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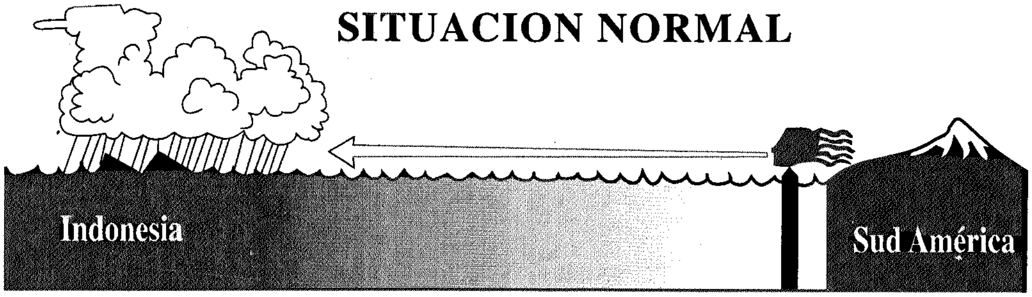
SEMINARIO EL FENOMENO DE EL NIÑO EN BOLIVIA EVALUACION, BALANCE Y PERSPECTIVAS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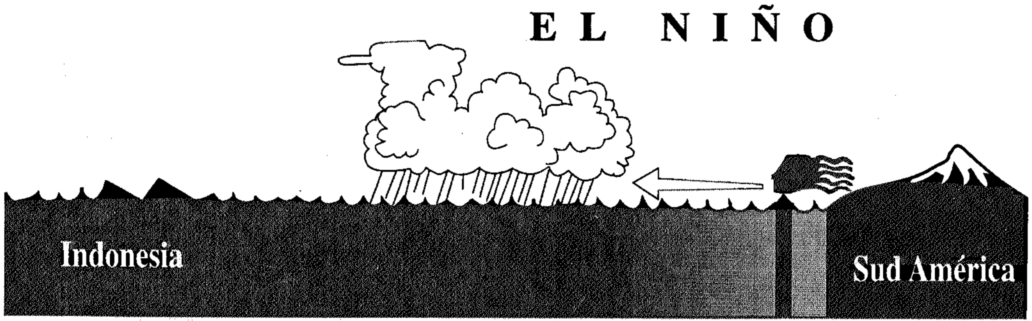
EL NIÑO

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EL IMPACTO DE LOS FENÓMENOS EL NIÑO / LA NIÑA EN LA REGIÓN DEL NEVADO SAJAMA, BOLIVA

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ABSTRACT

The atmospheric circulation during high / low index phases of the Southern Oscillation (El Niño / La Niña) over the Bolivian Altiplano was investigated using daily radio soundings from Antofagasta (Chile), Salta (Argentina), Lima (Peru) and La Paz (Bolivia), monthly precipitation data from the Bolivian / Chilean border between 18°-19°S and monthly gridded NCEP (National Centers for Environmental Prediction)-Reanalysis data between 1960 and 1998. Special emphasis was given to the region of Nevado Sajama (18°07'S, 68°53'W, 6542m), where an automatic, satellite-linked weather station was installed in Oct. 1996 and since provides hourly climatic data from the summit.

Summer (DJF) precipitation is generally lower during low index phases (El Niño), but only ~25% of the precipitation variability can be explained by the Southern Oscillation alone. This increased aridity is related to a higher zonal wind component (westerly wind anomalies) in the middle and upper troposphere, preventing moist air masses from the eastern interior of the continent to penetrate into the Sajama area. Geopotential height and temperature data show the warm structure of the atmosphere above the Altiplano during El Niño-periods. Typically the upper-air anticyclone located over the Altiplano ('Bolivian High') is situated far north during El Niño summers, giving way to dry westerly winds over the Sajama area. On the other hand, La Niña summers (DJF) are characterized by significantly lower temperatures, a more pronounced Bolivian High, located significantly further south and associated with easterly wind anomalies over the entire Bolivian Altiplano. The atmospheric circulation during the summer following El Niño (DJF +1yr) often shows some similarities with La Niña situations, which explains the above average precipitation amounts that tend to occur in summers following El Niño years. However, neither wind, temperature nor geopotential height anomalies are significantly different from the long-term mean during years following El Niño.

The data from Nevado Sajama covering the 97/98 El Niño period confirms these results showing increased temperatures and reduced snow accumulation, when compared to

the 1996/97 accumulation period. However, more data from Sajama summit will be needed to put these preliminary results into a longer-term perspective.

1. INTRODUCTION

The atmospheric circulation over the South American Altiplano during high and low Index phases of the Southern Oscillation (SO) has recently been investigated in a variety of studies. For some purposes, e.g. reconstruction of paleoclimate or interpretation of proxy records, knowledge of the atmospheric circulation during such climatic extremes is much more helpful, than analyses of mean annual cycles. Accordingly, the aim of this study is to analyze the atmospheric circulation during El Niño and La Niña periods over the broader Altiplano region and especially the area of Nevado Sajama (6542 m, 18°06`S, 68°53`W, Figure 1), in the western Bolivian Andes, where an ice core was recovered in June 1997 (Lonnie G. Thompson, 1997, pers. communication). The stratigraphy of this core is intrinsically linked to the climate and the atmospheric circulation during the deposition of the snow (Hardy et al., 1998; Vuille et al., 1998) and knowledge of the El Niño influence on the climate is therefore a prerequisite for an accurate interpretation of the core proxy data.

Summer precipitation on the Altiplano is associated with strong convection and daily moisture influx from the eastern interior of the continent (Fuenzalida and Ruttlant, 1987; Garreaud and Wallace, 1997; Garreaud, 1999; Hardy et al., 1998; Vuille, et al., 1998). More than 80 % of the annual precipitation in the order of 350 - 400 mm at the foothill of Nevado Sajama falls during the summer months December -March. The intense solar heating of the Altiplano surface destabilizes the boundary layer, induces deep convection and finally releases the moisture advected from the east during typical afternoon and evening showers (Garreaud, 1999). The episodic nature of precipitation on the Altiplano however, shows that solar heating might be a prerequisite, but that additional forcing is necessary for precipitation to occur. Jacobeit (1992) and Vuille et al. (1998) have shown that upper-air divergence or easterly disturbances are the dominant pattern, associated with precipitation periods over the Altiplano. Upper-air divergence is mostly associated with a high pressure system, a closed anticyclone named Bolivian High due to its climatological mean position over the Bolivian Altiplano in summer months (Virji, 1981). As shown by Aceituno and Montecinos (1993) and Vuille et al. (1998) precipitation amounts over the southern Altiplano significantly increase when the High is strengthened and displaced southward from its climatological position. On the other hand dry periods are related to enhanced westward flow over the Altiplano in all levels, thereby advecting dry air from the Pacific region and suppressing any moist air advection from the east.

During winter months conditions over the Altiplano are usually dry, associated with strong westerly flow over the entire region, interrupted only by occasional outbreaks of cold air masses from the planetary west wind zone (Vuille and Ammann, 1997). These winter snowfall events tend to occur between May and September, being most frequent in July and August in the Sajama region (Vuille and Baumgartner, 1998). However, these events are rather rare, therefore the focus of this study is mainly on the austral summer months December - February.

