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El Niño-Southern Oscillation (ENSO) influence on a Sajama volcano glacier (Bolivia) from 1963 to 1998 as seen from Landsat data and aerial photography

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Abstract. Sajama volcano, located in the Bolivian Altiplano, is the southernmost tropical glacier and, owing to its situation, approximately 100 km east of the Pacific coast, is well suited to study the El Niño-Southern Oscillation phenomenon. Landsat data from 1972 to 1998 and a 1963 aerial photograph are used to monitor the snow line fluctuations on a selected part of Sajama volcano. We assume that a few months after the rainy season, the snow line is representative of the previous rainy season, if no recent snowfall has occurred. By observing precipitation from the stations surrounding Sajama volcano and by verifying snow presence on surrounding summits, we detect images with recent snowfall likely to disturb the climatic significance of the snow line. A snow line evolution model takes into account the different image acquisition dates and adjusts the snow line elevation accordingly for the middle of the dry season. A progressive rise of the snow line elevation is observed from 1963 to 1998 with a sustained rise from 1984 to 1990. The snow line altitude is related to the Southern Oscillation Index. Even after the high precipitation of the 1996-1997 wet season, the following El Niño 1997-1998 leads to a substantial rise of the snow line. The snow line elevation is related primarily to the total rainy season precipitation and to a lesser degree to the maximum monthly mean temperature of the warmest month, thus confirming a greater snow line sensitivity to precipitation than to temperature.

1. Introduction

In Andean countries such as Bolivia, Peru, and Ecuador, glaciers are major natural reservoirs regulating freshwater flow during the year and providing water during the dry season. In a semiarid region (350 mm/yr) such as that encompassing the Sajama National Park (18°06′S, 68°50′W) (Figure 1), glaciers represent the major source of water for agriculture. At a continental scale, glacial meltwater from the Cordillera Real in Bolivia and the Cordillera Blanca in Peru contributes to river runoff in the Amazon basin.

Tropical glaciers are very sensitive to climatic changes and their response is relatively rapid. Since the 1980s, the central Andean glaciers have been retreating at an accelerated rate [*Kaser et al.*, 1990; *Francou and Ribstein*, 1995; *Klein et al*, 1999]. This tendency, which has been observed on a planetary scale, is more intense in the tropical regions than in temperate ones [*Allison and Peterson*, 1989; *Hastenrath and Kruss*, 1992a, 1992b; *Brecher and Thompson*, 1993]. Mass balances of African tropical glaciers [*Charnley*, 1959] and Andean glaciers [*Jordan*, 1991, 1998; *Kaser et al.*, 1990] have been studied, but the causes of their fluctuations are not yet well understood General circulation models suggest that tropical mountains may be particularly sensitive to greenhouse gas-induced warming [*Mitchell et al*, 1990; *Oerlemans and Fortuin*, 1992; *Oerlemans*, 1994]. *Hastenrath and Kruss* [1992a, 1992b] suggested that greenhouse forcing caused ice recession on Mount Kenya, and *Diaz and Graham* [1996] noticed that sea surface temperatures are linked with freezing level heights in the tropics.

The large-scale El Niño-Southern Oscillation (ENSO) influence on interannual climatic variability over the South American continent has been analyzed in a variety of studies [e.g., *Ropelewski and Halpert*, 1987, 1996; *Rogers*, 1988; *Aceituno*, 1988, 1989; *Kiladis and Diaz*, 1989]. Previous studies in the central Andes focused on present and late Pleistocene snow lines [*Fox*, 1993; *Klein*, 1997, *Klein et al*, 1999] or on the regional snowfall patterns in the high arid Andes [*Vuille and Ammann*, 1997]. The interannual variability of precipitation in Bolivia may be linked to tropical sea surface temperature anomalies and related atmospheric teleconnections [*Ronchail*, 1995; *Vuille*, 1999].

The response of the equilibrium line altitude (ELA) to climatic fluctuations has been studied in the Andes [*Kaser et al*, 1996, *Kuhn*, 1980], modeled in the Alps [*Kuhn*, 1989], and determined as well by using remote sensing to measure the

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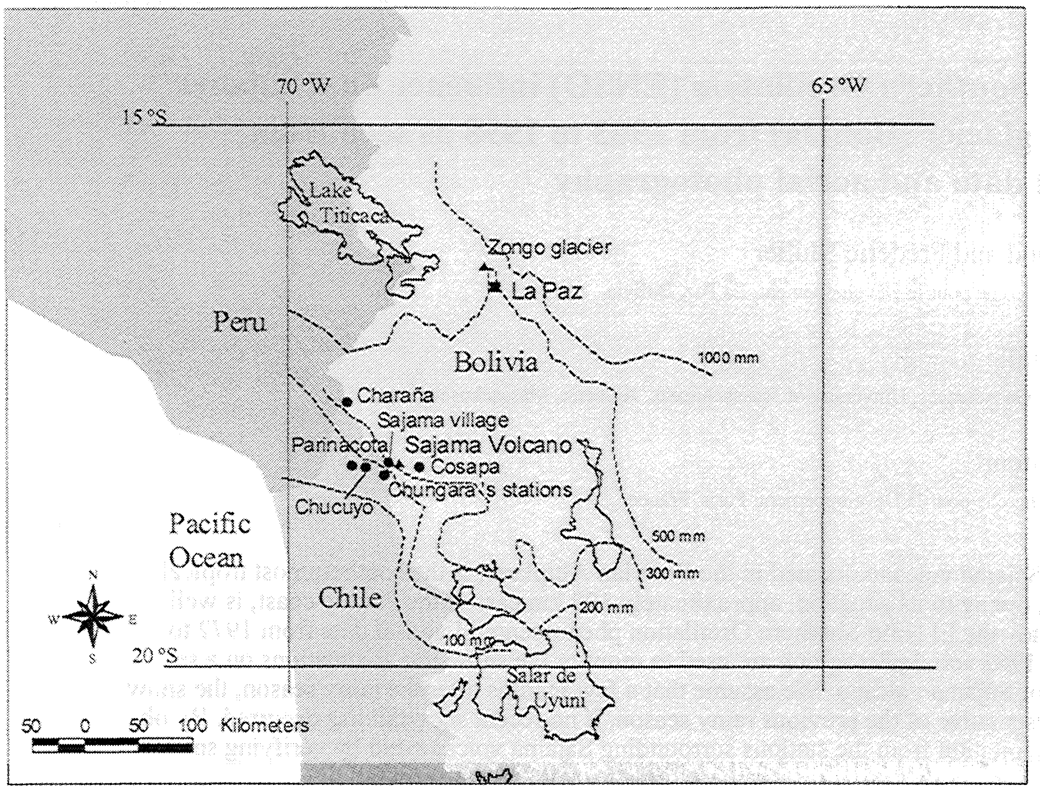

