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ATMOSPHERIC CIRCULATION OVER THE BOLIVIAN ALTIPLANO DURING DRY AND WET PERIODS AND EXTREME PHASES OF THE SOUTHERN OSCILLATION

M. VUILLE*
Department of Geosciences, University of Massachusetts, Amherst, MA 01003-5820, USA

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ABSTRACT

The atmospheric circulation over the Bolivian Altiplano during composite WET and DRY periods and during HIGH and LOW index phases of the Southern Oscillation was investigated using daily radiosonde data from Antofagasta (Chile), Salta (Argentina), Lima (Peru) and La Paz (Bolivia), daily precipitation data from the Bolivian/Chilean border between 18° and 19°S and monthly NCEP (National Centers for Environmental Prediction) reanalysis data between 1960 and 1998. In austral summer (DJF) the atmosphere during WET periods is characterized by easterly wind anomalies in the middle and upper troposphere over the Altiplano, resulting in increased moisture influx from the interior of the continent near the Altiplano surface. The Bolivian High is intensified and displaced southward. On the other hand, westerly winds usually prevail during DRY summer periods, preventing the moisture transport from the east from reaching the western Altiplano. Precipitation tends to be deficient over the western Bolivian Altiplano during LOW index summers and above average during HIGH and LOW + 1 summers, but the relation is weak and statistically insignificant. LOW summers feature broadly similar atmospheric circulation anomalies as DRY periods and can be regarded as an extended DRY period or as a summer with increased occurrence of DRY episodes. HIGH summers, and to a lesser degree LOW + 1 summers, are characterized by broadly opposite atmospheric characteristics, featuring a more pronounced Bolivian High located significantly further south, and easterly wind anomalies over the Altiplano. In winter (JJA) precipitation events are rare; these are associated with increased northerly and westerly wind components, reduced pressure and temperature, and increased specific humidity over the entire Altiplano. Atmospheric circulation anomalies during LOW periods are less pronounced in austral winter (JJA) than in summer, but generally feature similar changes (increased temperatures and a vertically expanded troposphere). However, the significance of these anomalies, especially with regard to the wind pattern, varies depending on station and pressure level. Accordingly, precipitation during austral winter shows no relationship with the extremes of the Southern Oscillation. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: Altiplano; precipitation; Southern Oscillation; composite analysis

1. INTRODUCTION

The atmospheric circulation over the South American Altiplano in its seasonal and diurnal cycle has been investigated in a variety of studies. For some purposes, however, e.g. reconstruction of palaeoclimate or interpretation of proxy records, knowledge of the atmospheric circulation during climatic extremes might be more helpful, than analyses of seasonal or diurnal cycles. Accordingly, the aim of this study is to analyse the atmospheric circulation over the broader Altiplano region during extreme climatic periods, which are likely to be prominent in high-resolution proxy records from this area. The main purpose is to provide new information for the calibration of an ice core, recently recovered from Sajama volcano (6542 m, 18°06′S, 68°53′W), in the western Bolivian Andes (Thompson *et al*., 1998). The stratigraphy of this core is intrinsically linked to the climate and the atmospheric circulation during the deposition of the

* Correspondence to: Department of Geosciences, University of Massachusetts, Amherst, MA 01003-5820, USA. Tel.: + 1 413 545 0659; fax: + 1 413 545 1200; e-mail: mathias@geo.umass.edu

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snow (Hardy *et al.*, 1998). Therefore, the main emphasis of this study is on extended dry and wet periods and the El Niño–Southern Oscillation phenomenon (ENSO), which has been identified in other palaeo records from tropical Andean ice cores (Thompson *et al.*, 1984).

Sajama Volcano is the highest peak in Bolivia, located in the western Andean Cordillera in closest proximity to the Chilean border (Figure 1). The Andes is split up into an eastern and a western range between 15°S and 22°S, encompassing a large intramontane plateau, the Altiplano, with a mean height of 3500–4000 m. With its height extending into the middle troposphere, the Central Andes act as a barrier, effectively separating low level circulation to the east and west of the mountain range (see Figure 2(a) and (d)). To the west, the Southeast Pacific Anticyclone produces dry and stable conditions with subsiding air masses, and moist air remains trapped below the very stable inversion at about 900 hPa, resulting in the world's driest climate along the north Chilean coast. To the east, in the interior of the continent, a thermal heat low (Chaco low) develops during the summer months and the lower troposphere is characterized by warm and humid conditions. Sajama volcano is located in between these two distinct climatic patterns, experiencing varying influences from both sides of the Andes, depending upon the prevailing circulation. Precipitation on the Altiplano is associated with strong summer convection and daily moisture influx from the eastern interior of the continent (Fuenzalida and Ruttlant, 1987; Horel *et al.*, 1989; Garreaud and Wallace, 1997; Vuille *et al.*, 1998; Garreaud, 1999). More than 80% of the annual precipitation (350–400 mm) falls during the summer months December–March (Hardy *et al.*, 1998; Vuille *et al.*, 1998). 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). However, the episodic nature of precipitation on the Altiplano shows that while solar heating might be a prerequisite, additional forcing is necessary for precipitation to occur. Several authors have emphasized the crucial role played by the upper-air circulation in the timing and duration of precipitation events. Jacobeit (1992) has 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 the Bolivian High due to its climatological mean position over Bolivia in summer months (Schwerdtfeger, 1961; Virji, 1981). In Figure 2(b) and (c) the anticyclonic rotation about the high is clearly visible in the 500 and 200 hPa geopotential height and wind field. Many of the transient features of this Bolivian High could be reproduced by Silva

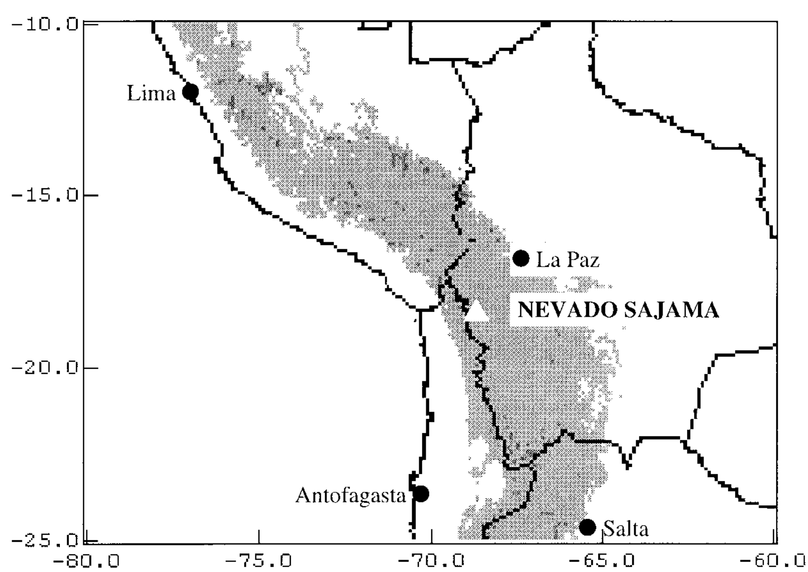

Figure 1. Map of the study area with location of Sajama Volcano (6542 m, 18°06′S, 68°53′W) and radiosonde stations. Altiplano (area above 3000 m) is shaded

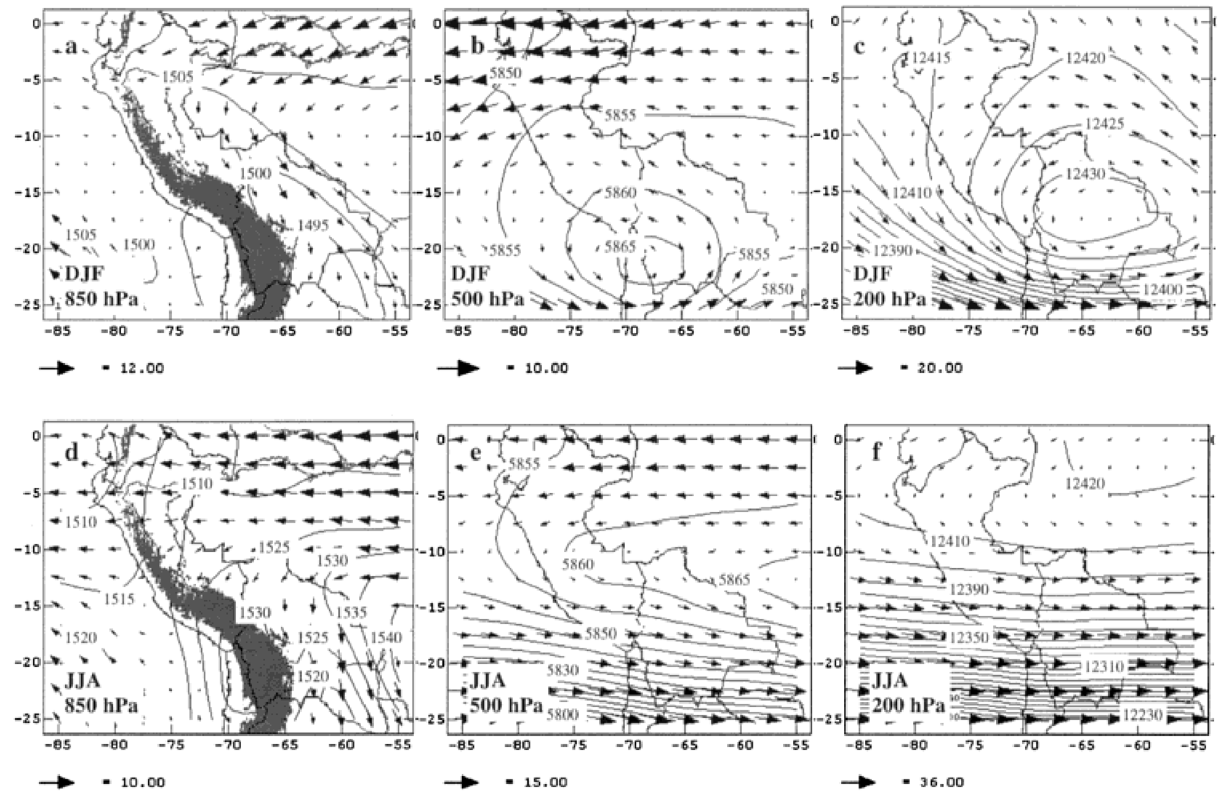

Figure 2. NCEP reanalysis long-term mean data of geopotential height and windfield for (a) summer (DJF) at 850 hPa; (b) as in (a) but for 500 hPa; (c) as in (a) but for 200 hPa; (d) winter (JJA) at 850 hPa; (e) as in (d) but for 500 hPa; and (f) as in (d) but for 200h Pa. At the 850 hPa level ((a) and (d)), the Andes (regions above 3000 m) are superimposed on the NCEP data as the shaded area

Dias *et al.* (1983) in a model simulation when using a continental heat source at 11°S. Their results suggest that the release of latent heat has a significant impact upon the upper-tropospheric circulation over tropical South America, and in particular upon the Bolivian High. Further modelling studies (e.g. Lenters and Cook, 1997) have since yielded additional evidence for the relationship between Bolivian High and latent heat release over the Amazon basin. However, the strength and positioning of this high pressure system is quite variable. As shown by Aceituno and Montecinos (1993) and Vuille *et al.* (1998) significantly higher precipitation amounts over the southern Altiplano are associated with a strengthened High, displaced southward from its climatological position. Garreaud (1999) recently presented a convincing linkage between large scale upper-air easterly winds over the Altiplano during rainy periods and the regional easterly upslope flow advecting moisture from the continental lowlands towards the Altiplano. His results suggest that the large scale upper-level easterly flow produces a turbulent entrainment of easterly momentum over the Andean ridge, thereby accelerating eastward upslope flow and moisture transport. 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, in association with strong westerly flow over the entire region (Figure 2(e) and (f)), interrupted only by occasional outbreaks of cold air masses from the planetary west wind zone. 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). Although rather rare, they can produce considerable amounts of snow, especially when cold air masses are cut-off from the general west wind flow and move over the Altiplano, thereby leading to a destabilization of the generally warmer atmospheric column. The low winter precipitation amounts reported from the sparse meteorological network in the area should therefore be interpreted with caution as they might represent an underestimation of the real amounts (Vuille and Ammann, 1997).