As a result of the convective nature, the spatial variability of precipitation episodes in this arid part of the Bolivian Altiplano is high (Ronchail, 1995). Therefore, only precipitation data from stations in the closest vicinity of Sajama volcano was used to determine the influence of El Niño and La Niña in the Sajama area. Upper-air soundings from the four closest stations with reliable and long enough records were used to determine atmospheric circulation anomalies during the corresponding periods. A similar approach has been used by Aceituno and Montecinos (1993) looking at the atmospheric circulation during wet and dry periods over the Chilean Altiplano. However, their study was limited to coastal soundings (Lima, Antofagasta and Quintero) and a relatively short time period (1980-1987).

Several Authors have analyzed the relationship between ENSO and interannual climatic variability over the South American continent (e.g. Ropelewski and Halpert, 1987; Rogers, 1988; Aceituno, 1988 and 1989; Kiladiz and Diaz, 1989; Pulwarty and Diaz, 1993). Although these studies helped to improve knowledge about the large scale ENSO influence over the South American continent, they were not able to spatially resolve ENSO features in areas such as the Altiplano, where this signal is spatially incoherent. A limited data base or the use of gridded precipitation data, which can not resolve regional ENSO signals in mountain areas where the response to such a signal can vary considerably within short distance, were the limiting factors.

Regional studies on the influence of ENSO have shed more light in certain regions of the Altiplano. Several authors have reported below average precipitation and increased temperatures associated with warm/low index phases (El Niño) of the Southern Oscillation. The significance level however varies considerably, depending on the area, data and time period that was analyzed. Aceituno and Garreaud (1995) reported below average levels of Lake Titicaca associated with ENSO periods, consistent with data published by Tapley and Waylen (1990) indicating reduced precipitation amounts in the Peruvian Altiplano during warm events. Below average snow accumulation on Quelccaya Ice Cap in Peru (Thompson et al., 1984; Thompson, 1993) and a negative glacier mass balance due to increased temperatures and reduced snowfall on Zongo glacier in the Cordillera Real, Bolivia (Francou et al., 1995), could also be attributed to climatic anomalies caused by El Niño. Ronchail (1998), could show that below average summer precipitation (JFMA) in the Bolivian Altiplano is frequent during negative phases of the SOI (El Niño), but also emphasized that many dry periods over the Altiplano are not related to the ENSO-phenomenon. During the last decades the driest summers in the Altiplano have often but not always been El Niño years. In addition, the most extreme precipitation values seem to be independent of the SOI. They can occur during extreme phases of the SOI as well as during normal years. Atmospheric circulation over the continent might more likely be a proxy for precipitation over the Altiplano, than surface conditions in the Pacific.

In the following section the data and methods that were applied in this study are described. Section 3 presents the results from the analysis of the upper-air soundings and the NCEP data during the summer months DJF. Section 4 shows some preliminary results from data recorded during the 1997/98 El Niño on Sajama summit while section 5 summarizes this study and presents some conclusions.

2. DATA AND METHODS

Monthly precipitation data from six Altiplano stations in the closest vicinity of Nevado Sajama was obtained from the Chilean and Bolivian Meteorological Services (Dirección General de Aguas, Santiago, Chile and Servicio Nacional de Meteorología e Hidrología, La Paz, Bolivia). Station names and their location are shown in Table 1. Total summer precipitation amounts (DJF) were computed for each station between 1960 and 1993, although some stations had considerably shorter records (see Table 1). A normalized Sajama Precipitation Index (SPI) was derived by computing an average long-term mean form all six stations, subtracting this long-term mean from the annual averaged DJF amounts and then dividing by its standard deviation.

Upper-air data from the stations closest to Nevado Sajama that showed reliable and long enough records was extracted from CARDS (Comprehensive Aerological Reference Data Set). The selected stations include two records to the west of the Andes on the Pacific coast (Antofagasta, Chile and Lima, Peru), one record on the Altiplano (La Paz, Bolivia) and one to the east of the Andes (Salta, Argentina). The length of each record is shown in Table 1 and the location of the stations is shown in Figure 1. From each station record daily values at 12.00 UTC were extracted, except for Lima where only data at 00.00 UTC was available. Recorded daily data include geopotential height (gpm), air temperature (°C), relative humidity (%), wind direction (°) and wind speed ($m\ s^{-1}$) for the standard pressure levels 850 hPa, 700 hPa, 500 hPa, 400 hPa, 300 hPa and 200 hPa (except for La Paz, where 850 hPa, and 700 hPa would be meaningless). From this original data, zonal and meridional wind components ($m\ s^{-1}$) and specific humidity ($g\ kg^{-1}$) were derived.

Three-monthly SOI-averages (standardized anomalies of the pressure difference between Darwin and Tahiti) were computed and then all DJF periods for which $SOI > 1$ (high) and $SOI < -2$ (low) were retained. The high and low index phases for DJF are listed in Table 2. One can argue whether the SOI or indices of Pacific SSTs (e.g. Niño 1-4) are the best proxy for the Pacific ENSO phenomenon (e.g. Trenberth, 1997). However, as only extreme phases of ENSO are considered in this composite approach, and the SOI and the Niño-indices are highly correlated during the last decades, the same periods would have been extracted independent from which index is used. The thresholds of 1 and -2 for the standardized SOI-anomalies are somewhat arbitrary but yielded an equal amount of 7 strong high and low index phases since 1958, the first year with soundings data (see Table 1). However, the La Paz record is considerably shorter and only covers 4 high and 4 low index phases. Finally DJF composites were computed for all parameters and stations and at all pressure levels for both high (SOI >1) and low index phases (SOI <-2) and a two-tailed Student's t-test (95% significance level) performed to see whether significant changes occur in the atmospheric circulation between high and low index phases. Such a composite approach is based on the assumption that only extreme periods are of considerable influence in this area. The climatic response of ENSO on the Altiplano however, is at least partially an indirect teleconnection via tropical Atlantic as intermediate agent (e.g. Enfield, 1996). At least parts of the tropical Andes tend to be anomalously wet in years following an ENSO event (DJF+1yr) (e.g. Henderson, 1996). This increased precipitation might be attributed to a climatic response of the tropical Atlantic to the Pacific ENSO-signal and hence increased easterly moisture influx towards the Andes. In order to account for this possible phase-lag relationship, an additional analysis was carried out, using 200 hPa NCEP (National Centers for Environmental Prediction) Reanalysis data. Monthly data for temperature, geopotential height, zonal and meridional wind component were extracted from the original data set. Anomalies were computed by subtracting the long term monthly mean (1960-1998) and then anomaly composites for the same high/low index phases were created. To account for the above mentioned phase-lag an additional low+1yr composite was created, including all DJF periods following a low index phase (first DJF period when averaged SOI >-1).

Finally some data from the 1997/98 El Niño event as recorded by an automatic satellite linked weather station, installed on Sajama summit in October 1996 (Hardy et al., 1998), are presented in section 4. These analyses are somewhat preliminary but show the direct influence of this phenomenon on the climate at the southernmost tropical Andean glacier, Sajama.