Figure 1. Map showing the location of Sajama volcano, the meteorological station network, and mean annual precipitation across the region (dashed lines).

snow line altitude in the Swiss Alps [*Haefner*, 1990]. *Hastenrath* [1993] has shown that remote sensing is a useful tool to study small tropical glaciers. In the case of Sajama, however, the extent of the glacier is difficult to delineate by using visible and near-infrared remote sensing data because snow cover may or may not extend to altitudes below permanent ice cover. The same problem of separating snow on soil and snow on glacier has been observed on the Tibetan plateau [*Li et al.*, 1998] Moreover, the available satellite data resolution is not sufficient to measure year to year glacier tongue variations. Because of these limitations and owing to the interannual variability of the snow cover extent, the snow line is used as a climatic indicator instead of the glacier tongue. In this paper, the term "snow line" refers to the boundary between bare soil and snow cover or sometimes between bare soil and bare ice.

Recently, an ice core was recovered from the summit of Sajama, yielding a climate record for the last 25,000 years [*Thompson et al*, 1998]. This core is an important paleoclimatic proxy source for this region and assists in establishing links between modern glacial systems and climate. The study of the relationship between glacier extent, snow line elevation, and contemporaneous climate is the first step in understanding their interactions and predicting their future evolution. Such a study on the response of the snow line to short-term climate fluctuations has been lacking so far in the Andes. The objective of the present paper is to link the fluctuations of the snow line altitude to meteorological variables and ENSO influence on a selected part of Sajama volcano.

In the following sections we present the climatic environment, the remote sensing methodology, and the analysis of meteorological data from the summit of Sajama volcano and surrounding stations. Finally, we discuss the results of our study and conclude with a short summary.

2. Climatic Environment

Sajama volcano, located in the Occidental Cordillera (18°06′S, 68°50′W, 6542 m above sea level (asl)), is the highest point of Bolivia and is capped by the southernmost glacier of the intertropical zone (Figures 1 and 2). The climate in this area is semiarid, with an annual precipitation of about 350 mm and more than 80% of the annual precipitation falling between December and March. This summer precipitation is the result of heating of the Altiplano surface by strong solar radiation, inducing convection and moist air advection from the eastern interior of the continent (Amazon and La Plata basins) [*Vuille et al*, 1998; *Garreaud*, 1999]. The role of large-scale atmospheric circulation mechanisms associated with summertime precipitation variability over South America has been examined by *Lenters and Cook* [1999]. Located 100 km to the east of the Peruvian Pacific Ocean coast, on the Altiplano plateau, Sajama is well suited to study the climatic impact of ENSO.

Ronchail [1998] has shown that dry periods over the Altiplano are generally but not always related to El Niño situations Nonetheless, mass balance and runoff studies from Zongo glacier (Figure 1) show a strong dependency on ENSO [*Francou et al*, 1995; *Ribstein et al.*, 1995]. *Thompson et al.* [1984] reported an ENSO signal in the stratigraphy of the tropical Quelccaya ice cap in Peru, and *Henderson et al.* [1999] attributed geochemical variability in an ice core record from Nevado Huascarán in Peru to ENSO. Recently, *Vuille*

[1999] established a linkage between climatic variability in the Nevado Sajama region and ENSO, demonstrating how atmospheric circulation anomalies associated with negative (positive) values of the Southern Oscillation Index (SOI, difference in sea level pressure between Tahiti and Darwin in standardized values) lead to a decrease (increase) in the recorded precipitation during El Niño (La Niña) periods This relationship is more pronounced during the wet season (December-March.). This is related to increased westerly (easterly) flow during El Niño (La Niña) periods, which inhibits (enhances) moisture advection toward Sajama summit. Another interesting feature, important for glacier mass balance and snow line estimates related to ENSO, is the fact that air temperatures are significantly higher (lower) during El Niño (La Niña) periods over the entire Altiplano [*Vuille*, 1999]

In this region, the maximum ablation and accumulation on the glaciers occur during the rainy season (from October through March), whereas for midlatitude glaciers ablation and accumulation seasons are distinct [i.e., *Ribstein et al.*, 1995; *Wagnon et al*, 1999]. Climatic factors such as temperature, precipitation, and solar short-wave radiation determine the altitude of the snow line and thus the glacier extent. As presented by *Wagnon et al.* [1999], net all-wave radiation is the main source of energy at the glacier surface, among that solar radiation is the largest positive term. An important peculiarity of tropical glaciers is that the contribution of the latent heat flux to the energy balance is very high and that this energy flux shows a pronounced seasonality, with strong sublimation rates during the dry season and low ones during the humid season, because of a reduced vertical humidity gradient. This variability of the sublimation and the continuously positive sensible heat flux throughout the year explain the mass balance fluctuations of tropical glaciers like those of Sajama. Contributing to glacier retreat during ENSO events is the lack of precipitation, which reduces the glacier surface albedo and increases the energy available for ablation [*Wagnon et al*, 2001]

3. Methodology

3.1. Meteorological Data

In order to be aware of images where the snow line altitude might be affected by recent snowfall and to compare the regional meteorological parameters with the snow line elevation, monthly precipitation and temperature data in the surroundings of Sajama volcano were used. The nearest available operational Bolivian station with substantial precipitation and temperature records (from 1945 to the present) is Charaña situated 80 km to the northwest of Sajama volcano. In addition, we used the Sajama village meteorological station at the base of the volcano, four Chilean meteorological stations situated in a radius of less than 50 km toward the west (Chungará Ajata, Chungará's dam, Chucuyo, Parinacota), and one Bolivian station situated 30 km toward the southeast (Cosapa).

