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Short Paper

Ice-core pollen record of climatic changes in the central Andes during the last 400 yr

Kam-biu Liu[a,*], Carl A. Reese[b], Lonnie G. Thompson[c]

[a]Department of Geography and Anthropology, Louisiana State University, Baton Rouge, LA 70803-4105, USA
[b]Department of Geography, University of Southern Mississippi, Box 5051, Hattiesburg, MS 39406, USA
[c]Byrd Polar Research Center and Department of Geological Sciences, The Ohio State University, Columbus, OH 43210, USA

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Abstract

This paper presents a high-resolution ice-core pollen record from the Sajama Ice Cap, Bolivia, that spans the last 400 yr. The pollen record corroborates the oxygen isotopic and ice accumulation records from the Quelccaya Ice Cap and supports the scenario that the Little Ice Age (LIA) consisted of two distinct phases—a wet period from AD 1500 to 1700, and a dry period from AD 1700 to 1880. During the dry period xerophytic shrubs expanded to replace puna grasses on the Altiplano, as suggested by a dramatic drop in the Poaceae/Asteraceae (P/A) pollen ratio. The environment around Sajama was probably similar to the desert-like shrublands of the Southern Bolivian Highlands and western Andean slopes today. The striking similarity between the Sajama and Quelccaya proxy records suggests that climatic changes during the Little Ice Age occurred synchronously across the Altiplano.

Keywords: Altiplano; Climate change; Ice core; Little Ice Age; Pollen; Sajama

Introduction

Proxy records from Lake Titicaca and other lake sites in the central Andes have revealed that significant climatic variability occurred in the region at decadal to centennial time scales during the late Holocene (Abbott et al., 1997a,b, 2000, 2003; Wolfe et al., 2001). However, little is known about the climatic and vegetational changes in the central Andes during the Little Ice Age (LIA; ca. AD 1500–1880), partly because existing proxy records from lake sediments typically lack the high temporal resolution or precise dating control to detect decadal to century-scale climate changes during the past 500 yr. The only high-resolution proxy record pertaining directly to the LIA in the Altiplano comes from ice-core records from the Quelccaya Ice Cap in southern Peru, where oxygen isotopic and ice accumulation data show a distinct, two-phased LIA that was cold and wet during AD 1500–1720 and cold and dry during AD 1720–1880 (Thompson et al., 1985, 1986). However, three questions remain concerning the spatial and temporal patterns of the LIA climatic changes in the central Andes: (1) What was the geographical extent and variability of the LIA climatic changes across the central Andes, or did the same pattern of wet-and-dry phases documented from the northern part of the Altiplano (Quelccaya) also occur in the south? (2) Did abrupt climatic changes such as the shift from wet to dry conditions at AD 1700 occur synchronously across the region? (3) Did these climatic changes, especially moisture fluctuations during the LIA, cause any vegetational response in the Altiplano? Here we present a high-resolution, 400-yr ice-core pollen record from the Sajama Ice Cap in the Bolivian Altiplano that sheds light on these questions.

The stratigraphic pollen analysis of ice cores has proven to be an effective tool in the reconstruction of past environmental changes. Though previous research efforts have primarily focused on polar (Lichti-Federovich, 1975; McAndrews, 1984; Bourgeois, 1986; Bourgeois et al., 2000; Andreev et al., 1997) or subtropical (Liu et al., 1998) ice

* Corresponding author. Fax: +1 225 578 4420.
E-mail address: kliu1@lsu.edu (K-b. Liu).

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caps, preliminary studies on tropical Andean ice caps have also shown promising results (Thompson et al., 1988, 1995). It is important to note, however, that pollen records produced from polar ice cores have often been called into question due to their low pollen concentrations, resulting from the great horizontal distances between the major vegetation sources and the ice caps (McAndrews, 1984). Tropical and subtropical ice cores and snow samples, on the other hand, typically produce pollen concentrations that are 10^2–10^4 times higher than those found in polar ice cores (Liu et al., 1998; Reese and Liu, 2002, 2005a; Reese et al., 2003). Therefore, the close proximity of the tropical ice caps to the surrounding pollen sources makes tropical ice cores good candidates for high-resolution pollen studies. Our study is the first systematic and high-resolution pollen analysis of a tropical ice core.