As a result of the convective nature of precipitation episodes in this arid part of the Bolivian Altiplano, the spatial variability is high (Ronchail, 1995). Therefore, only precipitation data from stations in the closest vicinity of Sajama volcano were used to determine the dry and wet periods for which the atmospheric circulation was analysed. Radiosonde data from the four closest stations with reliable and long enough records and monthly NCEP (National Centers for Environmental Prediction) reanalysis data were used to determine the atmospheric circulation during the corresponding periods. A similar approach was applied 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 radiosondes (Lima, Antofagasta and Quintero), the austral summer, and to a relatively short time period (1980–1987).

Several authors have analysed the relationship between ENSO and interannual climatic variability over the South American continent (e.g. Ropelewski and Halpert, 1987, 1989, 1996; Aceituno, 1988; Rogers, 1988; Aceituno, 1989; Kiladis and Diaz, 1989; Halpert and Ropelewski, 1992). 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 Central Andes, where this signal is spatially incoherent. 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 statistical confidence, however, varies considerably, depending on the area, data and time period that was analysed. Aceituno (1988) found a coherent pattern of weak positive correlations between the SO and precipitation over the Altiplano at the height of the rainy season (JF). 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 of Bolivia (Francou *et al.*, 1995), could also be attributed to climatic anomalies caused by El Niño. Ronchail (1999) showed that below average summer precipitation (JFMA) in the Bolivian Altiplano is frequent during negative phases of the SO (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 SO. They can occur during extreme phases of the SO, as well as during normal years. The relationship between Altiplano precipitation and ENSO has become of growing interest as El Niño events seem to become more frequent since the late 1970s, probably linked to decadal-scale climate changes in the Pacific domain (Trenberth and Hoar, 1996). The decadal-scale precipitation variability over the Bolivian Altiplano, however, shows a distinct disruption with significantly increased precipitation amounts between the early 1970s and the late 1980s (Ronchail, 1999). Although the relationship between ENSO, precipitation and atmospheric circulation over the Altiplano will only be discussed based on data from the last decades, one can assume, that similar mechanisms have functioned in the past. On Quelccaya Ice Cap in the Peruvian Andes the ENSO signal in the δ^{18}O record has remained stable over at least the last millennium (Diaz and Pulwarty, 1994).

In the following section the data and methods that were applied in this study are described. The section after this presents the results from the analysis of the radiosonde and NCEP reanalysis data during WET and DRY episodes during the summer and winter months. The section 'Atmospheric Circulation during High and Low Index Phases' is similar to the previous section but discusses the results for LOW- (El Niño) and HIGH-index phases of the Southern Oscillation (La Niña), respectively. The last section discusses the results presented in the previous sections, summarizes this study and presents some conclusions.

2. DATA AND METHODS

As precipitation on the dry western Altiplano has a very episodic nature, this study is based on both daily (radiosonde) and monthly (NCEP reanalysis) data. Wet periods normally last only a few days and are preceded and followed by dry periods without precipitation (Aceituno and Montecinos, 1993). Daily data therefore can help to resolve some atmospheric features associated with precipitation events, that might be masked when using monthly data alone.

Daily precipitation data from six Altiplano stations in the closest vicinity of Volcano Sajama were obtained from the Chilean National Direction of Waters (Dirección General de Aguas, Santiago, Chile) and the Bolivian National Meteorological and Hydrological Institute (Servicio Nacional de Meteorología e Hidrología, La Paz, Bolivia). Station names and the length of each record are given in Table I.

Upper-air data from the four stations closest to Nevado Sajama were 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 I and station locations are shown in Figure 1. From each station record, daily data at 12:00 UTC (except Lima where only data at 00:00 UTC were available) were extracted, including geopotential height (gpm), air temperature (°C), relative humidity (%), wind direction (°) and wind speed (m s^{-1}) for the standard pressure levels 850, 700, 500, 400, 300 and 200 hPa (except for La Paz, where 850 and 700 hPa would be rather meaningless and for relative humidity where no data was available at the 200 hPa level). From these original data, zonal and meridional wind components (m s^{-1}) and specific humidity (g kg^{-1}) were derived.

Monthly NCEP reanalysis data (Kalnay *et al*., 1996) of air temperature, geopotential height and zonal and meridional wind component were extracted from the original data set at the 850, 700, 500, 300 and 200 hPa level and for specific humidity at the 700, 500 and 300 hPa level. An additional variable, horizontal water vapour flux (g s^{-1} m^{-2}), was computed for the 700, 500 and 300 hPa level based on specific humidity, zonal and meridional wind and air density (e.g. Berri and Inzunza, 1993; Rao *et al*., 1996, 1998). Rao *et al*. (1998) have shown that NCEP reanalysis data is able to capture the general characteristics of moisture transport during El Niño and La Niña years, using vertically integrated water vapour flux.

In a first step, daily precipitation amounts were analysed for the summer months December–February (DJF) and the winter months June–August (JJA) between 1960 and 1993, although some stations had considerably shorter records (Table I). DJF represents the main precipitation period, while JJA is normally dry, but also characterized by occasional polar outbreaks of the west wind zone leading to rare but significant winter precipitation. Each day was classified as either WET, DRY or neutral. WET

Table I. Location and temporal coverage of precipitation and radiosonde data

Station name	Latitude (°S)	Longitude (°W)	Elevation (m a.s.1.)	Length of record
(a) Precipitation data				
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
(b) Radiosonde data				
Lima—Callao	12.00	77.12	11	1962–1992
LaPaz—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 II. HIGH (SOI > 1), LOW (SOI < −2) and LOW + 1 (DJF following a LOW episode and SOI > −1) index years for DJF and JJA (HIGH and LOW only)

Period	Events
(a) DJF	
LOW	**1958–1959**, 1972–1973, 1977–1978, 1982–1983, 1986–1987, 1991–1992, *1997–1998*
LOW + 1	**1959–1960**, 1973–1974, 1978–1979, 1983–1984, 1987–1988, *1993–1994*
HIGH	1961–1962, 1966–1967, 1970–1971, 1973–1974, 1975–1976, 1988–1989, *1996–1997*
(b) JJA	
LOW	1965, 1972, 1977, 1982, 1987, *1993*, *1994*, *1997*
HIGH	1964, 1973, 1975, 1981, 1988, *1996*

Periods in bold are covered by radiosonde data only, periods in italics by NCEP reanalysis data only.

includes periods when all stations recorded at least 0.5 mm day^{-1} over five or more consecutive days (DJF), or over at least 2 days (JJA). This differentiation between DJF and JJA was necessary because precipitation is very rare, and of short duration, during the winter months—no events would have met the 5 day summer criteria. DRY includes all periods of at least 5 days without precipitation at all stations (for both DJF and JJA). This procedure yielded 475 (425) days for WET (DRY) in DJF and 140 (2416) days for WET (DRY) in JJA between 1960 and 1993.

The corresponding data for WET and DRY were then extracted from the upper-air sounding records for both DJF and JJA. However, only the records from Antofagasta, Lima and Salta cover most of the WET and DRY periods, as the La Paz record is considerably shorter (Table I). Arithmetic means and standard deviations were computed for each parameter and a two-tailed Student's t-test was performed in order to evaluate significant differences in the atmospheric variables during DRY and WET periods for both the summer (DJF) and winter (JJA) months.

The same analysis was also applied to the NCEP reanalysis data, however on a monthly basis. Composites were built for all summers (DJF) when precipitation records near Sajama indicate anomalies above (WET) or below (DRY) one standard deviation, compared to the long-term mean. This procedure yielded four wet summers (1971–1972, 1972–1973, 1974–1975 and 1985–1986) forming the NCEP WET composite, and four dry summers (1965–1966, 1982–1983, 1989–1990 and 1991–1992) forming the NCEP DRY composite. This analysis was applied to austral summer only, since the temporal resolution of the monthly NCEP data used in this study would not allow to resolve the few and rare winter precipitation events, preceded and followed by extended dry periods.

Besides the classification into WET and DRY, both the CARDS and the NCEP data were also analysed as a function of HIGH and LOW index phases of the Southern Oscillation (standardized pressure difference between Tahiti and Darwin, using 1951–1980 as base period) obtained from the Climate Prediction Center (NOAA-CPC). Three-monthly SOI averages were computed for DJF and JJA and all periods for which SOI > 1 (HIGH) and SOI < −2 (LOW) were retained. The selected HIGH and LOW index phases for DJF and JJA are listed in Table II. The thresholds of 1 and −2 for the standardized SOI anomalies are somewhat arbitrary but yielded an equal number of seven strong HIGH and LOW index DJF periods since 1958, the first year with radiosonde data. However, as for the WET-DRY analysis, the La Paz record is considerably shorter and only covers four HIGH and LOW index phases. Only the SOI and no SST index (e.g. NINO3) was used, and only the three summer (winter) months DJF (JJA) were considered. Therefore, some of the extracted events differ from time periods commonly considered to be El Niño/La Niña events, mainly because SOI and SST anomalies in the Pacific have not been highly correlated at all times during the last decades (Deser and Wallace, 1987). Three-monthly composites were built for both HIGH and LOW phases during DJF and JJA and a two-tailed Student's t-test performed on all parameters of the radiosonde data to see whether significant changes occur in the atmospheric circulation between the two extreme phases of the Southern Oscillation.

Again a similar analysis was carried out based on the NCEP reanalysis data. Monthly anomalies were computed by subtracting the long-term monthly mean (1960–1998) and anomaly composites for the same

HIGH and LOW index phases were created. Again the NCEP analysis was applied to austral summer (DJF) only, since the results from the radiosonde analysis suggested only a weak relationship between the atmospheric circulation during JJA and the SO (see section 'Austral winter (JJA)'). In some areas the tropical Andes tend to be anomalously wet in summers following an ENSO event (e.g. Henderson, 1996), henceforth referred to as LOW + 1. This increased precipitation can presumably be attributed to a climatic response of the tropical Atlantic to the Pacific ENSO signal and hence increased easterly moisture influx towards the Andes (e.g. Enfield, 1996). In order to account for this possible phase-lag relationship, an additional composite was created (LOW + 1), including all DJF periods following a LOW index phase, after the SOI had started to rise again (first DJF when $\mathrm{SOI} > -1$). All anomaly composites, including water vapour flux, were compared with the long-term mean and tested for significance using a two-tailed Student's t-test.

