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A Potential Pollen Proxy for ENSO Derived From the Sajama Ice Core

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A potential pollen proxy for ENSO derived from the Sajama ice core

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[1]   An annually resolved pollen record spanning a 39-year period (1958–1996) from the Sajama Ice Cap, located on the western Bolivian Altiplano, reveals significant interannual variations in both pollen concentration and composition. The pollen assemblages within the annual layers are dominated by typical Altiplano taxa, especially Poaceae and Asteraceae. On an annual basis the pollen concentrations are strongly negatively correlated (Pearson's $r = -0.716$) with the Southern Oscillation Index (SOI). Studies from Sajama and other tropical ice caps have shown that during El Niño years, the weather on the Altiplano is decidedly warmer and drier, which enhances ablation on tropical ice caps through increased sublimation. This process results in the concentration of pollen within an annual layer, and thus provides a mechanism to reconstruct past El Niño events, so long as annual resolution is obtainable within the ice core. **Citation:** Liu, K.-B., C. A. Reese, and L. G. Thompson (2007), A potential pollen proxy for ENSO derived from the Sajama ice core, *Geophys. Res. Lett.*, *34*, L09504, doi:10.1029/2006GL029018.

1. Introduction

[2]   Pollen preserved in non-polar ice caps can provide sensitive records of climatic and vegetational changes over a wide variety of time-scales [*Liu et al.*, 1998, 2005; *Reese and Liu*, 2005; *Thompson et al.*, 1988, 1995]. The upper sections of these archives (above where compaction and laminar flow have made the annual layers too thin) allow for the analysis of pollen at very high resolutions, which can be used to measure vegetation response to short-term climatic oscillations and fluctuations. This resolution facilitates the derivation of modern pollen/climate analogs that can be used to sharpen paleoenvironmental reconstructions. For example, a previous pollen study of the annual ice layers for a 30-year period (1957–1986) from the Dunde ice cap on the northeastern Tibetan Plateau suggests that pollen concentration is correlated positively with summer precipitation and negatively with summer temperature; thus pollen can be used as a proxy for moisture availability in the Tibetan Plateau, which is largely controlled by the strength of the summer monsoon [*Liu et al.*, 1998]. In this study, we present results of a pollen study over a 39-year period (1958–1996) at annual resolution in an ice core taken from the Sajama ice cap on the Bolivian Altiplano.

[3]   The ENSO cycle is an important phenomenon that greatly influences the climate in the central Andes. Several studies have shown that warm-phase conditions (El Niño) result in dry, windy, and generally warmer conditions for the region [*Thompson et al.*, 1984; *Vuille*, 1999; *Hardy et al.*, 2003]. El Niño events have also been directly tied to significant changes in pollen assemblages and concentrations found on the Quelccaya ice cap in southern Peru [*Reese and Liu*, 2005]. From that study, however, it is still unclear whether these changes reflect a change in pollen production amounts at the plant level, or a change in atmospheric circulation (transport mechanism) due to the breakdown of the South American Summer Monsoon [*Zhou and Lau*, 1998]. Regardless, the response of the Sajama ice cap pollen to the ENSO cycle could provide a base to reconstruct warm-phase, El Niño events further in the past.

2. Methods

[4]   In 1997, two parallel long cores, C-1 and C-2, were drilled to bedrock at the summit of the Sajama ice cap (18°06′S, 68°53′W, elevation 6542 m above sea level) on the western Bolivian Altiplano [*Thompson et al.*, 1998] (Figure 1). C-1 was cut into 5063 continuous samples that were analyzed for oxygen isotopic ratios, dust concentration, and major anion contents. C-2 was cut into 803 continuous samples that were analyzed for ^{18}O only. Only samples from C-2 were used for this pollen study. Time control for the most recent 100 years in both cores was established by the counting of annual layers, which was then calibrated by the identification of the 1964 tritium radioisotope (^3H) peak [*Thompson et al.*, 1998].

