial plant coverage over the western Altiplano and adjacent Andes slopes, a response we attribute to a notable rise in regional precipitation between 2400-1600 cal yr BP. Consistent with this interpretation, both percentage and PAR of *Botryococcus* spp. show above-mean values during this interval, suggesting persistent high lake stands. Similarly, diatom assemblages and geochemical data from Lago Chungará agrees with these pollen-climate inferences, pointing to increased moisture after 3500 cal yr BP (Bao et al., 2015; Giralt et al., 2008; Pueyo et al., 2011), and overall higher lake levels based on the reduction of periphylic diatoms (Bao et al., 2015) .

The climate trend described above finished abruptly with both the decline in percentage of Apiaceae and Ast. *Baccharis*-type; and expansions of Brassicaceae, Ast. *Ambrosia*-type and Ast. *Ophryosporus*-type. These latter taxa correspond to elements commonly present in the lower Prepuna and Puna belts, and therefore their expansion clearly points toward drier climates between 1600-1000 cal yr BP. The PAR of all major terrestrial taxa shows rapid declines after 1800 cal yr BP, except for the low-elevation Ast. *Ophryosporus*-type and Brassicaceae. These series of abrupt changes are suggestive of a general decrease in terrestrial plant productivity in the Altiplano and western slopes which more likely resulted from a regional decrease in precipitation. This climate interpretation is further supported by the increase in the PAR of the

macrophyte *Potamogeton* spp., suggesting a drastic reduction of lake levels; and by the relative low lake levels inferred from minor peaks in benthic diatoms at 2200 and 1500 cal yr BP (Bao et al., 2015).

5.3 Drivers and teleconnections

Based on the modern pollen-climate relationships in the Chungará area discussed in Sect. 5.1, we interpret the aforementioned precipitation anomalies as responding to long-term variations in the mean strength of the SASM, with a weakened SASM between 4100-3300 and 1600-1000 cal yr BP and a notable strengthening between 2400-1600 cal yr BP. To identify potential drivers of past SASM-related precipitation anomalies at Lago Chungará, Figure 6 shows our pollen-climate indicators (Fig. 6a-b) and a previously published hydrological reconstructions from Lago Chungará (Giralt et al., 2008) (Fig. 6c), along with a selection of paleoclimate reconstructions from the Altiplano, the Tropical Andes and the tropical Pacific region (10° N-18° S). It is evident from this composite plot that the inferred dry conditions for the 4100-3400 cal yr BP interval based on the pollen data seem at odds with the previous reconstruction of water availability based on geochemical data from Lago Chungará, which exhibits an alternation of dry and humid conditions without a consistent trend during this interval (Fig. 6c). These differences could be explained in the light of dissimilar climate-sensitivity of the sediment geochemistry and pollen proxies. Nonetheless, we note that the transition from humid (2400-1600 cal yr BP) to dry conditions (1600-1000 cal yr BP) revealed by our pollen record agrees with similar hydrological changes (Giralt et al., 2008)i, as well as with a dry event at 1500 cal yr BP detected in the Lago Chungará diatom profile (Bao et al., 2015; not shown). We will therefore focus our hemispheric comparison to identify the forcing mechanism behind these two latter climate anomalies.

The centennial wet/dry anomalies experienced in Lago Chungará between 2400-1000 cal yr BP can be reconciled with some hydrological records from the western Andes slopes and adjacent Atacama Desert. For instance, pollen preserved in fossil rodent middens in Salar del Huasco (20° S) reveal the onset of a humid period at around 2100 cal yr BP (Maldonado and Uribe, 2012); while radiocarbon dating of organic deposits at Quebrada Maní (21° S) indicates a moist interval between 2500-2000 cal yr BP (Gayo et al., 2012). Humid conditions during this interval are recorded as south as 23° S, as indicated by an increase in terrestrial plant productivity around 2000 cal yr BP inferred from macrofossil assemblages in rodent middens (Latorre et al., 2002). Further north, the Chungará chronology is partially correlated with precipitation records from Lago Titicaca (15° S) in the core of the Altiplano. A $\delta^{13}C$ record from this lake shows a long-term increase in lake levels over the last 4500 years without any appreciable centennial-scale excursion comparable to the observed at Lago Chungará (Baker et al., 2005) (Fig. 6e). In fact, the highest lake levels are recorded between 1400-1000 cal yr BP, coetaneous with the inferred low stands at Lago Chungará. However, we note that the steady rise in Lago Titicaca water levels halts at ~1400 cal yr BP, suggesting an interruption in this long-term trend. Notably, a more recent precipitation reconstruction based on δ Deuterium (δD) values on terrestrial leaf waxes from the same lake suggests a marked strengthening of the SASM inferred

from rapid isotopic depletion between 2500-1400 cal yr BP (Fornace et al., 2014) (Fig. 6f). Thus, the Titicaca records reveal an overall intensification of the SASM and sustained rise in lake levels until 1400 cal yr BP, and stable lake stands after that time.