Seven stations (Table 1 and location in Figure 1) were used to estimate the monthly precipitation for the Sajama volcano region from 1963 to 1998. Depending on the date, between

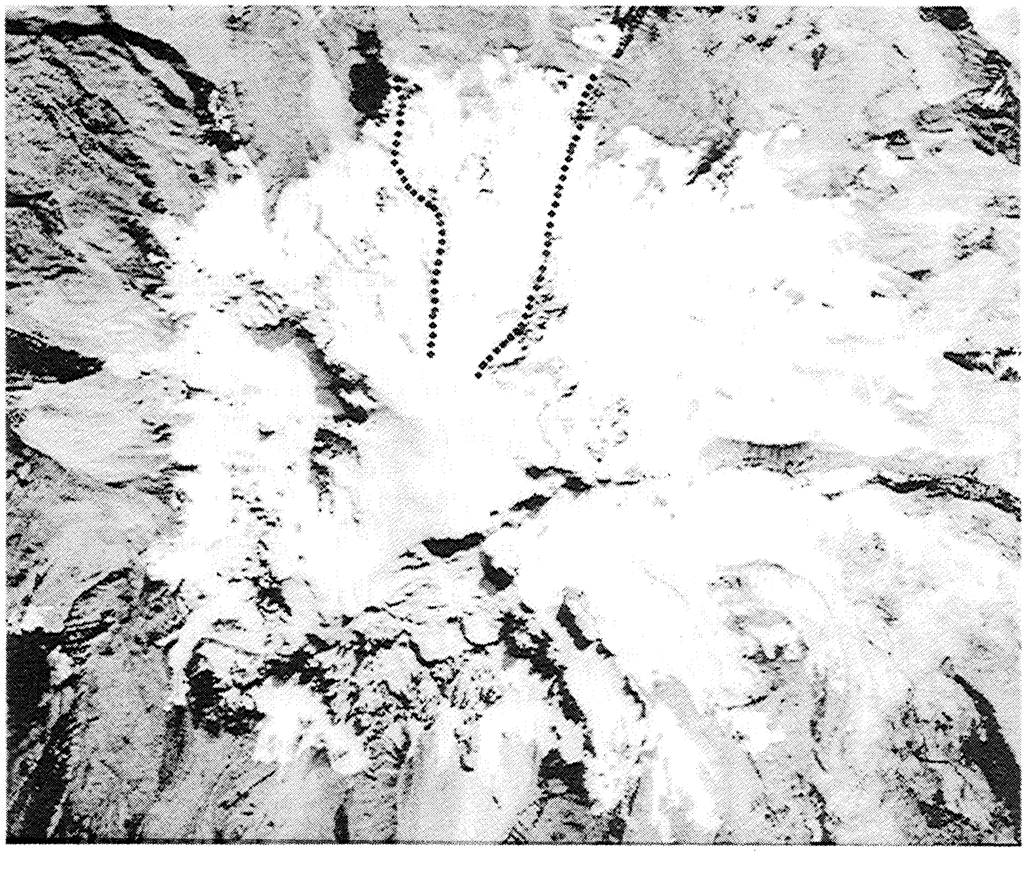

Figure 2. Aerial photograph (approximate scale 1:45,000) of Sajama volcano (June 6, 1963) with study area (toward north) indicated by solid dots.

Table 1. Names of the Meteorological Stations With Their Respective Latitude, Longitude, and Altitude

Meteorological Station	Latitude, Longitude	Altitude, m
Sajama village	18°08′S, 68°59′W	4220
Charaña	17°35′S, 69°27′W	4057
Chungará Ajata	18°14′S, 69°07′W	4570
Chungará's dam	18°13′S, 69°07′W	4570
Chucuyo	18°13′S, 69°20′W	4200
Parinacota	18°12′S, 69°16′W	4390
Cosapa	18°10′S, 68°43′W	3685

one and four stations were available per month to calculate an average monthly precipitation amount (Table 2).

In order to assess whether the precipitation at the surrounding weather stations is representative of the snowfall on the Sajama volcano, we compared the average monthly precipitation with an estimation of the monthly snowfall amounts from the summit based on accumulation (including wind-redistributed snow), as recorded by an automatic weather station installed at 6500 m in 1996 [*Hardy et al*, 1998; *Vuille et al.*, 1998]. Despite the limited data availability ($n = 6$), snowfall estimation at Sajama summit and average precipitation from surrounding stations are highly correlated ($r = 0.94$, significant at the 99% level), thereby corroborating existing evidence on spatial coherence of precipitation in the Sajama area and confirming previous assumptions that the use of station precipitation as a proxy for Sajama snowfall is legitimate [*Vuille*, 1999].

The only complete temperature record in the region is Charaña station The longest, but incomplete, temperature record closer to Sajama volcano, Chungará Ajata, was used as a reference to assess the temperature for the Sajama region. The correlation ($r = 0.86$) between Chungará Ajata and Charaña temperatures from 1989 to 1998 (Figure 3) lead us to conclude that the temperature at Charaña is representative of Chungará's, with coherence between the two stations sufficient for our study requirements. The Chungará station gives a good representation of the temperature variability in the Sajama region and captures temperature variations in the snow ablation zone of the volcano. We calculated Chungará temperatures based on Charaña's by using a linear regression function,

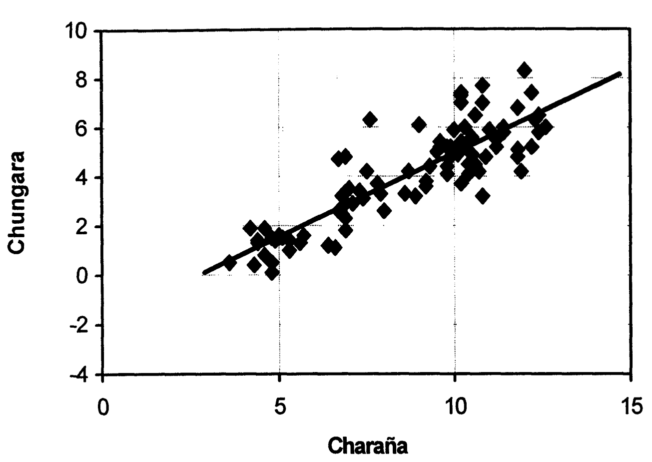

Figure 3. Chungará Ajata versus Charaña mean monthly temperatures (degrees Celsius) from 1989 to 1998. Correlation coefficient $r = 0.86$, significant at the 99.9% level.

$$T\,(\text{Chungará}) = 0.68 * T\,(\text{Charaña}) - 1.9°\text{C}, \tag{1}$$

and used the calculated Chungará temperature for the remainder of the study.

In addition, we calculated the mean monthly temperature at the snow line elevation during the month of image acquisition by using a lapse rate of 0.7°C/100 m, based on La Paz 1991 and 1992 radiosonde data (location in Figure 1). As shown in Table 3, all calculated temperatures are below 0°C.

