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Atmospheric Circulation Anomalies Associated with 1996/1997 Summer Precipitatipn Events on Sajama Ice Cap, Bolivia

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Abstract. The analysis of atmospheric circulation anomalies related to snowfall events on Sajama volcano (Bolivian Andes) provides important information for the calibration of an ice core, recently recovered from the summit. Seventeen precipitation episodes were recorded on Sajama volcano during the 1996/1997 summer season (November 1996 to March 1997) by snow depth sensors and additional measurements of an automatic weather station located on the summit. The analysis of atmospheric circulation patterns during these events is based on zonal and meridional wind, air temperature, relative humidity, geopotential height and horizontal divergence at three pressure levels (400, 500, and 700 hPa levels), atmospheric thickness (700 hPa-400 hPa), and precipitable water (vertically integrated), all extracted from the National Centers for Environmental Prediction (NCEP) data set. Highly convective situations prevailed through most of December and January, with strong vertical motion over the Bolivian Altiplano. In February and March, increased moisture advection from the east occurred in midtropospheric levels. These results are confirmed by isobaric 5-day back trajectories and transit time analysis at the 400 hPa level. The extremely southern position of the upper air high-pressure system ("Bolivian High") in February and March is the main reason for the unusually high precipitation amounts on the Altiplano in 1996/1997. Highly variable patterns of atmospheric circulation can lead to snowfall on Sajama during the summer months.

1. Introduction

During June and July 1997, two complete ice core records of ~130 m were recovered from the Sajama volcano (6542 m, 18°06'S, 68°53'W), a tropical ice cap in the dry, western Bolivian Andes (Figure 1) (L.G. Thompson, personal communication, 1997). Paleorecords from tropical glaciers have provided excellent information about past environmental conditions and climatic variability in the tropics. They have revealed hitherto undocumented periods of tropical climatic anomalies, prolonged droughts with severe impacts on human societies [*Thompson et al.*, 1988] evidence for climatic disturbances such as El Niño [*Thompson et al.*, 1984], the Little Ice Age [*Thompson et al.*, 1986], and the Younger Dryas [*Thompson et al.*, 1995]. These records enable us to put contemporary climatic conditions in the high mountains of the tropics into a longer-term and larger-scale perspective. Recent analyses also show that proxy records from the tropics might even be more relevant and representative of global mean annual temperature than records from higher latitudes [*Bradley*, 1996].

Unfortunately, the interpretation of climatic signals from tropical ice cores has often suffered from a lack or poor quality of climatic information, required for an accurate calibration of the geochemical signals within the ice. As a result, the climatic signals, represented by the variation of microparticles (dust), concentration of chemical species (Cl^-, NO_3^-, SO_4^{2-}), precipitation amount (water equivalence), and stable isotope content ($\delta^{18}O$, δD) are still poorly understood. Of particular interest are isotopic variations in snowfall which have been important in interpreting paleoclimatic conditions based on ice cores from Antarctica and Greenland. However, at present there is an inadequate understanding of the climatic significance of isotopic variations ($\delta^{18}O$, δD) in low-latitude ice core records.

As shown by *Aravena et al.* [1989] and *Grootes et al.* [1989], knowledge of the transport history of humid air masses preceding snowfall events is a prerequisite for an accurate calibration. The model established by *Grootes et al.* [1989] to analyze the $\delta^{18}O$-record from the Quelccaya ice cap, Peru, cannot be applied to the Sajama core however, because the transport history of water vapor precipitating on Sajama is different from Quelccaya. Sajama is located in the dry western Cordillera at the very southern edge of the tropics, separated from the Amazon Basin by the the eastern Cordillera Real and the high Andean Plateau (Altiplano) and is therefore influenced by tropical circulation only during the summer months. The main rainy season is restricted to the months of December to March (Figure 1). In contrast to Quelccaya, during winter, Sajama is dominated by a strong and constant northwesterly flow (D. R. Hardy et al., Annual and daily meteorological cycles at high altitude on a tropical mountain, submitted to *Bulletin of the American Meteorological Society*, 1998 (hereinafter referred to as H98)), as a result of the northward shift of the westerly circulation, which occasionally leads to snowfall when cold frontal systems or cutoff lows penetrate into the Altiplano region [*Vuille and Ammann*, 1997]. Therefore different moisture sources have to be considered when analyzing stable isotopes on Sajama. Ac-

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cordingly, the identification of moisture sources, transport velocity, and moisture exchange processes (precipitation, evaporation, and evapotranspiration) preceding snowfall events on Sajama is crucial to obtain an accurate calibration.

Here we present an analysis of midtropospheric circulation, transport history, and moisture source detection associated with snowfall events recorded on the Sajama summit during the first rainy season (November 1996 to March 1997). An automatic weather station, installed in October 1996 on the summit near the drilling site, is providing us with automatic hourly measurements of snow accumulation and ablation on Sajama via telemetry (H98). These data allow us to identify single snowfall events and to relate them to the atmospheric circulation above the Altiplano. By digging snow pits and analyzing each snowfall layer in detail for its geochemistry, we will be able to understand atmospheric sources of geochemical variability. In these terms this study is complementary to the one presented by H98 where the annual and daily cycles of climate on the Sajama summit are analyzed.

In the next section we provide a description of the climatic characteristics associated with summer precipitation events over the southern Altiplano and present a brief summary of the present understanding of the atmospheric circulation over tropical South America, related to these wet episodes. Section 3 is a discussion of the data and methods used, while section 4 presents the results of these analyses and discusses the mean summer circulation over tropical South America and the main anomaly patterns that led to precipitation on Sajama during the 1996-1997 wet season. Section 5 is a discussion of the results from the previous section, showing how differences in atmospheric circulation might account for different geochemical signals in the accumulated snow layers, while section 6 summarizes this study and presents some conclusions.

2. Precipitation Regime and Atmospheric Circulation Over the Altiplano

Figure 1 shows the monthly mean precipitation values for Sajama village (18.13°S, 68.98W, 4220 m) at the base of the mountain and the stations Arica (18.33°S, 70.33°W, 20 m), La Paz El Alto (16.52°W, 68.18°W, 4050 m), and Apolo (14.70°S, 68.50°W, 1383 m). The enormous longitudinal precipitation gradient is evident: the arid coastal station Arica with an annual amount of 1.0 mm, the Altiplano station located in the dry western cordillera (Sajama: 315.6 mm), the Altiplano station close to the more humid eastern Cordillera (La Paz El Alto: 594.0 mm), and the station toward the Amazon Basin (Apolo: 1333.4 mm). Both Altiplano stations show a clear summer precipitation regime, with more than 80% of the annual amount falling between December and March. This 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 Chaco basins). The build-up of convective