The SASM anomalies reconstructed from Lago Chungará do not correspond with the $\delta^{18}O$ changes in the Sajama ice record, just 35 km northeast of Lago Chungará (18° S; Thompson et al., 1998). This isotopic record exhibits a sustained trend towards isotopically enriched values between 2500-1600 cal yr BP (decreased SASM intensity), followed by an abrupt depletion between 1600-1200 cal yr BP (increased SASM intensity) (Fig. 6d). Similarly, high-resolution $\delta^{18}O$ records from the Tropical Andes such as Lago Junín and Huagapo Cave (11°S) also exhibit enrichment between 2500-1500 cal yr BP, in overall disagreement with Lago Chungará (Seltzer et al., 2000; Kanner et al., 2013) (Fig. 6g). The isotopic record from Laguna Pumacocha (10° S) reveals a slight depletion between 2500-1500 cal yr BP, followed by an overall enrichment between 1500-1000 cal yr BP, more closely aligned with the Lago Chungará trends (Fig. 6h). Further north, the record of metal concentration from the Cariaco Basin off the Venezuelan coast (10° N; Haug et al., 2001) does not show any noticeable change between 2300-1100 cal yr BP (Fig. 6i), suggesting that the SASM changes recorded at Chungará were largely decoupled from north-south shifts of the Intertropical Convergence Zone

In sum, correlations between Lago Chungará and paleoclimate reconstructions from the Atacama Desert and the Altiplano indicates that the centennial-scale precipitation anomalies detected at Lago Chungará were regional paleoclimate events caused by strengthening/weakening of the SASM in those regions. On the other hand, the timing, direction and magnitude of our reconstructed anomalies are considerably less replicated in SASM reconstructions from the Tropical Andes and further north. Such discrepancies could emerge from different climate sensitivities, chronological uncertainties, and/or distinct sources of SASM precipitation between northern and southern sites. Comparisons between isotopic values in proxy record and modern rainfall timeseries, as well as model outputs suggest that the $\delta^{18}O$ signal from ice, autogenic lacustrine calcite and speleothems carbonates from the Tropical Andes reflects primary changes in the isotopic composition of precipitation associated with the intensity of the SASM; that is to say, these proxy are sensitive recorders of past monsoonal precipitation (Vuille and Werner, 2005; Hurley et al., 2016; Bird et al., 2011a). In addition, most of these reconstructions are supported by accurately U/Th and ^{14}C chronologies, and therefore chronological uncertainties are unlikely. Hence, the discrepancies between reconstruction from the Tropical Andes and the Altiplano-Atacama region did probably result from different climate drivers.

A 2000-yr record of ENSO-like changes based on several published precipitation records in the western and eastern tropical Pacific Ocean (Yan et al., 2011) offers an interesting comparison with our reconstructed precipitation anomalies. These Pacific records depict predominantly El Niño-like conditions between 2000-1500 cal yr BP, followed by a La Niña-like interval between 1500-950 cal yr BP (Yan et al., 2011) (Fig. 6j). Hence, increased SASM-derived summer precipitation at

Lago Chungará occurred predominately under El Niño-like conditions, whereas decreased SASM precipitation occurred under overall La-Niña-like conditions. In fact, the percentage of sands from El Junco Lake in the Galapagos Island (1° S; Conroy et al., 2008) (Fig. 1), one of the proxies presented in the Yan et al. (2011) ENSO reconstruction, extends the interval of El Niño-like conditions back to 2200 cal yr BP, while variations in the concentration and isotopic signal of the algae *Botriococcus spp.* from the same lake suggest that strong a frequent El Niño events extended back to 3000 cal yr BP (Zhang et al., 2014); encompassing the humid anomaly observed at Lago Chungará completely. In addition, enhanced El Niño conditions between 2600-2000 cal yr BP have recently been reconstructed from a $\delta^{13}C$ records in Subtropical Eastern Australia (27°S) (Barr et al., 2019).