To ensure that no fresh snowfall would affect our results, we considered all images suspect where monthly precipitation

Table 2. Monthly Precipitation (Millimeters) From March to the Date of Image Acquisition

	Number of Available Stations	March	April	May	June	July	Aug.	Sept.	Oct.
June 6, 1963	1	118.5	25.5[a]	9[a]	0[a]				
Oct 31, 1972[b]	1	124 1	6	0	0	0	0[a]	2[a]	10.4[a]
July 8, 1984	3	103.7	0.1	0[a]	0[a]	0[a]			
Oct 2, 1986	3	87.7	18.1	0	0	0.9	11.1[a]	0[a]	0[a]
May 30, 1987	3	28 3[a]	0.8[a]	2 9[a]					
Sept 3, 1987	3	28.3	0.8	2.9	3.2	19.4[a]	0[a]	1[a]	
June 12, 1989	4	64 5	22 2[a]	0[a]	3.9[a]				
June 25, 1990[b]	4	31 7	7 7[a]	7.4[a]	28 2[a]				
May 17, 1994	4	16.8[a]	14 8[a]	0.6[a]					
Oct 24, 1994	4	16.8	14.8	0.6	0	0	0[a]	1.7[a]	0.1[a]
April 18, 1995[b]	3	74.2[a]	12.8[a]						
June 7, 1996	2	46.1	4.2[a]	0[a]	0[a]				
June 10, 1997	2	41 3	4[a]	1[a]	0[a]				
May 28, 1998	2	3 5[a]	0[a]	0[a]					

[a] Precipitation data taken into account in the image selection process

[b] Images potentially affected by recent snowfalls.

Table 3. Satellite-Derived Snow Line Altitude, Corrected Snow Line Altitude to August 15, Standard Deviation of the Corrected Snow Line, and Estimated Temperature at Time of Image Acquisition at the Snow Line Elevation for Each Date of Acquisition[a]

	MSS Snow Line Altitude	Aerial Photo Snow Line Altitude	MeanTM Snow Line Altitude	Mean Corrected Snow Line Altitude to August 15	Corrected Snow Line Standard Deviation	Estimated Temperature at the Snow Line Elevation
June 6, 1963		5113		5253	39	-2 3
Oct. 31, 1972[b]	5390			5240	40	-1.0
July 8, 1984	5232		5268	5342	71	-3.0
Oct 2, 1986	5464		5460	5366	104	-0 8
May 30, 1987	5497		5570	5720	73	-3 8
Sept 3, 1987	5596			5560	76	-3 8
June 12, 1989			5527	5653	96	-5 0
June 25, 1990[b]			5928	6028	117	-8 4
May 17, 1994			5592	5768	110	-4 2
Oct 24, 1994			5853	5713	89	-3 7
April 18, 1995[b]			5515	5749	76	-2 1
June 7, 1996			5612	5748	81	-6 4
June 10, 1997			5449	5577	106	-5 3
May 28, 1998			5967	6121	119	-7 8

[a] Mean and standard deviation were calculated by using altitude values under the snow line mask

[b] Images potentially affected by recent snowfalls

during the 3 months preceding the image acquisition exceeded the estimated potential ablation (i.e., all dates where fresh snow might still be present in the image, see section 3.4). Potential ablation was calculated by using an application of the Penman model in the Altiplano [*Chaffaut,* 1998]. This model takes into account humidity, wind speed, solar radiation, temperature, pressure, and surface albedo. We used climatic data from the Sajama automated weather station published by *Hardy et al* [1998] and estimated ablation values at the summit (considering only sublimation because subfreezing temperatures prevent major melting) to be between 17 mm (water equivalent) in March and 52 mm in September (Table 4). This is in broad agreement with the 69-cm surface lowering recorded at the summit between July and September 1997 [*Hardy et al.,* 1998], although snow settling and wind scour may have contributed significantly to this lowering. *Wagnon et al* [1999] reported monthly mean dry season sublimation rates from Zongo glacier (21.8 mm in 1997 (April-October) and 18.3 mm in 1998 (April-September)), which are in very close agreement with our minimum estimate. Based on those results and to be on the safe side, we chose to use a conservative estimate of only 20 mm (mean monthly ablation in water equivalent), corresponding to the lowest calculated ablation value between April and October (see section 3.4).

Table 4. Results of the Penman Model to Estimate Monthly Sublimation on Sajama Summit (Millimeter Water Equivalent)

Month and Year	Sublimation
Oct. 1996	36
Nov 1996	18
Dec 1996	18
Jan 1997	19
Feb 1997	19
March 1997	17
April 1997	20
May 1997	35
June 1997	45
July 1997	48
Aug. 1997	52
Sept. 1997	52

3.2. Remote Sensing Data Processing

Satellite and airborne data from 1963 to 1998 were used in this study: Landsat multispectral scanner (MSS) with a resolution of 79 m x 79 m, thematic mapper (TM) with a resolution of 30 m x 30 m and aerial photography from 1963 (Table 3). A digital elevation model (DEM) was generated from contour lines digitized from a 1:50,000 map sheet with a 20-m contour interval. The DEM has a grid spacing of 30 m and an error estimated at ±50 m in both the horizontal and vertical dimensions.

Owing to very low temperatures on Sajama, the presence of bare ice is rare, as it is frequently snow covered. This prevents detection of the ablation area in the lower part, which is rather unusual for a classic glacier tongue.

Although the differentiation between snow, ice, and rocks is relatively easy using the TM channels 5 (1.55-1.75 μm), 4 (0.76-0.9 μm), and 2 (0.52-0.60 μm) [*Alonso and Moreno,* 1996], the differentiation between snow on ice and snow on soil is impossible. Unless snow cover is very thin so that the albedo of the underlying surface contributes to the signal received at the sensor, there is no physical reason that snow on a glacier should appear different from snow on soil. Owing to these limitations, it was not possible to determine the exact glacier extents on Sajama using remote sensing techniques.

Since visible and near-infrared remote sensing data are particularly well suited to snow line monitoring in clear-sky conditions (which is generally the case in the dry season), the snow line was considered instead and superimposed on a DEM to obtain the altitude of the snow line

Each TM image was first radiometrically calibrated using the formula from *Markham and Barker* [1986]:

$$R = a * DC - b - h, \tag{2}$$

where R is the satellite reflectance, DC is the satellite digital count, a and b are the gain and offset, respectively, taken from the ancillary information files on the Landsat image, and h is the haze calculated using the modified blackbody method of *Chavez* [1988].

Coregistration of all images and the DEM was necessary in order to compare the snow line altitudes. A third-order transformation model using the DEM and the geographical map as a reference was used to geometrically correct each image. The horizontal root-mean-square (RMS) error was approximately 50 m for TM images, 120 m for MSS images, and 30 m for the aerial photography. These errors are similar to the ones found in the study of *Li et al.* [1998], measuring glacier variations in the Tibetan plateau using Landsat data. Finally, each image was corrected with the solar zenith angle using the following formula.

$$R^* = R * \mathrm{Cos}\,(\theta), \tag{3}$$

where R^* is the corrected reflectance, R is the satellite reflectance, and θ is the angle between the solar beam and the normal to the surface.