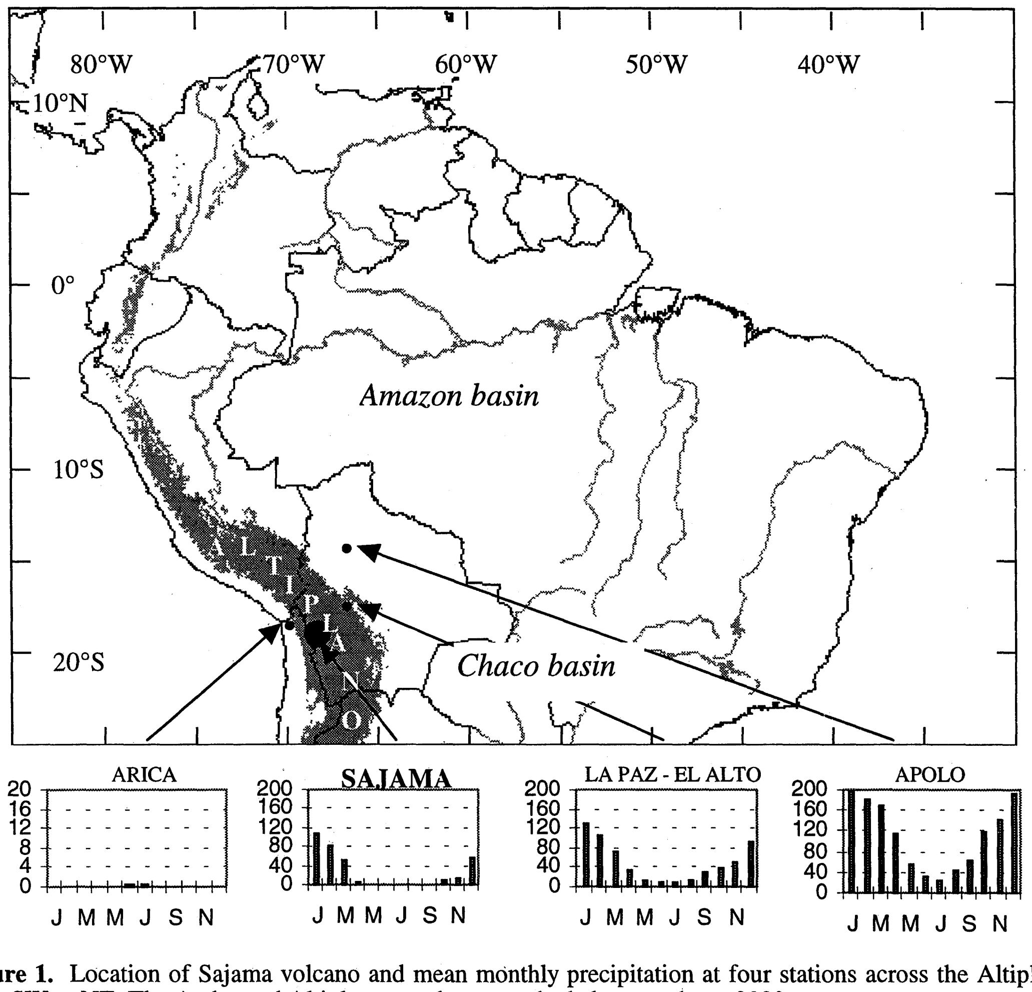

Figure 1. Location of Sajama volcano and mean monthly precipitation at four stations across the Altiplano from SW to NE. The Andes and Altiplano are shown as shaded areas, above 3000 m.

Table 1. Snowfall Events on Sajama Volcano October 1996 to March 1997

Event	Period	Snow Accumulation	Group
N1	Nov. 07 - 13	18 cm	D
N2	Nov. 16 - 18	14 cm	A
D1	Dec. 01 - 04	15 cm	A
D2	Dec. 14 - 18	19 cm	A
D3	Dec. 23 - 28	24 cm	A
J1	Jan. 01 - 02	29 cm	A
J2	Jan. 09 - 11	11 cm	B
J3	Jan. 13 - 15	21 cm	B
J4	Jan. 20 - 28	58 cm	A
F1	Feb. 05 - 08	-	C
F2	Feb. 16 - 17	-	C
F3	Feb. 20 - 21	-	C
F4	Feb. 23 - March 01	-	C
M1	March 11 - 12	-	C
M2	March 16 - 18	-	A
M3	March 20 - 23	-	A
M4	March 26 - 29	-	C

cloudiness normally increases rapidly between 1200 and 1700 LT, reaching a maximum around 1800, together with the maximum expansion of the tropospheric column, followed by a gradual decrease until midnight [*Garreaud and Wallace,* 1997]. Accordingly, precipitation shows a similar diurnal cycle, being most frequent between 1800 and 2200 [*Aceituno and Montecinos,* 1993]. Moisture advection is most pronounced near the 500 hPa level, about 1000 m below the Sajama summit and is normally accompanied by easterly winds in the surface and midtropospheric layers (P. Aceituno et al., Meteorological annual and daily cycles in the Chilean sector of the South American Altiplano, submitted to *Revista Geofisica,* 1997). This moisture input, however, becomes limited with increasing distance from the water vapor source which lies in the tropical lowlands to the east. As a result, precipitation amounts decrease from E to W across the Altiplano (Figure 1).

Despite high daily solar radiation receipts throughout the summer months, precipitation occurs in discrete episodes rather than as a constant process [*Aceituno and Montecinos,* 1993]. This change from rainy to dry periods and vice versa is related to the upper air circulation, which plays a key role in sustaining or suppressing precipitation events over the Altiplano. *Jacobeit* [1992], analyzing 200 hPa wind fields during dry and wet summer months in a principal component analysis, emphasized the importance of strong easterly disturbances or upper air divergence over the Altiplano in order to sustain convection and precipitation. This upper air divergence is often related to an anticyclonic vortex, named the Bolivian High, due to its climatological position over the Bolivian Altiplano during the summer months. *Aceituno and Montecinos* [1993] were able to show that precipitation amounts on the Altiplano were significantly higher when the Bolivian High was intensified and displaced south of its climatological position. This displacement of the High to the south of the Altiplano leads to enhanced easterly flow on its northern side and increased moisture influx from the interior of the continent

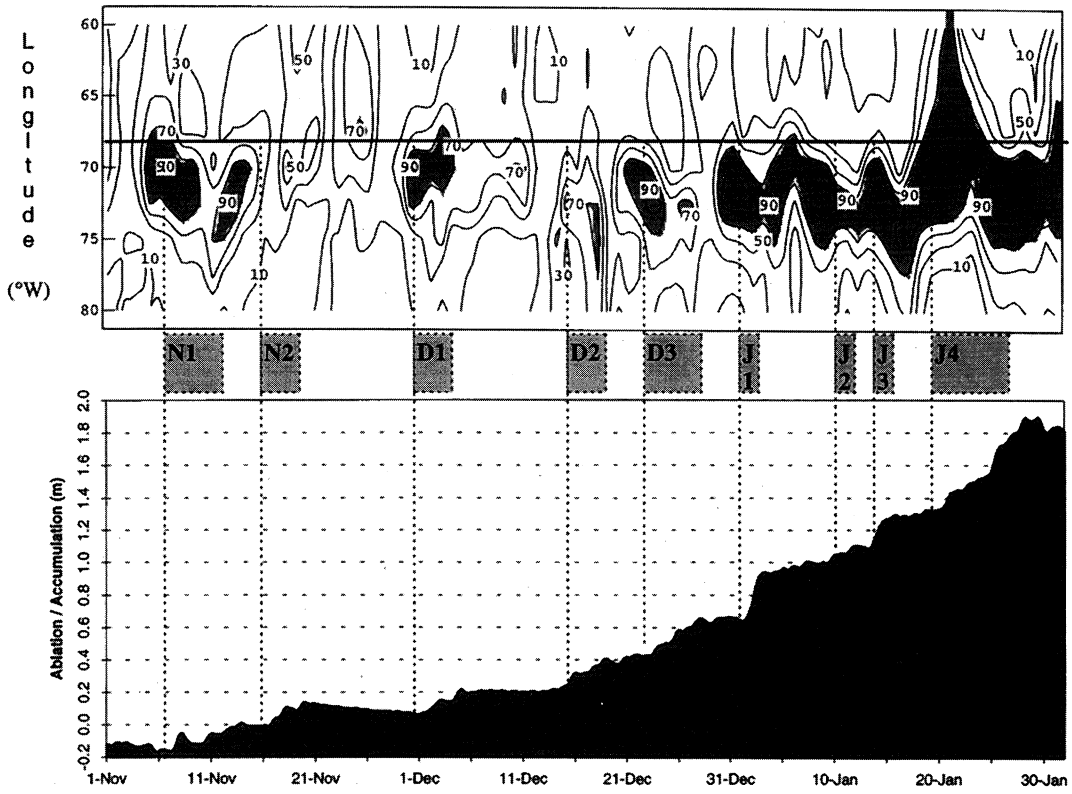

Figure 2. Comparison of snow accumulation /ablation on Sajama (bottom) and time - longitude section of 400 hPa level relative humidity at 17.5°S (top) between November 1996 and January 1997. Relative humidity values > 70% are shaded. Snowfall events on Sajama are indicated by gray boxes. Longitude of Sajama indicated by dark horizontal line.