These multiple correlations indicates that the modern ENSO-precipitation relationship in the Altiplano (i.e. high precipitation during La-Niña conditions and vice versa) observed at interannual timescales in the instrumental records (Vuille, 1999), as well as at decadal timescales in tree ring chronologies (Morales et al., 2012), fails to explain the centennial-scale anomalies detected at Lago Chungará.

Then what climatic mechanisms were driving the observed SASM changes? We note that a latitudinal gradient in precipitation anomalies over the Altiplano and Tropical Andes has already been pointed out in a recent speleothem $\delta^{18}O$ record from the Chiflonkhakha cave system on the eastern slopes of the Andes (18° S; Apaéstegui et al., 2018) (Fig. 1). This study shows that overall humid conditions occurred between 1050-850 cal yr BP, a trend that is progressively weakening in northern records until is no longer detected in sites north of 10° S. According to the authors, this latitudinal gradient can be explained if the source of precipitation is not tropical in origin, but originated in southeastern South America and the South Atlantic Ocean (>20° S). The lack of correspondence between Lago Chungará and tropical records of past ITCZ and ENSO behaviour, summed to the latitudinal gradient in centennial-scale SASM responses, is consistent with this explanation, suggesting an extra-tropical source of SASM precipitation that could explain the wet/dry anomalies detected in Lago Chungará and other sites in the Atacama Desert-Altiplano region between 2400-1000 cal yr BP. This interpretation is also consistent with the modes of modern Altiplano precipitation presented by Vuille and Keimin (2004), which demonstrated that changes in the source of precipitation can generate distinctive spatial variability across the Altiplano. Whilst present-day inter-annual precipitation in the northern Altiplano (<18° S) and the Tropical Andes is largely tropical in origin and closed linked to modern ENSO and north-south shifts of the ITCZ, convective activity in the southern Altiplano (>18° S) is strongly correlated with humidity fluctuations in the Gran Chaco basin (25° S), southeastern from Chungará (Garreaud et al., 2009). Interestingly, a sea surface temperature (SST) reconstruction from Core GeoB6211-1/2 in the South Atlantic coast (32° S) shows increased SST between 2300-1500 cal yr BP and decreased SST between 1500-1100 cal yr BP (Chiessi et al., 2014). In this region, positive SST anomalies are linked to an intensification and northward migration of the South Atlantic Convergence Zone (SACZ), a band of convective activity that connects the South Atlantic to the core of the South American continent (Garreaud et al., 2009) (Fig.2b). The SACZ is a major contributor to the SASM in South Eastern South America,

as evidenced in modern climatological studies (Chaves and Nobre, 2004). In fact, a strong connection between the SACZ and the SASM has been suggested in a precipitation reconstruction based on speleothem $\delta^{18}O$ variations in Lapa Grande Cave in Southeastern Brazil (14° S; Stríkis et al., 2011) (Fig. 1), which features rapid short-lived increases in precipitation at 2300, 2200 and 1900 cal yr BP, in correspondence with the Lago Chungará positive precipitation anomaly. Thus, based on all this evidence we hypothesize that the precipitation anomalies observed at Lago Chungará and the southern part of Altiplano are explained by centennial-scale changes in the humidity levels to the southeast of South America and the South Atlantic Ocean, which could have been decoupled from changes in the tropics at certain intervals in the past.

6 Summary and conclusion

Our late Holocene pollen-based reconstruction from the sedimentary section of Lago Chungará reveals that significant changes in the altitudinal distribution of vegetation communities, terrestrial plant productivity, and lake levels occurred in the Altiplano. We interpret these changes as resulting from anomalies in precipitation associated with changes in the mean strength of the SASM at centennial timescales. In particular we detected dry conditions suggestive of a weakening of the SASM between 4100-3300 and 1600-1000 cal yr BP, and a conspicuous humid interval reflecting a strengthening of the SASM between 2400-1600 cal yr BP. Comparison with multiples paleoclimate records from the Altiplano and the Tropical Andes shows spatially coherent changes in SASM intensity at centennial timescales which are largely decoupled from records of variations in the position of the ITCZ and ENSO activity. Hence, the close relationship between ENSO and precipitation in the Altiplano documented at interannual and decadal timescales seems not to be extended to the centennial domain. We further note a clear south-north gradient in the magnitude of precipitation responses, with southern records in the Altiplano and the Atacama Desert responding more markedly than northern sites in the Tropical Andes. All this evidence is consistent with an extra-tropical source of moisture driving centennial-scale changes in SASM precipitation in the former regions, supporting modern climatological studies (Vuille and Keimig, 2004) and interpretations made from recent reconstructions (Apaéstegui et al., 2018). Finally, our results highlight: (1) the lack of correspondence between past changes in the strength of the SASM at centennial timescales and climate components sourced in the tropics, which are the dominant drivers of the SASM at the present; and (2) a strong teleconnection between the southern Altiplano and the extra-tropics during the most recent millennia. Hence, caution is required in assuming that the tropical drivers of precipitation in the Altiplano represent the exclusive forcings from which future conditions should be expected.