3. PRECIPITATION ANOMALIES AND ATMOSPHERIC CIRCULATION DURING EL NINO AND LA NINA

Figure 2 shows the correlation between DJF precipitation in the Sajama area and the Southern Oscillation Index (SOI) between 1960 and 1993. The Sajama Precipitation Index (SPI) is a normalized mean of the stations listed in Table 1. Unfortunately not all stations have a continuos record, but computations using only data from stations available throughout the whole period did not yield significantly different results. Obviously there is a positive correlation between the SOI and the SPI, showing below average summer precipitation in the Sajama area during negative phases of the SO (El Niño) and above average precipitation during positive phases of the SO (La Niña). However, the correlation is rather weak (r = 0.50), explaining only 25% of the precipitation variability. These results are consistent with the analysis made by Aceituno (1988) who reported a coherent pattern of weak positive correlations between Jan./Feb precipitation and the SOI over the Peruvian/Bolivian Altiplano. In addition the results confirm the analysis of Ronchail (1998), showing that below average summer precipitation is frequent during negative phases of the SOI, but nevertheless many dry periods over the Altiplano are not related to the ENSO-phenomenon. (e.g. 1979/80, 1988/89; see Figure 2)

Increased aridity and dry phases in general are normally related to weakened easterlies and/or strengthened westerlies in the middle and upper troposphere over the Altiplano. Indeed the analysis of the zonal wind component over Antofagasta, Salta, Lima and La Paz (Figure 3) during El Niño and La Niña events shows a similar pattern. The difference is most pronounced over Lima, where the zonal wind component is significantly higher (95% level) at all levels between 500 - 200 hPa during El Niño periods. Over Antofagasta and Salta the difference is only significant at the 200 hPa level, while over La Paz westerly winds are significantly higher in mid-tropospheric levels only (500-400 hPa) during El Niño summers. Associated with the change in the zonal wind component (increased westerly anomalies during El Niño, increased easterly anomalies during La Niña) are changes in the specific humidity, as during austral summer high humidity levels are strictly tied to moisture influx from the east. Accordingly Figure 4 shows the reduced specific humidity in mid tropospheric levels with significantly (95% level) lower values over Lima (significant between 500 - 300 hPa), Salta (significant at 500 hPa and 400 hPa) and La Paz (not significant) during low index (El Niño) periods. Over Antofagasta however, the humidity change is reversed, showing slightly higher humidity values (not significant) during El Niño periods.

The geopotential height and temperature data (not shown) shows the typical characteristics of the tropics during Pacific warm events. Both parameters are significantly increased during El Niño periods and significantly lowered during La Niña events. Geopotential height values are significantly higher at all levels between 700 - 200 hPa over all four stations during low index phases, except for La Paz at 300 hPa and 700 hPa (no data). Associated with the warm and vertically expanded troposphere over the Altiplano region are increased temperatures, although there significance varies widely. Only Lima shows significantly higher El Niño - related temperatures throughout the troposphere. Over Antofagasta and La Paz temperatures are only significantly higher at the 200 hPa level and in the lower troposphere (Antofagasta 850 hPa and 700 hPa), while Salta shows significantly higher temperatures at lower and mid-tropospheric levels (700 hPa and 500 hPa).

Although not significant at all levels, the general pattern seems clear: stronger zonal winds (westerly anomalies), reduced specific humidity, increased temperatures and an expanded troposphere characterize the atmosphere over the Altiplano region during low index phases (El Niño periods) in the austral summer (DJF). During high index phases of the Southern Oscillation (La Niña periods), atmospheric characteristics are generally reversed. Similar results have been obtained in an earlier study (Aceituno, 1989), but it is difficult to draw conclusions regarding a general circulation pattern from these sounding results alone. Therefore gridded 200 hPa upper-air data from the NCEP (National Centers for Environmental Prediction)- Reanalysis Project was analyzed between 1960 and 1998, using the same composite technique as previously described.

Figure 5 shows the 200 hPa DJF geopotential height for the strongest positive and negative SOI-anomalies (standardized SOI-anomaly >1 and <-2) between 1960 and 1998. Note that the time period is slightly different from the time covered by soundings data (see also Table 1 and 2). As some areas in the tropical Andes tend to be wet in years following an El Niño event and to account for such a phase-lag relationship via indirect teleconnection through the tropical Atlantic (e.g. Enfield, 1996; Henderson, 1996), an additional composite including all post El Niño summers (El Niño+1yr) was created and analyzed. The left column shows the composite for El Niño, El Niño+1yr and La Niña events (from top to bottom), while the right column shows the anomaly pattern (deviation from long-term mean, 1960-1998) for the corresponding composites. The shaded grid boxes indicate areas where the anomalies are significant at the 95% level (two-tailed t-test). As shown in Figure 5, the geopotential height at the 200 hPa level is indeed significantly higher over most of the Altiplano during El Niño summers (DJF) and significantly lower during La Niña summers. However the increased geopotential height is not associated with a strengthened Bolivian High. On the contrary, the meridional pressure gradient to the north of the Bolivian High is much more pronounced during La Niña periods, when the Bolivian High is located further to the south. This pressure gradient leads to enhanced easterly winds and increased humidity levels over the Altiplano. Figure 6 shows that La Niña periods are indeed associated with significant negative zonal wind anomalies over major parts of the Altiplano. The opposite pattern emerges during El Niño periods when the zonal wind component is significantly higher than normal (westerly anomalies) over the southern part of the Altiplano, the adjacent Pacific and the tropical lowlands to the northeast. The geopotential height and wind pattern during El Niño+1yr interestingly show a lot of similarities with the La Niña pattern, but only one summer falls into both categories (1973/74, see Table 2). This similar pattern might explain why many post-El Niño years tend to be unusually wet, however neither wind nor geopotential height anomalies during these years are significant in any areas over the Altiplano at the 95%-level. The warm temperature anomalies during El Niño (Figure 7) are significant over almost the whole study area, reaching values of more than +0.9 °C near 5°S, and still +0.7 °C in the Sajama area. During La Niña the values are similar but of opposite sign. Again during El Niño+1yr temperature anomalies are insignificant in all of the study area.

4. EL NINO 1997/98 ON SAJAMA SUMMIT

An interesting and important question is the influence of El Niño on the glacier mass balance in the South American tropics. Many glaciers in the tropics are retreating at an accelerating rate, causing problems for future water resource management in the region. Besides rising freezing levels in the tropics (Diaz and Graham, 1996), the fact that the ENSO phenomena seems to have become more frequent in recent decades (Trenberth and Hoar, 1996) might also contribute to this trend. Studies on the Zongo Glacier in the Cordillera Real show, that the glacier mass balance becomes negative during El Niño periods due to the higher temperatures and the reduced snow accumulation (Francou et al., 1995). More insight into this phenomenon will soon be gained from Nevado Sajama, where an automatic satellite-linked weather station was installed at the summit in October 1996 and since provides hourly data on air temperature, relative humidity, wind direction and speed at two levels, barometric pressure, snow accumulation and ablation, incoming solar radiation, albedo, snow surface temperature and snow temperature at various snow depths (Hardy et al., 1998). Here we only focus on some preliminary results from the austral summer 1997/98, showing the influence of the El Niño on air temperature and the snow accumulation as recorded at the summit. A longer data record and a more thorough analysis will be necessary to put the 1997/98 El Niño in a longer-term context.