toward the Altiplano and Sajama region. On the other hand, dry periods over the Altiplano are normally related to either upper air convergence or strong westerly flow. The Bolivian High was first described by *Schwerdtfeger* [1961], who related it to the release of sensible and latent heat over the Altiplano. A model study by *Silva Dias et al.* [1983] showed that forcing by latent heat release over the Amazon Basin instead of the Altiplano could still reproduce many aspects of the Bolivian High and its position over the Altiplano as a southwestward propagating Rossby wave. While *Rao and Erdogan* [1989] still attributed the Bolivian High to the release of sensible and latent heat over the Altiplano itself, new modeling studies have demonstrated that the Andes do not strongly affect the upper levels of the atmosphere during summer [e.g., *Kleeman,* 1989; *Gandu and Geisler,* 1991; *Figueroa et al.,* 1995; *Lenters and Cook,* 1997]. The climatological position of the Bolivian High indeed seems to be related to a southwestward propagating Rossby wave with subsequent decay, generated by latent heat release over the Amazon Basin, rather than to a direct thermal influence of the Altiplano surface.

3. Data and Methods

3.1 Snowfall Episodes

Individual snowfall episodes were identified by analyzing the change in snow accumulation and ablation as recorded by the hourly measurements of two snow depth sensors from the

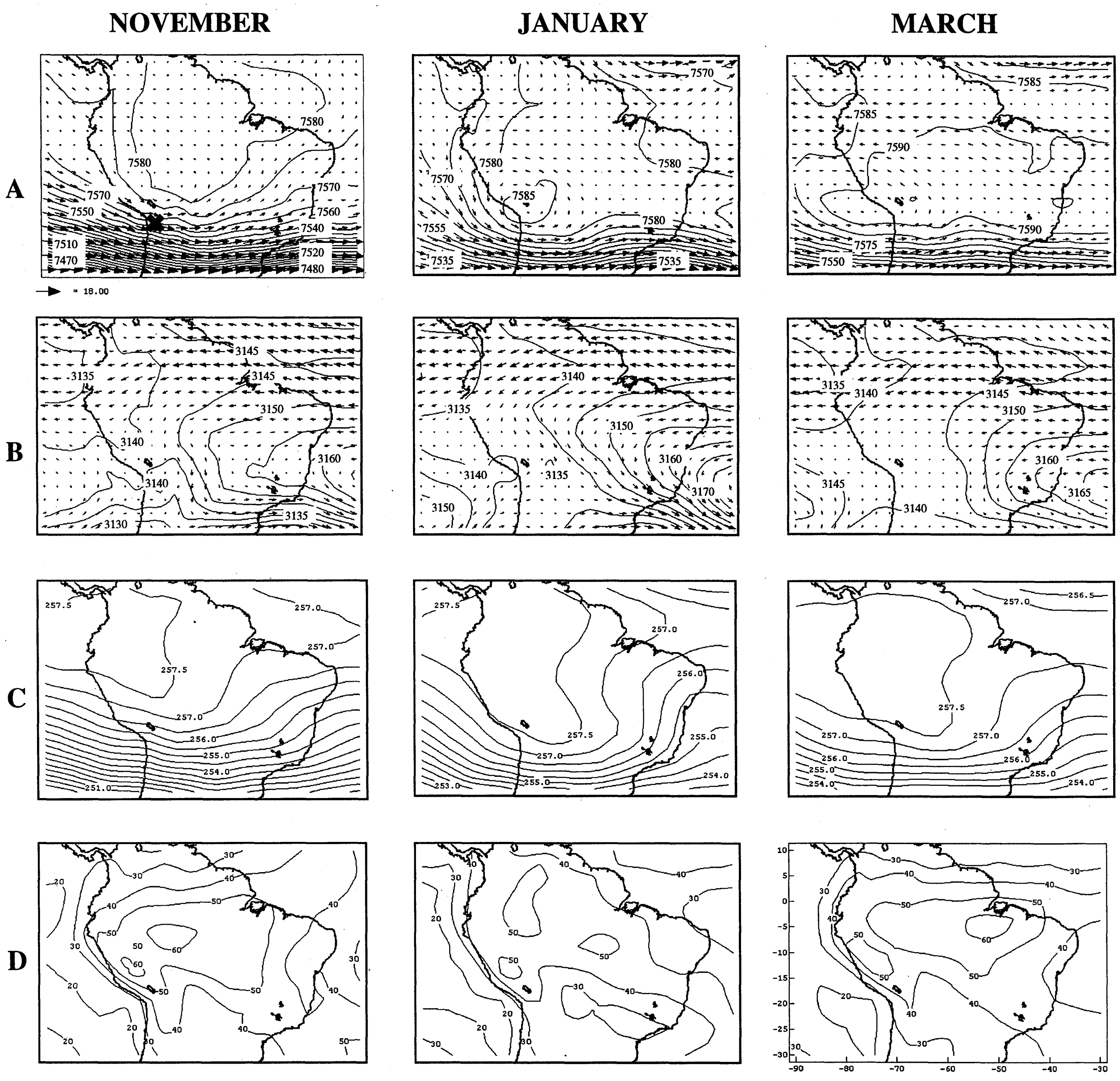

Figure 3. Patterns of midtropospheric circulation based on (National Centers for Environmental Prediction) long-term monthly mean data (1985-1995). Row A: geopotential height (gpm) and wind field (arrow denotes 18 m/s) at 400 hPa. Row B: geopotential height (gpm) and wind field at 700 hPa. Row C: air temperature (°K) at 400 hPa. Row D: relative humidity (%) at 400 hPa. Latitudinal and longitudinal extent is shown at lower right. Location of Sajama volcano (cross) is shown in top left.

automatic Sajama weather station (H98). Here, only events resulting in a net increase of the snow surface of 5 cm or more were considered. The 1996-1997 rainy season was unusually humid, resulting in a net accumulation of ~ 4 m of snow on the summit of Sajama. At La Paz El Alto, monthly precipitation totals between November and March ranged between 115 and 203% of normal. These above-average precipitation rates resulted in the burial of both snow-depth sensors on Sajama by snow, at the end of January. Precipitation periods for February and March were therefore determined from station data by the analysis of relative humidity, air temperature, and incoming short-wave radiation. It is clear from the events recorded prior to the burial of the sensors that summer snowfall events on Sajama are characterized by sustained high relative humidity, minimal daily temperature amplitudes, and reduced incoming short-wave radiation. Additional information can be obtained by the comparison of incoming and outgoing short-wave radiation, as during snowfall, the sensor measuring incoming short-wave radiation normally becomes snow covered, resulting in unreasonable albedo values. Table 1 lists all snowfall episodes on Sajama either directly recorded or inferred during the 1996/1997 rainy season, and the associated amount of snowfall (until end of January only).

3.2. Atmospheric Circulation

Analysis of the atmospheric circulation before and during precipitation events was carried out using gridded upper air data from the National Centers for Environmental Prediction (NCEP). The data consist of a daily analysis at 0000 UTC (2000 LT), provided on 13 pressure levels, except for relative humidity (7 levels) and precipitable water (one vertically integrated value) on a 2.5° × 2.5° grid. Daily data were extracted from the original data sets for zonal wind, meridional wind, air temperature, geopotential height and relative humidity for the 700, 500, and 400 hPa pressure levels, and precipitable water, covering the area of South America (20°N - 60°S; 90°W - 30°W). In addition, corresponding data sets were extracted for the daily and monthly long-term mean for November to March, computed from the 11 year period 1985-1995. Atmospheric thickness (400 hPa - 700 hPa geopotential height) and horizontal divergence fields were then derived from the original data. Composite fields were computed in all three layers and for all parameters by averaging the daily data for each snowfall episode. The same approach was applied to the daily long-term mean data. Anomaly fields were derived for each event by subtracting the long-term mean from the 1996/1997 data.