Owing to the extremely rough topography in some parts of the Sajama volcano and the varying aspect, both of which influence the snow line altitude, we chose to work on a specific region of the volcano, rather than considering the snow line for the entire volcano. The selected study zone is on a gentler slope between two ridges and is located in the north-facing slope of the Sajama volcano, receiving higher Sun illumination in winter (Figure 2). Owing to the spatial variations in snow line altitude as a function of aspect, the inferred absolute snow line altitude is only representative of the north-facing slope. The snow line was drawn manually on three-channel color composites (TM 5, 4, 2 and MSS 2, 3, 4), using the two ridges to delineate the study zone. The snow line altitudes were obtained by superimposing the snow line masks on the DEM, and the mean and standard deviation were calculated by taking into account the DEM values under the snow line mask. Table 3 shows, based on the images of July 8, 1984, October 2, 1986, and May 30, 1987, that the snow line elevation for MSS and TM are comparable. The error in the determination of the snow line altitude is difficult to estimate It depends on the image coregistration error in relation to the horizontal and vertical DEM resolution, but it also depends on the local terrain slope. On a flat terrain, a horizontal error would not have any impact on the altitude determination, and on a 45° slope, a horizontal error would have the same magnitude of error on the altitude. The resulting estimated vertical errors, however, are still in agreement with the precision required for this work.

3.3. Snow Line Altitude and Its Climatic Significance

Our analysis is based on the hypothesis that for a given dry season (from April through September), the Sajama snow line altitude is dependent on the preceding rainy season (from October through March), specifically, precipitation and temperature. In addition, we assume that the snow line altitude is independent of the previous rainy seasons climatic parameters, an assumption we will prove below Each rainy season initializes the snow line altitude, but during the dry season, the snow line altitude is not stable with respect to its position at the end of the rainy season, and this needs to be taken into account Even if ablation due to melting is nonexistent owing to cold temperatures in the dry season, sublimation is still present and even higher than in the rainy season owing to predominantly clear sky conditions and the presence of a high vertical humidity gradient [*Wagnon et al*, 1999]. Consequently, the snow line rises progressively during the dry season, and this rise needs to be quantified. Using two sets of images, (May 30, 1987, September 3, 1987) and (May 17, 1994; October 24, 1994), we analyzed the magnitude of the snow line rising between the beginning and the end of the dry season to model the snow line evolution. For the two sets of images the determined rise is 0.5 m/d (1987) and 2 m/d (1994). The low rate (0.5 m/d) obtained in 1987 is due to a wet period in July 1987 (19.4 mm of precipitation averaged over surrounding stations), which lowered the snow line altitude. The second set of images is much more representative because in 1994 almost no precipitation occurred during the dry season (see Table 2). Nonetheless, since there is considerable uncertainty about the correct average daily snow line rise, we conducted several tests with varying assumptions (between 0.5 and 3 m/d) for this snow line rise to test its sensitivity.

By referencing the images to the middle of the dry season (August 15) and by taking into account a daily snow line rise of 2 m/d, we found the largest adjustments for the following dates (+234 m for the image of April 18, 1995; +176 m for May 17, 1994; +154 m for May 28, 1998; and −150 m for October 31, 1972) We feel that this rate of snow line rise is appropriate for the study of other years as well because in the dry season, ablation is due mainly to sublimation processes which are sufficiently similar from year to year to allow for the comparison of data for the months of May to October. At such elevations and latitudes, the extremely high near-surface humidity and temperature gradient result in very high vapor pressure gradients, which drive sublimation. In winter, temperatures are mostly below freezing at the snow line altitude (see Table 3) and have a moderate effect on the sublimation processes if we consider that, during the winter, the temperature gradient is quite stable from year to year. Applying a linear correction might seem inappropriate, since one would expect a much faster rise in the beginning (at low elevation) than toward the end of the dry season, when the snow line is high Nevertheless, the maximum snow line altitude correction of +234 m corresponds to a variation of temperature of 1 5°C, which is not sufficient to induce considerable variations in the sublimation rates. In addition, section 4 (Figure 4) shows that changes in snow line elevation due to this correction do not modify the overall conclusions of this study, and they are small in comparison with the observed interannual variability of the snow line elevation.

The snow line can drop substantially if there are significant winter snowfall episodes [*Vuille and Ammann*, 1997] during the months prior to the image acquisition. This was taken into consideration when selecting the images as discussed in the following section.

Following the above considerations, we felt it was more suitable to work with the snow line as a representative pa-

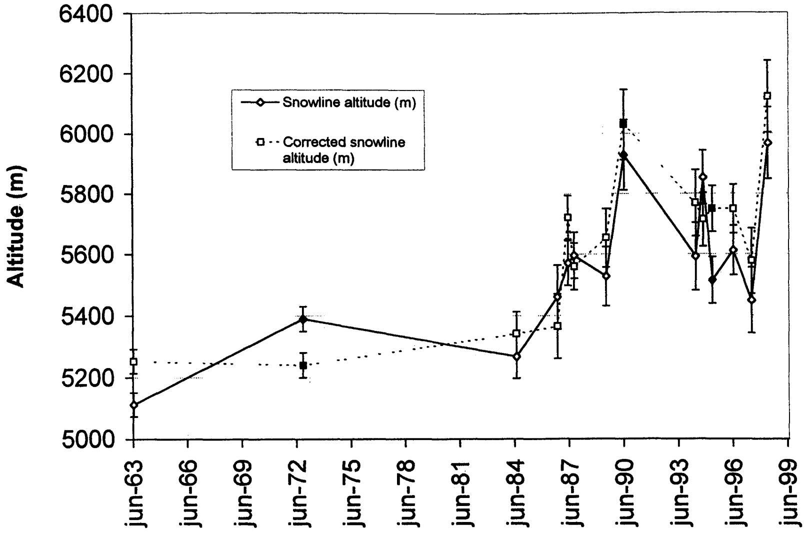

Figure 4. Corrected and uncorrected snow line altitude evolution with error bars (indicating 1 standard deviation) from 1963 to 1998. Solid symbols correspond to questionable dates.

rameter of the rainy season instead of using the glacier front, which integrates several years or decades and furthermore is difficult to detect under the snow cover.

