JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D22, 4693, doi:10.1029/2003JD003623, 2003

Variability of snow accumulation and isotopic composition on Nevado Sajama, Bolivia

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Received 21 March 2003; revised 15 July 2003; accepted 19 August 2003; published 19 November 2003.

[1] High-elevation ice caps develop an archive of atmospheric constituents and properties through the accumulation of snowfall. The timing of precipitation events, therefore, fundamentally governs the environmental information that ice core records can provide. These events are often highly seasonal, as are various postdepositional processes influencing the snow's physical and chemical properties. Knowledge of climatic conditions at an ice core site is essential to a full understanding of the ice core record. This work reports on 4 years of meteorological measurements near the summit of Nevado Sajama, an ice-capped peak rising ~2500 m above the South American Altiplano (elevation 6542 m), from which a 25,000-year ice core record was recovered in 1997. On-site measurements were combined with National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis results and Altiplano station data to reconstruct 50-year time series of air temperature, snowfall, and net accumulation at the summit. These time series were examined in the context of the Sajama δ^{18}O profile over the same time interval. A strong relationship exists between Sajama δ^{18}O and precipitation; both snowfall and net accumulation explain nearly half of the isotopic variance. In contrast, no significant association exists between air temperature and δ^{18}O over this time period. The Sajama ice core record represents a relatively short proportion of time centered on the months of January or February, when net accumulation takes place, and cannot be interpreted in terms of annual mean conditions. On Sajama, interannual δ^{18}O variability provides a sensitive measure of interannual precipitation variability, closely tied to ENSO and conditions in the equatorial Pacific Ocean.

INDEX TERMS: 1655 Global Change: Water cycles (1836); 1863 Hydrology: Snow and ice (1827); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 9360 Information Related to Geographic Region: South America; *KEYWORDS:* snow, accumulation, ice cores, Altiplano

Citation: Hardy, D. R., M. Vuille, and R. S. Bradley, Variability of snow accumulation and isotopic composition on Nevado Sajama, Bolivia, *J. Geophys. Res.*, *108*(D22), 4693, doi:10.1029/2003JD003623, 2003.

1. Introduction

[2] Ice cores from glaciers provide high resolution records of environmental change. Initial drilling efforts focused on the high-latitude ice sheets, but retrieval of a record from the Quelccaya ice cap at 5670 m in the Andes [*Thompson et al.*, 1985] led to recognition that high-elevation sites outside the polar regions could also yield valuable records. At least 15 such nonpolar sites have now been investigated in the 20 years following the Quelccaya drilling. Many of these sites are located within the Tropics, where most of the world's inhabitants reside, and have provided important new information regarding ENSO and sea surface temperatures [*Thompson et al.*, 1992; *Bradley et al.*, 2003], the Asian monsoon [e.g., *Hou et al.*, 2002; *Thompson et al.*, 2000], drought history [*Thompson et al.*, 1988; *Thompson et al.*, 2002], and climatic variability over many timescales.

[3] Ideally, high-elevation ice cores contain a continuous record of atmospheric and climatic conditions that are representative of a large area, as mountain ice caps typically extend high into the free atmosphere. The temporal resolution of such records is usually high (e.g., subannual) and many span long periods of time (e.g., millennia). However, the full value of any ice core record cannot be realized without a fundamental understanding of what the record represents. The extreme environmental conditions on high-elevation glaciers, combined with their difficult and dangerous access, has hindered development of this understanding. Additional studies, both observational and theoretical, are needed to improve knowledge about how high-elevation glacier ice records environmental conditions.

[4] Ice core records primarily represent precipitation events, when mass accumulates on the glacier surface. The constituents and properties of this accumulation must be interpreted in the context of precipitation frequency, magnitude and seasonality, as well as the source areas and trajectories of the air masses involved [*Vuille et al.*, 1998].

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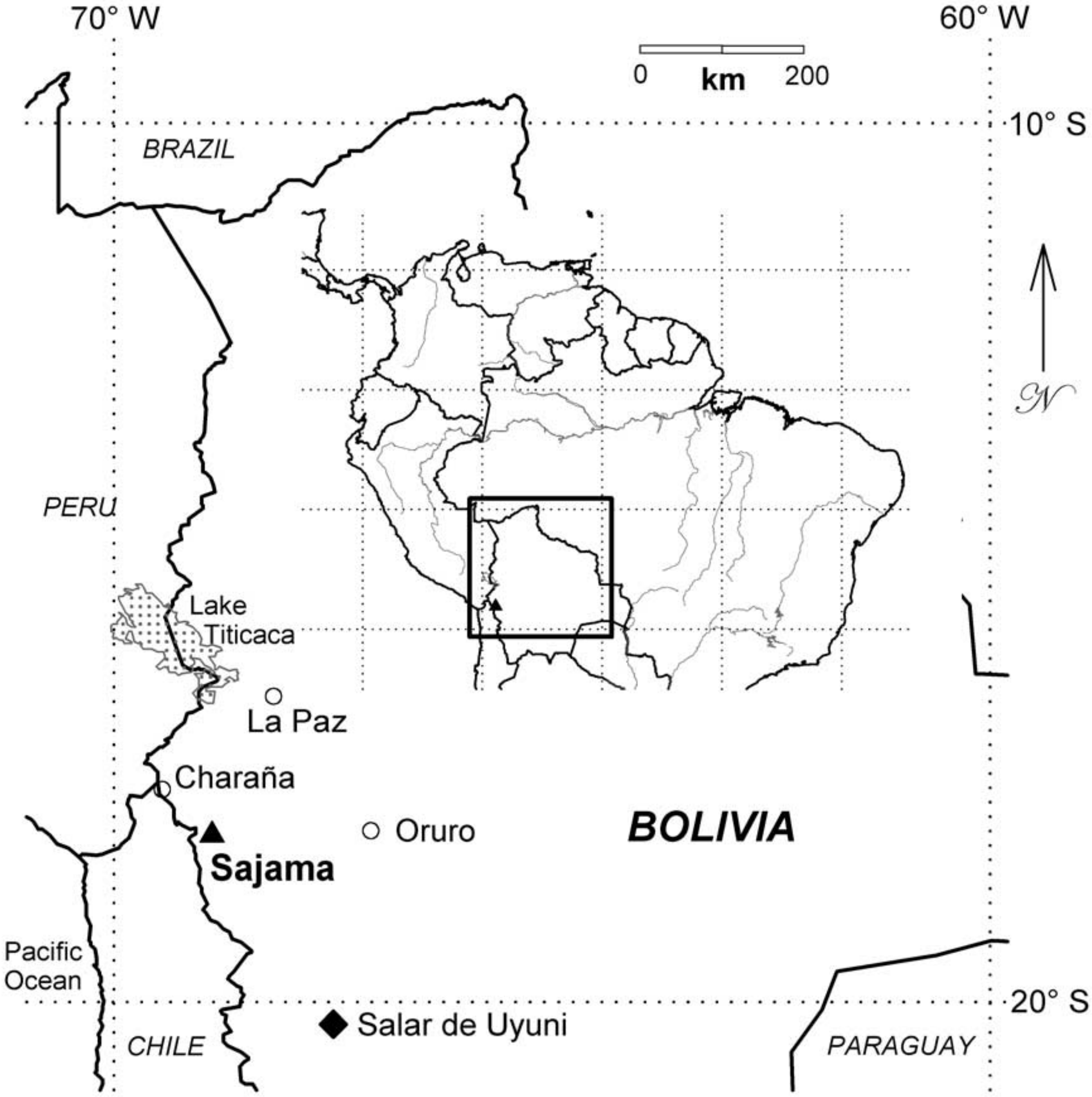