The mean annual barometric pressure on the Sajama summit is ~ 460 hPa, with hourly values ranging through the year only between 453 hPa and 464 hPa (H98). Therefore the emphasis of this study is on midtropospheric circulation patterns (400, 500, and 700 hPa). The 400 hPa and 500 hPa pressure levels encompass Sajama and are thus ideal in order to analyze the circulation at the summit altitude. The 700 hPa level is a compromise between lower-level circulation (e.g., 850 hPa), where major moisture advection toward the Altiplano takes place, and higher levels (e.g., 600 hPa) which are above the Altiplano surface of 3500 - 4000 m and characterize the mountain region in general. As a first approximation however, the 400 hPa and 700 hPa patterns can be considered as representative of upper and lower-level circulation.

Global data sets with a coarse spatial and temporal resolution might not be the best choice to analyze precipitation events recorded by a single weather station, especially in the tropics of the southern hemisphere, where such data sets seem to be less reliable [*Trenberth and Olson*, 1988]. However, validity of NCEP data pertaining to this study can be seen in Figure 2, which illustrates the atmospheric conditions from NCEP data leading to precipitation events on Sajama. Time series of the change in snow accumulation/ablation as recorded on Sajama (13 hour running mean from two sensors) is compared with a time-longitude cross section of 400 hPa level relative humidity at 17.5°S, the grid point closest to Sajama. The coincidence between snow accumulation (i.e., snowfall periods) and high humidity values is clear. In addition, such episodes are generally associated with large-scale changes in the atmospheric circulation over the Andes and can be traced in upper air soundings both to the east and to the west of the Andes. It should also be kept in mind that the goal of this study is to analyze the large-scale, midtropospheric circulation and motion of air masses, rather than single grid values above Sajama. On-site climatology and diurnal features such as daily temperature and pressure fluctuations cannot be resolved by the NCEP data, but they are perfectly monitored by our weather station (H98).

3.3 Airmass Trajectory Models and Transit Time Analysis

Despite substantial uncertainties, trajectory models are capable of identifying large source regions which may contribute material to the receptor location. To this end, 6 hourly, isobaric back trajectories over 5 days at the 400 hPa level were computed, yielding isobaric upwind air trajectories describing the 5 day pathways of air masses arriving every 6 hours during snowfall episodes on Sajama. Back trajectories provide a useful qualitative estimate of the general pathway of an advected air mass. They are an ideal tool to determine distant source regions and can help to assign typical geochemical compositions of precipitation episodes to a given synoptic weather pattern [e.g., *Dorling et al.*, 1992; *Davidson et al.*, 1993; *Kahl et al.*, 1997]. In principle, isentropic trajectories (where the air motions take place on surfaces with constant potential temperature) are preferable to isobaric trajectories (where the motion follows a surface of constant pressure) because they also include the vertical transport component. Isentropic trajectories are therefore more accurate, especially in baroclinic atmospheres, because of a better treatment of vertical motion. However, isobaric assumptions are tolerable when general pathways and large-scale moisture sources are considered, rather than single source-receptor relationships, and have successfully been applied over the Altiplano [e.g., *Fuenzalida and Ruttlant*, 1987]. The assumption that trajectory lines of any type provide a direct connection between a source and a receptor is problematical anyway [e.g. *Kahl*, 1993]. The choice of 5 day trajectories, although common, is somewhat arbitrary and rather short but was chosen because the accuracy decreases substantially with time [e.g., *Haagenson et al.*, 1987]. Besides assumptions about vertical motion, the accuracy of estimated trajectories is mainly limited by the temporal and spatial resolution of the meteorological data upon which the calculations are based. Here the daily NCEP wind field was linearly interpolated into 6 hourly time steps. Linear interpolation has been shown to yield superior results than the other interpolation methods [*Kahl and Samson*, 1988]. Spatial bilinear interpolation was applied to the wind field by resampling the data into a 1° × 1° grid. Individual displacements of air particles were then computed using the horizontal wind field according to

$$\Delta\lambda = \frac{u\Delta t}{c\cos\phi} \qquad (1)$$

$$\Delta\phi = \frac{v\Delta t}{c} \qquad (2)$$

where $\Delta\lambda$ and $\Delta\phi$ are longitudinal and latitudinal displacements, u and v are zonal and meridional wind components, c = 111.1 is the ratio of kilometers to degrees latitude, and Δt = 6 hours is the time interval between two calculations.