3.4. Selection of Images

To examine whether fresh snow was still present in an image, we relied on the following assumptions: an image was considered suspect if monthly precipitation during the 3 months preceding the image acquisition exceeded the calculated monthly potential ablation. Table 2 shows monthly precipitation from March to the date of image acquisition. The snow line may be temporarily lowered by snowfall occurring during the dry season just prior to image acquisition. In this case the snow line would most likely not be related to summer precipitation. This problem is especially evident if the time period between the last snowfall and the image acquisition is not long enough for the snowfall to be sublimated. Snowfall occurring during the rainy season itself, however, is considered to be the determining factor of the snow line elevation a few months later. We chose a conservative estimate of the mean monthly ablation of 20 mm (water equivalent) per month corresponding to the lowest calculated ablation value between April and October (Table 4). Taking into account the monthly precipitation calculated in the Sajama region and the previous mean monthly ablation, we were able to select and flag the appropriate images.

Another way to perform this selection is to observe the snow cover on the surrounding lower summits. If snow can be detected on these lower summits, recent snowfall most likely influenced the snow line elevation analysis on Sajama volcano. Clearly in such a case, the snow line would be higher if no recent snowfall had occurred. Nonetheless, the determined snow line elevation was not completely rejected but considered as a lower limit. Using these methods, three images (April 18, 1995; June 25, 1990; and October 31, 1972) were detected as being potentially influenced by a dry season snowfall and therefore needed to be interpreted with caution (see Table 2).

4. Results

The remotely sensed snow line altitudes are in agreement with the ones found by *Graf* [1981, 1991], precisely, 5300 m in 1981 and 5800 m in 1991. As shown in Figure 4, there is a general rising trend in the snow line over the three decades analyzed, with an accelerated rate during the 1980s similar to the accelerated recession of various tropical glaciers [*Francou et al*, 2000]. The snow line rises constantly from 1984 to 1990 and returns to values comparable to the late 1980s during the mid-1990s. The snow line elevation reaches its maximum in 1998 after a progressive drop during the mid-1990s. The corrected snow line altitude values (Figure 4) show a clearer tendency toward a higher snow line in the 1980s than the raw snow line altitudes. However, given the limited number of images analyzed, further studies are warranted to reach valid conclusions on the observed trend. In order to verify the influence of ENSO on Sajama volcano snow line altitudes, these were compared with the mean Southern Oscillation Index from October through March (data obtained from http://www.cpc.ncep.noaa.gov/data/indices). Because of the limited number of events ($n = 14$) and the fact that the last event considered (May 28, 1998) is an outlier, a simple ordinary least squares (OLS) regression approach may not be the best estimate of the dependency of the snow line elevation on the SOI, rainy season precipitation, or mean maximum summer temperature. Trend estimates based on OLS regression are heavily influenced by outliers, especially if these occur at the beginning or the end of a series. We therefore chose to complement our analysis with an additional more robust approach, based on a least absolute residuals (LAR) regression estimate [i.e., *Li*, 1985]. Both trend lines as well as the 95% confidence interval for the slope β are shown in the scatterplots of Figures 5-7, indicating the relationship between corrected snow line altitude and the independent parameters SOI (Figure 5), rainy season precipitation (Figure 6), and mean maximum summer temperature (Figure 7). The basic statistics (correlation coefficient r and slope β) are given in Table 5 (including all available dates) and Table 6 (three flagged dates

Table 5. Correlation Coefficients (r) and Slope (β) for Snow Line Altitude (Including All Available Dates) as a Function of Southern Oscillation Index (SOI), Total Rainy Season Precipitation (P), and Maximum Mean Monthly Temperature (T)[a]

	Altitude-SOI	Altitude-P	Altitude-T
		r	
0 5 m/d	-0 64[b]	-0 80[c]	0 66[c]
1 m/d	-0 64[b]	-0 84[c]	0 66[c]
2 m/d	-0 62[b]	-0 88[c]	0.63[b]
3 m/d	-0 57[b]	-0 88[c]	0 58[b]
		β	
OLS			
0 5 m/d	-164 9 m/unit[b]	-1 49 m/mm[c]	227.4 m/°C[c]
1 m/d	-168 8 m/unit[b]	-1 60 m/mm[c]	231 8 m/°C[c]
2 m/d	-176 4 m/unit[b]	-1 83 m/mm[c]	240 8 m/°C[b]
3 m/d	-184 1 m/unit[b]	-2 06 m/mm[c]	249 7 m/°C[b]
LAR			
0 5 m/d	-90 7 m/unit[b]	-1 22 m/mm[c]	249 1 m/°C[b]
1 m/d	-105 4 m/unit[b]	-1 42 m/mm[c]	277 4 m/°C[b]
2 m/d	-163 6 m/unit[b]	-1 66 m/mm[c]	299 2 m/°C[b]
3 m/d	-300 7 m/unit[b]	-1 85 m/mm[c]	301.4 m/°C[b]

[a] Analysis is performed for corrected snow line assuming a daily snow line rise of 0 5, 1, 2, and 3 m Regression analysis are based on both an Ordinary Least Squares (OLS) and a more robust Least Absolute Residual (LAR) approach

[b] At the 95% confidence level

[c] At the 99% confidence level

excluded). While only the relationship for an assumed 2-m/d snow line rise is shown in Figures 5-7, we have listed the corresponding values for an assumed rise of 0.5, 1, 2, and 3 m/d in Tables 5 and 6 for comparison. Clearly, it matters little whether a very conservative estimate such as 0.5 m/d or a very high estimate such as 3 m/d is applied. The emerging results are very similar and always significant (tested for both r and slope β) at least at the 95% level when including all available dates (Table 5). In addition, the numbers in Table 5 indicate that our results are very robust; despite outliers such as 1998, the correlation is always significant at least at the 95% level and the slope β is always significantly different from 0, even if a robust regression (LAR) method is applied. The numbers in Table 6 indicate slightly less significant results for the relationship with the SOI and temperature (if a high daily snow line rise is assumed). The position of the flagged data points in Figures 5-7, however, is not outside the general trend, which suggests that our image selection criterion may have been too severe and that the flagged images were not necessarily influenced by recent precipitation.

Figure 5 shows that there is a negative relationship between SOI and the snow line altitude on Sajama volcano. In general, high snow line altitudes correspond with negative SOI (El Niño events) and low snow line altitudes correspond to positive or near-zero SOI (La Niña events). The significant snow line drop of 1997 is due to increased snowfall occurring in the rainy season of 1996-1997 (weak La Niña event, SOI = 0.33), whereas the El Niño event in 1997-1998 (SOI = -2.35) led to the most significant rise of the snow line during the period analyzed. The fact that this snow line rise occurred only a year after a very wet season such as 1996-1997 shows that the previous year is of little relevance and thus confirms our hypothesis of the year to year independence of the snow line and its importance as an annual climatic indicator. This observed relationship is most likely due to the combined effect of increased (reduced) precipitation and lower (higher) temperatures on the Altiplano during positive (negative) SO phases.