Figure 8 shows the daily mean austral summer temperatures between October and May for 1996/97 and 1997/98. It is obvious, that temperatures where significantly higher for most of the time during the El Niño summer 97/98. Starting in mid October the temperatures were about 1°C higher until mid February in the latter year, then the discrepancy rose to more than 2 °C for most of March, April and May. However it has to be kept in mind, that the summer 1996/97 was unusually cold (Hardy et al., 1998) and according to the definition of high index phases used in this paper even is considered a La Niña period (see Table 2). Obviously a longer time period needs to be analyzed to put the recent El Niño event into perspective.

The same is true with regard to Figure 9 showing the snow accumulation history for both austral summers between November and March. While the snow accumulation reached more than 2 m already by the end of January 1997, thereby burying the snow depth sensors, the total snow amount was only 1.01 m at the end of January 1998. The exact total snow accumulation is unknown for the 1996/1997 period, but on February 22, 1997 the snow accumulation must have reached 3.15 m, because the upper wind sensors at this level was affected by the snow. In the following year, total snow accumulation did not rise above 1.5 m. Again the snow accumulation in 1996/97 was probably unusually high, as all surrounding Altiplano stations including La Paz recorded above average precipitation amounts (Hardy et al.,1998). Additional years will be necessary to put the 1.5 m of the 1997/98 El Niño event into a longer-term perspective. However it seems clear, that the anomalies seen during El Niño periods in soundings and gridded upper-air data (higher temperatures, stronger westerly wind components and reduced humidity levels in mid-tropospheric levels) have a considerable impact on the climate recorded at the summit of Nevado Sajama.

5. SUMMARY AND CONCLUSIONS

The atmospheric circulation during high / low index phases of the Southern Oscillation (El Niño / La Niña) over the Bolivian Altiplano was investigated, with special emphasis of the Nevado Sajama area in the western Bolivian Cordillera. As precipitation is mainly restricted to the austral summer months, this study only analyzes the influence of the ENSO phenomena during the months December - February (DJF).

Although precipitation in the Nevado Sajama area is generally lower during low index phases (El Niño), only 25% of the precipitation variability can be explained by the influence of the Southern Oscillation alone. Obviously factors other than ENSO play a crucial role in determining precipitation amounts over the Altiplano. It seems as if the atmospheric circulation over the South American continent might more likely be a proxy for precipitation over the Altiplano, than surface conditions in the Pacific alone. It has also been suggested recently, that precipitation variability in the tropical Andes on interannual and interdecadal timescales might rather be attributed to Atlantic than Pacific SST-forcings (Enfield, 1996).

Nevertheless, the atmospheric circulation over the Altiplano region shows significant anomalies compared with its mean state during the extreme phases of the Southern Oscillation. The generally increased aridity can at least partially be attributed to a higher zonal wind component (westerly wind anomalies) in the middle and upper troposphere, preventing moist air masses from the eastern interior of the continent to penetrate into the Sajama area. These westerlies are associated with a northward displaced and rather weak Bolivian High. La Niña summers on the other hand are characterized by broadly opposite characteristics of the atmosphere (lower temperatures, a more pronounced Bolivian High, located significantly further south and easterly wind anomalies). The atmospheric circulation during the summer following El Niño (DJF +1yr) often shows some similarities with La Niña situations, but the anomalies are statistically insignificant.

The data from Nevado Sajama covering the 97/98 El Niño period is in good agreement with these results and shows the influence of El Niño on the glacier mass balance of the southernmost tropical Andean glacier. Snow accumulation during summer 97/98 was significantly lower than during the preceding year and the recorded temperatures were 1-2 °C higher than during the summer 1996/97. However caution is needed when analyzing these preliminary results, as the year preceding the 1997/98 El Niño was unusually cold and humid and therefore additional years will be needed to put the latest ENSO event into a longer-term perspective.

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Precipitation data

Station name	Lat. (°S)	Long. (°W)	Elev. (m a.s.l.)	Lenght of record
Sajama	18.13	68.98	4220	1975-1985
Cosapa	18.16	68.70	3890	1975-1995
Cotacotani	18.20	69.23	4500	1960-1992
Chucuyo	18.22	69.33	4200	1960-1993
Chungará Reten	18.28	69.13	4500	1962-1993
Guallatire	18.50	69.16	4280	1968-1993

Soundings data

Station name	Lat. (°S)	Long. (°W)	Elev. (m a.s.l.)	Lenght of record
Lima - Callao	12.00	77.12	11	1962 - 1992
La Paz - JFK Intl.	16.50	68.17	4051	1970-1982 / 1987-1990
Antofagasta	23.41	70.47	137	1958-1990
Salta Airport	25.85	65.48	1221	1965-1990

Table 1: Latitude, longitude, elevation and length of record of precipitation and soundings data.

Period	Definition	Events
low index DJF (El Niño)	mean DJF SOI anomaly <-2	1958/59 1972/73 1977/78 1982/83 1986/87 1991/92 1997/98
El Niño+1yr	DJF following an El Niño-year and SOI anomaly > -1	1959/60 1973/74 1978/79 1983/84 1987/88 1993/94
high index DJF (La Niña)	mean DJF SOI anomaly >1	1961/62 1966/67 1970/71 1973/74 1975/76 1988/89 1996/97

Table 2: El Niño, El Niño+1yr and La Niña periods (DJF) used in composite analysis based on SOI thresholds. Note that data period covered by NCEP composites (1960-1998) is slightly different than for the sounding composites (see Table 1).

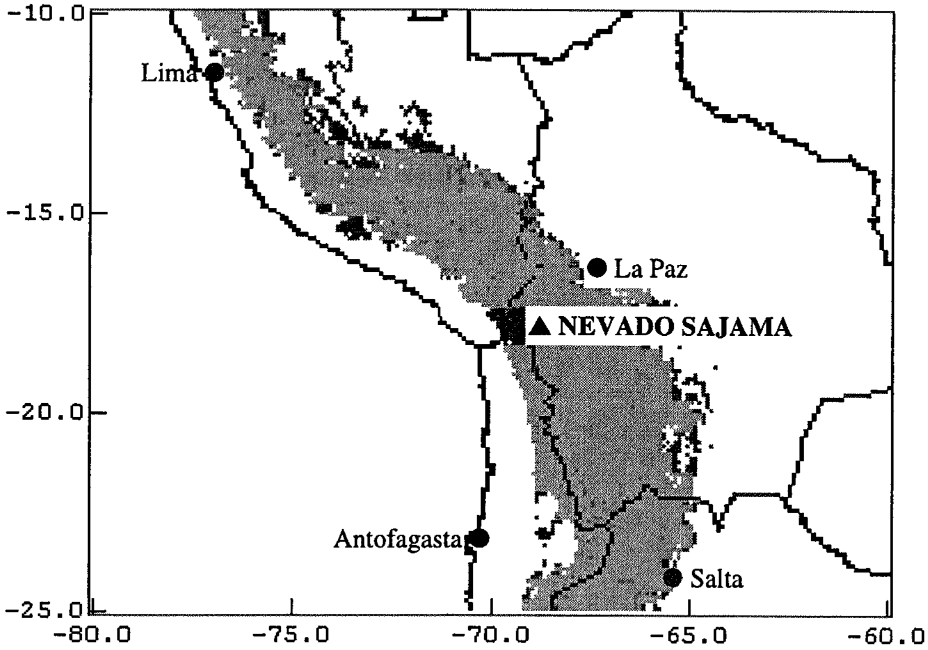

Figure 1: Map of the study area with location of Sajama Volcano (6542 m, 6542 m, 18°06'S, 68°53'W), and upper-air soundings stations. Altiplano (above 3000 m) is shown as shaded area.