[5]   For the period 1965–1996, where the relatively thick seasonal accumulation layers are clearly identifiable based on the variations in ^{18}O and dust contents, samples were taken separately from the summer (wet season) and winter (dry season) layers. The annual ice layers for 1958–1964 were sampled at an annual resolution. The samples cut from the ice core were transferred to leakproof Nalgene® sample bottles and allowed to melt at room temperature. The volumes of meltwater in these seasonal or annual samples range from 0.25 to 1.15 liter, with a mean of 0.75 liter. The meltwater samples were processed following the procedures outlined by *Reese and Liu* [2002]. All pollen and spores were identified at 400X magnification and counted until a minimum of 300 grains was reached, or until 1000 *Lycopodium* marker spores were counted.

[6]   In our study involving both seasonal and annual samples, a year is defined by combining the pollen count of a dry season sample with that of the following wet season (i.e., the annual pollen count for the year 1996 = dry season of 1996 + wet season of 1996/1997). In calendar months, this translates to a year beginning in April and ending the following March. Thus the year 1996 in our pollen study

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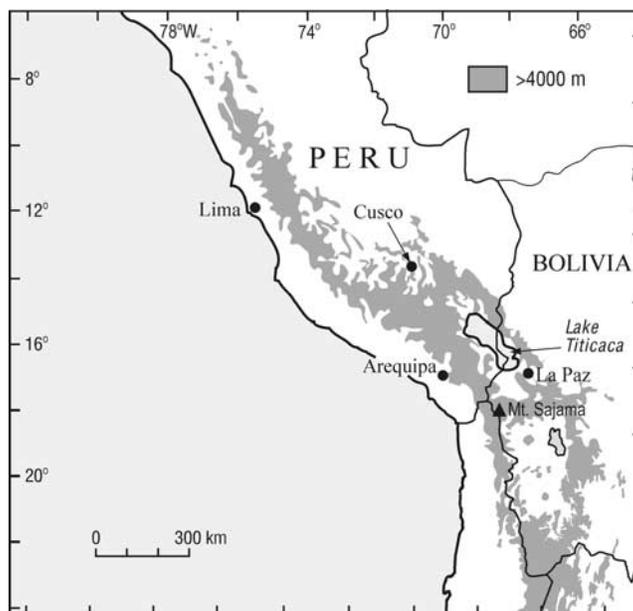[3]Byrd Polar Research Center, Ohio State University, Columbus, Ohio, USA.

Figure 1. Map of the central Andes showing the location of Mt. Sajama (adapted from *Reese et al.* [2003]).

represents April 1996 through March 1997. Pollen concentration was estimated by the exotic marker spore method [*Stockmarr*, 1971], and expressed as number of grains per liter (grains l^{-1}) of meltwater. Pollen influx was calculated by dividing the pollen concentration value by 1000, then multiplying this number by the reconstructed accumulation rate (cm per yr) to obtain the number of grains deposited on the ice surface per cm^2 per year (grains cm^{-2} yr^{-1}). Pollen data are missing for the years 1967, 1982, 1985, 1989, and 1990 due to the intense sampling of core C-2 from previous studies. Not enough material was left at these levels to yield enough meltwater for seasonal pollen analysis.

[7] SOI data are obtained from the Climate Research Unit at the University of East Anglia (http://www.cru.uea.ac.uk/cru/data/soi.htm). The reconstructed summit temperature and precipitation data from Mt. Sajama were provided by Doug Hardy and Mathias Vuille at the Climate System Research Center at the University of Massachusetts. Their reconstructions were obtained by combining four years of weather data recorded on the summit of Sajama (1996–2000), with National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis results and data from other Altiplano weather stations (for details refer to *Hardy et al.* [2003]).

3. Results

[8] Pollen occurs abundantly in the Sajama ice cores (Figure 2). Pollen concentrations in the annual layers from 1958 to 1996 range from 700 to 6250 grains per liter, with an average of 2821 grains per liter. These values compare favorably with those found in modern snow samples collected at the surface of the Quelccaya ice cap in the Peruvian Andes [*Reese and Liu*, 2002, 2005], but are about 2–3 times higher than those reported from the annual layers from the Dunde ice cores for a comparable period, 1957–1986 [*Liu et al.*, 1998]. On the whole, pollen from Altiplano plant taxa dominate the 39-year pollen record from the