The observed snow line is significantly correlated with the composite of the rainy season precipitation at the seven nearby stations (Figure 6) and with monthly maximum temperature calculated at Chungará during the warmest month of the rainy season, October through March (Figure 7). Generally, in the tropics, the rainy season is also the season with higher temperatures and therefore of primary importance for concurrent accumulation and ablation processes occurring at the same time [e.g., *Francou et al.*, 1995]. This is a fundamental difference between tropical and temperate glaciers and snow cover. The snow line variability is more closely related to the precipitation amount than to temperature, yet both parameters are significantly correlated with snow line altitude at the 95% level (Table 5). This result is in agreement with conclusions reached by *Kuhn* [1980], who reasoned that in the dry regions of the tropics, snow line is controlled primarily by precipitation. The rather moderate influence of temperature can be partially explained by the fact that temperatures at the snow line altitude are always negative (see Table 3); thus little melting occurs and temperature has only a minor impact on sublimation and consequently on ablation processes.

Table 6. Correlation Coefficients (r) and Slope (β) for Snow Line Altitude (Including Only Nonquestionable Dates) as a Function of Southern Oscillation Index (SOI), Total Rainy Season Precipitation (P), and Maximum Mean Monthly Temperature (T)[a]

	Altitude-SOI	Altitude-P	Altitude-T
		r	
0 5 m/d	-0 65[b]	-0 79[c]	0.67[b]
1 m/d	-0 64[b]	-0 82[c]	0 66[b]
2 m/d	-0 59	-0 83[c]	0.63[b]
3 m/d	-0 53	-0.81[c]	0.56
		β	
OLS			
0 5 m/d	-149 9 m/unit[b]	-1 70 m/mm[c]	205.4 m/°C[b]
1 m/d	-147.6 m/unit[b]	-1 75 m/mm[c]	203.3 m/°C[b]
2 m/d	-143 1 m/unit	-1.86 m/mm[c]	199.0 m/°C[b]
3 m/d	-138 5 m/unit	-1 97 m/mm[c]	194.7 m/°C
LAR			
0 5 m/d	-118 5 m/unit	-1 19 m/mm[c]	208 7 m/°C[b]
1 m/d	-107 6 m/unit	-1 54 m/mm[c]	195.1 m/°C[b]
2 m/d	-93 7 m/unit	-1.65 m/mm[c]	122 0 m/°C
3 m/d	-100.3 m/unit	-1 49 m/mm[c]	137.8 m/°C

[a] Analysis is performed for corrected snow line assuming a daily snow line rise of 0.5, 1, 2, and 3 m. Regression analysis are based on both an Ordinary Least Squares (OLS) and a more robust Least Absolute Residual (LAR) approach

[b] At the 95% confidence level

[c] At the 99% confidence level

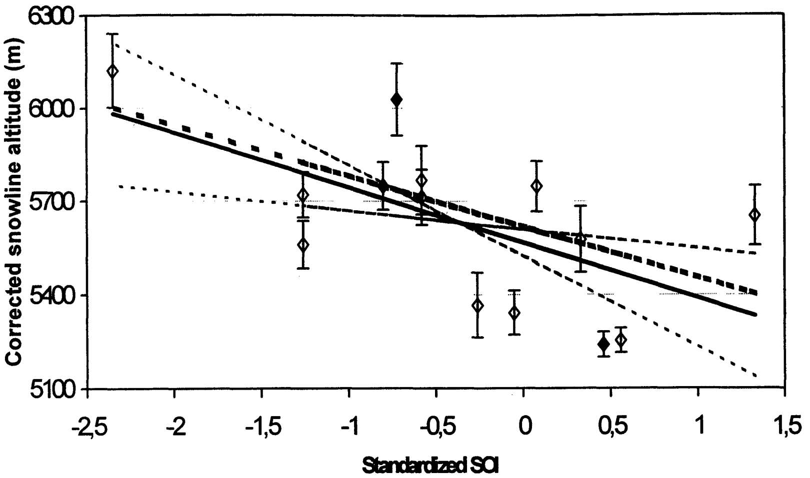

Figure 5. Mean standardized SOI (from October through March) versus corrected snow line altitude. Solid symbols correspond to questionable dates. Bold solid (bold dashed) line indicates OLS (LAR) regression estimate; 95% confidence interval for slope (β) is shown with thin dashed lines.

Because of the dominant role of ENSO upon climate variability on the Altiplano on interannual timescales [*Vuille et al*, 2000], humid (dry) summers at the same time also tend to be colder (warmer) than usual. Thus to ensure that the rather weak correlation between snow line altitude and maximum mean monthly temperature is real and not an artifact related to the autocorrelation between the two variables temperature and precipitation, we performed a stepwise multiple regression analysis. The snow line altitude was used as the dependent variable, while maximum mean monthly temperature and total rainy season precipitation entered the regression computation as independent variables. The resulting model (for an assumed 2-m/d snow line rise),

$$\mathrm{SLA} = 5444.8 + 118.9{*}T_{\mathrm{mm}} - 1.6{*}P_{\mathrm{rs}}, \qquad (4)$$

where SLA is the snow line altitude, T_{mm} is maximum mean monthly temperature, and P_{rs} is total rainy season precipitation (Figure 8), features a significant improvement (multiple r = 0.93, significant at 99.9%) over the simple linear model using precipitation alone (r = 0.88). The fact that the variable "maximum mean monthly temperature" is not rejected by the stepwise regression model yields evidence that it is indeed an important complementary factor that should not be neglected when determining the snow line altitude on Sajama.

