Isotopic variability on Nevado Sajama on sub-century timescales

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The Sajama ice core has provided a 25,000-year Altiplano paleoenvironmental record with unparalleled chronological control (Thompson et al., 1998). In conjunction with ice-core records from Quelccaya and Huascarán, Thompson et al. (2000) argue convincingly that Andean ice cores record temperature fluctuations on century-to-millennial timescales. However, it is widely recognized that complex interactions between numerous processes control the isotopic composition of precipitation on the Altiplano (e.g., Aravena et al., 1999), resulting in uncertainty about the precise climatic interpretation of short-term (less than century-scale) oxygen isotopic variability in the Sajama stratigraphy. This is the "tropical paleothermometry conundrum" discussed by Thompson et al. (2000), in which the most negative $\delta^{18}O$ values are associated with precipitation during the summer, rather than winter. Furthermore, greater than 80 percent of the annual snowfall on Sajama occurs during the summer wet season. The isotopic signal in the ice core therefore represents atmospheric conditions during only a relatively small proportion of the year (although the signal also records dry-season enrichment). Wind scour and sublimation further condense the period of time (snowfall) each year that is ultimately preserved in the ice core record. It is therefore *essential* that the distribution of snow accumulation through the year be considered, in the interpretation of the isotopic record.

Here we investigate empirical relationships between Sajama oxygen isotopic values and two climate variables, temperature and precipitation, using two different approaches. One examines relationships over three years between weather measurements close to Sajama's summit and the $\delta^{18}O$ of snow samples collected from nearby pits. This provides information on relationships at very short timescales (i.e., daily to seasonal). However, these relationships are not necessarily maintained, as fractionation and other processes subsequently alter the oxygen isotopic profiles following deposition. Therefore, a second analysis approach considers oxygen isotopic measurements from the Sajama ice core in terms of reconstructed air temperatures and precipitation at the summit. The results of both approaches demonstrate a strong association between precipitation amount and $\delta^{18}O$.

We operated an automated weather station (AWS) near the summit of Sajama (Fig. 1) between October 1996 and October 2000 (Hardy et al., 1998). Measurements included aspirated air temperature and changes in snow surface height (accumulation & ablation). Snowpack samples were obtained at an interval of 3 cm following each wet season (except 1997 interval = 6.4 cm), and analyzed at Byrd Polar Research Center. The $\delta^{18}O$ value representing each snowfall event was then determined, using AWS data and a simple snow compaction model. Isotopic variability was assessed relative to the magnitude of each event, and the corresponding air temperatures.

Figure 1. Nevado Sajama viewed from the west, 20 September 1999 (18°06' S; 68°53' W and 6,542 m a.s.l). Inset illustrates the AWS at 6,515 m (note 2 people for scale).

The second approach used measurements of air temperature and snow accumulation/ablation at the AWS in conjunction (respectively) with NCEP/NCAR reanalysis temperatures at the 450 hPa level ($r = 0.88$, $P < 0.001$), and precipitation data from Bolivian stations ($r = 0.88$, $P < 0.001$), to reconstruct 49-year series of monthly temperature and precipitation at the summit. Reconstructed summit precipitation was then adjusted slightly to account for evaporative loss. Finally, Sajama $\delta^{18}O$ values from the ice core ($n = 4 – 27\ a^{-1}$), for each year 1948-97, were then attributed to individual months based upon the distribution of precipitation through each year.

Between 1948 and 1996, annual mean $\delta^{18}O$ was strongly associated with annual precipitation on Sajama (Fig. 2). As annual precipitation increases, $\delta^{18}O$ becomes more depleted, a pattern also observed in our event-based analysis, and among precipitation samples from a Chilean station at 4,100 m (Aravena et al., 1999). A weaker, less significant association was found between Altiplano surface temperature and $\delta^{18}O$ ($r = 0.34$, $P = 0.02$), which we attribute to autocorrelation between temperature and precipitation.

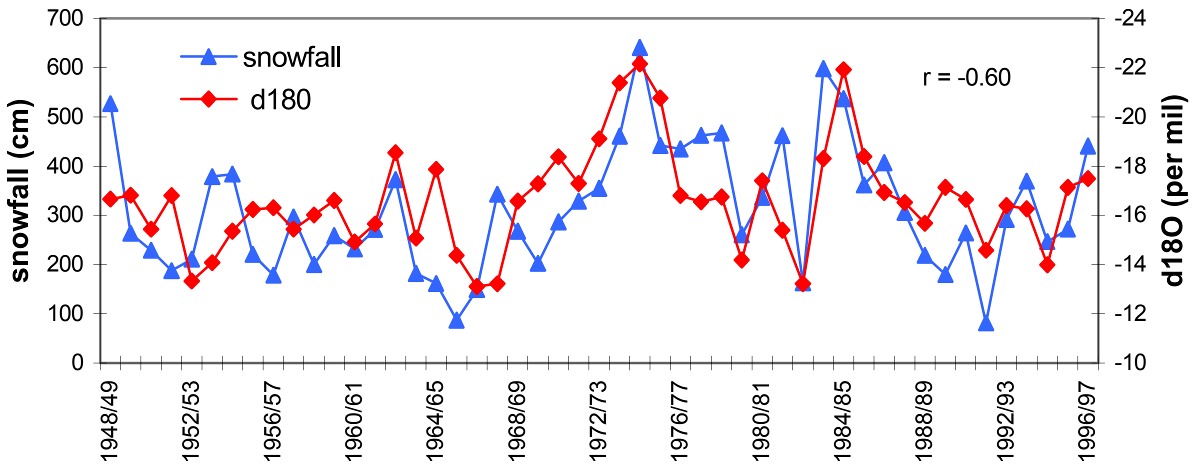

Figure 2. Reconstructed Sajama snowfall (cm) and mean annual $\delta^{18}O$, precipitation weighted ($r = -0.60$, $P < 0.001$). When a 3-year unweighted running mean is applied to the $\delta^{18}O$ series, which would reduce error associated with a slight error in chronology, the r-value increases to –0.70 ($P < 0.001$).

The relationship between snowfall and $\delta^{18}O$ established over the 49-year period provides an important new tool for assessing how precipitation may have varied on Sajama through time. Our reconstructions are based upon a time period encompassing one of the most extreme ENSO cycles this century (Niño 3.4 anomalies: 2.85 to -1.79). This calibration does not support interpreting the paleo-record simply in terms of temperature. Rather, the evidence strongly points to the isotopic record as being primarily an indicator of past changes in precipitation amount.

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