Sajama ice core. Asteraceae (Tubuliflorae-type, sensu *McAndrews et al.* [1973]) and Poaceae account for an average of 32.7% and 33.6% of all the pollen and spores counted, respectively. However, there is significant interannual variability, ranging from 4–75% for Asteraceae and 12–85% for Poaceae from one annual layer to another. Other ecologically important pollen taxa include *Polylepis*, *Dodonaea*, Urticaceae/Moraceae, Apiaceae, *Plantago*, Chenopodiaceae, and Cyperaceae, but individually their frequencies are generally <10%. The overall pollen assemblage confirms results from other pollen studies [*Liu et al.*, 2005; *Reese and Liu*, 2005; *Reese et al.*, 2003] that most of the pollen in the Sajama ice cores is derived from the puna grasslands of the Altiplano.

[9] The pollen percentage curves for the two dominant taxa (Asteraceae and Poaceae) as well as the minor taxa do not show any clear trend throughout the 39-year period. Total pollen concentration values, however, seem to have an increasing trend from a low of <2000 grains/liter in the early 1960s to a maximum of ca. 6000 grains/liter in the early 1990s. To explore the climatic significance of these changes, we plot the annual values of the Southern Oscillation Index (adjusted to match our pollen year, April through March), the reconstructed summit temperatures and precipitation at Sajama, and the pollen influx values next to the total pollen concentration curve (Figure 2). Generally, positive SOI values (cold phases or La Niña conditions) are more prevalent before 1975, with distinct La Niña conditions occurring in 1988–1989, 1973–1975, 1970–1971, 1967–1968, 1964, 1962, and 1960. Negative SOI values seem to be more prevalent after 1975, with distinct El Niño events occurring in 1991–1994, 1987, 1982–1983, 1977, 1972, and 1965–1966. The increasing trend of total pollen concentrations and the more frequent occurrence of strong El Niño events seem to suggest a negative relationship, which is confirmed by a correlation coefficient (r) of −0.716 between pollen concentrations and SOI, which is significant at the 0.01 level (Figure 3).
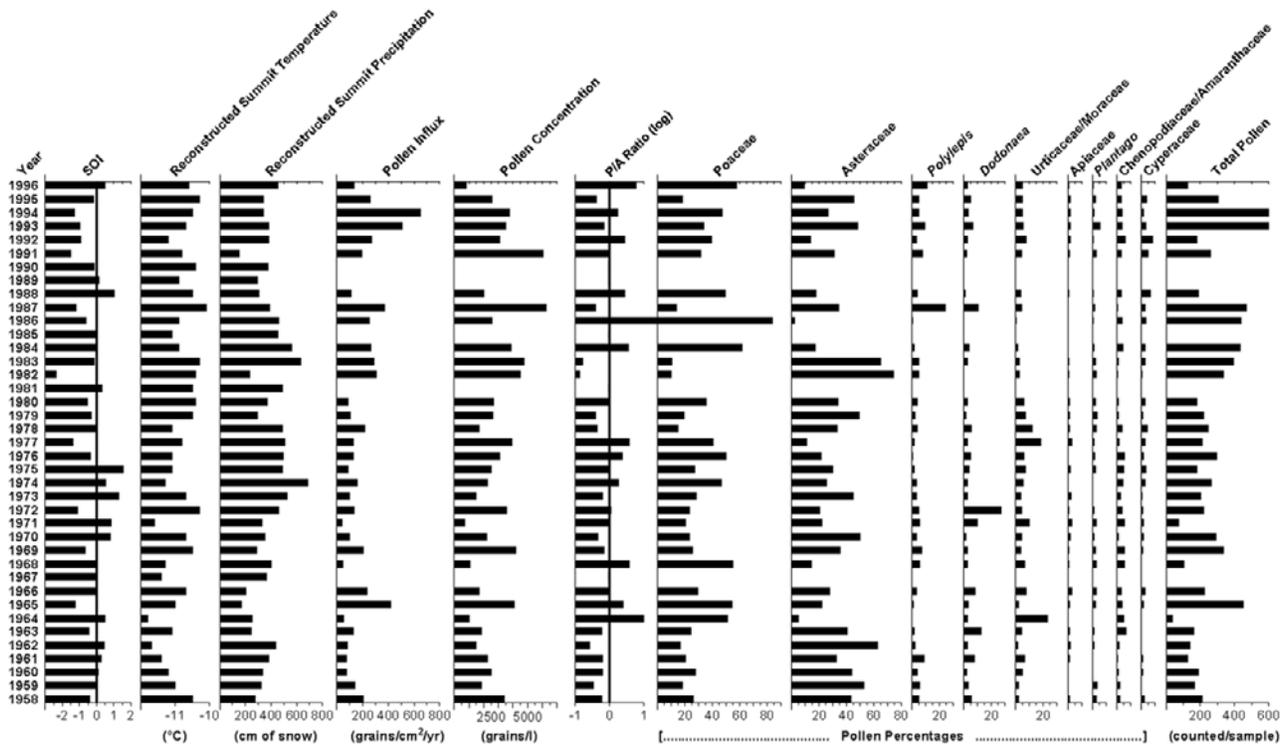
Figure 2. Pollen influx, concentration, and percentage diagram from Mt. Sajama plotted with the Southern Oscillation Index and reconstructed summit precipitation and temperature data (1958–1996).