3. ATMOSPHERIC CIRCULATION DURING DRY AND WET PERIODS

The results from the composite analysis of DRY and WET periods in the Nevado Sajama area are presented in Figures 3–6. Results are discussed separately for summer (DJF) and winter (JJA). Emphasis is on middle and upper tropospheric levels, as 850 and 700 hPa are strongly influenced by diurnal cycles and boundary layer processes, which are of less relevance to this study.

3.1. Austral summer (DJF)

The most coherent pattern during WET periods in austral summer (DJF) is the more negative zonal wind component over the entire Altiplano (Figure 3(a)). All four radiosonde stations show significantly lower zonal wind values during WET as compared to DRY periods in the middle and upper troposphere. This confirms earlier results by Aceituno and Montecinos (1993) and Garreaud (1999), which show that precipitation events over the western Altiplano during austral summer are strictly tied to easterly wind anomalies. However, it is interesting to see that these easterlies (or weakened westerlies in the case of Antofagasta and Salta) are present and significant at all levels, not only at the 500 hPa level where major moisture advection towards the western Altiplano takes place (Aceituno and Montecinos, 1996). It is further noteworthy that the circulation anomalies associated with precipitation events in the Sajama region are obviously of a larger scale, as the associated wind anomalies can be traced in radiosonde data far away from Nevado Sajama. The meridional wind (Figure 3(b)) also shows a very interesting pattern, with an increased southerly component to the east of the Altiplano (Salta and La Paz) and an increased northerly component to the west (Lima). Differences over Antofagasta are insignificant. As mentioned earlier, summer precipitation over the Altiplano is generally associated with upper-air anticyclonic outflow from a high pressure system (Bolivian High). Accordingly, as this anticyclone intensifies and moves southward during precipitation events, winds to the east of the Altiplano become more southerly, while to the west a more northerly component prevails. This interpretation is further supported by the analysis of the geopotential height pattern (Figure 3(c)). While the geopotential height is significantly increased over the southernmost Altiplano (Antofagasta and Salta) in the middle and upper troposphere during WET, the change is insignificant over the central Altiplano (La Paz), but negative to the north over Lima. This is consistent with the picture of a southward displacement and intensification of the Bolivian High during precipitation events on Nevado Sajama. Mid-tropospheric temperatures increase significantly during precipitation events over the Altiplano due to latent heat release (Figure 3(d)), which is consistent with similar results obtained by Aceituno and Montecinos (1993), and decrease at the 200 hPa level. The change in the large-scale atmospheric circulation from DRY to WET periods also affects the humidity levels recorded over the four stations. Instead of presenting the measured relative humidity, a more conservative value, the specific humidity is shown in Figure 3(e). Not surprisingly, increased humidity values show up throughout the entire troposphere in all four radiosonde records during WET periods over the Sajama area, confirming the large-scale nature of these events.

Figures 4 and 5 show the same analysis based on monthly NCEP reanalysis data. Although monthly data might mask some of the differences between dry and wet periods, which last only a few days, the results are in good agreement with those obtained from the daily radiosonde data. Figure 4(a–c) shows the easterly wind anomalies during WET, when compared to DRY. These anomalies become more significant with increasing height. At the 200 hPa level easterly anomalies dominate over the entire Peru–Bolivian Altiplano (Figure 4(c)). The geopotential height difference in Figure 4(e–f) also confirms the radiosonde data, by featuring an increase at mid- and upper-tropospheric levels over the southern

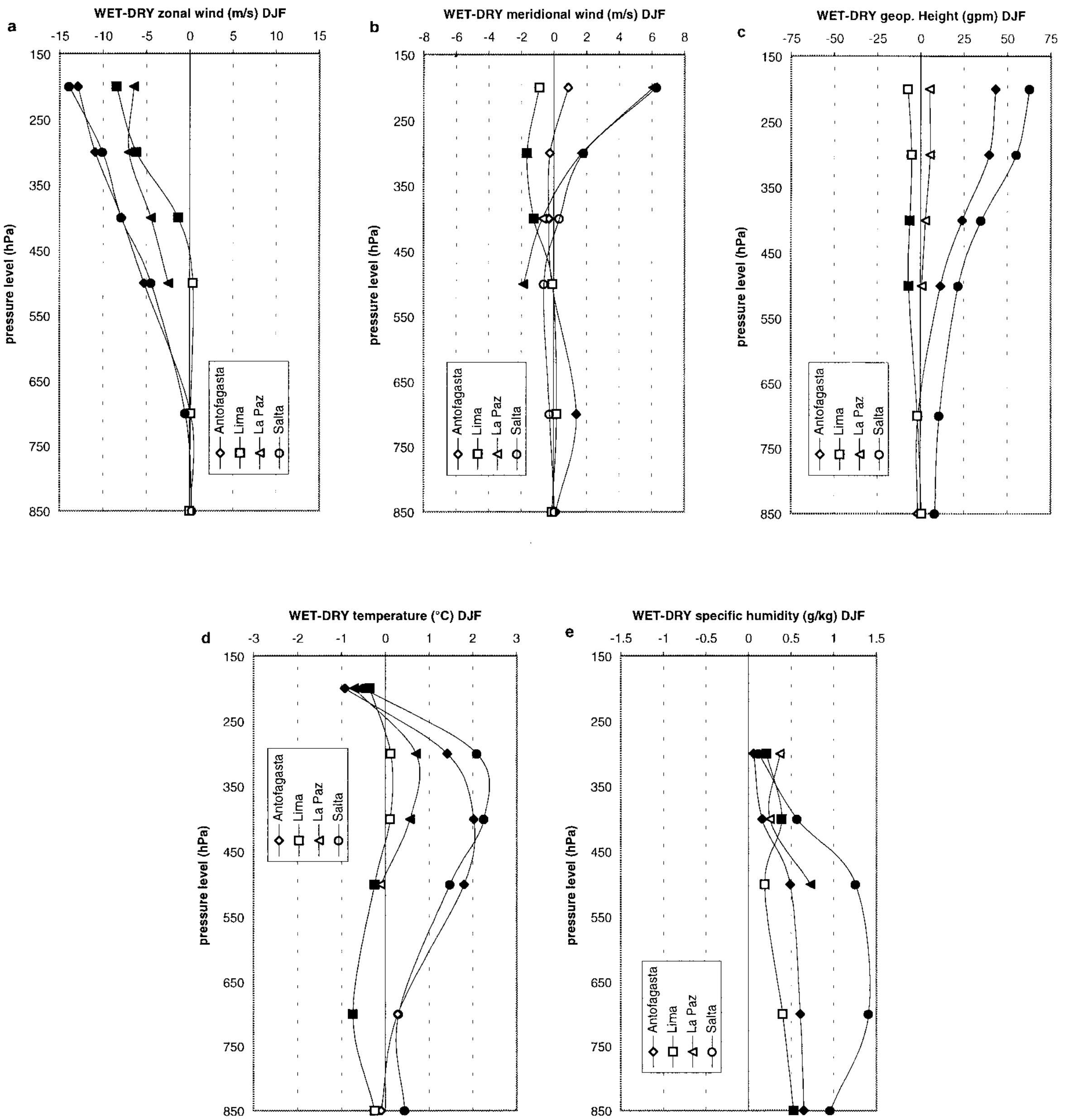

Figure 3. WET-DRY summer (DJF) composite from daily radiosonde data for: (a) zonal wind component (m s^{-1}); (b) meridional wind component (m s^{-1}); (c) geopotential height (gpm); (d) air temperature (°C); and (e) specific humidity (g kg^{-1}) over Antofagasta, Salta, Lima and La Paz. Filled markers indicate significant difference at the 95% level between WET and DRY composite