Study region

The Sajama Ice Cap (18°06′ S, 68°53′ W, at 6542 m above sea level), sitting atop Bolivia's highest peak, is situated on the drier, western side of the Bolivian Altiplano (Fig. 1). The summit temperatures at Sajama range from −7.5°C in January to −14.0°C in June, with 440 mm (water equivalent) of precipitation per year (Hardy et al., 1998). The average annual temperature at the base of Sajama is roughly 1°C. The mean annual precipitation is around 316 mm, about 80% of which falls in the summer (Hardy et al., 1998; Vuille et al., 1998; Garreaud et al., 2003). The prevailing winds in the region are typically from the west during the 6-month dry season (May–October), but easterly flow dominates in the wet season (December–March) (Vuille et al., 1998). November and April serve as transitional months in this dynamic circulation regime that is dominated by the South American summer monsoon (Zhou and Lau, 1998).

The vegetation that comprises the Altiplano, and the area around Sajama, is puna, which is dominated by bunch grasses (Poaceae) (Fig. 1). Other common plants include Asteraceae shrubs and herbs (e.g., *Gynoxys* and *Baccharis*), small trees (*Polylepis*), cushion plants (*Yareta*, Apiaceae), and a host of other xerophytic shrubs and herbs including *Ephedra*, Cactaceae, Euphorbiaceae, Caryophyllaceae, and Solanaceae (Hansen et al., 1984, 1994). In the southernmost part of the Altiplano south of 19°S is the Southern Bolivian

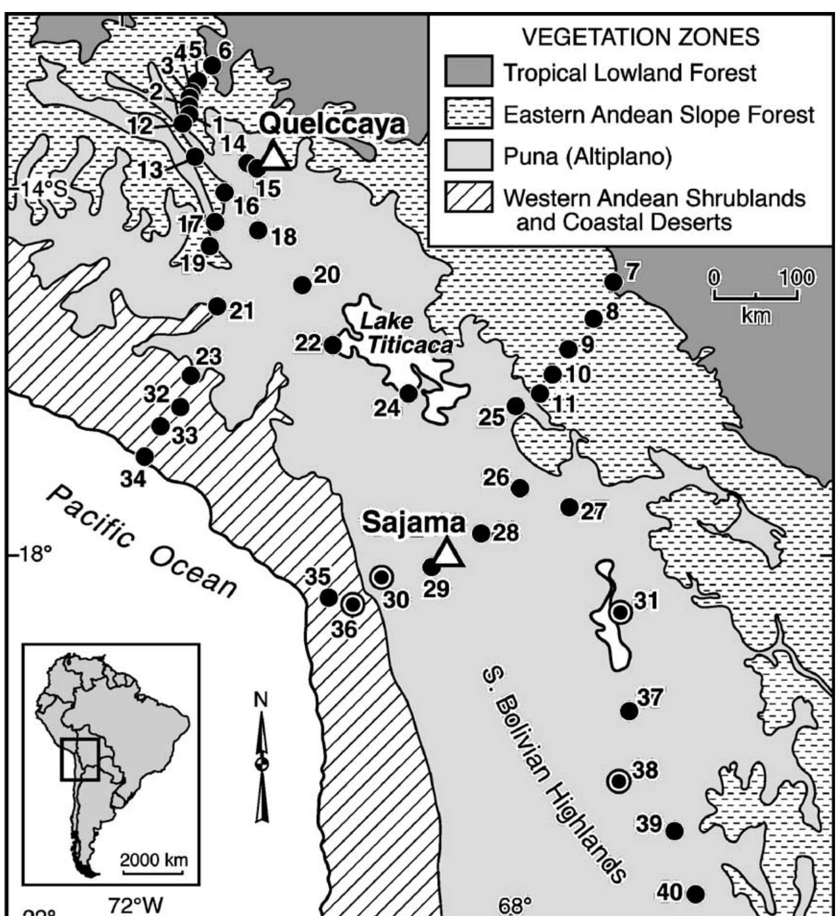

Figure 1. Map of the central Andes showing location of Sajama ice cap and Quelccaya ice cap and 40 pollen surface samples (dots) in relation to vegetation zones. See Reese and Liu (2005b) for detailed description of surface samples. Vegetation zones are based on Olson et al. (2001) and modified by Reese and Liu (2005b). Samples (30, 31, 36, 38) having a negative P/A ratio are indicated by double circles.