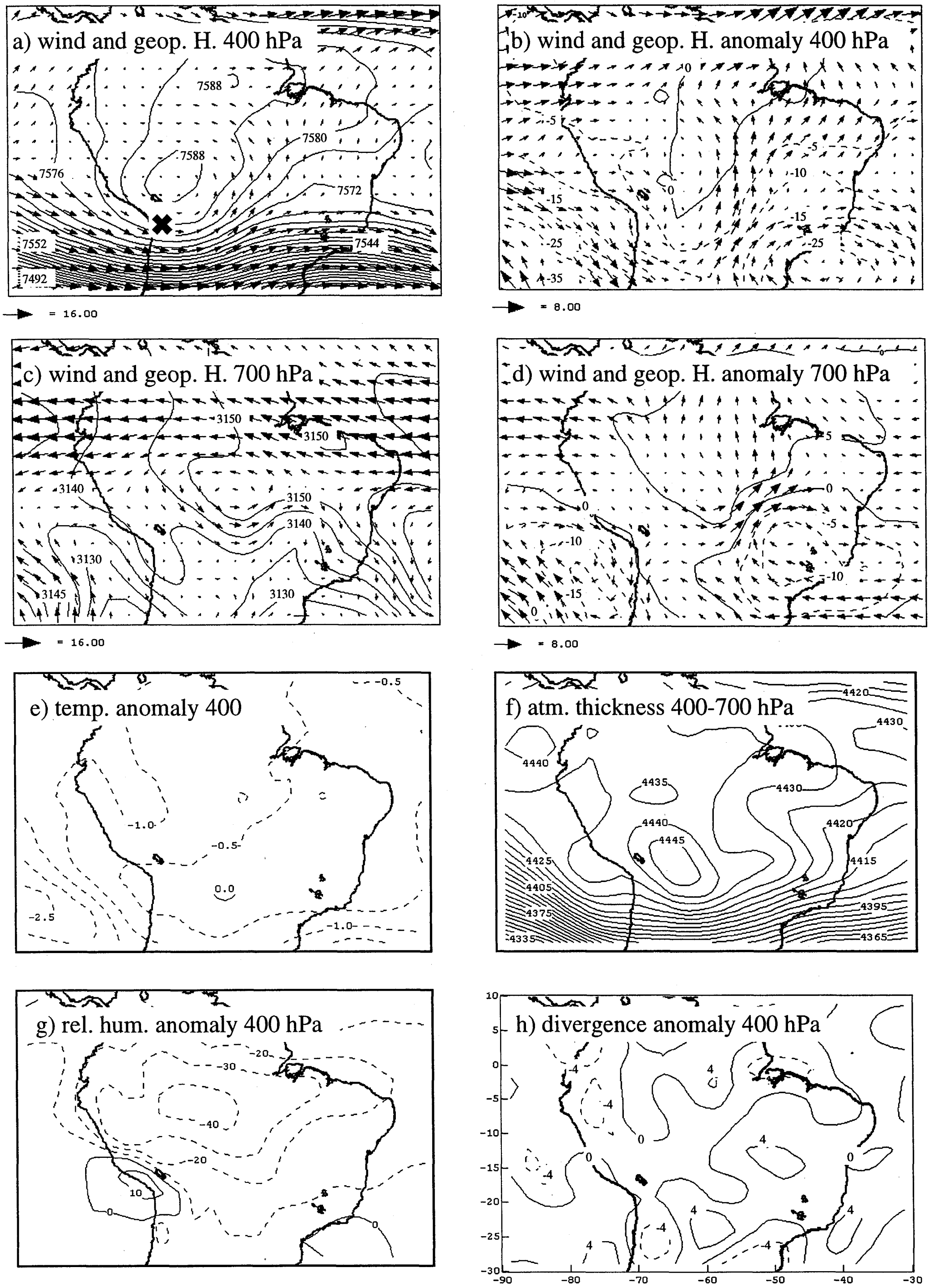

Figure 4. Composite of midtropospheric circulation patterns associated with group A: (a) geopotential height (gpm) and wind field (scaling indicated by arrow below the figure) at 400 hPa; (b) as in Figure 4a but anomalies (deviation from long-term mean), negative values are indicated by dashed lines; (c) and (d) as in Figures 4a and 4b but at 700 hPa; (e) temperature anomaly at 400 hPa (°K), negative anomalies are indicated by dashed lines; (f) atmospheric thickness, 400 hPa - 700 hPa (gpm); (g) relative humidity anomaly (%) at 400 hPa, dashed lines indicate negative anomalies; (h) divergence anomaly (10^{-6} s^{-1}) at 400 hPa. Latitudinal and longitudinal extent is shown in Figure 4h. Location of Sajama volcano (cross) is shown in Figure 4a.

With regard to the stable isotope content ($\delta^{18}O$), it is of special interest to analyze how fast transport in the midtroposphere occurs and where air particles spent most of their time before arriving over Sajama. Therefore a procedure known as transit time analysis [e.g., *Davidson et al.*, 1993] was applied. A simple linear interpolation was used to determine the position of air masses for each hour during the 5 days of each trajectory. The set of hourly trajectory points was then sorted by $1° \times 1°$ grid squares, and the total number of hours corresponding to all trajectories belonging to the same episode was summed for each grid point. The cumulative density function for these hourly values was then determined, showing which values were above certain percentiles. Finally, isoline plots were drawn, enclosing all grid squares containing values greater than these percentile limits, showing within which area air particles spent 25, 50, 75, and 90% of their time during the 120 hours before arriving on Sajama.

In the following section we discuss the main synoptic weather situations that led to snowfall on Sajama during summer 1996/1997. On the basis of midtropospheric composite and anomaly fields of wind and geopotential height, 5 day back trajectories and transit time analysis, we classified all episodes into four groups (see Table 1). Where classification was not possible based on these parameters alone, addi-

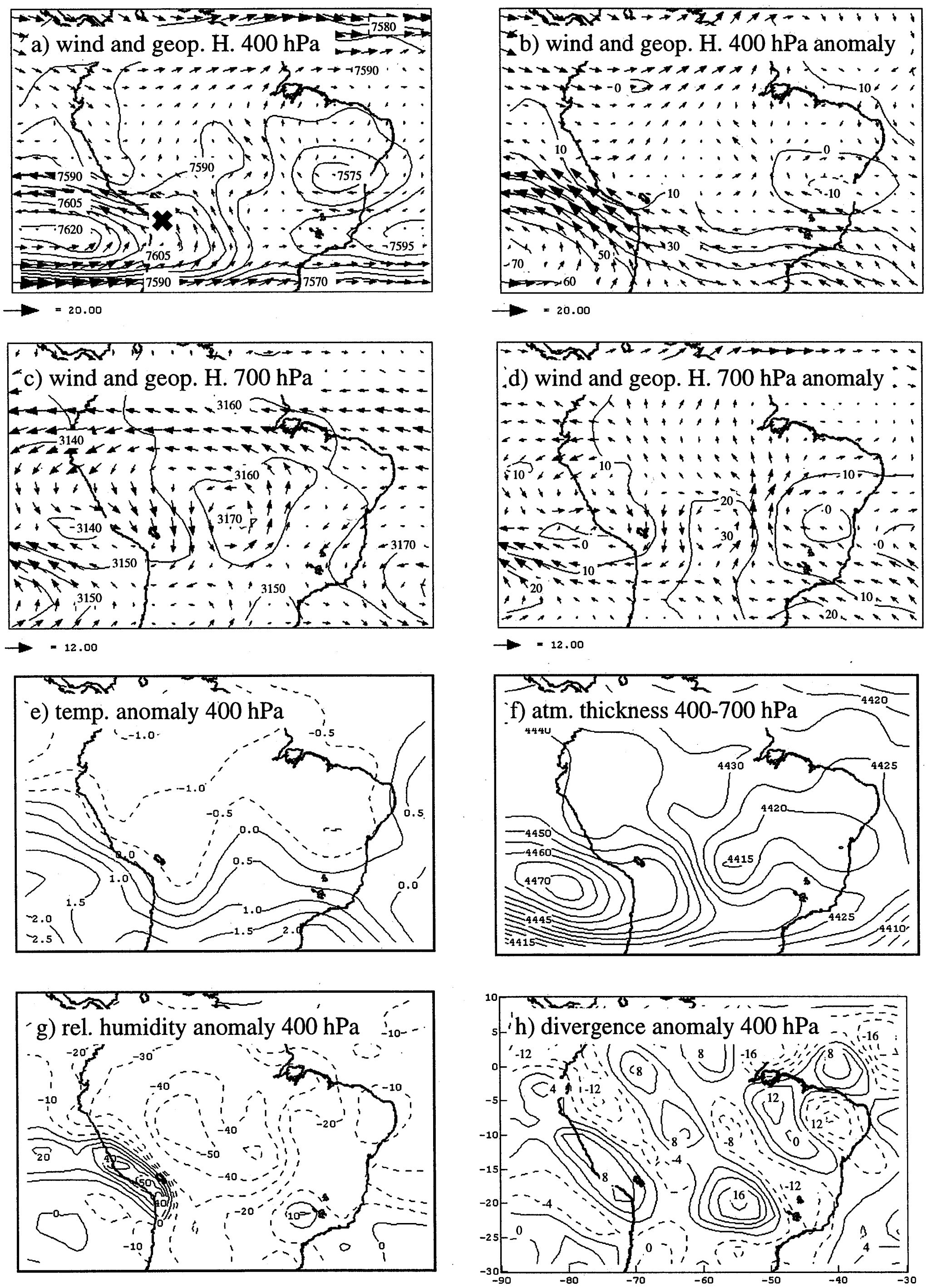

Figure 5. As in Figure 4 but composite of group B.

tional information was used (i.e., composite and anomaly fields of atmospheric thickness, horizontal divergence, air temperature, relative humidity, and precipitable water). Because of the limited number of episodes (n = 17) this classification was done subjectively, based on the above mentioned information, trying to minimize within-group variability and maximize variability between groups. A longer time period than only one rainy season would be necessary to apply multivariate classification analysis, for example, cluster analysis [e.g. *Moody and Samson*, 1989; *Harris and Kahl*, 1990; *Dorling et al.*, 1992].

4. Results

4.1 Long-Term Mean Circulation

The first part of this section focuses on the long-term mean climatology (1985-1995) during the summer months of November to March over tropical South America, as derived from the NCEP data. As many comprehensive observational studies have been published on this issue [e.g. *Virji*, 1981; *Nishizawa and Tanaka*, 1983; *Chu*, 1985; *Horel et al.*, 1989; *Jacobeit*, 1992; *Kousky and Kayano*, 1994; *Rao et al.*, 1996; *Hastenrath*, 1997], we will concentrate on features relevant to precipitation over the Altiplano and pertinent to the anomaly fields presented in the next section. Figure 3 presents monthly mean wind and geopotential height patterns in the 400 hPa level (row A) and the 700 hPa level (row B), and temperature and relative humidity in the 400 hPa level only (rows C and D) for November, January, and March.