Figure 1. Location map. Sajama village is ∼12 km WSW of Nevado Sajama summit.

The relative amount of time represented in an ice core by precipitation events varies greatly among sites, depending upon geographic location and elevation, and has proven difficult to establish. For example, even at the well-studied Summit site, Greenland, the timing of snowfall events remains poorly known. Complicating the situation further, not all snowfall is preserved as accumulation on high-elevation glaciers, due to wind scour and sublimation. It is important to recognize that intervals without precipitation can also be represented in ice core records. Numerous air-snow bi-directional transfer processes have been shown to supplement and/or alter the precipitation "signal" [e.g., *Davidson et al.*, 1985, 1993; *Bales and Choi*, 1996; *Ginot et al.*, 2001]. In extreme situations, multiyear intervals may occur without net accumulation [cf. *Humphries*, 1959]; these must be recognized to prevent errors in chronology development. Together, the ensemble of various processes and their timing, leading to the acquisition and preservation of atmospheric constituents and properties on glaciers, is both complex and site specific. Nonetheless, these form the link between ambient environmental and atmospheric conditions and the paleoenvironmental record.

[5] Oxygen isotopic records constitute the primary source of paleoclimatic information from ice cores. Isotopic fluctuations are used in conjunction with other parameters to delineate annual accumulation increments, and as a direct measure of environmental conditions (see *Bradley* [1999] for a synopsis). The precise interpretation of isotopic fluctuations in low-latitude ice cores is undergoing considerable debate [e.g., *Hoffmann et al.*, 2003; *Vuille et al.*, 2003a, 2003b], for while polar and tropical ice core δ^{18}O records generally agree over centennial to millennial timescales, relationships between δ^{18}O and climate differ over shorter timescales. Very few observational studies have documented how high-elevation isotopic records relate to air temperature or snow accumulation.

[6] Here, we report on environmental conditions near the summit of Nevado Sajama, in the Cordillera Occidental of western Bolivia (Figure 1), as they pertain to snow accumulation and the oxygen isotopic record. Using 4 years of

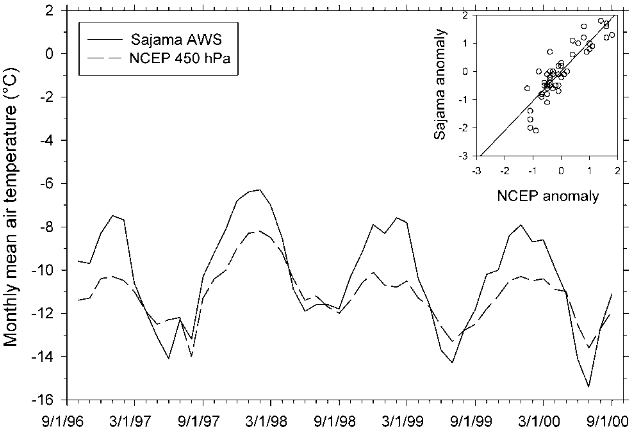

Figure 2. Monthly mean air temperature (T_a) at the Sajama AWS and from the NCEP Reanalysis at 450 hPa, October 1996 to September 2000. Inset scatterplot shows monthly anomalies for each month, described by the following equation ($r = 0.88$, $P < 0.01$ when taking autocorrelation of the time series into consideration [cf. *Weatherhead et al.*, 1998]): Sajama summit T_a anomaly (°C) = 0.002 + (1.051 * NCEP 450 hPa T_a anomaly, °C).

on-site meteorological measurements, along with surface observations and upper air data, we reconstruct 1948–1996 summit air temperature and snow accumulation time series, and compare these to the Sajama record of δ^{18}O over the same time interval. The objective is to evaluate empirically the significance of interannual δ^{18}O variability in terms of air temperature and snow accumulation.

[7] Nevado Sajama is an isolated volcano rising ~2500 m above the Altiplano (18°06′S, 68°53′W and 6542 m). We operated an automated weather station (AWS) and conducted field measurements over a 4-year period (October 1996 to October 2000), at a summit site close to where the 1997 ice core was drilled [*Thompson et al.*, 1998]. Details of the Sajama AWS instrumentation and our measurement program are described in the work of *Hardy et al.* [1998].