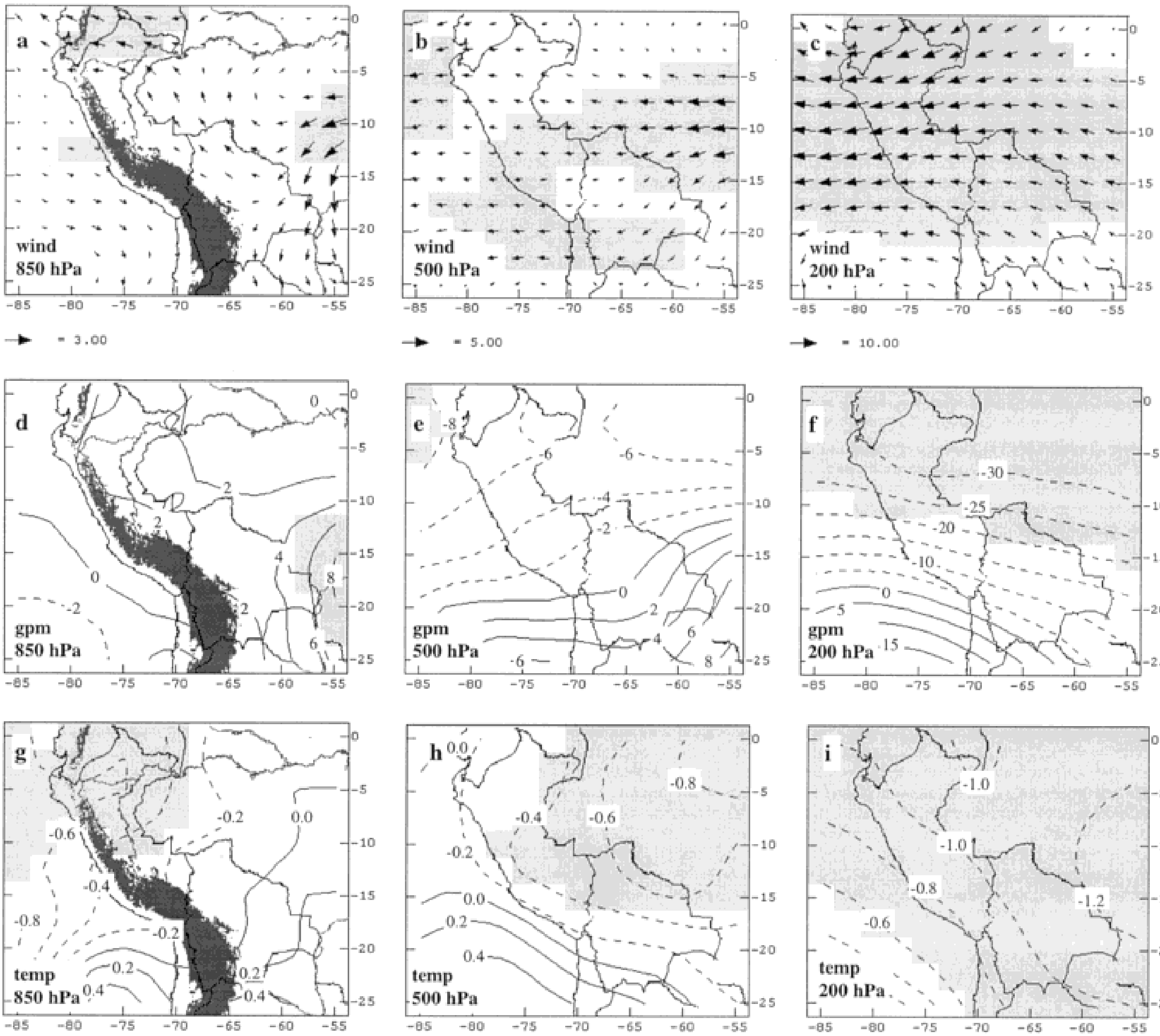

Figure 4. WET-DRY summer (DJF) composite from monthly NCEP reanalysis data showing: (a) windfield at 850 hPa (m s^{-1}); (b) as in (a) but for 500 hPa; (c) as in (a) but for 200 hPa; (d) geopotential height (gpm) at 850 hPa; (e) as in (d) but for 500 hPa; (f) as in (d) but for 200 hPa; (g) air temperature (°C) for 850 hPa; (h) as in (g) but for 500 hPa; and (i) as in (g) but for 200 hPa. Negative contour lines are dashed. Shaded grid boxes indicate areas with significant difference at the 95% level between WET and DRY composite. At the 850 hPa level ((a), (d) and (g)), the Andes are superimposed on the NCEP data as the shaded area above 3000 m

Altiplano and a decrease over the northern part of the study area. Although the difference between WET and DRY is significant in the northern part and at the 200 hPa level only, the pattern confirms the notion of a southward displaced Bolivian High. This displacement is also evident in the individual WET and DRY composites (not shown). Temperature is lowered during WET as compared to DRY over the entire study area at the 200 hPa level (Figure 4(i)), and over the northern part at the 500 hPa level (Figure 4(h)), consistent with the radiosonde data (see Figure 3(d)). An additional measure in terms of the origin of the humidity is provided by the computation of the water vapour flux. Figure 5 shows the water vapour transport over the Altiplano during WET (Figure 5(a–c)) and DRY (Figure 5(d–f)) at the 700, 500 and 300 hPa level. To simplify the interpretation, the actual DRY and WET composites are shown, rather than the difference between the two. Note that Figure 5 is zoomed in and shows a smaller region (10°S–25°S; 75°W–55°W) than Figure 4. Both the 500 and the 300 hPa level show a strengthened

Bolivian High during WET with increased easterly winds to the north of the anticyclone. Accordingly, moisture influx from the east is significantly enhanced during WET, when compared with DRY. Although the differences between WET and DRY are more significant at the 300 hPa level, the absolute values show that moisture advection takes place in lower levels and not in the upper troposphere. At the 700 hPa level increased moisture convergence occurs to the east of the Altiplano during WET, when the NW Andean low-level jet and easterly winds originating over southern Brazil converge over eastern Bolivia (Figure 5(a)). This moisture convergence leads to vertical motion and increased convection along the eastern Andean foothill. During DRY this easterly water vapour flux over southwestern Brazil is completely absent and water vapour flux is directed away from the Andes (Figure 5(d)).

3.2. Austral winter (JJA)

The atmospheric circulation over the Altiplano during austral winter (JJA) is characterized by strong and steady westerly and northwesterly winds associated with a northward shift of the planetary west wind zone (Figure 2(e) and (f)). Although this period is usually dry, the few winter precipitation events (WET) show some characteristics that are significantly different from the normal DRY conditions. The most remarkable feature associated with these precipitation events is the increase in wind speed. Although the wind direction (northwest) remains the same, the increased wind velocity and accordingly both higher zonal and lower (more negative) meridional wind components can be observed over the entire Altiplano region (Figure 6(a) and (b)). Antofagasta, Salta, Lima and La Paz all show higher zonal wind components during WET, all significant at the 95% level except the station furthest to the northeast (La Paz). This clearly demonstrates the origin of these events; they are related to outbursts of cold polar air from the

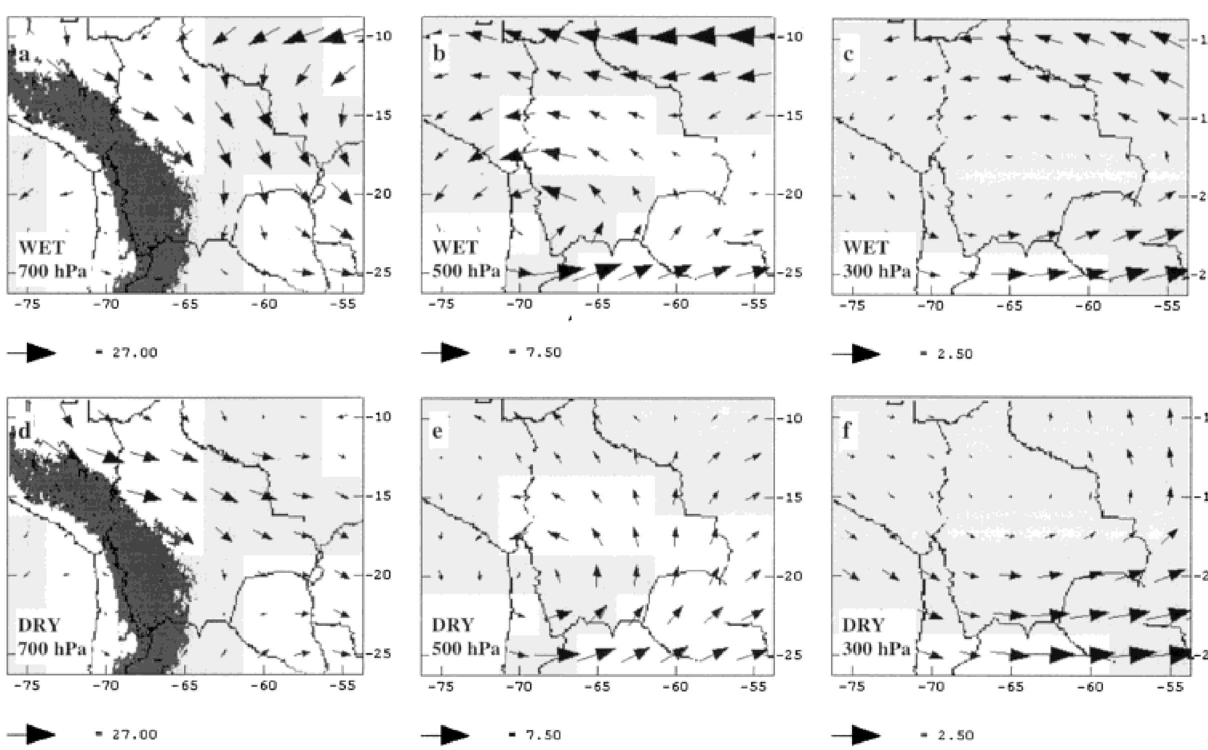

Figure 5. DJF water vapour flux (g s^{-1} m^{-2}) composites from NCEP reanalysis data showing: (a) WET composite at 700 hPa; (b) as in (a) but for 500 hPa; (c) as in (a) but for 300 hPa; (d) as in (a) but for DRY composite; (e) as in (d) but for 500 hPa; and (f) as in (d) but for 300 hPa. Shaded grid boxes indicate areas with significant difference at the 95% level between WET and DRY composite. At the 700 hPa level ((a) and (d)), the Andes (regions above 3000 m) are superimposed on the NCEP data as the shaded area

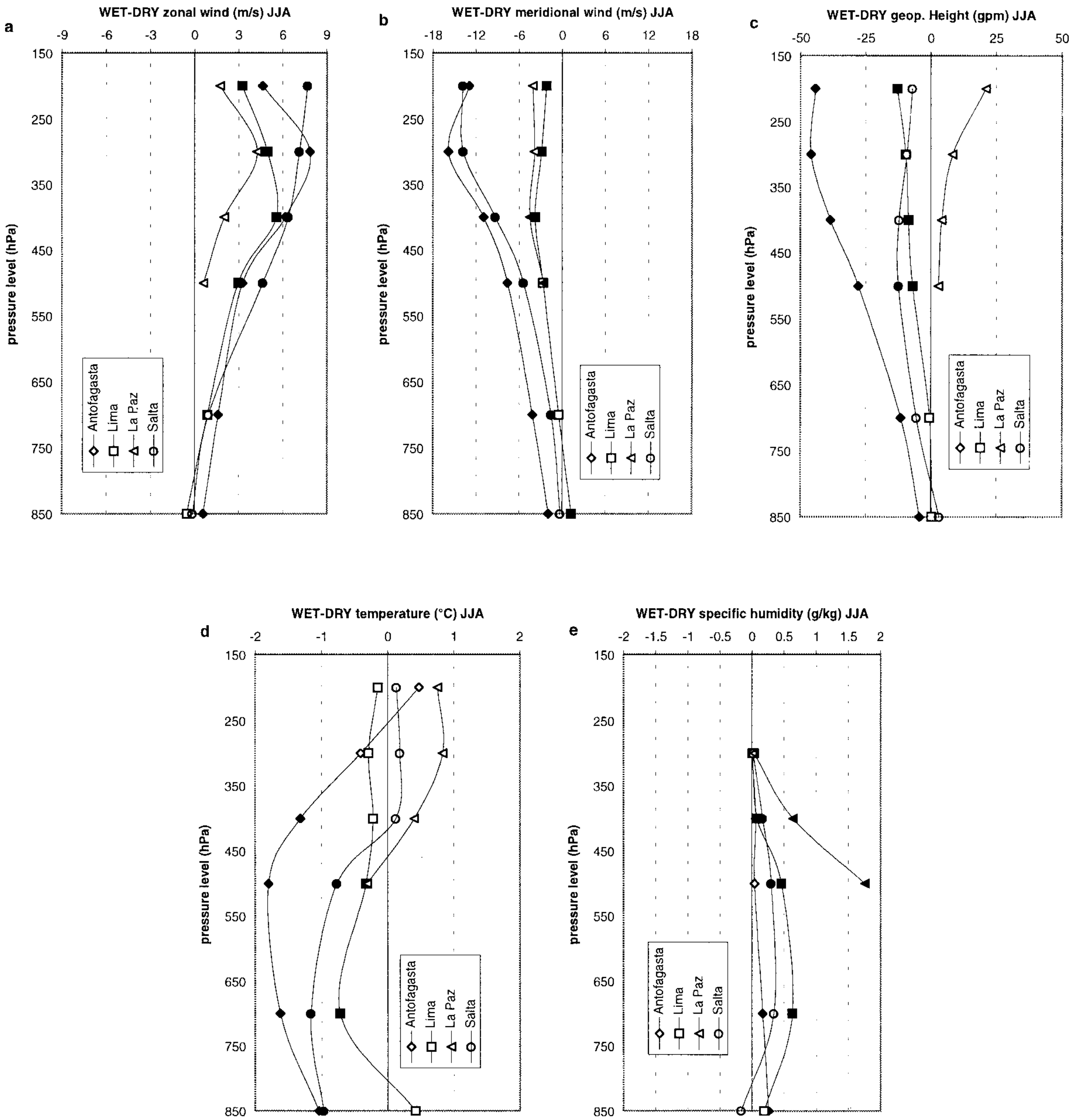

Figure 6. As in Figure 3 but for austral winter (JJA)