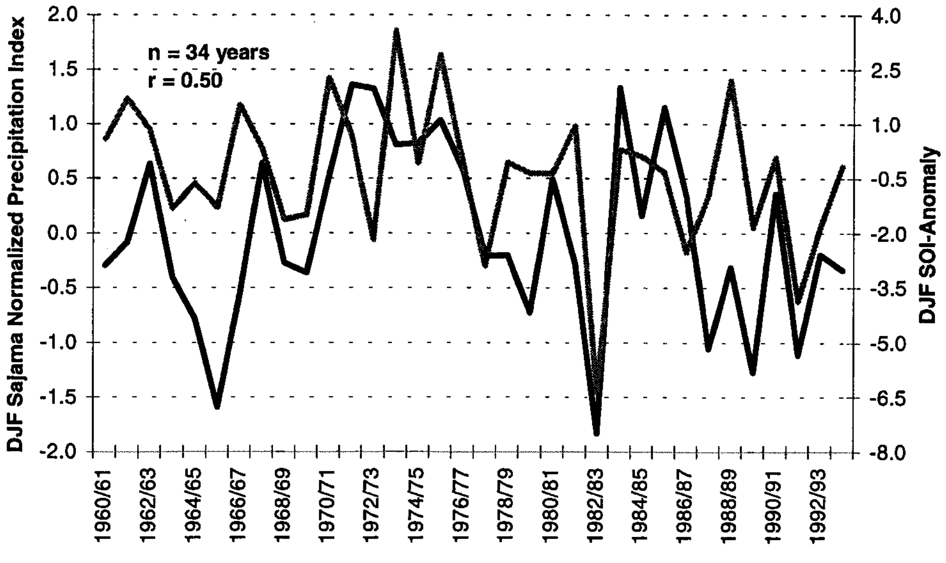

Figure 2: Correlation between DJF precipitation in the Sajama area (Sajama Precipitation Index, SPI, black line) and the Southern Oscillation Index (SOI, gray line) between 1960 and 1993. The Sajama Precipitation Index (SPI) is a normalized mean of the stations listed in Table 1.

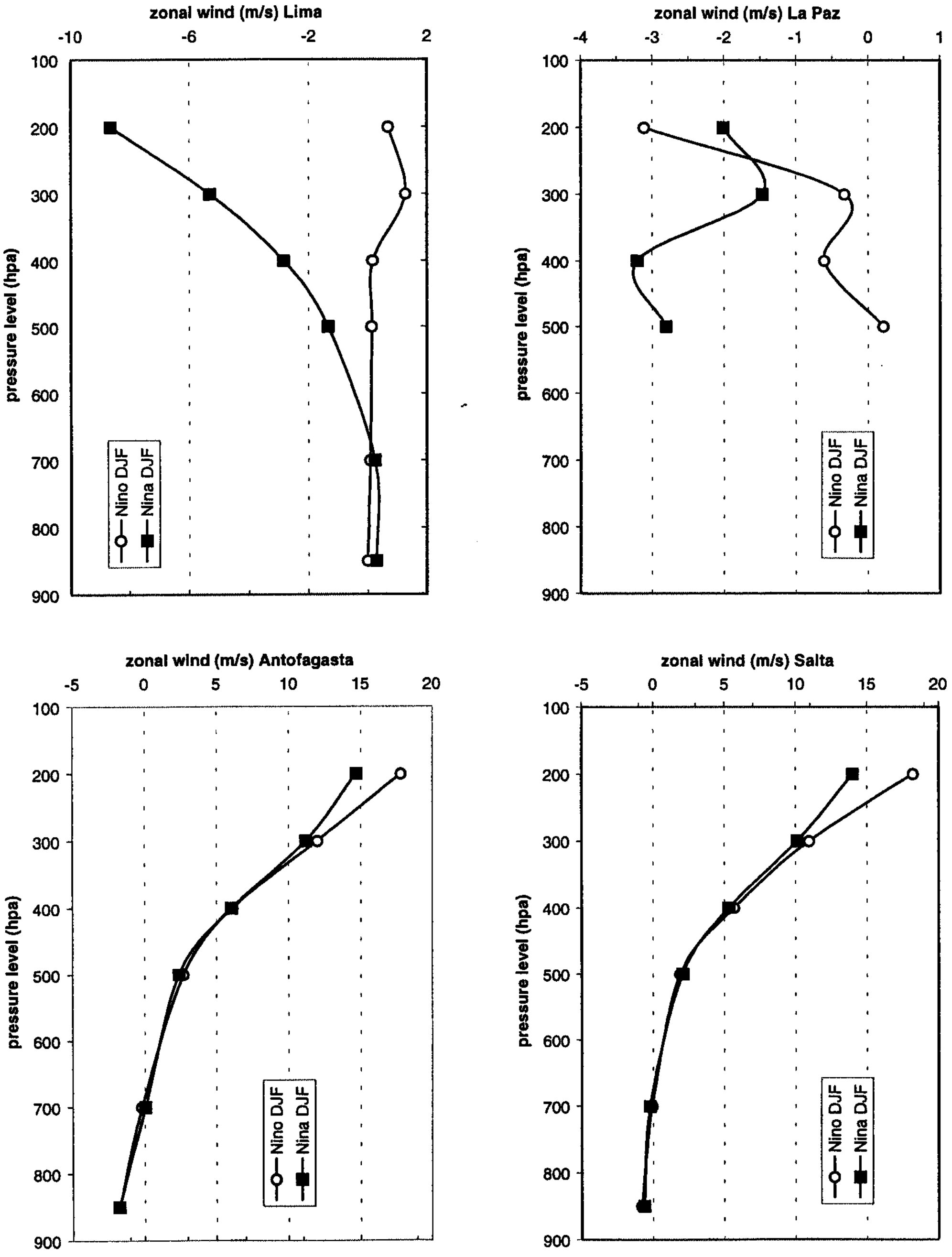

Figure 3: DJF composite of zonal wind component (m s^{-1}) over Lima, La Paz, Antofagasta and Salta during El Niño and La Niña events.