[10] In addition to this, Table 1 shows the correlation coefficients between SOI, pollen concentration, and the other meteorological and pollen data in the study. In general, reconstructed summit temperatures have a negative relationship with the SOI (r = −0.378, significant at the 0.05 level), while reconstructed summit precipitations show a positive correlation with the SOI (r = 0.322, significant at the 0.05 level). These data confirm that El Niño conditions translate to generally warmer and drier weather on the Andean Altiplano [Hardy et al., 2003]. The pollen concentration values show a positive correlation with summit temperatures (r = 0.560, significant at the 0.01 level), but no correlation with summit precipitation. The pollen influx curve closely follows the pollen concentration curve (r = 0.560, significant at the 0.01 level). Asteraceae pollen percentages are correlated negatively with the SOI, but no significant relationship exists between the SOI and the Poaceae/Asteraceae (P/A) pollen ratio, an indicator of regional vegetation change in the Altiplano [Liu et al., 2005].

4. Discussion

[11] We attribute the increase in pollen concentration in the ice core during an El Niño year to increased sublimation under warmer and drier conditions, and vice versa. Conventionally in ice-core studies, the thickness of the annual ice layer (from which the net accumulation is estimated) is taken as an approximation of the annual precipitation (snowfall). However, the annual layer thickness in low-accumulation environments like the summit of Sajama can be complicated by a number of factors other than precipitation, especially wind scour and loss from sublimation

during the austral fall and winter, when humidity drops and wind speeds increase dramatically [Wagnon et al., 1999; Ginot et al., 2001; Hardy et al., 2003]. This process can be exacerbated with the drier and windier conditions associated with a strong El Niño event [Hardy et al., 2003].

[12] For the Sajama Ice Cap, the annual accumulation rates from October 1996 through October 2000 have been measured by Hardy et al. [2003]. Their study shows that the primary accumulation period for the mountain occurs from December to March, and is then follow by a nine-month period of net ablation. During the non-El Niño years within
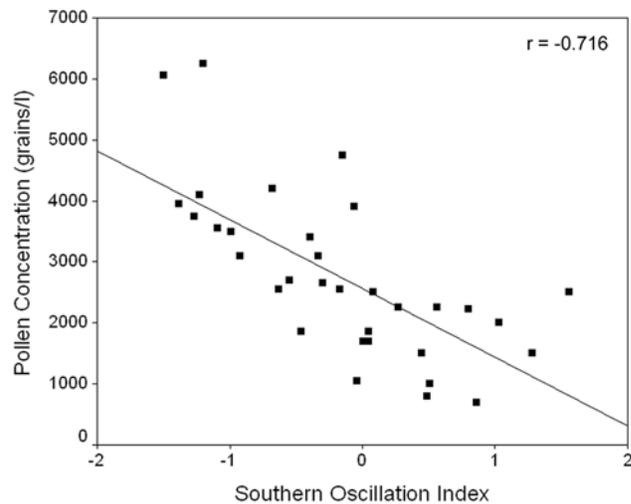

Figure 3. Scatterplot of SOI and pollen concentration values (1958–1996).