[8] Sections two and three describe measurements and reconstruction procedures for Sajama air temperature and net accumulation, respectively. Differences between snowfall and net accumulation are highlighted. In section 4 the δ^{18}O stratigraphy is matched with the temporal pattern of accumulation, allowing determination of a mean isotopic value for each monthly accumulation increment. Last, section five presents time series of mean annual summit temperature, accumulation, and δ^{18}O, demonstrating how the isotopic record on Sajama records climatic variability.

2. Sajama Air Temperature

2.1. Summit Measurements

[9] Air temperature at the Sajama AWS was measured every ten minutes, following one minute of mechanical ventilation of the sensor within an R. M. Young model 43408 radiation shield. Two different Vaisala model HMP35 probes, calibrated before and after each deployment, were each installed for ~2 years. Measurements were averaged and recorded hourly, allowing calculation of mean daily and monthly air temperature. The sensor height averaged ~3.25 m above the seasonally varying snow surface elevation. Mean temperature at Sajama summit over the 4 years was −10.3°C, the same temperature measured at 10 m depth in the ice cap in July 1997 during ice core drilling (V. Zagoradnov, personal communication, 1997); englacial temperatures at this depth are often used as a proxy for mean annual temperature [*Paterson*, 1969]. The mean daily temperature range on Sajama is 7.7°C. Figure 2 illustrates monthly mean values of air temperature.

2.2. Reconstructed Temperature, 1948–1996

[10] Summit temperature measurements correspond closely with Reanalysis data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; see *Kalnay et al.* [1996]). Free-air temperature values were extracted for each month from the 400 and 500 hPa levels for the grid cell where Sajama is located (centered at 17.5°S, 70.0°W). The 450 hPa average provided temperature values very close to the mean pressure level of the Sajama AWS (461 hPa). Comparing monthly mean temperatures (Figure 2) reveals that annual fluctuations are damped in the NCEP/NCAR data. Over 4 years, the greatest seasonal bias appears during the austral summer (DJF) when the Reanalysis temperatures average 2.3°C lower. Overall, NCEP/NCAR air temperatures represent those at Sajama summit well (Figure 2). Indeed, the relationship is stronger than that between Sajama summit and Altiplano surface station temperature (not shown). Accordingly, NCEP/NCAR Reanalysis 450 hPa temperature anomalies were used to reconstruct summit temperature anomalies, for each month 1948–1996, according to the equation shown in Figure 2. Although inhomogeneities within the NCEP/NCAR time series are known to exist, on an interannual timescale these data provide a better proxy for summit air temperature than surface station data. Relationships between the air temperature series and Sajama's isotopic record are discussed in section 5.

3. Sajama Snowfall and Net Accumulation

3.1. Summit Measurements

[11] Owing to the well-known difficulty of measuring solid precipitation, at the summit we chose to measure changes in snow surface height and then used the difference between one measurement and the next as a proxy for accumulation (mass gain) or ablation (mass loss). Two sonic-ranging sensors were attached on either side of the AWS, separated by 2 m horizontally. At their nominal installation height on Sajama, the target areas were 1 m in diameter. Distance measurements were made hourly, and corrected for variations in air-path temperature. Under such circumstances, the manufacturer's stated measurement accuracy is ±0.01 m.

[12] We produced a composite surface-height record by filtering and graphically inspecting the measured temperature-corrected heights to delete spurious values, as are sometimes recorded during periods of blowing snow (Figure 3). Although wind speeds frequently exceeded 20 m s^{-1}, on average 90% of values from individual sensors were reasonable. Our two-sensor system increased the overall reliability rate to 98% of the time that sensors were not buried. Measurements were referenced to a datum

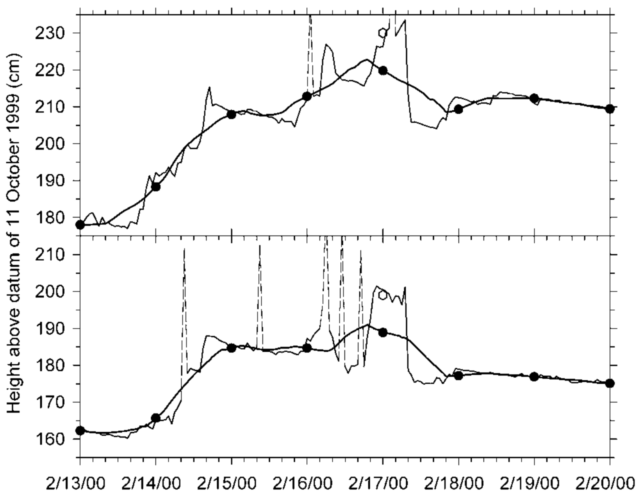

Figure 3. Sajama distance-to-snow-surface measurement processing. Hourly measurements from two sensors are shown both as acceptable (thin lines) and spurious values (dashed lines); a 25-hour smooth is indicated by the heavier line. Filled circles are midnight values along the smoothed curve, and used to derive the daily changes in snow surface height. One open symbol, on each raw value curve shown, demonstrates an occasion when the midnight snow height was manually adjusted (required for 5.1% of values). Most of the height record was less noisy than the example shown here.

established at the time of each site visit when sensors were raised. A 25-hour running mean was then applied (Figure 3) to remove residual diurnal cycles imparted by the influence of the variable air temperature structure above the snow on sound propagation. Daily snow surface heights were determined as averages from the two smoothed records (Figure 3), after adjusting for changes of the datum (Figure 4).