While strong meridional pressure and temperature gradients and westerly winds dominate in November over the region of Sajama at the 400 hPa level, in January a well-defined warm core anticyclone develops (Figure 3, row A). This warm core can be found in the midtropospheric temperature distribution as well as in the thickness pattern (400-700 hPa, not shown). The anticyclonic flow about the High is evident and wind speeds above Sajama are minimal. The proximity of the Bolivian High to the elevated inter-Andean Plateau (Altiplano) is obvious and explains why this possible relationship has drawn so much attention. However, this position is a climatological mean and does not show the significant variations it experiences in its position and intensity. The High deflects the westerly flow and influences the strength of the subtropical jet to the south of the anticyclone, while weak easterlies extend to the north of it. The trough to the east of the High, often referred to as the Nordeste Low and dynamically linked with the Bolivian High [*Lenters and Cook*, 1997], is not evident in the midtropospheric circulation and can only be assumed from the temperature distribution (Figure 3, row C), showing relatively cold temperatures over NE Brazil. In March the High over the Altiplano is no longer so pronounced as in January and is longitudinally stretched. It is important to note that the maximum geopotential height does not represent the region of maximum horizontal wind divergence. Regions of high divergence are instead located throughout the region, the strongest being to the southeast of the Bolivian High (not shown). Humidity values show a relative maximum over the northern Altiplano in all months (Figure 3, row D), associated with the moist air advection and rising motion over the Altiplano surface. Other relative humidity maxima are located over the Amazon Basin throughout the summer. The location of Sajama within the strong humidity gradient toward the dry atmosphere over the Pacific Ocean to the SE is noteworthy, resulting in a sensitivity to slight shifts in this pattern.

At the lower level (700 hPa), the atmospheric circulation is dominated by the South Atlantic High, extending deeply into interior Brazil (Figure 3, row B). In January the trade winds in the equatorial Atlantic penetrate into the Amazon region and then turn anticyclonic east of the mountains to flow southward and southeastward, toward a not very well defined low in the central parts of the continent near 20°-25°S, known as the Chaco Low. The thermal character of this heat low is evident in the low-level temperature pattern throughout the summer (not shown). The anticyclonic turn is caused by the Andes and leads to a strong northwesterly flow along the eastern Andean slope [e.g., *Virji*, 1981; *Gandu and Geisler*, 1991]. This low-level jet is an important and effective transport mechanism for the southward moisture flux from the Amazon Basin toward higher latitudes [*Nogués-Paegle and Mo*, 1997]. An extended zone of low-level convergence, known as the South Atlantic Convergence Zone (SACZ) is oriented northwest to southeast in the subtropics near the coast of southeast Brazil, projecting into the adjoining South Atlantic Ocean.

4.2 1996/1997 Snowfall Episodes

The classification of summer snowfall events on Sajama resulted in four groups (coded A-D; see Table 1). In the following section the midtropospheric circulation is presented based on composites for each group. (Figures 4-7). Again, only the situation in the 400 hPa and 700 hPa levels are shown, as 400 and 500 hPa levels have very similar characteristics.

Figure 4 shows the composite for the weather pattern of group A, being the most frequent synoptic situation overall (eight events). The midtropospheric circulation is dominated by the Bolivian High, centered slightly northeast of the Altiplano. The wind and pressure situation in the 400 hPa level (Figure 4a) very much resembles the long-term mean pattern for January (Figure 3, row A); however, the group A situation was most frequent during December (see Table 1). Wind speeds were very low over the Altiplano, with anticyclonic rotation about the High at the 400 hPa level, but westerly winds rapidly increased toward the south. In general, the geopotential height pattern features very little anomalies compared with the long-term mean (Figure 4b), showing that composite A is a very typical situation during southern hemisphere summer. The temperature and the thickness pattern (400-700 hPa) show the warm core to the east of the Altiplano, while slightly negative temperature anomalies prevail in most of the tropics (Figures 4e-4f). Divergence anomalies are rather insignificant at the 400 hPa level, further confirming the typical nature of this event (Figure 4h). The 700 hPa wind and geopotential height pattern is also very similar to the long-term mean, with only minor anomalies (Figures 4c-4d). Enhanced easterlies over the Amazon Basin and a stronger jet to the east of the Andes are most pronounced during D1, D2, J1, J4, and M3 (not shown). Low horizontal wind velocities in both levels, divergence in the 400 hPa level (low positive anomaly), and convergence in the 700 hPa level (not shown) indicate the vertical motion and the convective nature of precipitation events related to group A. Relative humidity is higher than normal over the Altiplano, while most of tropical South America exhibits a rather dry midtroposphere (Figure 4g). NCEP humidity and divergence patterns have to be interpreted with caution however, as they sometimes bear little resemblance with reality in the southern hemisphere. The exact position of the maximum geopotential height in the 400 hPa level varies slightly between the events assigned to this group but always remains over the broader Altiplano region. *Aceituno and Montecinos* [1993] reported that precipitation over the Altiplano is significantly higher when the Bolivian High is intensified and displaced to the south. However, all events within this category accounted for considerable amounts of snow on Sajama (see Table 1).

In mid-January a different situation prevailed, leading to two major snowfall events, clustered in group B (see Table 1). Figure 5 shows the composite for this weather pattern. The high-pressure system is centered off the South American coast over the subtropical Pacific, to the southwest of its climatological position (Figure 5a). Positive thickness and temperature anomalies characterize this midtropospheric warm core (Figures 5e-5f). On its eastern side an anomalous southeasterly flow prevails over the southern part of the Altiplano, and strong upper air divergence dominates over most of the central Andes. The coincidence of divergence and positive humidity anomalies at the 400 hPa level over the central An-