Highlands (Reese and Liu, 2005b). This much drier region contains several paleo salt lakes, and the vegetation is a scrub desert dominated by the Solanaceae family instead of puna grasses. Xerophytic shrubs such as Asteraceae, Chenopodiaceae, Amaranthaceae, Cactaceae, and *Ephedra* dominate the dry slopes of the western Andes and the coastal deserts, whereas dense forests (*Yungas*) cover the humid eastern Andes slopes (Fig. 1).

Materials and methods

In 1997, four ice cores (two short cores and two long cores to bedrock) were extracted from the summit of the Sajama Ice Cap (Thompson et al., 1998). The two long cores (C-1 and C-2), drilled only 3 m apart from each other, were used for our palynological investigation. The 149 samples used in this study, ranging in age from AD 1600 to 1996, were primarily derived from the top 64.84 m of C-2, although some samples were taken from C-1 in instances where sections of the primary core had already been depleted due to intense sampling. Dating control for the two long cores during the last 400 yr was based on an empirically derived depth-age function using multiple calibration points, including tritium (^{3}H) assay, physical layer counts for the most recent 100 yr, a tephra horizon (the Huaynaputina volcanic eruption of AD 1600), and one ^{14}C date (Thompson et al., 1998). The samples were collected at bi-yearly or tri-yearly resolution (i.e., two or three samples per year) from AD 1996 to the tritium peak at AD 1964. Samples from AD 1963 to AD 1600 ranged in resolution from 1 to 5 yr.

The amount of meltwater for each sample varied between 400 and 1100 ml. Each sample was evaporated down to 50 ml of water and processed for pollen following the standard methods for ice-core meltwater processing (Liu et al., 1998; Reese and Liu, 2002). All pollen and spores were identified until a minimum of 1000 *Lycopodium* marker spores were counted. The pollen sum, consisting of all pollen and spores, generally ranges from 100 to 200 grains at most levels. All data were then standardized by grouping the samples into 5-yr aggregates for display and analysis.

Results and discussion

The Sajama ice-core pollen record

The 400-yr pollen record from the Sajama ice core is dominated by the pollen of Asteraceae (29–79%) and Poaceae (8–49%) (Fig. 2). Other significant pollen taxa (normally at <10%) include *Polylepis*, *Dodonaea*, *Plantago*, Chenopodiaceae/Amaranthaceae, Cyperaceae, and Urticaceae/Moraceae. The pollen of *Podocarpus* and *Alnus*, typically transported by wind from the humid eastern Andean forests below 3500 m, occurs only sporadically. These pollen assemblages, compared with the results of modern pollen rain studies from the Altiplano and other Andean ice caps (Reese and Liu, 2002, 2005a,b; Reese et al., 2003), suggest that the majority of the pollen present in the Sajama ice core was derived from the vegetation of the Altiplano or the upper Andean slopes.

The pollen diagram can be divided into three zones based on the changes in the percentages of the two dominant pollen types (Fig. 2). Zone 1 (ca. AD 1600–1700) contains relatively high pollen percentages of Poaceae and low percentages of Asteraceae. Zone 2 (ca. AD 1700–1880) is characterized by a sharp decline in Poaceae pollen percentages to its lowest level in the last 400 yr, while Asteraceae pollen increases to its maximum frequencies. In