[13] The height compilation shown in Figure 4 contains three gaps, together representing 28.7% of the more than 35,000 hours over which the Sajama station operated. Except for the latter portion of the third gap, when the sensors ceased functioning, these gaps represent times when the sensor to snow surface distance was within the minimum distance specification, or the sensor was completely buried. In general, snow accumulation on Sajama was greater than anticipated, as three of the four wet seasons coincided with La Niña conditions in the tropical Pacific (anomaly as low as -1.79°C for Niño 3.4 region; 5°N–5°S, 120°–170°W). Consistent with previous findings for the Altiplano [*Vuille et al.*, 2000; *Garreaud and Aceituno*, 2001], La Niña conditions led to anomalously high accumulation that eventually resulted in temporary burial of the depth sensors on Sajama. Our station design was based upon a mean net snow accumulation of less than 2 m a^{-1}, determined from a short reconnaissance core taken by L. G. Thompson (personal communication, 1995). In contrast, seasonal snow accumulation exceeded ~3.25 m during three of the 4 years of measurements.

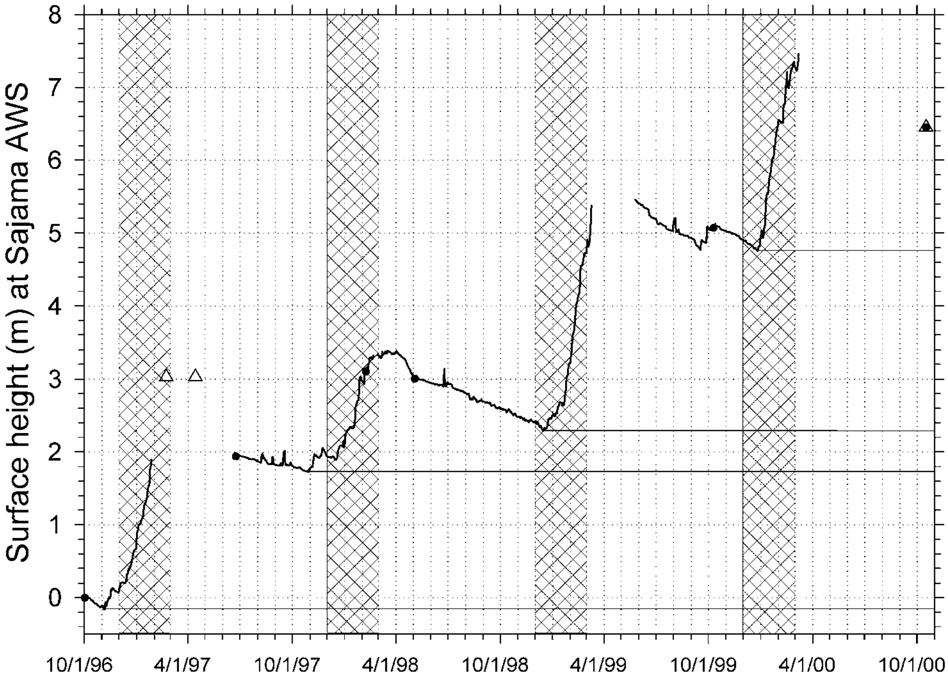

Figure 4. Snow surface height record at Sajama AWS, relative to height datum of October 1996. Solid line illustrates average daily height. Three triangle symbols (22 Feb and 14 April 1997; 17 October 2000) represent indirect determinations of surface height (i.e., burial and emergence of upper wind sensor, and manual measurement of distance to snow, respectively). On-site observations at the AWS are indicated by closed circle symbols. Cross-hatched pattern highlights the December–February wet season each year. Horizontal lines to the right-hand axis indicate annual net accumulation for each year through the measurement period.

[14] The Sajama snow-surface height profile (Figure 4) forms a continuous record of mass exchange at the snow surface. Atmospheric and snowpack processes associated with the addition and loss of mass produce the net accumulation stratigraphy that is sampled during recovery of an ice core. A full understanding of ice core records, therefore, requires knowledge of the timing and nature of all relevant accumulation and ablation processes. Clearly, such a height profile results from interaction at the site between a variety of accumulation and ablation processes, some of which are more apparent than others in the figure. For example, increases in surface height at a site can be caused by snowfall (i.e., precipitation) and/or by wind redistribution (i.e., drifting) of either contemporaneous or older snow. Decreases in height, on the other hand, can be caused by at least four processes: redistribution caused by wind (scour), diagenesis (settling), melting, and sublimation. Figure 4 illustrates a distinct seasonality of accumulation and ablation processes, with minor variability in timing from year to year. Estimating net accumulation requires consideration of how each process varies seasonally, as discussed below.

[15] The most important process on Sajama each year is an interval of precipitation, typically centered on January or February, when the highest accumulation rate can be described by a linear trend ranging between 129 and 181 cm month^{-1}. This is the primary accumulation period on the mountain [*Hardy et al.*, 1998; *Vuille et al.*, 1998], coinciding with the Altiplano wet season [*Garreaud et al.*, 2003]. In most years (Figure 4) an interval of lesser accumulation was observed during November or December. Few days of surface lowering were observed during the wet season months of January and February. Although wet season precipitation on Sajama overwhelms all ablation processes combined, studies elsewhere [*Francou et al.*, 1995, 2003] have shown that ablation is also greatest during this period of year. Occasional subsurface melting at 6500 m on Sajama may cause some alteration to the chemical and physical profiles, but little mass is lost from the snowpack as the temperature remains subfreezing and generally high vapor pressure limits sublimation.