west wind zone, mainly affecting the southern and western parts of the Altiplano. The meridional wind shows a similar behaviour during WET, with lowered (more negative) values, indicating the increased northerly component. Here even La Paz shows significant changes in the meridional component in mid-tropospheric levels. The geopotential height is significantly lower during these WET episodes at all pressure levels to the west and south of the Altiplano (Antofagasta, Salta and Lima) but higher (although insignificant) over La Paz (Figure 6(c)). Accordingly during JJA WET episodes on Sajama a strengthened NE–SW pressure gradient is established over the Altiplano and is responsible for the increase in wind speed. These results are in good agreement with previous studies on winter precipitation in this region by Vuille and Ammann (1997), based on GOES satellite and ECMWF reanalysis data, showing that these events are associated with northward displaced extra-tropical cold front passages or cut-off low pressure systems. Temperatures are significantly lower in low- and mid-tropospheric levels over Antofagasta, Lima and Salta (Figure 6(d)) during WET episodes, confirming the cold, extratropical nature of these events. Figure 6(e) shows the specific humidity change between WET and DRY periods, respectively. Although humidity levels are considerably lower than during summer months, the increase during WET is still significant when compared to DRY over the entire Altiplano in mid-tropospheric levels. In strong contrast to the summer months, however, the main water vapour transport during WET in the winter (JJA) occurs with northwesterly winds.

4. ATMOSPHERIC CIRCULATION DURING HIGH AND LOW INDEX PHASES

4.1. Austral summer (DJF)

Figure 7 shows the DJF precipitation amounts and one standard deviation for Cosapa, Cotacotani and Chucuyo (see Table I) during HIGH, LOW and LOW + 1, compared to the long-term mean. Although amounts tend to be lower during LOW and higher during HIGH and LOW + 1, none of the anomalies are significant at the 95% level (two tailed Student's t-test). This result confirms the rather weak tendency towards below average precipitation during El Niño summers on the Bolivian Altiplano reported by Ronchail (1999). In addition, La Niña summers and summers following an El Niño period appear to be associated with slightly increased rainfall.

The associated changes in the atmospheric circulation are presented in Figures 8–14 in the same way as in the previous section. Figure 8(a) and (b) show increased easterly and southerly (except for Lima) wind components during HIGH, when compared to LOW. Accordingly, reduced summer precipitation amounts during LOW phases are obviously the result of increased northwesterly wind anomalies, which prevent humid air masses from the eastern interior of the continent to penetrate into the Sajama area. Strengthened westerly wind anomalies (weakened easterlies) are very pronounced over Lima, where the zonal wind component is significantly increased (95% level) at all levels between 500 and 200 hPa during LOW as compared to HIGH. Over Antofagasta and Salta the difference is only significant at the 200 hPa level, while over La Paz westerly wind anomalies are significantly increased in mid-tropospheric levels (500, 400 hPa) during LOW. The meridional wind component shows significantly lower values (increased northerly component) between 200 and 500 hPa (Antofagasta), and 200 and 300 hPa (Salta and La Paz) during LOW as compared to HIGH (Figure 8(b)). Lima is the only station where the northerly wind

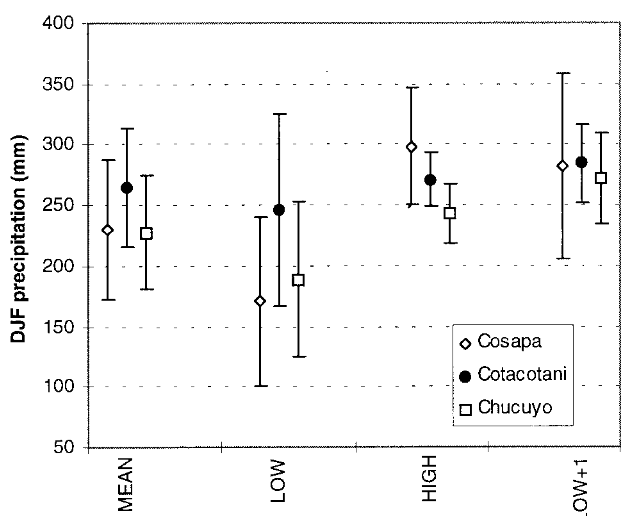

Figure 7. DJF precipitation amounts (mm) for Cosapa, Cotacotani and Chucuyo during LOW, HIGH and LOW + 1 periods, compared to the long-term mean. Error bars indicate 1 standard deviation

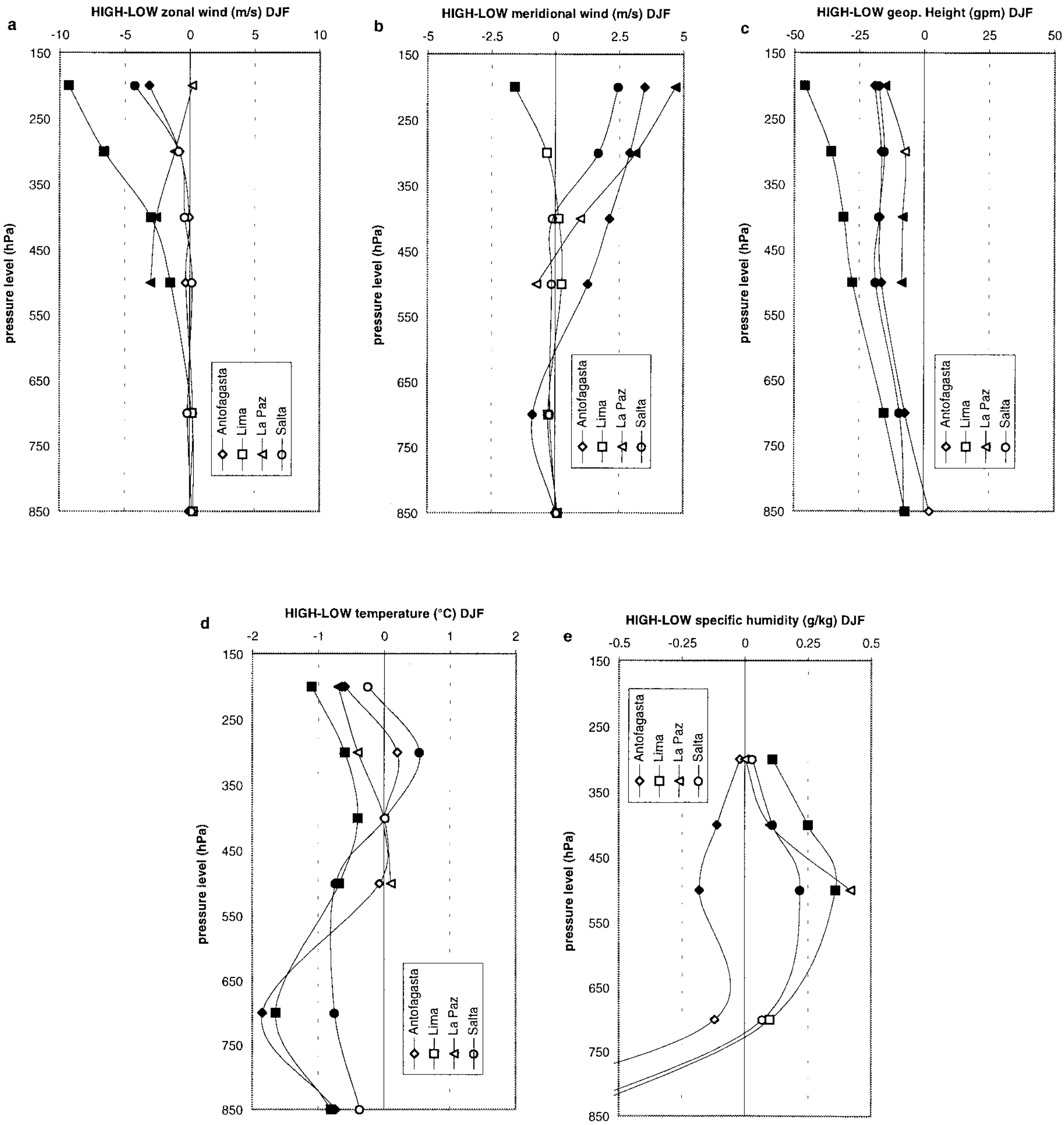

Figure 8. HIGH-LOW index summer (DJF) composite from daily radiosonde data for the: (a) zonal wind component (m s^{-1}); (b) meridional wind component (m s^{-1}); (c) geopotential height (gpm); (d) air temperature (°C); and (e) specific humidity (g kg^{-1}) over Antofagasta, Salta, Lima and La Paz. Filled markers indicate significant difference at the 95% level between WET and DRY

component is weakened during LOW, associated with a northward retreat and weakening of the Bolivian High during El Niño summers. This change in the position of the anticyclone and the associated change in the wind pattern is shown for the LOW, HIGH and LOW + 1 composites at the 200 hPa level in Figure 9. Although geopotential height values are significantly higher at all levels between 700 and 200 hPa over the entire Altiplano during LOW index phases and significantly lower during HIGH index summers (Figure 8(c), Figure 10(b), (c), (e) and (f)), the increased geopotential height is clearly 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 HIGH, when the Bolivian High is intensified and located further to the south (Figure 9(b)). This pressure gradient leads to enhanced upper-air easterlies, entrainment of easterly momentum over the Andean ridge, increased eastward upslope flow and moisture transport from the interior of the continent towards the western Altiplano (Garreaud, 1999). Figure 11(e–f) shows that HIGH index summers are indeed associated with negative zonal wind anomalies over major parts of the Altiplano, although significant only at the 200 hPa level. The opposite patterns emerges during LOW index periods when the zonal wind component is significantly higher than normal (westerly anomalies) at the 200 hPa level over the Altiplano, the adjacent Pacific and the tropical lowlands to the northeast (Figure 11(c)). In the lower troposphere stronger easterly trade winds prevail during LOW in the western part of the Amazon basin (Figure 11(a)). In the rest of the study area, low-level wind anomalies are insignificant in all composites. Interestingly the geopotential height and wind pattern during LOW + 1 (Figure 9(c)) resembles the HIGH pattern (Figure 9(b)), although only one summer falls into both categories (1973–1974, see Table II). The similar pattern might explain why many post-El Niño years (LOW + 1) tend to be rather wet, however, both wind and geopotential height anomalies during these years are insignificant over most parts of the Altiplano at both the 500 and 200 hPa levels (see Figure 10(h–i) and Figure 11(h–i)).