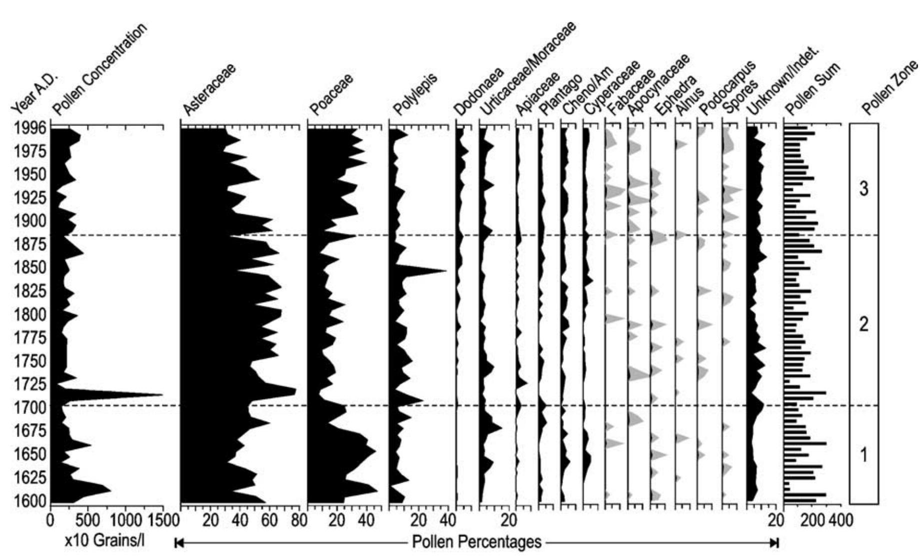

Figure 2. Abbreviated pollen percentage diagram for the last 400 yr (AD 1600–1996) from the Sajama ice core, plotted in 5-yr intervals. Pollen curves shaded light gray are exaggerated 10×. Only 16 of the 32 pollen and spore taxa counted are shown, including unknown and indeterminable (indet.) pollen. Pollen taxa not shown were rare and never exceeded 1% of the assemblage. Dotted lines mark the pollen zone boundaries.

zone 3 (AD 1880–1996), Poaceae pollen percentages increase again, accompanied by a marked decrease in Asteraceae pollen. These changes in the pollen abundance of Poaceae versus Asteraceae probably reflect significant changes in the populations of these two important plant taxa in the Altiplano, hence significant changes in the vegetation communities.

Except for a spurious spike, pollen concentration remains relatively uniform throughout the 400 yr, ranging from 800 to 8200 grains per liter and with a mean of ca. 2800 grains per liter. These pollen concentration values are generally about an order of magnitude higher than those reported from the Dunde ice core in the Tibetan Plateau, which range from 50 to 1300 grains per liter (Liu et al., 1998). The relatively uniform pollen concentration values may suggest that the density of vegetation on the Altiplano has remained relatively constant during the study period, though the vegetation composition has changed in response to climatic fluctuations.

Poaceae/Asteraceae pollen ratio as humidity index

The changes in the relative abundance between Poaceae and Asteraceae – the two dominant taxa in the Sajama pollen record – can be effectively captured by the ratio of pollen percentages between these two taxa, i.e., the P/A ratio. Based on the modern ecology and geographical distribution of these two plant taxa, the P/A pollen ratio can be used as a proxy for humidity in the Altiplano environment. Grasses (Poaceae) are typically shallow-rooted plants that tend to proliferate in wetter conditions, whereas the Asteraceae plants are xerophytic, deeply rooted shrubs that proliferate in drier environments (Betancourt et al., 2000; Latorre et al., 2002). The different ecological adaptations of these two plant types are reflected in a distinct vegetational gradient on the Altiplano, which changes from a grass-dominated puna in the more humid part in the north and east, to a xerophytic shrubland with few grasses in the drier Southern Bolivian Highlands in the south (Reese and Liu, 2005b). Therefore, we can use the logarithmic P/A ratio as a humidity index for the Altiplano. Accordingly, the P/A ratio (all expressed in logarithmic values) would be 0 if the Poaceae and Asteraceae pollen percentages are equal. Positive numbers show the dominance of grasses and therefore wetter conditions. Negative values suggest the dominance of the Asteraceae over grasses and therefore drier conditions. A similar pollen ratio between *Artemisia* and Chenopodiaceae (the A/C pollen ratio) has been used as a humidity index in another ice-core pollen study in the Tibetan Plateau (Liu et al., 1998).

In the modern pollen rain over the Altiplano (Reese and Liu, 2005b), Poaceae pollen percentages generally exceed those of Asteraceae by a factor of 2–10 (Fig. 3). In a study of 40 pollen surface samples collected from four vegetation zones (eastern Andean slope forest, puna, western Andean shrublands, and coastal deserts, Southern Bolivian Highlands) in the central Andes (Fig. 1), the P/A ratios range from 1.58 to −0.73. However, among the non-forest vegetation zones the P/A ratios decrease from an average of 0.63 in the Altiplano puna to 0.41 in the western Andean slopes and coastal deserts, and to 0.27 in the Southern Bolivian Highlands (Fig. 3). This decreasing trend in P/A ratios from north to south broadly follows the regional gradient in annual precipitation, which decreases from 700 mm in the northeastern Altiplano in Peru, to <400 mm in the southwestern Bolivian Altiplano, and to <100 mm in the northern Atacama Desert in Chile (Garreaud et al., 2003). In fact, all four samples with negative P/A ratios in the modern pollen data set come from sites in the southernmost (driest) part of the study region, where annual precipitation is <400 mm (Fig. 1).