[16] As the accumulation season on Sajama ends, seasonal changes in meteorological conditions promote the surface-lowering processes of scour and sublimation. Climate seasonality is marked on Sajama, and seasonal gradients are especially pronounced during autumn. Air temperature, for example, changes most dramatically during April and May, with monthly means decreasing by ~1.7°C per month. Humidity also decreases sharply during April and May. At the location of Sajama (18°S), while top-of-the-atmosphere solar radiation receipts are decreasing rapidly during April as the sun moves into the Northern Hemisphere, incoming radiation on the ice cap is increasing, as the cloudy wet season comes to a close. Last, the seasonal transition to autumn is marked by a sharp increase in wind speed, with a doubling of monthly mean values. Wind speeds were especially high during May and June of 1997, with the highest monthly mean speeds of the observation period during that June (10.2 m s^{-1}). These changes in meteorological conditions all promote both scour and sublimation of the fresh, wet-season snowpack, coincident with a decreased rate of settling as the snowpack ages, and decreased melting as temperature and vapor pressure both decrease. This interpretation is consistent with observations elsewhere at high elevations in the Andes [e.g., *Wagnon et al.*, 1999; *Ginot et al.*, 2001], but not well-documented by the Sajama record due to snow sensor burial (Figure 4).

[17] Ablation processes dominate throughout a prolonged austral winter dry season, expressed as an interval each year when the rate of surface lowering averages ~10 cm month^{-1}. Sajama observations (Figure 4) show this period generally beginning in May or June and continuing through October or November, and net snow-surface lowering occurs on 17 to 25 days each month. Scour likely becomes less effective due to aging of the wet season accumulation, allowing sublimation to dominate the lowering processes. The Sajama snow-height record (Figure 4) illustrates the result of lowering during autumn and winter due to scour and sublimation: snow that fell late in the accumulation season is typically not retained, and thus will not be represented in an ice core record.

[18] Daily snowfall on Sajama was determined from the snow-surface height record, after accounting for observed height increases likely caused by redistribution of snow (drifting). Without human observations, the magnitude of drifting must be determined indirectly, inferred on the basis of the height record and other meteorological variables. Numerous scatterplots of daily height change, plotted against different measures of wind speed, solar radiation and temperature, were inspected to distinguish between intervals of snowfall and those when drifting was likely. Outliers relative to other days were assumed to be the result of drifting snow, and values were adjusted downward accordingly. To reduce subjectivity, we chose to adjust only those days when more than one additional variable suggested drifting; height increases were therefore partially or wholly attributed to drifting on only 19 of 415 days (4.6%). After these adjustments, daily increases were summed for each month, yielding proxy totals of monthly snowfall for the 33 months with complete height records. These snowfall totals (vs. net accumulation values) were then used to reconstruct past snowfall, as discussed below.

3.2. Reconstructed Snowfall, 1948–1996

[19] Altiplano station data provide a context for summit precipitation measurements. Two Altiplano stations were chosen for comparison with monthly Sajama snowfall sums, due to their proximity to the mountain and the integrity of their records. Oruro is located ~180 km east of Sajama at an elevation of 3702 m, and Charaña is at 4057 m, ~80 km to the northwest (Figure 1). Backward stepwise linear regression demonstrates that the two stations together account for 78% of the variance in the monthly snowfall on Sajama (adjusted as noted above). The resulting equation (see Figure 5) was used to reconstruct monthly snowfall at the summit for the period 1948 to 1996. The inset plot on Figure 5 demonstrates good agreement between reconstructed summit snowfall and precipitation measured at the base of Sajama (period of record = 1975 to 1985).

3.3. Reconstructed Accumulation Stratigraphy, 1948–1996

[20] Two accumulation stratigraphies were developed to investigate relationships with the isotopic profile. The first

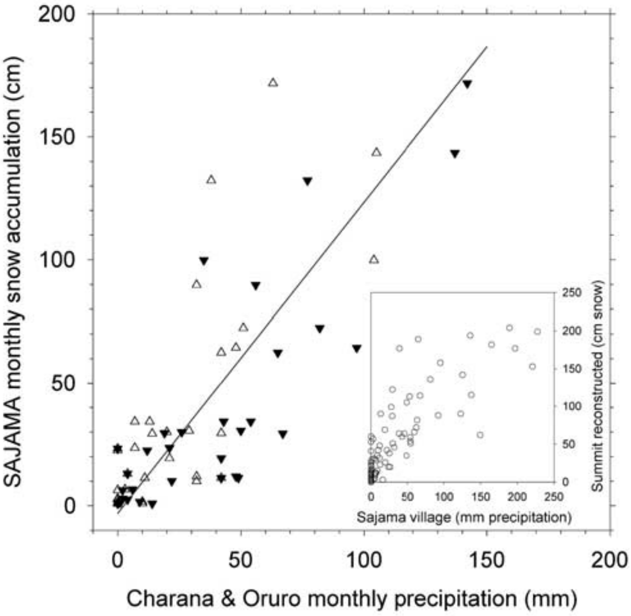

Figure 5. Sajama monthly snow accumulation (cm) plotted with monthly precipitation (P) in mm, at Oruro (solid triangles) and Charaña (open triangles), October 1996 to February 2000 (n = 33 months). The linear relationship (r = 0.88) is described by: Sajama snowfall, cm = −3.020 + (0.571 * Charaña P, mm) + (0.693 * Oruro P, mm). Inset plot shows reconstructed Sajama snowfall (cm) and precipitation at Sajama village (mm), September 1975 to August 1985 (r = 0.84; n = 118).

method was simply to sum the monthly reconstructed snowfalls (the "no prior knowledge" scenario) and henceforth referred to as the raw reconstructed accumulation stratigraphy or RRAS. However, as already discussed, the reality of net accumulation as observed on Sajama is more complex (Figure 4); snowfall is sometimes augmented by drifting, some snowfall is lost to scour, and other seasonally varying processes result in further ablation. Accordingly, we reconstructed a second accumulation stratigraphy to reflect these observed processes, by subjecting all monthly reconstructed snowfall totals (1948–1996) to three adjustments, as described below. Figure 6 illustrates the effect of each adjustment on mean monthly reconstructed snowfall.

[21] 1. Reconstructed snowfall each month was increased by a uniform 7% to account for supplemental accumulation due to drifting (Figure 6). No significant seasonality in the relative importance of drifting was recognized among the events identified in the data. Of 33 months with complete height records, a threshold of 3 cm month^{-1} snowfall was set to exclude computational errors, which reduced the number of months to 25. Among these, drift was recognized as discussed above in 10 of the months, and ranged between 2 and 34% of snowfall (median is 16%); the average of all months with at least 3 cm of snowfall was 7%.