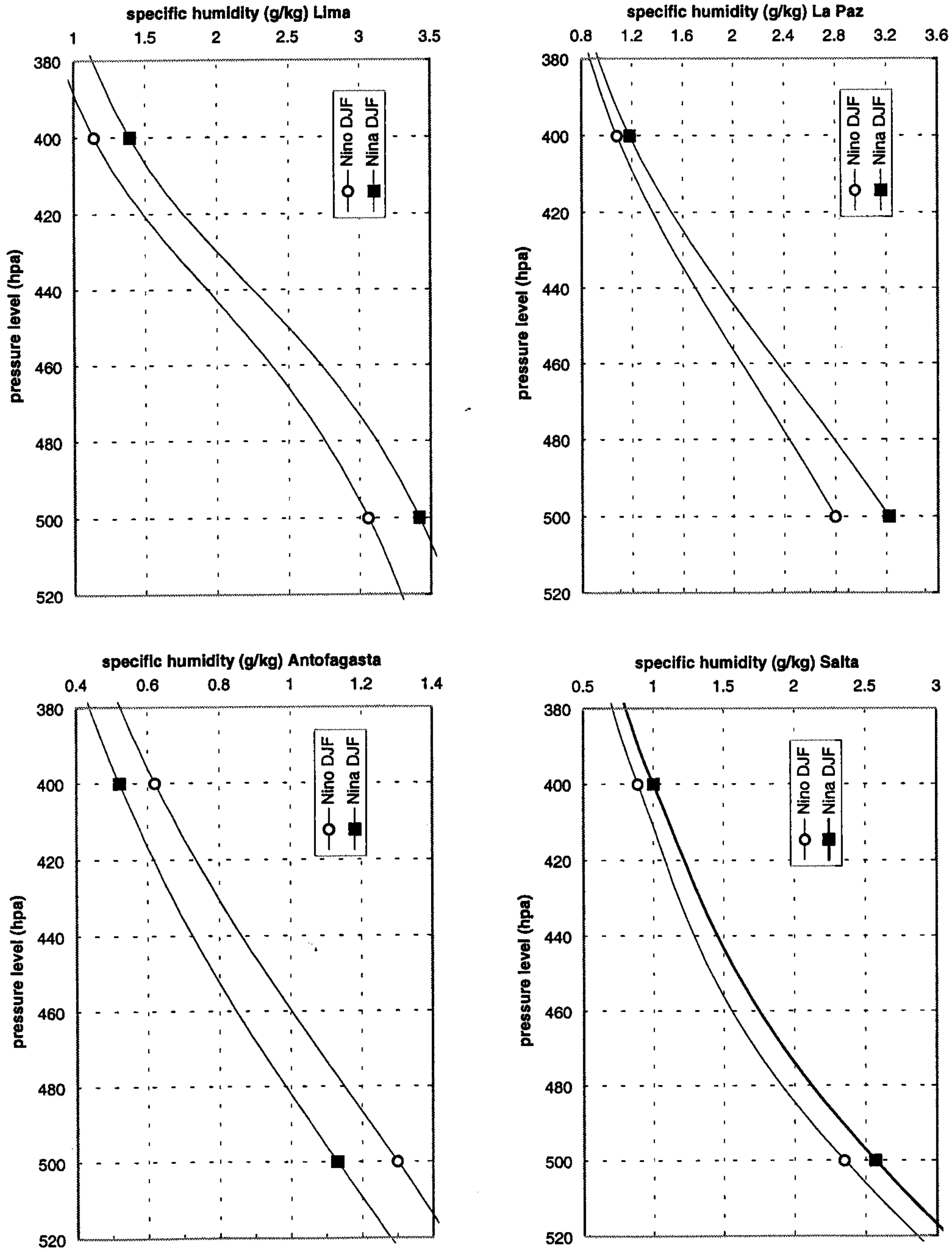

Figure 4: DJF composite of specific humidity (g kg^{-1}) over Lima, La Paz, Antofagasta and Salta during El Niño and La Niña events.

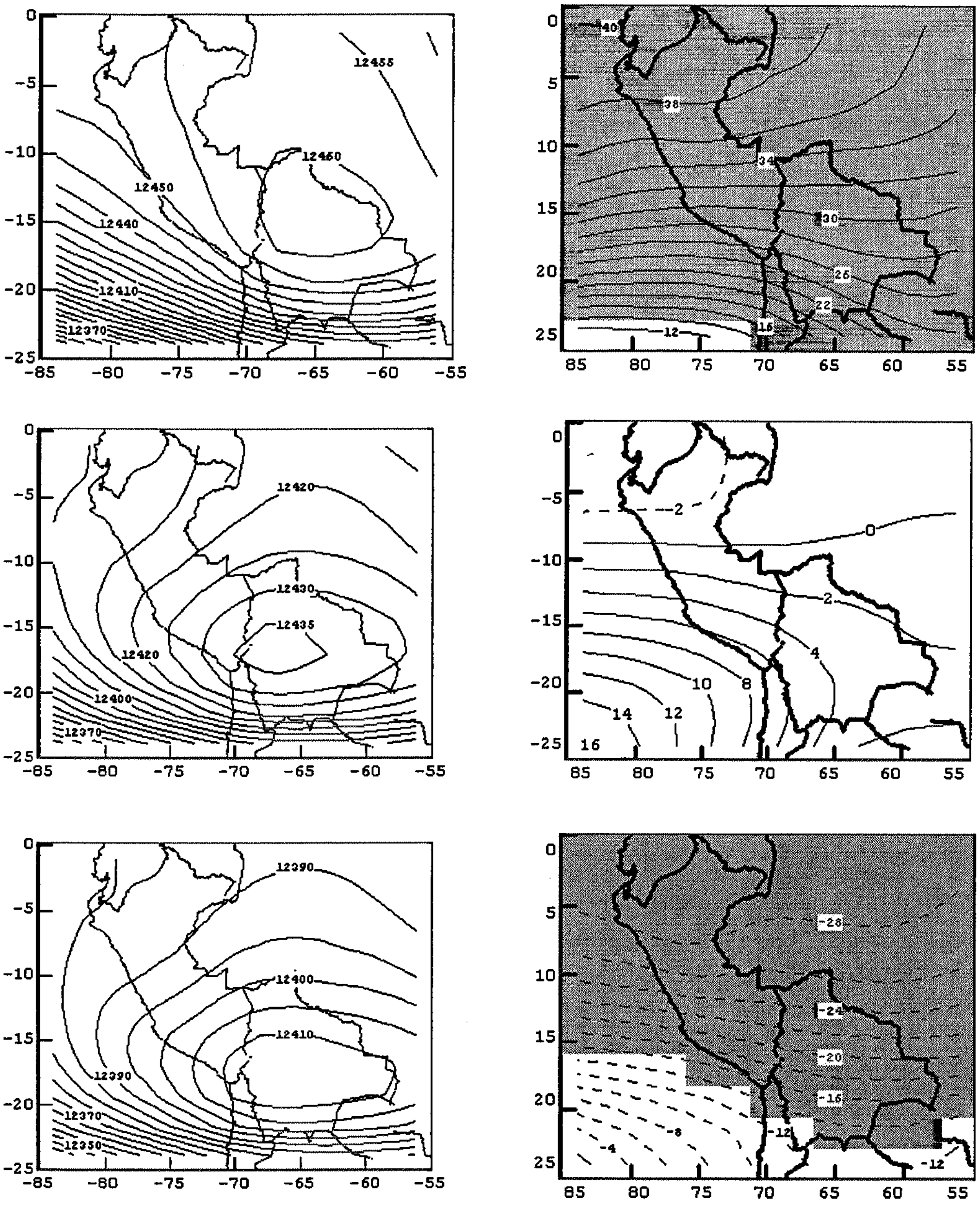

Figure 5: 200 hPa NCEP geopotential height (gpm) composites for austral summer (DJF) during El Niño (top), El Niño+1yr (middle) and La Niña events. Left column shows composite, right column shows anomaly pattern (deviation from 1960-1998 long-term mean). Areas where anomalies are significant at the 95% - level are shaded.