Table 1. Pearson Correlation Coefficients Between SOI and Pollen Concentration Values and Other Important Meteorological and Palynological Data Within the Study[a]

	SOI	Temperature	Precipitation	Influx	Concentration	P/A Ratio	Poaceae	Asteraceae
SOI Pearson's r		**−0.378**	**0.322**	**−0.586**	**−0.716**	0.056	−0.285	**−0.383**
Concentration Pearson's r	**−0.716**	**0.560**	−0.090	**0.560**		−0.223	0.264	**0.524**

[a]Numbers appearing in bold are significant at the 0.05 level.

their study, net accumulation ranged from approximately 1.6 m to 2.5 m. However, during the 1997 El Niño event, reduced summer snowfall and increased scour/sublimation loss resulted in an annual net accumulation of only 0.5 m.

[13] No studies to date have explored the effects of wind scour and sublimation on pollen trapped within an ice cap. It is assumed that snow loss due to wind scour would also remove any pollen that was trapped within the snow, which would reduce net accumulation but would have no effect on pollen concentration. However, unlike wind scour, the process of sublimation should only remove snow, but not pollen from the surface. Thus, if a high rate of sublimation occurred during a particular year, then the same amount of pollen would be contained within a smaller volume of ice, resulting in a higher pollen concentration for that year. This would also affect the annual pollen influx numbers in a similar fashion. Pollen influx is calculated as grains per cm^2 per year, however if sublimation removed the medium (snow) but not the trapped pollen, then pollen influx should also increase with increased loss due to sublimation. So if the annual pollen input remains relatively constant, sublimation is the most likely explanation for variations in both the pollen concentration and pollen influx values within an ice cap.

[14] The lack of a significant relationship between the SOI and the P/A ratio implies that vegetation composition in the Altiplano did not change significantly or consistently between El Niño and La Niña years. No data exist on the relationship between ENSO events and pollen production of plants in the Altiplano, but there is no reason to expect that flowering intensity or pollen productivity should increase during an El Niño year, when Altiplano plants endure greater stress under the warmer, drier, and windier conditions. To the contrary, in their study of short-term pollen deposition (sampled from the top 5 cm of snow on ice cap surface), *Reese and Liu* [2005] reported higher pollen concentrations in surface snow deposited in a La Niña year (2000) than in an El Niño year (2001), implying higher pollen productivity in a La Niña year as would be expected under more favorable moisture conditions. We therefore conclude that snow loss due to sublimation, and not fluctuations in the amount of pollen that the ice cap receives, is responsible for the higher pollen concentrations in ice core samples associated with El Niño years.

[15] The statistically significant negative relationship between SOI and annual pollen concentration values could prove useful for reconstructing paleo-El Niño events from ice-core pollen data. Once pollen survives the initial year on the ice cap (firn), there should be no other processes that work to concentrate pollen within an annual layer. Compaction and the resulting laminar flow within a glacier should work to move both ice and pollen laterally (thus thinning each annual layer), but would not necessarily concentrate the pollen. Thus in an Andean ice core where annually resolvable pollen concentration data are available,

spikes in pollen concentration values are likely to represent El Niño years (as in the case of 1965, 1982–83, 1987, and 1991–92 in the Sajama ice core).

5. Conclusions

[16] This study has shown that pollen concentration within the Sajama ice cap is significantly negatively correlated with the SOI on an annual basis. This relationship could be used in the future to use pollen concentration as a proxy for reconstructing paleo-SOI as long as annual resolution is available within an ice core. In this study, we chose to end our annual resolution in 1958 to ensure that we had enough meltwater (thus pollen) per sample. Due to the relatively high concentrations of pollen found in Andean ice cores [*Reese and Liu*, 2002, 2005; *Reese et al.*, 2003; *Liu et al.*, 2005] we now know that meltwater volume as little as 200 ml is sufficient for pollen analysis. So for Andean ice cores at least, it is possible to sample at even finer resolutions than chosen in this study, and extend the pollen record, and potentially the paleo-SOI, at annual resolution back centuries.

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