[22] 2. Reductions to the reconstructed totals above (snowfall with drifting) were made to account for scour (Figure 6). Scour events clearly identifiable in the snow-surface height record exhibited a distinct seasonality, consistent with the seasonality in climate discussed above. As with drifting, identification required agreement between multiple meteorological variables, and probably underestimates the total extent of scour. The monthly scour reduction was determined by plotting the average scour each month as a percentage of the total snow-surface height increase. Scour was least during January (2%), while June and July (when snowfall events are rare) showed the greatest scour. To provide an estimate of scour during the austral autumn, when Sajama observations are limited (Figure 4), a fourth-order regression was fit to data from the other 10 months (r value = 0.97). Note that the net effect of this adjustment, in conjunction with that for drifting, was relatively minor (Figure 6).

[23] 3. Reconstructed snowfall values were then uniformly reduced each month by 10 cm to account for ablation evident in Figure 4. Monthly sums of measured surface lowering not clearly attributable to scour averaged 12.5 cm, with the smallest sums ($\sim$9 cm) during the wet season months (i.e., December–February), consistent lowering during the dry season of $\sim$13 cm month^{-1}, and lowering greater than 20 cm during autumn months. Limited precise measurements of daily surface lowering during March–April–May (Figure 4) suggested using 10 cm to represent conservatively the monthly reduction in accumulation (Figure 6), rather than a seasonally varying amount. Note that this reduction is equivalent to the rate of net surface lowering during the extended dry season, and is relatively consistent from year to year (Figure 4). Subjecting the monthly reconstructed snowfall values to the three adjustments above resulted in the second, alternative accumulation stratigraphy. For months without snowfall, or in which the amount after adjustments 1 and 2 was less than 10 cm, the above procedure resulted in a net decrease. Accordingly, that decrease was deducted from accumulation of the previous month(s) (e.g., March in Figure 6), yielding a net accumulation stratigraphy (NAS).

[24] A final step in the development of the two accumulation stratigraphies (i.e., RRAS and NAS) was to recalculate each monthly increment of accumulation as a percentage of the annual total. Figure 7 demonstrates the importance of

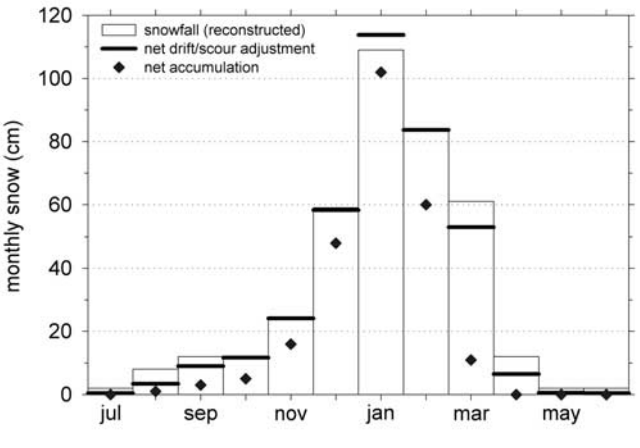

Figure 6. Climatology (1948–1996) of reconstructed monthly snowfall at Sajama summit (bars), shown with net adjustment for drifting and scour (dark lines). Symbols indicate average net accumulation each month after the three adjustments detailed in text.

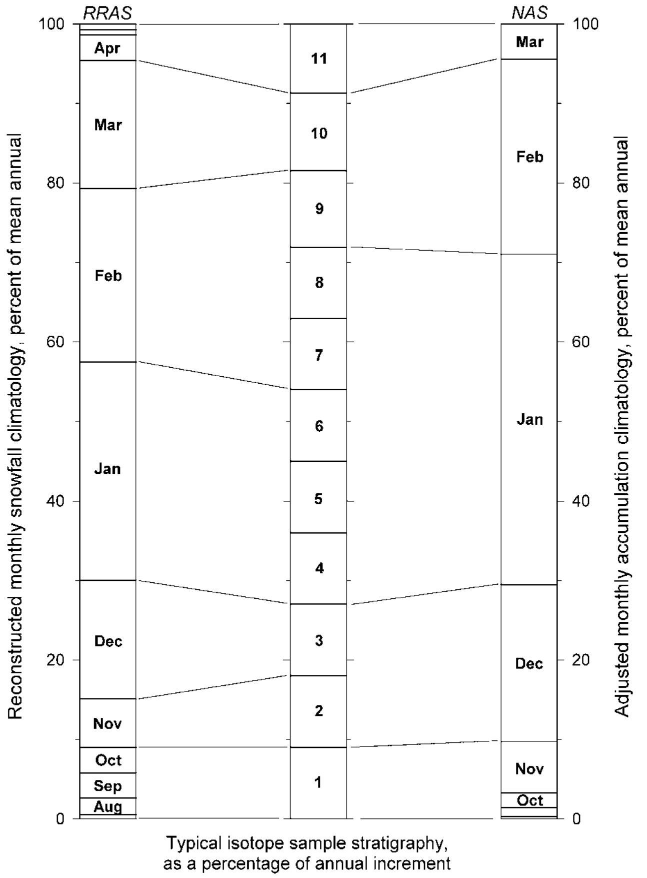

Figure 7. Accumulation and isotopic stratigraphies. At center is a typical profile of δ^{18}O samples through an annual layer, expressed as a percentage of annual layer depth. (Mean number of samples is 11, following Figure 8 stratigraphy.) Left-hand column labeled RRAS represents a raw reconstructed accumulation stratigraphy, while the right-hand column (labeled NAS) illustrates a net accumulation stratigraphy; both expressed as percentages of reconstructed accumulation using 1948–1996 climatologies, July–June. Tie lines, between isotope profile and the two stratigraphies, illustrate how each isotope sample was apportioned to a particular month, based upon its representation in the annual stratigraphy.

on-site observations, in the interpretation of isotopic profiles. Without any information regarding the seasonality of accumulation, the 11 isotope samples shown would each represent about one month of time (0.091 year), and thus be incorrect. The RRAS (left column, Figure 7) allows assignment of isotope samples to particular months based upon the seasonality of precipitation, while the NAS illustrates that each sample (ice core increment) represents even less time.