7 Data Availability

All data used to interpret the Lago Chungará record is provided in the article. All the information from other records is given in their respective reference on the main text. The pollen data from Lago Chungará will be freely available in the Neotoma paleoecological database (https://www.neotomadb.org/) once this article is accepted for publication. Additional data regarding this investigation can be requested to: Ignacio A. Jara (ignacio.jara@ceaza.cl)

8 Author contributions

AS, AH, SG, RB, BVG and AM, carried out the field campaign and obtained the sediments. LG analysed the pollen samples. IAJ and AM designed the study, analysed and interpreted the data. IAJ wrote the manuscript and prepared all the figures with the assistance of AM, AS, AH, SG, RB and BVG.

9 Competing interests

The Authors declare that they have not conflict of interest.

10 Acknowledgments

This investigation was funded by Fondecyt grant 1181829 and the International Cooperation Grant PI20150081. The Spanish Ministry of Science and Innovation funded this research through the projects ANDESTER (BTE2001-3225), Complementary Action (BTE2001-5257-E), LAVOLTER (CGL2004- 00683/BTE), GEOBILA (CGL2007-60932/BTE) and CONSOLIDER Ingenio 2010 GRACCIE (CSD2007-00067). In addition, we acknowledge funding from the Spanish Government through the MEDLANT project. IAJ would like to thanks David López from CEAZA for his assistance in the drawing of Fig. 1-2. IAJ was supported by Fondecyt posdoctoral grant #3190181. AH as supported by a Beatriu de Pinós–Marie Curie COFUND contract within the framework of the FLOODES2k (2016 BP 00023) project.

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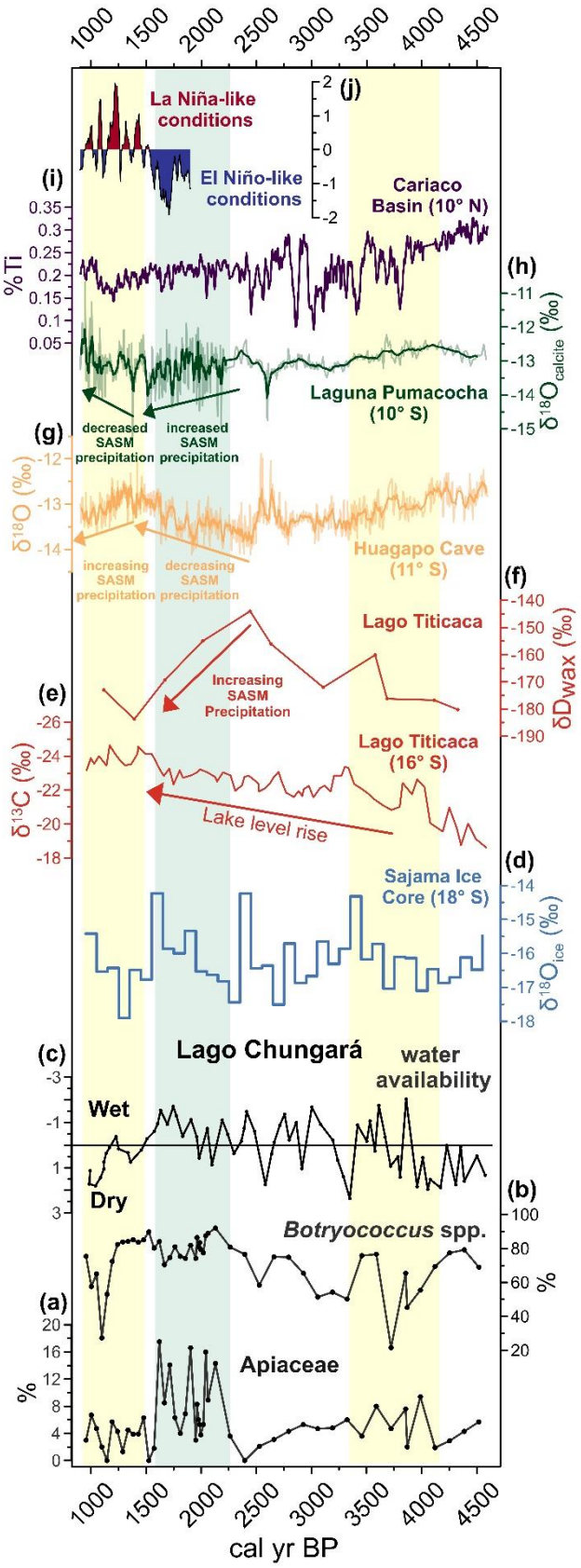
PLEASE NOTE THAT Fig. 01 AND Fig. 06 HAS BEEN CHANGED IN THIS REVISED VERSION