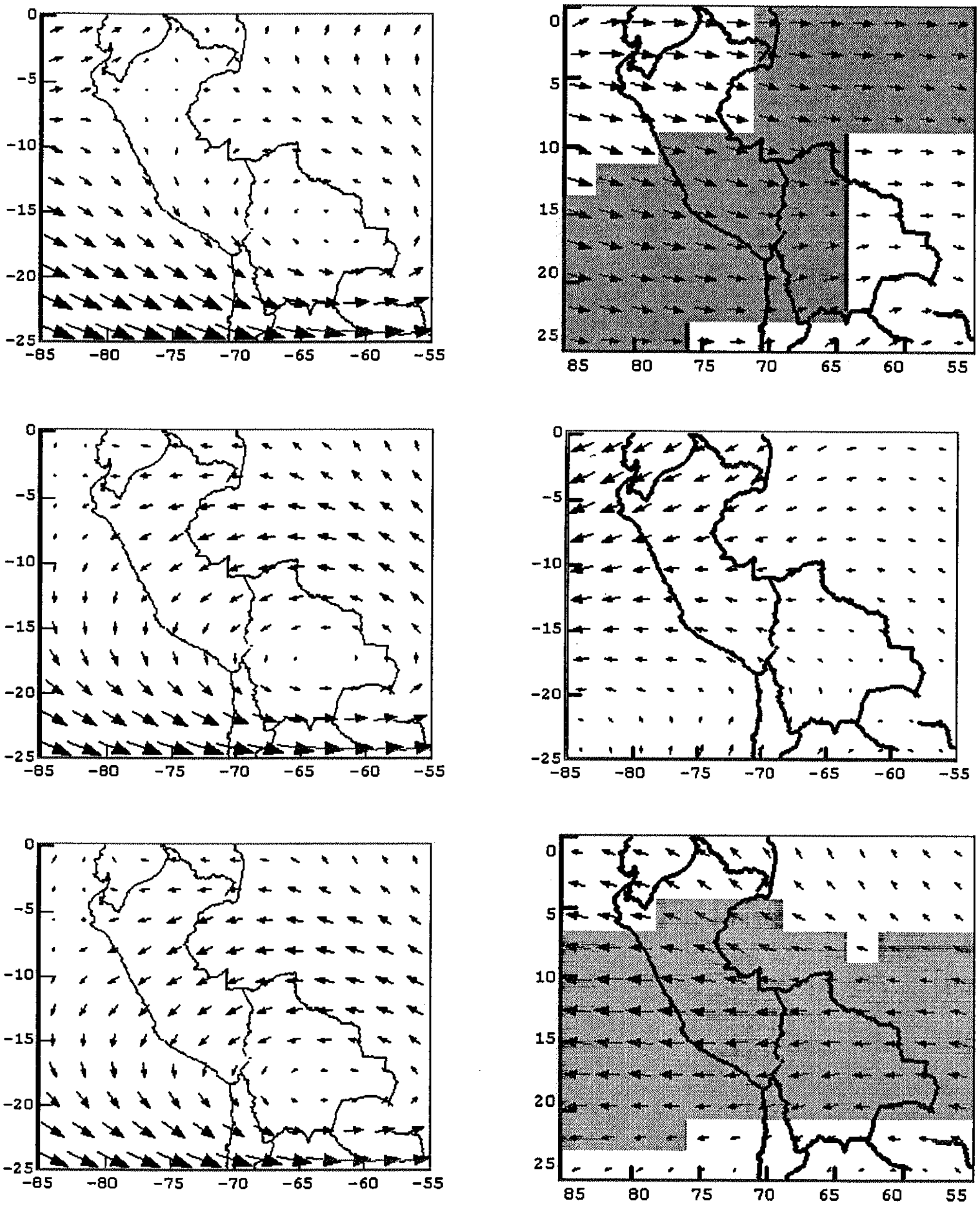

Figure 6: 200 hPa NCEP wind composites for austral summer (DJF) during El Niño (top), El Niño+1yr (middle) and La Niña events. Left column shows composite, right column shows anomaly pattern (deviation from 1960-1998 long-term mean). Areas where zonal wind anomalies are significant at the 95% - level are shaded.