4. Isotopic Stratigraphy, 1948–1996

[25] We used a δ^{18}O stratigraphy from the upper 33.5 m of Sajama core 2 to compare with the meteorological data. The isotopic profile is shown as a function of depth in Figure 8, with two different annual layer delineations. The left-hand timescale is a slightly altered version of *Thompson et al.* [1998], which was dated by a tritium concentration peak at 25.2 m (1966 dry season) and curve matching with isotopic profiles from Quelccaya [*Thompson et al.*, 1985] and Huascarán [*Thompson et al.*, 1995]. We developed an adjustment to this chronology (Figure 8, right-hand side) based on equating the annual dry season with δ^{18}O minima, and placing the tritium peak in 1964 (as done by *Knüsel et al.* [2003] for an ice core from nearby Illimani). Each annual layer is represented by 4 to 27 δ^{18}O samples (mean = 11). Based upon the right-hand chronology shown in Figure 8, each sample (isotopic value) in the stratigraphy was then expressed as a percentage of the annual layer thickness (Figure 7, center column).

5. Annual Time Series, 1948–1996: Summit Temperature, Accumulation, and δ^{18}O

[26] Production of annual time series required first merging the isotopic stratigraphy with the two different accumulation scenarios (RRAS and NAS). With monthly accumulation increments expressed as percentages of the annual total (Figure 7), we developed a monthly resolution chronology for the isotope profile. Each monthly increment of accumulation between July 1948 and June 1996 was attributed to one or more isotope samples, as shown by the tie lines in Figure 7. Each month represented in the

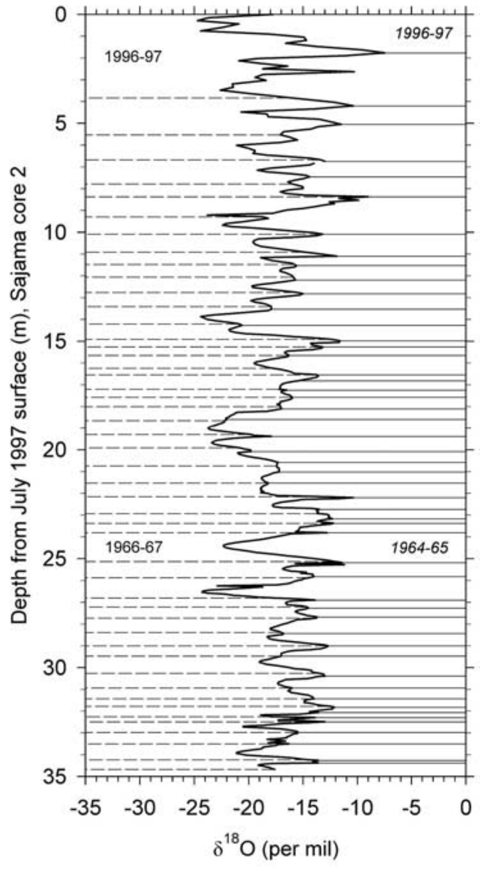

Figure 8. The Sajama core 2 δ^{18}O profile to 34.67 m depth. The annual stratigraphy is shown as slightly modified from *Thompson et al.* [1998] (left-hand side) and for the present analysis (right-hand side).

Table 1. Statistics Calculated for Two Methods of Reconstructing Accumulation, Temperature, and $\delta^{18}O$ at the Summit of Sajama, 1948/1949 through 1996/1997[a]

	RRAS			ARAS		
	Accumulation	Summit T	$\delta^{18}O$	Accumulation	Summit T	$\delta^{18}O$
Mean	387	−9.0	−16.7	245	−8.6	−16.6
Standard Deviation	116	0.6	2.1	109	0.6	2.1
Maximum	688	−7.7	−12.9	488	−7.3	−12.8
Minimum	159	−10.9	−22.3	45	−10.6	−22.3

[a] Monthly temperature and isotopic values used to compute annual averages are weighted by the accumulation that month.

accumulation stratigraphies was thus associated with a mean isotopic value.

[27] Annual values of reconstructed accumulation were obtained by summing the monthly values each year, while those for summit temperature and $\delta^{18}O$ were calculated as means, weighted by the amount of precipitation (RRAS) or accumulation (NAS) each month. Table 1 summarizes these values.

6. Discussion: Significance of Interannual Isotopic Variability

[28] Over the past ~50 years, the interannual variability of $\delta^{18}O$ at the summit of Sajama is clearly associated with reconstructed accumulation and hence with regional precipitation variability ($r = -0.618$). Taking autocorrelation of the time series into consideration [cf. *Weatherhead et al.*, 1998], this correlation is significant at the 0.01 (99%) level; other stated p-values in this section also account for autocorrelation. Annual $\delta^{18}O$ values become increasingly depleted in the ice core as annual snowfall increases (Figure 9). When a 3-year unweighted running mean is applied to the $\delta^{18}O$ and precipitation series (NAS), which would reduce any error in chronology, the correlation increases to −0.71. Comparable results using our simpler scenario (RRAS), in which reconstructed snowfall forms the accumulation stratigraphy without any adjustments, demonstrates that this finding is robust: the same pattern emerges (not shown), with a slightly weaker association ($r = -0.59$, $P < 0.01$). With a 3-year unweighted running mean, unadjusted accumulation (RRAS) accounts for only 3% less of the Sajama $\delta^{18}O$ variance than the filtered NAS series, over the past ~50 years. This finding, with little difference between the two accumulation scenarios, demonstrates that the relationship between precipitation and isotopic variability is robust.