The temperature data (Figure 8(d)) show the typical characteristics of the Tropics during Pacific warm events (e.g. Aceituno, 1988, 1989; Karoly, 1989; Kiladis and Diaz, 1989), featuring a significant increase during LOW as compared to HIGH. Associated with the warm and vertically expanded troposphere are increased temperatures, although their 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 and 700 hPa), while Salta shows significantly higher temperatures at lower and mid-tropospheric levels (700 and 500 hPa) but a reversed pattern at 300 hPa. The NCEP data confirm these results, showing significant positive (negative) temperature anomalies during LOW (HIGH) over almost the entire study area at the 850, 500 and 200 hPa level (Figure 12(a–f)). Again during LOW + 1 temperature anomalies are insignificant in all of the study area (Figure 12(g–i)).

Changes in specific humidity recorded over the four stations (Figure 8(e)) are the result of the wind pattern presented above. As high humidity levels over the Altiplano are strictly tied to moisture influx from the east during austral summer, the increased westerly wind component during LOW index periods results in significantly lowered humidity values. Figure 8(e) shows the reduced specific humidity in mid-tropospheric levels with lower values over Lima (significant between 300 and 500 hPa), Salta (significant at 500 and 400 hPa) and La Paz (not significant) during LOW index phases. Only over Antofagasta and near the boundary layer (850 hPa level) humidity values are slightly increased during LOW. The water vapour flux computed from the NCEP data near and over the Altiplano confirms these results (Figure 13). As in Figure 5 the individual composites, rather than anomaly patterns are shown to

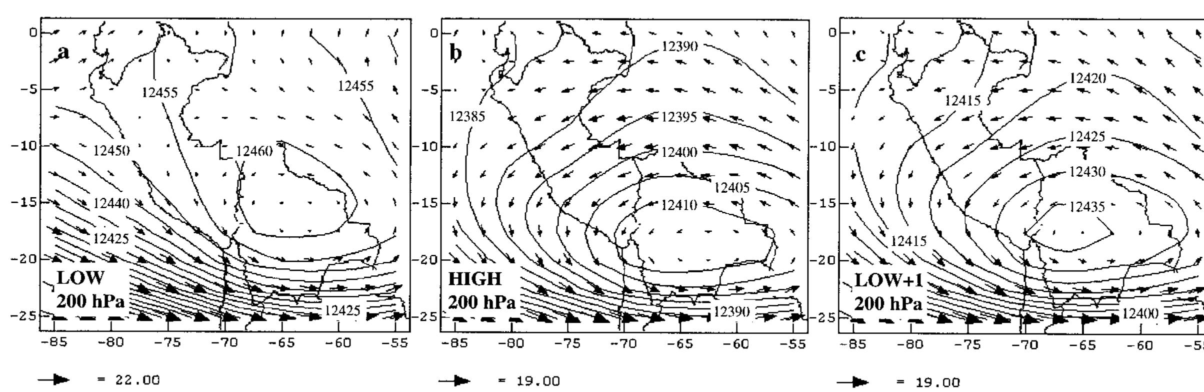

Figure 9. 200 hPa NCEP reanalysis composites for wind field (m s^{-1}) and geopotential height (gpm) in austral summer (DJF) during: (a) LOW; (b) HIGH; and (c) LOW + 1 periods

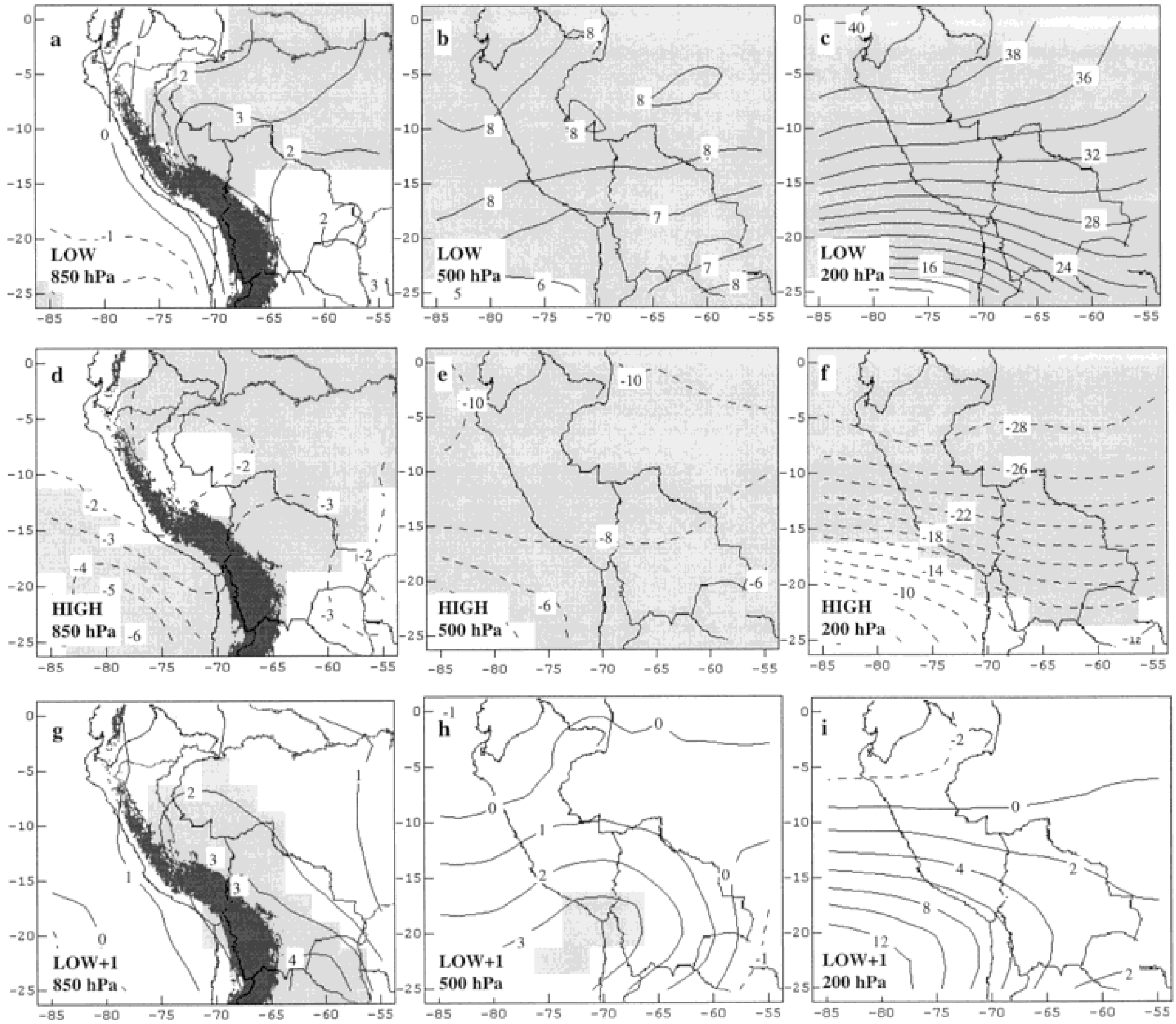

Figure 10. Geopotential height (gpm) anomaly fields (deviation from long-term mean) during austral summer (DJF) for: (a) LOW and 850 hPa; (b) as in (a) but for 500 hPa; (c) as in (a) but for 200 hPa; (d) HIGH and 850 hPa; (e) as in (d) but for 500 hPa; (f) as in (d) but for 200 hPa; (g) LOW + 1 and 850 hPa; (h) as in (g) but for 500 hPa; and (i) as in (g) but for 200 hPa. Negative contour lines are dashed. Shaded grid boxes indicate areas with significant anomalies at the 95% level. At the 850 hPa level ((a), (d) and (g)), the Andes (regions above 3000 m) are superimposed on the NCEP data as the shaded area

simplify the interpretation. The long-term mean DJF water vapour flux is shown in Figure 13(a–c) for comparison. The weakening and northward displacement of the Bolivian High during LOW leads to a significant reduction of the water vapour flux over the northern part of the Altiplano (Figure 13(e–f)), very similar to the situation observed during DRY (compare with Figure 5(e–f)). On the other hand moisture flux is increased over the Altiplano during HIGH (Figure 13(h–i)) and LOW + 1 (Figure 13(k–l)), although the anomalies do not reach statistical significance at all levels and over the entire study area. At the 700 hPa level the flow from the NW along the eastern Andean slope is reduced during HIGH (Figure 13(g)) when compared to LOW or the long-term mean. On the other hand an increased northerly component leads to enhanced moisture convergence over the eastern Bolivian lowlands during LOW + 1 (Figure 13(j)), similar to the WET composite (Figure 5(a)).

4.2. Austral winter (JJA)

Precipitation events in austral winter are rare in the Altiplano and the recorded amounts are sometimes very dubious (Vuille and Ammann, 1997). In addition, the Southern Oscillation tends to peak during austral summer, and exhibits less extreme values during the winter months. Accordingly it is no surprise that precipitation data from the stations near Nevado Sajama show no relationship with the Southern Oscillation during austral winter months (JJA, not shown). Changes in the atmospheric circulation between HIGH and LOW index phases are also less pronounced and the patterns generally less consistent between the analysed records. Therefore, only results from the radiosonde analysis are presented here. Most obvious are the increased temperatures (Figure 14(d)) and the vertically expanded troposphere (increase in geopotential height, Figure 14(c)) during LOW as compared to HIGH, consistent with results by Aceituno (1989), who reports that the atmospheric response during LOW periods in austral winter is