Despite the relationship between SOI and temperature and precipitation in the Sajama area and thus between SOI and snow line elevation, the questions regarding the physical mechanisms associated with climatic variability over the Altiplano due to ENSO remain. Several recent publications have addressed this problem [e.g., *Vuille*, 1999; *Vuille et al.*, 2000; *Wagnon et al*, 2001]. According to *Vuille* [1999], one of the most striking atmospheric anomalies that can be observed during extreme phases of the SO during austral summer is the strengthening (weakening) and southward (northward) displacement of the Bolivian High during positive (negative) SO phases. These circulation anomalies are extremely important in order to understand precipitation variability in the Nevado Sajama area, because summer precipitation over the dry western Altiplano is intrinsically linked with easterly wind

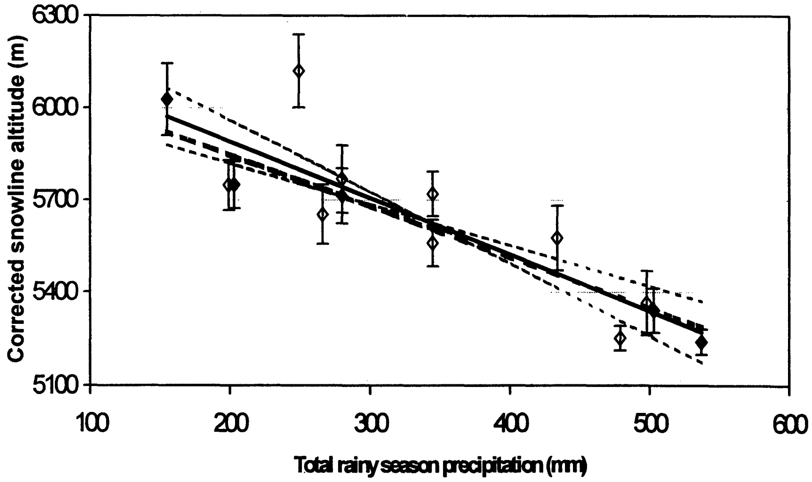

Figure 6. Total rainy season precipitation (from October through March) versus corrected snow line altitude. Solid symbols correspond to questionable dates. Bold solid (bold dashed) line indicates OLS (LAR) regression estimate; 95% confidence interval for slope (β) is shown with thin dashed lines.

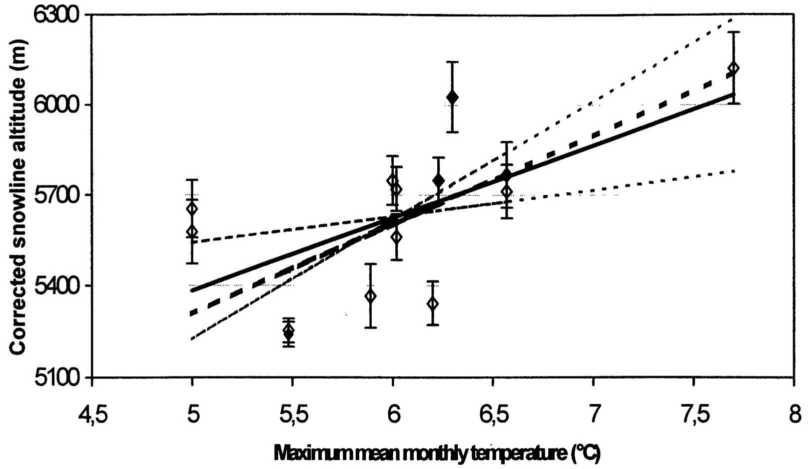

Figure 7. Maximum mean monthly temperature (from October through March) versus corrected snow line altitude. Solid symbols correspond to questionable dates. Bold solid (bold dashed) line indicates OLS (LAR) regression estimate; 95% confidence interval for slope (β) is shown with thin dashed lines.

anomalies in the middle and upper troposphere, thereby giving way to moisture influx from the interior of the continent near the Altiplano surface [*Garreaud*, 1999].

ENSO events affect primarily the coast of Peru or Ecuador, but also the interior part of Peru as already reported by *Francou and Pizarro* [1985] or *Thompson et al.* [1984]. Our results confirm ENSO impacts on the snow line altitude. The snow line altitude is controlled by several parameters such as precipitation and temperature and may be more adequate than only rainfall data in detecting ENSO signals on the Altiplano.

5. Conclusion

This study analyzes the ENSO influence on precipitation and temperature near the Sajama volcano by examining a portion of the Nevado Sajama snow line altitude from 1963 to 1998. A clear relationship between the SOI and snow line altitude was established which can be attributed to ENSO-related precipitation and temperature anomalies. Our data set shows a general rise of the snow line from 1963 to 1998 and a sustained rise between 1984 and 1990. Although we detected a tendency toward a higher snow line, the limited number of images analyzed warrants further analysis before a conclusive answer on this issue will be possible. The significant snow line drop of 1997, followed in 1998 by the most significant rise of the snow line during the period analyzed, confirms the importance of the snow line as an annual climatic indicator. The lack of reliable long-term meteorological information in this region is a handicap for climate studies. In this context, remote sensing can provide a complementary source of information provided that a sufficient number of images is available.

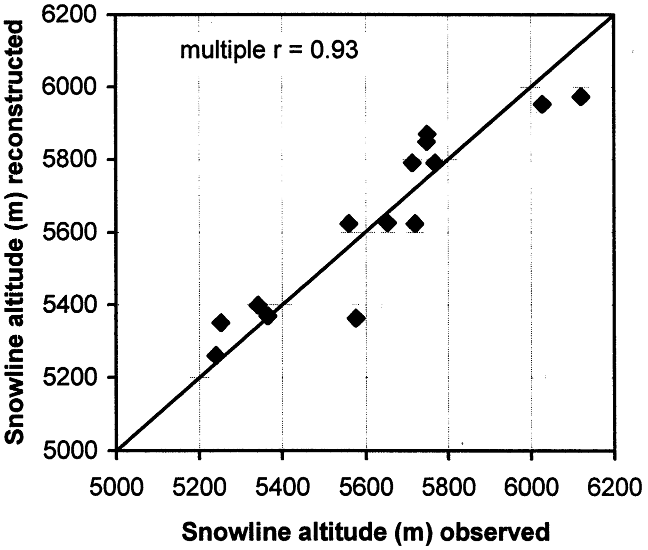

Figure 8. Observed versus reconstructed snow line altitude (meters). Reconstructed snow line altitude is based on stepwise multiple linear regression with total rainy season precipitation and maximum mean monthly temperature as independent variables.

In the future, however, contemporaneous glacier and snow line evolution needs to be compared in order to better understand their link. The accuracy of glacier area classification could not be clearly established owing to considerable snow cover and the logistical problems associated with field measurements. However, the use of the snow line instead of glacier extent was very successful and may be more suitable for short-term climate monitoring. Visible and near-infrared satellite data obtained at the end of the dry season are best suited for this type of study, limiting the influence of recent snowfalls. By applying a simple snow line evolution model, we were even able to compare images taken at the beginning and at the end of the dry season. Therefore this study still yields significant results, despite the fact that no snow line annual survey was possible owing to limited availability of satellite data.

Future studies will focus on the monthly snow line variation throughout the year, which will help to obtain information during the rainy season. Microwave sensors, which are able to penetrate cloud cover, should allow us to distinguish between thin snow cover and glaciers, and Sajama ice core information will be used to verify the relationship between snow accumulation and snow line altitude.

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