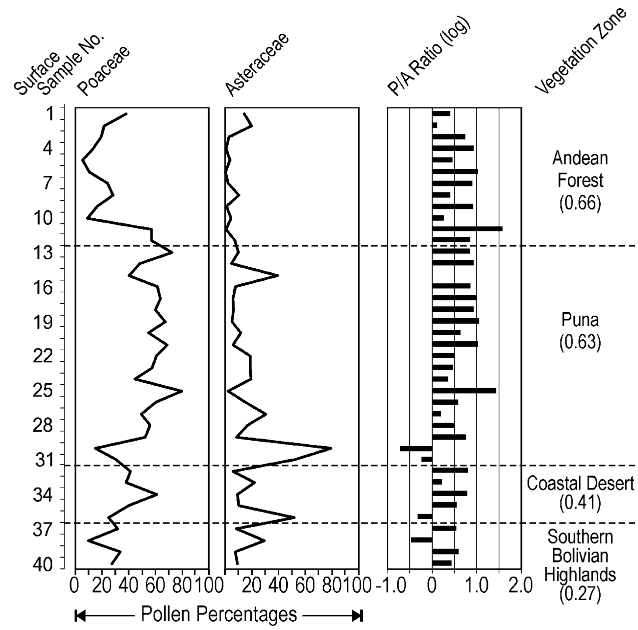

Figure 3. Percentage curves for Poaceae and Asteraceae pollen and corresponding P/A ratios (bars) for 40 surface samples collected from four vegetation zones in the central Andes. The samples generally follow a gradient of decreasing precipitation from north to south. The number in parentheses under each vegetation zone label (far right) denotes the mean value for P/A ratios within that zone.

In the Sajama ice core the P/A ratio ranges from 0.16 to −1.03, with a mean of −0.37 (Fig. 4). The generally more negative ratios in the ice-core samples compared with the soil surface samples is perhaps due to the greater dispersal ability of Asteraceae pollen over Poaceae, or the greater abundance of Asteraceae plants in the periglacial desert and superpuna surrounding the Sajama Ice Cap. Chronologically the P/A ratio shows a remarkable trend of changes over the last 400 yr. Prior to AD 1700, the ratios are high with an average of −0.11. From AD 1700 to 1880, the ratio drops to highly negative values (average = −0.60). For the post AD 1880 period, the average is again near the pre-1700 levels at −0.22. The lower values of P/A ratios during the period AD 1700–1880 suggest a dry climate, which favored the xerophytic Asteraceae shrubs at the expense of the less drought-resisting

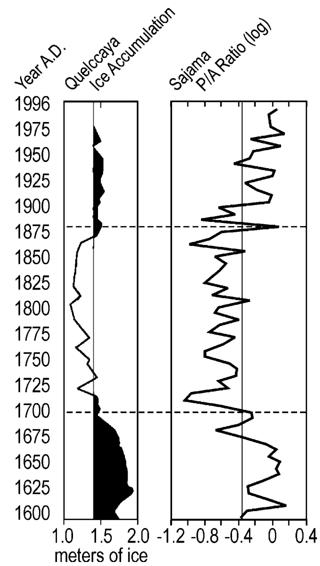

Figure 4. Comparison of the Sajama P/A ratio curve and the Quelccaya ice accumulation (net balance) curve (Thompson et al., 1986) for the last 400 yrs. Solid line through each curve represents the mean value of each data set. Horizontal dotted lines are pollen zone boundaries.

puna grasses. During this arid period the vegetation around Mt. Sajama was probably dominated by Asteraceae shrubs, similar to the desert-like shrublands occurring in the Southern Bolivian Highlands and the western Andean slopes of northern Chile today. Therefore, it is likely that the annual precipitation was reduced to values (<200 mm) that are typical of the southernmost part of the Bolivian Altiplano and much lower than the 300- to 400-mm that occurs in the vicinity of Mt. Sajama at the present.