Figure 1. Physiography of the study area in the southern Altiplano (a) Digital Elevation Model (DEM) of the Chungará area depicting Lago Chungará and the position of Core 7, Nevado Sajama and the surface pollen transect, (b) South America DEM with the location of climate reconstructions mentioned in the text (1) Quebrada Maní and Salar del Huasco, (2) Chiflonkhakha cave system, (3) Lago Titicaca, (4) Lago Junín, (5) Nevado Huascarán, (6) Laguna Pumacocha, (7) El Junco Crater Lake, (8) Cariaco Basin, (9) Lapa Grande Cave, (10) Core GeoB6211-1/2.

Figure 6. Summary plot including key Lago Chungará climate indicators (black curves) and selected paleoclimate records from the Tropical Andes and the Pacific Ocean, (a) Apiaceae pollen percentage, (b) Botryococcus spp. percentage, (c) Lago Chungará second eigenvectors (15%) of Principal Component Analysis from geochemical dataset (Giralt et al., 2008), (d) $\delta^{18}O$ record of ice water from Sajama Ice core (Thompson et al., 2000), (e) $\delta^{13}C$ record from Lago Titicaca (Baker et al., 2005), (f) δD record of terrestrial leaf waxes from Lago Titicaca (Fornace et al., 2014), (g) $\delta^{18}O$ record of calcite in sediments from Laguna Pumacocha (Bird et al., 2011), (h) %Ti from Cariaco Basin (Haug et al., 2001), (i) Southern Oscillation Index (SOI) reconstruction from eastern and western tropical pacific records (Yan et al., 2011). Yellow bands indicate dry anomalies, whereas the green band shows the wet anomaly as recorded in Lago Chungará.

Figure 1

(a)
70°W
69°W
17°S
Altiplano
Nevado
Sajama
Chile
Perú
18°S
(b)
Lago Chungará
Surface pollen sample
Bolivia
19°S
Atacama
Desert
0 25 50 km
20°S
(b)
69.20°W
69.15°W
69.10°W
18.15°S
Volcán
Parinacota
18.20°S
Lago Chungará
Core 7
18.25°S
0 4 km
(c)
80.0°W
60.0°W
40.0°W
6
Tropical Andes
5
4
Altiplano
3
7
(a)
2
20.0°S
1
Study
Area
Atacama
Desert
8
40.0°S


1000
1500
2000
2500
3000
3500
4000
4500
(j)
La Niña-like conditions
El Niño-like conditions
(i)
Cariaco Basin (10° N)
%Ti
(h)
Laguna Pumacocha (10° S)
δ18Ocalcite (‰)
decreased SASM precipitation
increased SASM precipitation
(g)
δ18O (‰)
Huagapo Cave (11° S)
increasing SASM precipitation
decreasing SASM precipitation
(f)
Lago Titicaca
Increasing SASM Precipitation
δDwax (‰)
(e)
Lago Titicaca (16° S)
δ13C (‰)
Lake level rise
(d)
Sajama Ice Core (18° S)
δ18Oice (‰)
(c)
Lago Chungará
water availability
Wet
Dry
(b)
Botryococcus spp.
%
(a)
Apiaceae
%
cal yr BP

710