[29] Summit air temperature is not significantly associated with isotopic variability in the Sajama ice core over the past ~50 years ($r = 0.06$, $P = 0.84$; Figure 9). A 3-year unweighted mean degrades the relationship further and changes its sign ($r = -0.04$). However, a weak association was found ($r = 0.30$, $P = 0.26$) with an unsmoothed, composite Altiplano temperature series (stations: El Alto and Oruro). We discount the importance of this association, because precipitation and temperature on the Altiplano are correlated on an interannual timescale. That is, temperature cannot account for any additional variance in the accumulation-isotope relationship (r value between these residuals and Altiplano temperature = 0.11, $P = 0.67$). Any association between air temperature and isotopic variability, on a local scale, is not evident.

[30] Field measurements at ice core drill sites are critically important to understand how climate is recorded by glacier ice. There are a small number of appropriate ice core sites at high elevations in the tropics, rendering on-site measurements even more critical to the development of the best possible understanding of each record. Accumulation and ablation processes each operate at seasonally varying rates, and each has a different influence on net accumulation, as well as on the snowpack's physical and chemical properties. Our Sajama calibration, based on 4 years of measurements, does not support interpreting the paleorecord simply in terms of temperature. Rather, the evidence strongly points to the isotopic record as being primarily an indicator of past changes in local precipitation amount, likely governed by larger-scale controls on regional precipitation [*Vuille*, 1999; *Bradley et al.*, 2003; *Hoffmann et al.*, 2003; *Vuille et al.*, 2003b]. In support of this conclusion is a strong, inverse relationship between the entire Sajama isotopic record (25,000 years) and a record of natural γ-radiation from a drill hole at nearby Salar de Uyuni [*Baker et al.*, 2001]. At Salar de Uyuni (Figure 1), high values of natural γ-radiation are associated with lacustrine mud deposited during periods of abundant effective moisture in the region [*Baker et al.*, 2001].

[31] Summit measurements on Sajama reveal a strong seasonality in both precipitation and the degree to which snowfall is preserved. Snowfall typically begins to accu-

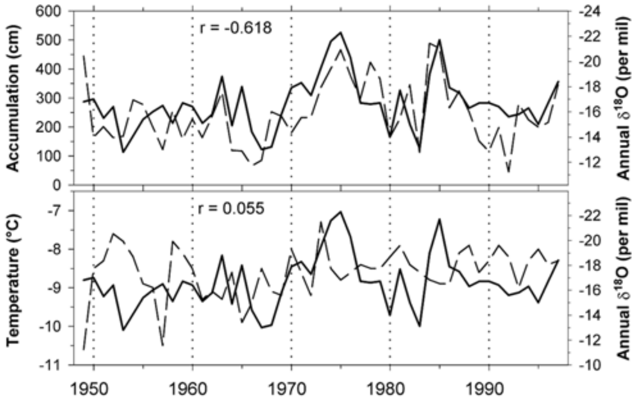

Figure 9. Time series of annual $\delta^{18}O$ (thick lines) and two variables of Sajama summit climate. Annual $\delta^{18}O$ determined from monthly mean values (see text), weighted by net monthly accumulation. Thin dashed line in upper plot is annual net accumulation (i.e., NAS, see text); lower plot thin dashed line is annual mean reconstructed summit temperature (net monthly accumulation weighted).

mulate each year during November or December, and continues accumulating into March. During the long dry season that follows, wind scour and evaporation prevent preservation of winter snowfall events, and effectively remove late-summer accumulation. The proportion of wet-season accumulation remaining at the end of each dry season varies from year to year, but in general, approximately one-third of all snowfall on Sajama does not contribute to net accumulation (Table 1). Interannual differences in accumulation can be large. For example, net accumulation averaged only ~28% of the annual snowfall during the 1991–1992 El Niño. During extreme El Niño events, it is conceivable that wet season accumulation would be lost entirely, and thus any record of the event (e.g., see 1997–1998 in Figure 4). Conversely, the La Niña event of 1974–1975 resulted in both enhanced snowfall (140 and 178% of normal, for 1973/1974 and 1974/1975, respectively), and greater retention of accumulation (164 and 190% of normal, for 1973/1974 and 1974/1975, respectively).

[32] The distribution of snow accumulation through the year must be considered in the interpretation of the isotopic record, particularly if the objective is to look at the seasonality of isotopic variability. The ice core record does not represent all months or seasons of the year equally, but rather, only a relatively short portion of time when net accumulation takes place. This finding calls into question, at least where accumulation is strongly seasonal, approaches which partition annual accumulation equally into monthly or quasi-monthly increments and then matches these with isotopic profiles [cf. *Henderson et al.*, 1999]. Seasonal biases in net accumulation on Sajama, and perhaps on other tropical ice caps, preclude calibrating or interpreting such ice core records in terms of annual mean conditions.

[33] The relationship between snowfall and δ^{18}O established over the ~50-year period at Sajama provides an important new tool for assessing how precipitation may have varied through time. The Altiplano is a region of strong interannual climate variability closely tied to ENSO [*Vuille*, 1999], and 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). The sensitivity of Sajama accumulation to ENSO, and the link our results reveal between snowfall and δ^{18}O, demonstrate that the Sajama δ^{18}O record provides an important proxy for SSTs in the central and eastern equatorial Pacific Ocean.

[34] **Acknowledgments.** This work was funded in part by grant NA66GP0404 from the National Oceanic and Atmospheric Administration, to the University of Massachusetts. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies. N. Graham, G. Seltzer, and an anonymous reviewer are thanked for their helpful comments, which improved the clarity and accuracy of this paper. We thank Carlos Escobar and the staff of Nuevos Horizontes, as well as Carsten Braun, for field assistance.

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