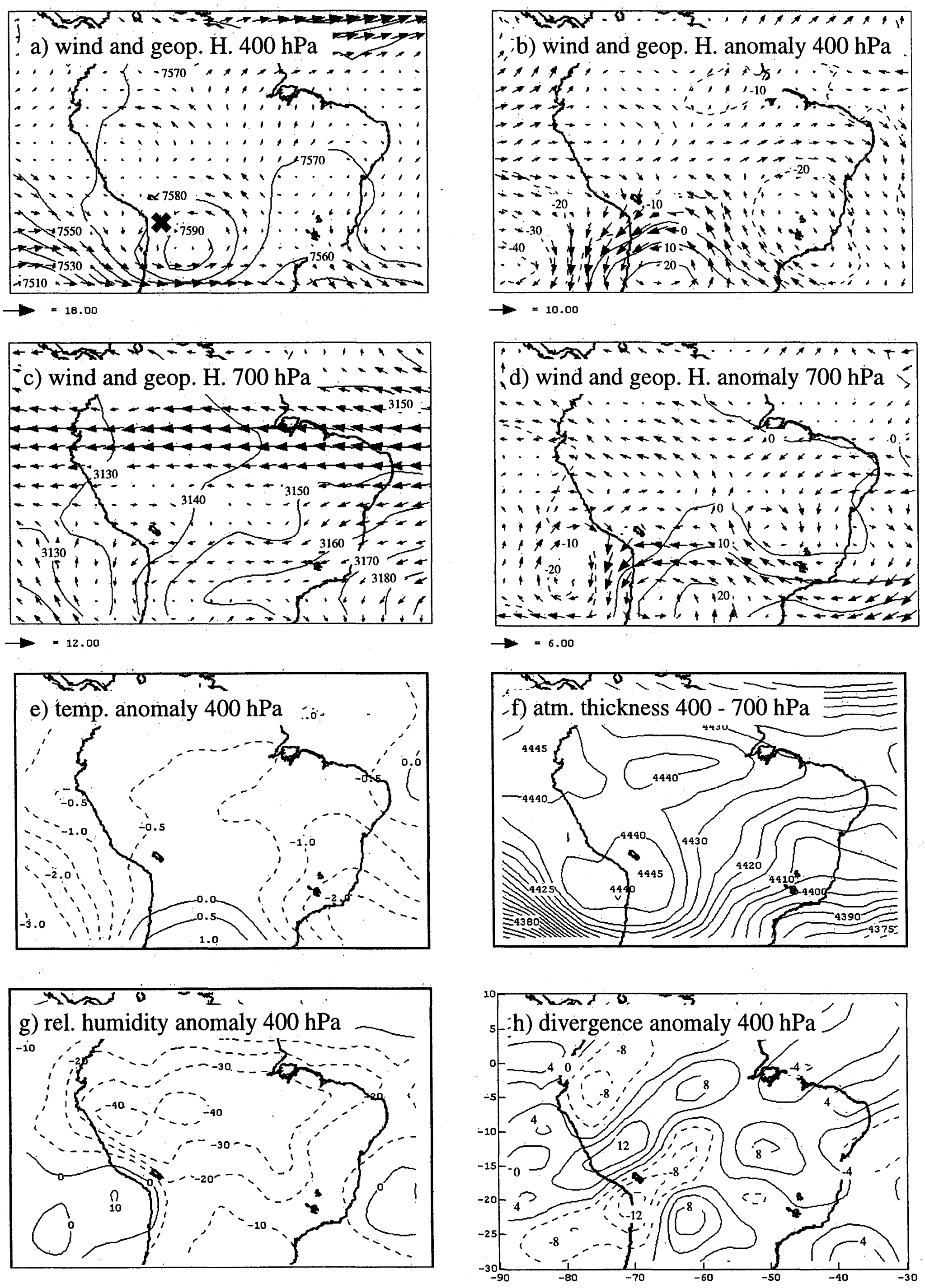

Figure 6. As in Figure 4 but composite for group C.

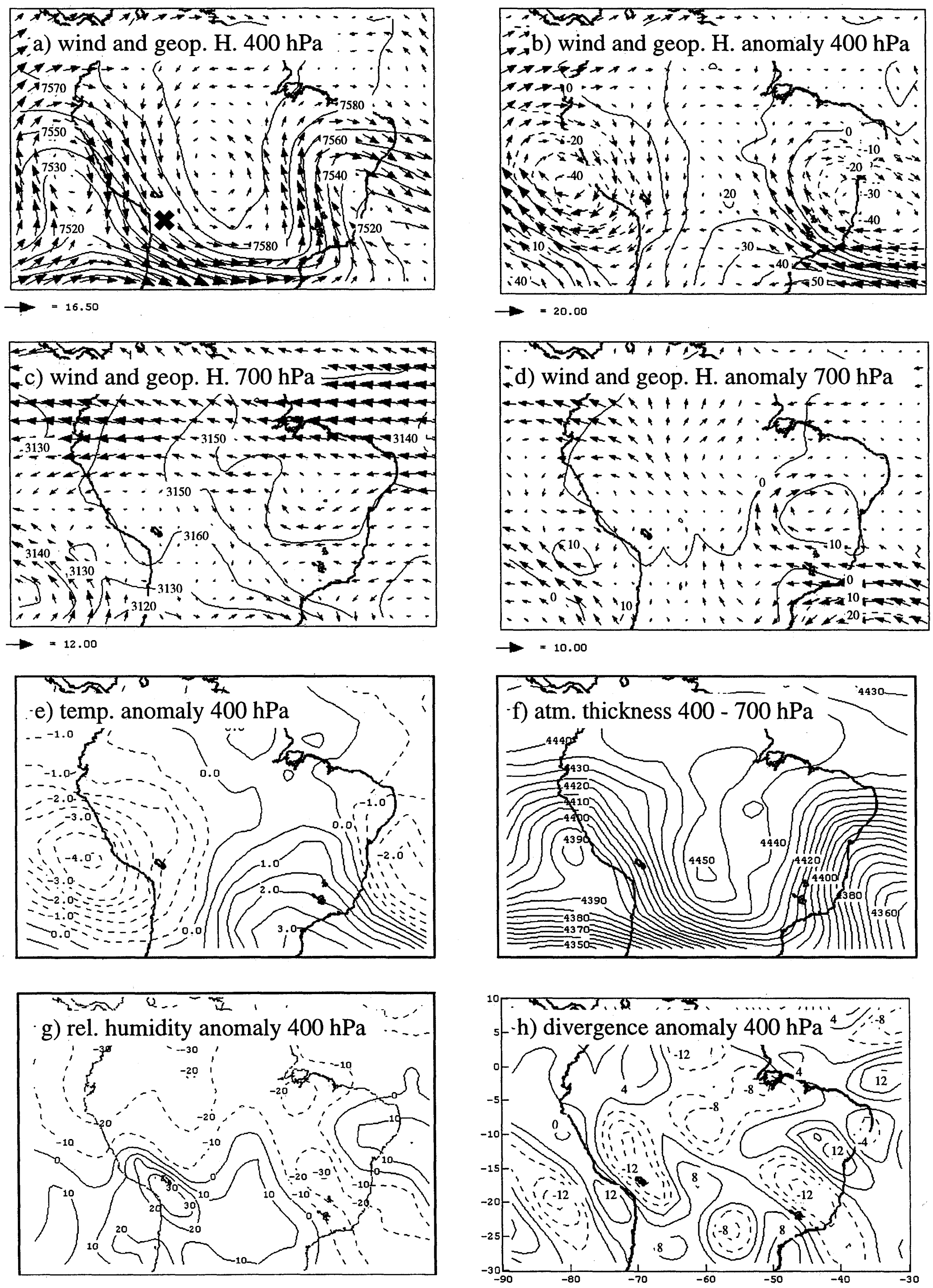

Figure 7. As in Figure 4 but composite for group D.

des is noteworthy (Figures 5g-5h). Again divergence, atmospheric thickness, geopotential height, and wind patterns indicate strong vertical motion over the Altiplano, to the NE of the high-pressure system. However, in comparison with group A, stronger winds at both levels suggest more horizontal moisture influx. Southeasterly flow, as shown by the 400 hPa level wind pattern, was indeed predominant at the summit during this period (H98). The low-level wind pattern (Figure 5c) suggests moisture influx from the north and wind convergence (not shown) to the east of the Andes. It is noteworthy that *Jacobeit* [1992] found a very similar pattern, with an anticyclonic vortex off the Pacific coast and divergence to the NE of it, to be the first principle component in his analysis of atmospheric circulation during wet periods over the Altiplano in the 200 hPa level.

The third group (C) is represented in Figure 6 by a composite of the atmospheric conditions that prevailed during most of February and during two events in March (see Table 1). Again, the synoptic situation can best be characterized by the positioning of the Bolivian High. The location of the maximum in geopotential height at the 400 hPa level is clearly anomalous, far to the south over the subtropical part of the continent. The meridional pressure gradient between tropical and subtropical South America is completely reversed, leading to unusually strong easterly winds over the southern Altiplano (Figures 6a-6b). It is important to note that this general enhancement in the easterly flow occurs in all pressure levels, although to a lesser degree in the lower atmosphere. The divergence pattern reveals enhanced convergence in the 400 hPa level over the Altiplano (Figure 6h). The strong easterly wind anomalies in all levels, and the fact that major vertical motion cannot take place under these conditions, suggests enhanced moisture advection from the east (Figures 6b and 6d). Temperature and thickness patterns (Figures 6e-6f) again show a positive anomaly in the subtropical and a negative anomaly over the tropical part of South America. It is unclear how much snow fell on Sajama during these events because the snow depth sensors were both buried below the snow surface, but in total the months of February and March must have accounted for ~2 m of snow accumulation (H98). The humidity pattern is very similar to that of groups A and B, although the maximum positive anomaly is slightly displaced toward the west over the Pacific (Figure 6g).