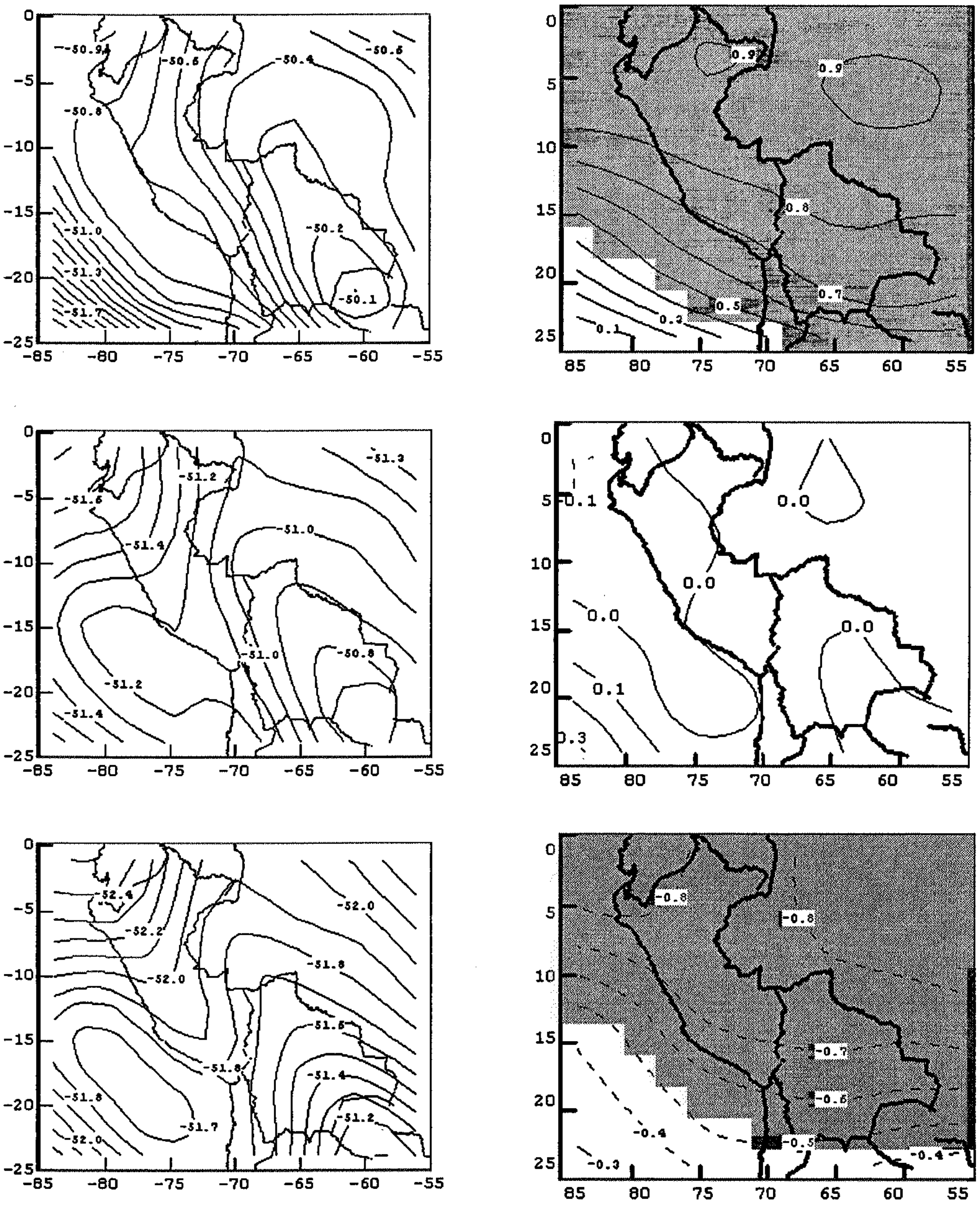

Figure 7: 200 hPa NCEP temperature (°C) composites for austral summer (DJF) during El Niño (top), El Niño+1yr (middle) and La Niña events. Left column shows composite, right column shows anomaly pattern (deviation from 1960-1998 long-term mean). Areas where anomalies are significant at the 95% - level are shaded.

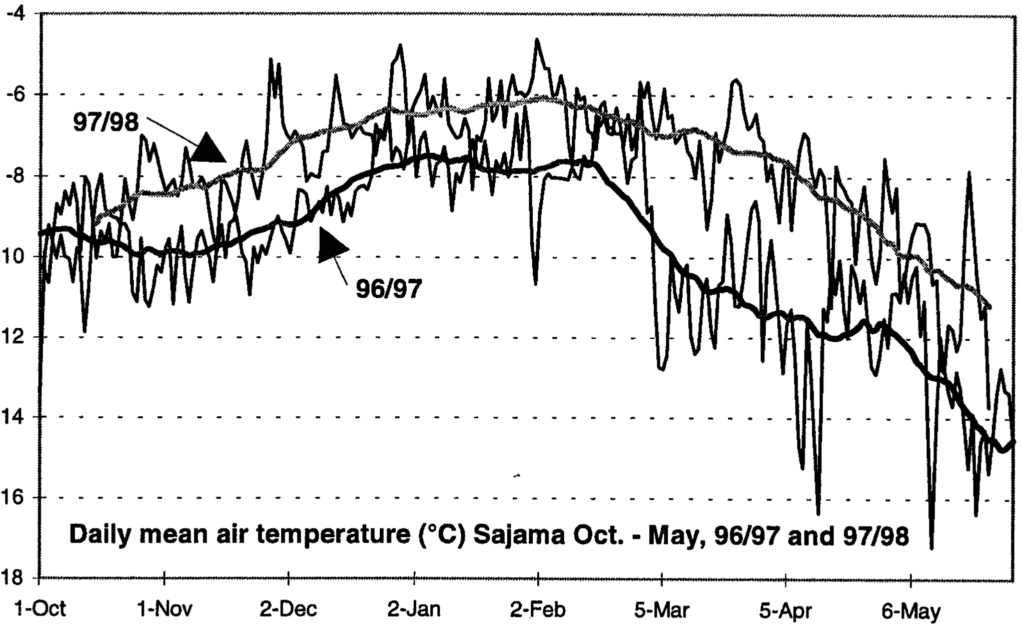

Figure 8: Air temperatures (°C) recorded on Sajama summit between October and May for 1996/97 (black line) and 1997/98 (gray line). Thin line shows daily mean, thick line is a 30-day running mean.

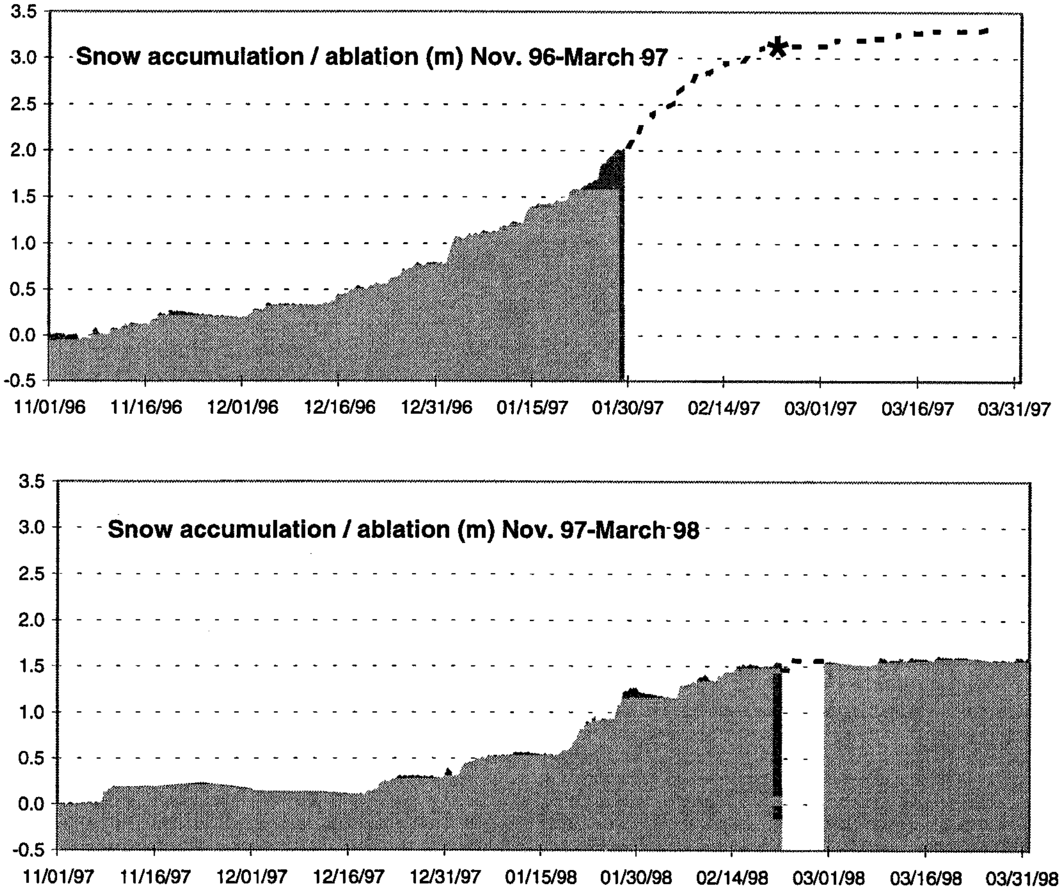

Figure 9: Snow accumulation (13 hour running mean from two snow depth sensors) on Sajama summit between November and March for periods 1996/97 (top) and 1997/98 (bottom). For better comparison snow accumulation was set to 0.0 m on 1.Nov. of both years. Sensors were buried by snow after January 28, 1997. * indicates February 22, 1997 when 3.15 m were reached (wind sensor located at 3.15 m above ground was buried by snow).