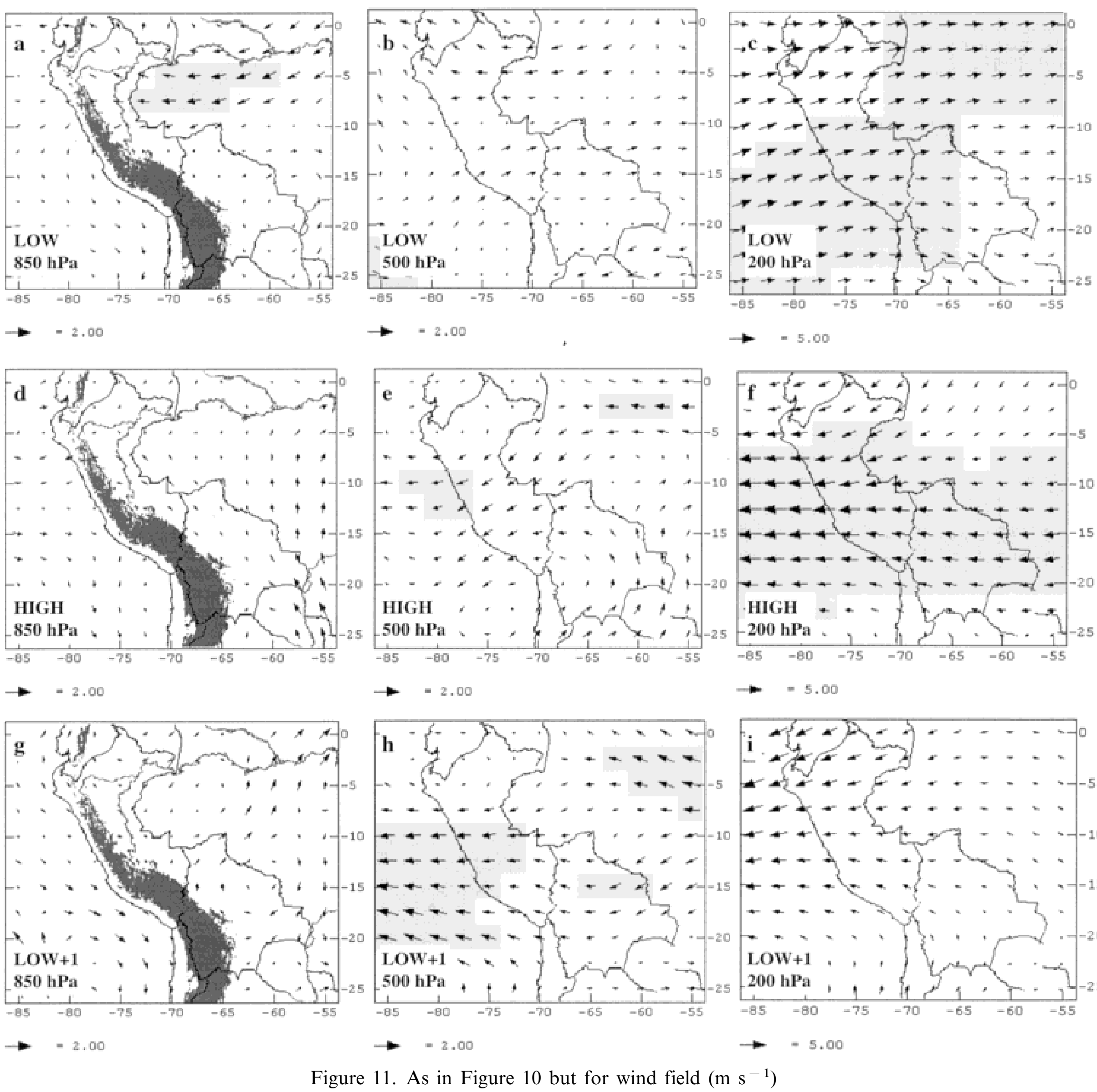

Figure 11. As in Figure 10 but for wind field (m s^{-1})

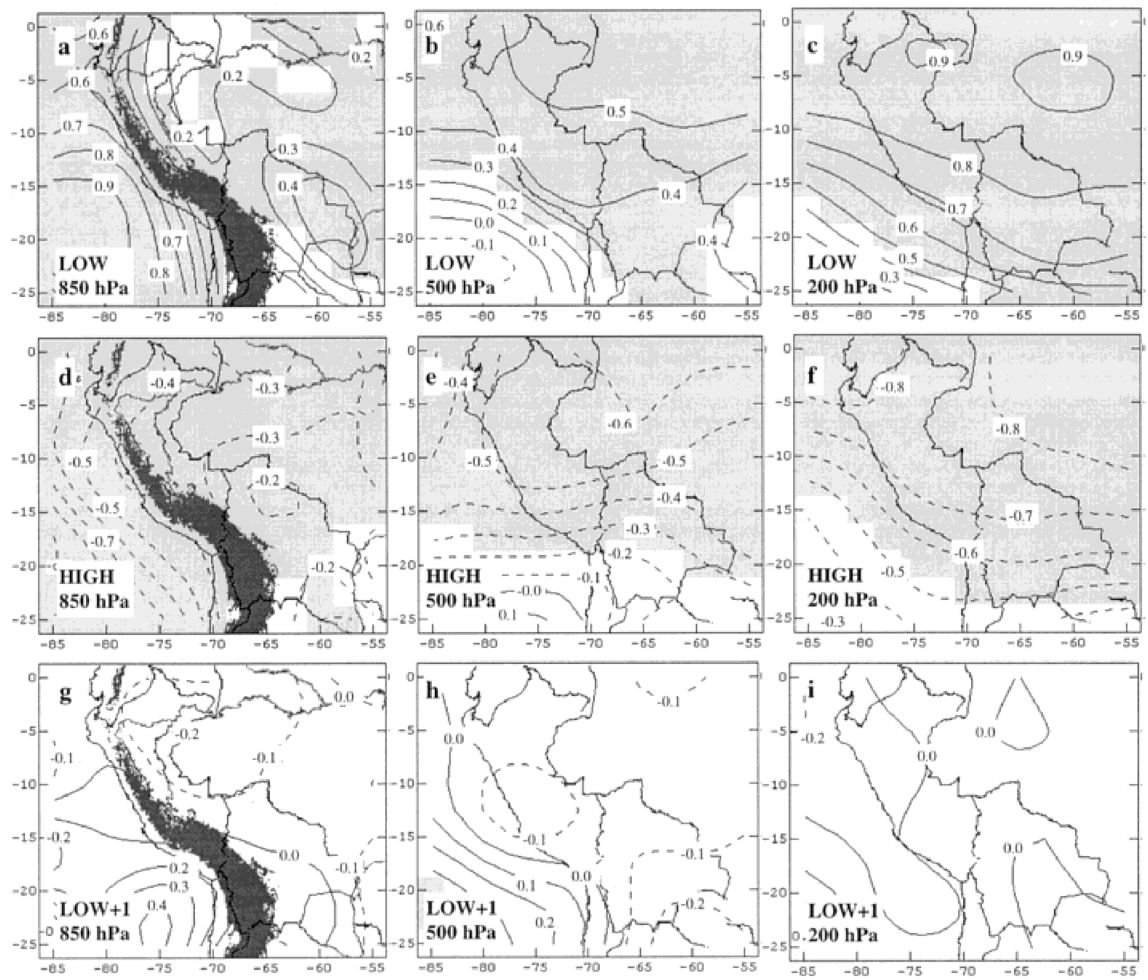

Figure 12. As in Figure 10 but for air temperature (°C)

in broad agreement with the response in austral summer. Lima is the only station which does not agree with this pattern, featuring slightly decreased (increased) geopotential height values and lower (higher) mid-tropospheric temperatures during LOW (HIGH). The wind pattern shows a less evident picture, featuring reduced zonal wind components over the southern stations Salta and Antofagasta (weaker westerlies) in the upper and middle troposphere during LOW as compared to HIGH, while the same component is enhanced over Lima and La Paz (Figure 14(a)). The significance of these anomalies however, varies widely, depending on station and pressure level. The response of the meridional wind component is more consistent, featuring positive anomalies (weakened northerly winds) during LOW as compared to HIGH over the entire area, although not significant at all levels (Figure 14(b)). The specific humidity is higher during LOW than during HIGH over Antofagasta, Salta, and La Paz, while Lima again shows a different behaviour with higher values during HIGH (Figure 14(e)). In general variations in the atmospheric circulation over the Altiplano during austral winter show a rather weak relationship to the Southern Oscillation. Interannual variability during austral winter might more likely be determined by other factors, such as the strength and frequency of extra-tropical waves (frontal systems and cut-off low pressure systems) originating in the Pacific and penetrating into the Altiplano region.

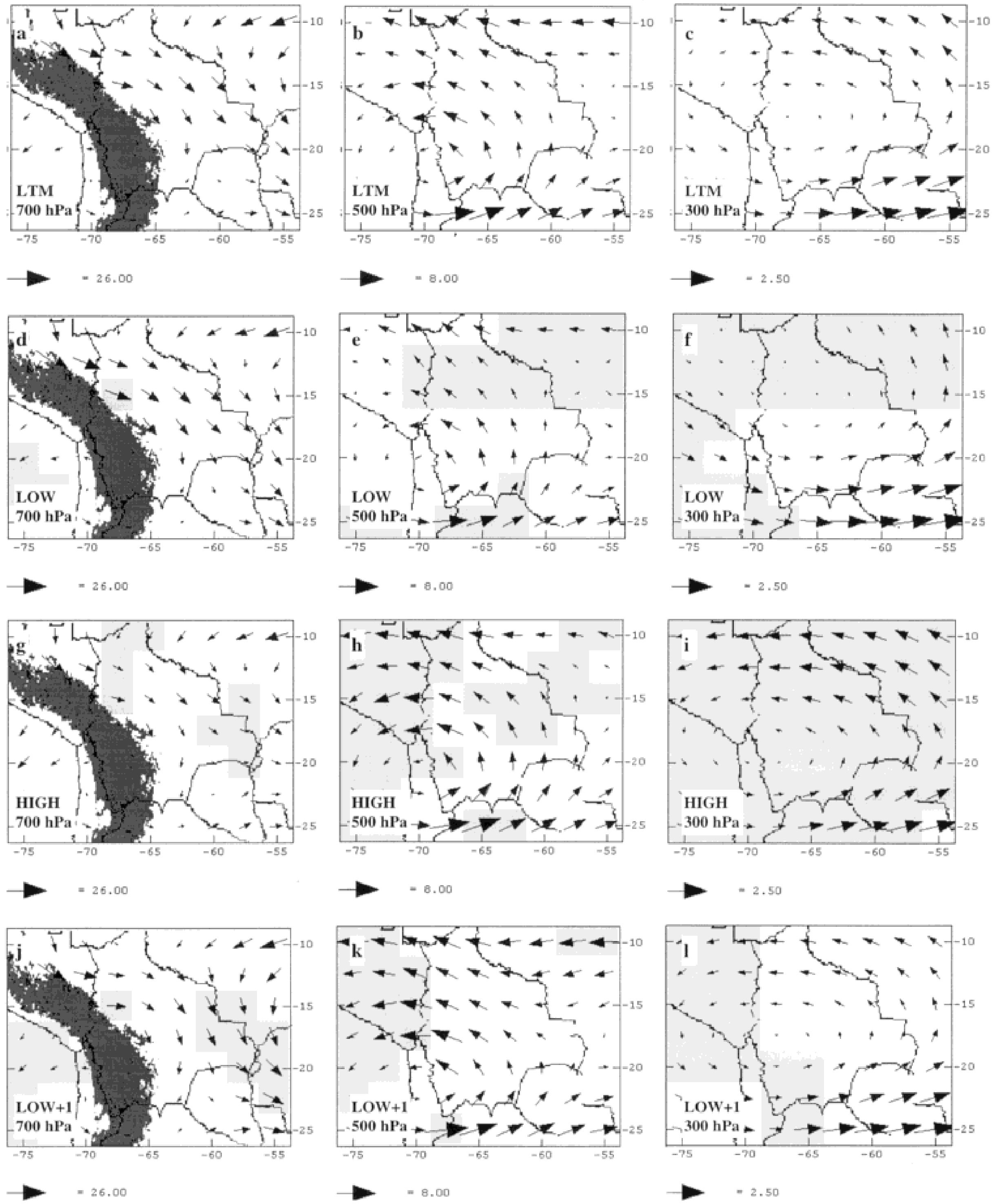

Figure 13. DJF water vapour flux (g s^{-1} m^{-2}) composites from NCEP reanalysis data showing: (a) long-term mean at 700 hPa; (b) as in (a) but for 500 hPa; (c) as in (a) but for 300 hPa; (d) LOW composite at 700 hPa; (e) as in (d) but for 500 hPa; (f) as in (d) but for 300 hPa; (g) HIGH composite at 700 hPa; (h) as in (g) but for 500 hPa; (i) as in (g) but for 300 hPa; (j) LOW + 1 composite at 700 hPa; (k) as in (j) but for 500 hPa; and (l) as in (j) but for 300 hPa. Shaded grid boxes indicate areas with significant anomalies at the 95% level. At the 700 hPa level ((a), (d), (g) and (j)), the Andes (regions above 3000 m) are superimposed on the NCEP data as the shaded area