Little Ice Age climatic changes in the Altiplano

Our 400-yr pollen record from the Sajama ice core is the only pollen record from the Altiplano that has the high temporal resolution that is essential for detecting century-scale climate variability during the Little Ice Age. It shows a two-phased LIA characterized by a transition from a wet phase during AD 1600–1700 to a dry phase during AD 1700–1880. Since no detailed data on annual ice accumulation rates have been produced for the Sajama ice core to correlate with the pollen data (Thompson et al., 1998), the ice accumulation data from the Quelccaya Ice Cap, 350 km to the north, provide the only other high-resolution paleo-precipitation record in the Altiplano for regional comparison (Thompson et al., 1985, 1986). The pattern and chronology of LIA climatic changes documented in the Sajama and Quelccaya ice cores are strikingly similar to each other (Fig. 4). Both records show a distinct dry period occurring in AD 1700–1880. More important, these records show that this century-scale dry period occurred synchronously between the northern and south-central parts of the Altiplano. A key question in central Andean paleoclimatology concerns whether climatic changes occurred synchronously or asynchronously across the Altiplano at various time scales. For example, Abbott et al. (2000, 2003) pointed out that the onset of wetter conditions after the middle Holocene period of extreme aridity occurred earlier (3500 yr ago) in Lake Titicaca and its northern watershed than at Lago Taypi Chaka Kkota (2300 yr ago) and other sites in the south, and attributed the apparent asynchroneity to the progressive southward shift of the Intertropical Convergence Zone (ITCZ) controlled by orbital forcing over millennial time scales. Our data, however, indicate that climatic changes during the LIA occurred synchronously across the Altiplano without any significant time lag between Quelccaya and Sajama. Thus, century-scale climatic changes such as the AD 1700–1880 drought event must be explained by other large-scale climatic mechanisms such as the El Nino-Southern Oscillation (ENSO), which strongly affects precipitation patterns over the Altiplano (Vuille, 1999; Vuille et al., 2000).

The proxy records from Quelccaya and Sajama therefore suggest that the LIA was a significant and widespread climatic event across the central Andes. Other than these two high-resolution proxy records, ice accumulation and isotopic data from the Huascaran ice core from northern Peru (9°S) also seem to show a significant arid period during the late LIA, AD 1730–1870 (Thompson et al., 1995). Unfortunately, other proxy records from central Andean lakes lack the high temporal resolution or climate sensitivity to confirm definitively the existence and timing of a wet-and-dry two-phased LIA. Sediment cores from the Marcacocha basin in southern Peru suggest a long arid period from AD 900 to 1800 (Chepstow-Lusty et al., 2003). Proxy records from Lake Chungará and Lake Miscanti in northeastern Chile (Valero-Garcés et al., 2003) do not go back to the 18th century and lack the resolution to decipher decadal-scale climate variability, but for the last 200 yr they show conflicting trends with the Sajama or Quelccaya records, or even between these two records themselves. Other proxy records from Lake Titicaca (Abbott et al., 1997a) and its watershed—particularly Paco Cocha (Abbott et al., 2003) and Lago Taypi Chaka Kkota (Abbott et al., 1997b, 2000, 2003; Wolfe et al., 2001), as well as those from Lago Potosi (Wolfe et al., 2001), Laguna Seca (Schwalb et al., 1999), and lakes in north-central Peru (Hansen et al., 1984, 1994), also lack sufficient resolution to permit detailed reconstruction of climatic fluctuations for the last 500 yr. Thus, more high-resolution records from multiple proxies are needed to reconstruct the timing, magnitude, and geographical variability of the climatic changes during the LIA, and especially the vegetational response to these moisture fluctuations in the Altiplano.

Conclusions

This paper presents the first high-resolution pollen study of a tropical ice core. As in the case of the pollen record from the subtropical Dunde Ice Cap (Liu et al., 1998), the results of this study demonstrate the ability of pollen data from tropical ice cores to record the vegetation responses to climate fluctuations at decadal to centennial time scales. Our pollen data from the Sajama ice core corroborate the isotopic and accumulation data from two other ice-core studies from the Peruvian Andes (Quelccaya and Huascaran) and support the reconstruction of a two-phased LIA marked by a wet phase before AD 1700 and a distinctly drier phase during AD 1700–1880. The fact that a pollen record—an independent biological proxy—from a Bolivian ice cap (Sajama) shows the same paleoclimatic trend as registered by the traditional chemical and physical parameters in two Peruvian ice cores hundreds of kilometers away suggests that climatic changes associated with the LIA occurred synchronously across the central Andes. Equally important, the high-resolution pollen data from Sajama suggest that the vegetation in the Altiplano responded sensitively to moisture fluctuations at the centennial time scale.

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