5. SUMMARY AND CONCLUSIONS

WET periods during austral summer in the region of Nevado Sajama are associated with easterly wind anomalies in the middle and upper troposphere, resulting in increased moisture influx from the interior of the continent. Specific humidity levels are significantly higher during these periods of easterly winds over the Altiplano. On the other hand, westerly winds usually prevail during DRY periods, preventing moisture transport from the east from reaching the western Altiplano. These results are consistent with a recent mesoscale model study presented by Garreaud (1999). The meridional wind shows an increased southerly component to the east (Salta and La Paz), while a more northerly component dominates to the west (Lima) during WET, indicating an intensification and southward displacement of the Bolivian High. This pattern is confirmed by the analysis of the geopotential height, which shows a significant southward shift of the upper-air high pressure system during WET (geopotential height increase over Antofagasta

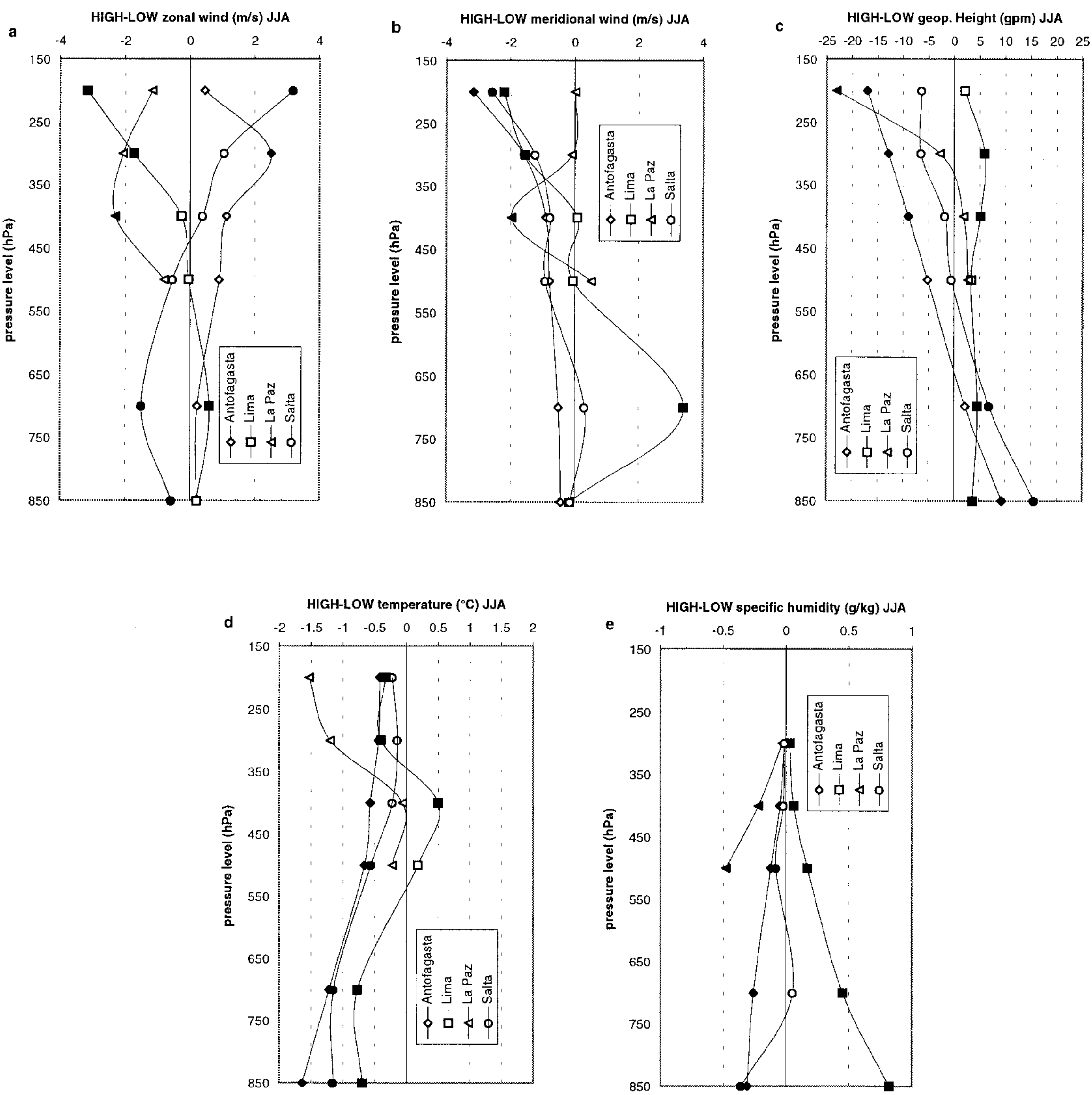

Figure 14. As in Figure 8 but for austral winter (JJA)

and Salta, no change over La Paz and a decrease over Lima). The fact that this anticyclone is intensified and centred over the southern Altiplano, south of its climatological position, during rainy periods, is further corroborated by the analysis of monthly NCEP reanalysis data and consistent with similar results reported by Aceituno and Montecinos (1993). Besides the upper-air divergent outflow related to the high pressure system, upper-air easterly winds to the north of the anticyclone lead to a turbulent entrainment of near-surface winds, accelerating moisture transport in lower levels towards the Altiplano (Garreaud, 1999). Often the upper-air high pressure system is located off the Pacific coast, to the southwest of the Altiplano, enhancing the southeasterly flow and upper-air divergence over the Altiplano (Jacobeit, 1992; Vuille *et al*., 1998).

Circulation mechanisms during WET periods in winter (JJA) are entirely different from in the summer, yet very little has been published to date about atmospheric circulation during WET periods on the Altiplano in austral winter. This period is generally believed to be entirely dry. However, recent snow accumulation measurements on the summit of Nevado Sajama yielded 53 cm of snowfall from July through September 1997 (Hardy *et al*., 1998), and Vuille and Baumgartner (1998) reported an average of three to five snowfall events per winter in the southern Altiplano. Vuille and Ammann (1997), analysing winter snowfall events on the Altiplano between 1984 and 1993 using NOAA/AVHRR and GOES satellite data, ECMWF gridded upper-air data and radiosonde data from Antofagasta, have shown that precipitation between May and September is associated with outbursts or northward intrusions of polar air masses from the planetary west wind zone. Cold fronts, or upper-air low pressure systems (cut-off lows), that penetrate into the southern Altiplano trigger the rare winter precipitation events on Nevado Sajama. The radiosonde analysis presented here confirm these results, revealing increased northerly and westerly wind components, reduced pressure and temperatures, and increased specific humidity over the entire Altiplano during such events. The fact that these anomalies are more pronounced over the southern and western stations Antofagasta, Lima and Salta than over La Paz provide clear evidence for the Pacific origin of these events.

The results from this analysis of atmospheric circulation during WET and DRY periods over the South American Altiplano in austral summer (DJF) and winter (JJA) have clear implications for the interpretation of the proxy data obtained from ice cores from Sajama summit. Most importantly they show that precipitation events on Sajama are related to large-scale circulation changes over the entire Altiplano region, and can be traced in radiosonde data to the east and the west of the Central Andes. Accordingly, proxy data from the ice core are of more than just local significance, and can be linked to circulation features on a larger scale. Furthermore, Nevado Sajama lies in an area which is influenced by two entirely different circulation regimes during the course of the year. Due to the seasonal shifts of the circulation zones, it experiences tropical as well as extra-tropical precipitation events. This is of importance because past climatic changes, recorded in the ice cores, might have been caused by shifts in circulation zones. In these terms, Nevado Sajama is an excellent place for palaeoclimatic studies.

The El Niño–Southern Oscillation phenomenon has a significant impact on the Altiplano climate, especially during austral summer. Atmospheric circulation anomalies however are more significant than changes in precipitation, which are statistically insignificant in the Nevado Sajama region. Nonetheless, precipitation tends to be deficient during LOW index summers (El Niño), and above average during HIGH (La Niña) and LOW + 1 (DJF following El Niño) summers. The tendency towards increased aridity during LOW summers can at least partially be attributed to a higher zonal wind component (westerly wind anomalies) in the middle and upper troposphere, preventing penetration of moist air masses from the eastern interior of the continent into the Sajama area. These westerlies are associated with a northward displaced and weakened Bolivian High. In this sense LOW index periods are characterized by similar anomalies as DRY periods, and can be regarded as an extended DRY period or a summer with an increased occurrence of DRY episodes. Furthermore, both LOW and DRY summers feature significantly above average upper-air temperatures (200 hPa). Although not always significant at all pressure levels, the general state of the atmosphere over the Altiplano during austral summer LOW index phases can be characterized by an increased westerly and northerly wind component, reduced specific humidity, an increase in atmospheric temperatures and a vertically expanded troposphere.

HIGH index summers are characterized by broadly opposite atmospheric characteristics also mostly typical for WET summer periods (lower temperatures at 500 and 200 hPa, a more pronounced Bolivian High located significantly further south, and easterly wind anomalies over the Altiplano). The atmospheric circulation during the summer following an El Niño event (LOW + 1) shows some similarities with the HIGH index situation, however the anomalies are statistically insignificant when compared to the long-term mean.

Precipitation during austral winter (JJA) shows no relationship with the extremes of the Southern Oscillation. Atmospheric circulation anomalies are also less pronounced, and generally feature the same changes as in summer (increased temperatures and a vertically expanded troposphere during LOW). However, the significance of these changes, especially with regard to the wind pattern, varies depending on station and pressure level. In general winter circulation anomalies over the Altiplano show little relation to the Southern Oscillation and are more likely determined by other factors such as the penetration of extra-tropical frontal systems and cut-off low pressure systems, not directly linked to ENSO.

Despite the clearly demonstrated influence of ENSO on the atmospheric circulation over the Altiplano, precipitation anomalies near Nevado Sajama are statistically insignificant (95% level). Factors other than surface conditions in the Pacific apparently play a crucial role in determining precipitation amounts. It has also been suggested recently, that precipitation variability on interannual and interdecadal timescales in the tropical Andes might rather be attributed to Atlantic than Pacific SST forcings (Enfield, 1996; Henderson, 1996; Melice and Roucou, 1998; Vuille *et al*., 1999). Studies are under way, to learn more about what forcing factors other than ENSO contribute to climatic variability on interannual timescales over the South American Altiplano.

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