Group D consists of a single event (N1) which does not fit within any of the described groups and therefore forms its own category (Figure 7). N1 (November 7-13) is the first event that leads to snowfall on Sajama during the 1996/1997 rainy season and rather resembles a winter snowfall situation, as described by *Vuille and Ammann* [1997]. A cold upper air low forming a trough off the west coast of Peru and a high-pressure system over the interior of the continent form a steep zonal pressure and temperature gradient, which enhanced northerly flow over the central Andes (Figure 7a). Associated with this strong meridional circulation is increased relative humidity over the Altiplano (Figure 7g) and 18 cm of snow accumulation on Sajama. Besides the strong convergence of northerly and northwesterly winds over the Altiplano (Figure 7h), which excludes major vertical motion, the increasing humidity during periods of rather high wind speeds on Sajama are indicative of the horizontal moisture advection. The cold character of the event is obvious from the atmospheric thickness pattern and the temperature anomaly distribution (Figures 7e-7f).

5. Discussion

The differences in transport history between the four synoptic situations A-D are best revealed by looking at the com-

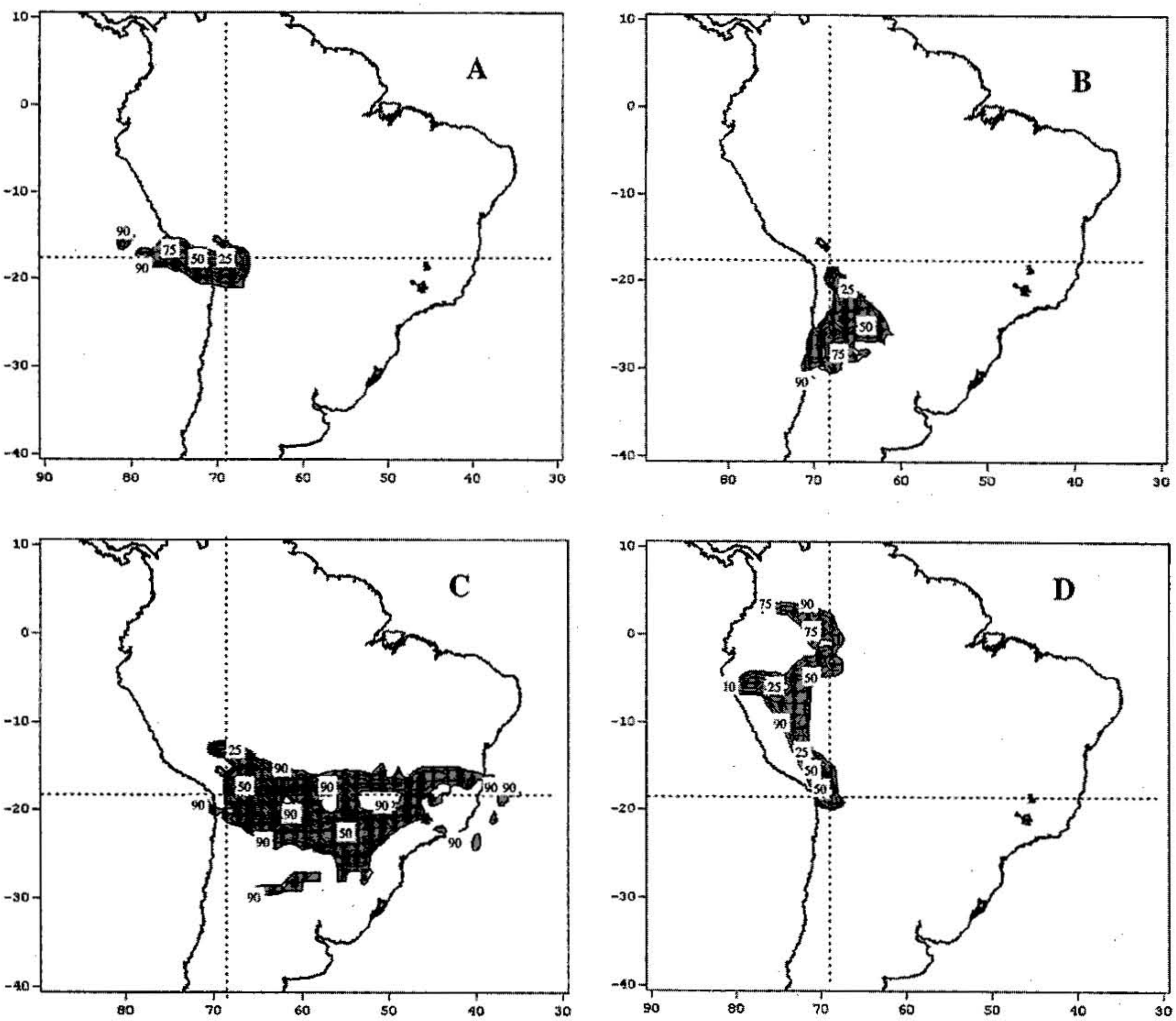

Figure 8. Transit time analysis for groups A-D at the 400 hPa level. Latitude and longitude of Sajama is shown by dotted line. For explanation, see text.

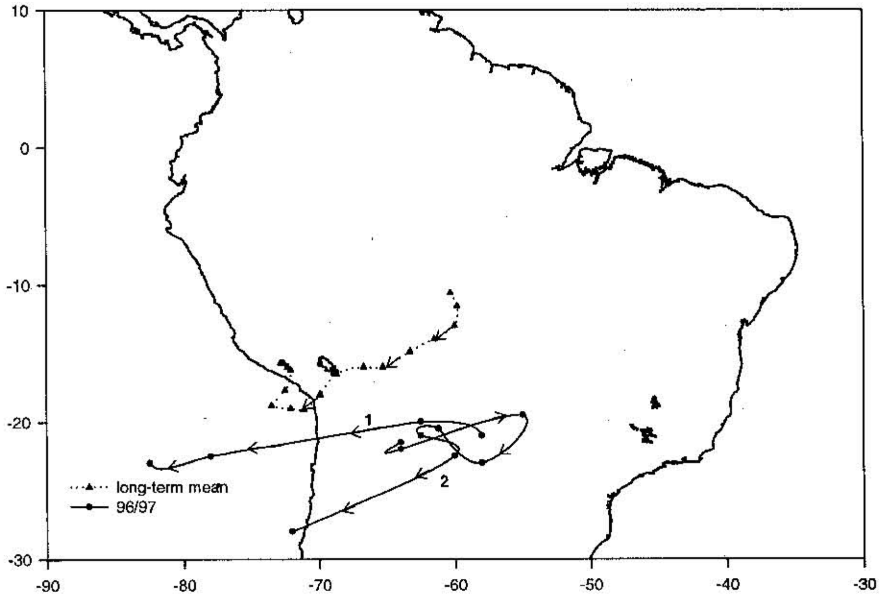

Figure 9. Map showing long-term mean (dashed line) and 1996/1997 (solid line) position of the Bolivian High in the 400 hPa level. Long-term mean is plotted every 5 days from December to February (triangles) and interpolated in between (dashed line). 1996/97 position is plotted every 5 days (dots) and interpolated in between (solid line) for two periods only: December 25, 1996 to January 15, 1997 (1) and January 25 to February 28, 1997 (2). Arrows denote direction of displacement.

posite transit time analysis for each group (Figure 8). Groups A and B reveal patterns somewhat similar and typical for strong vertical motion and low upper level winds (Figures 8a-8b). The air particles in the 400 hPa level spent most of their last 5 days before reaching Sajama in a very limited area over the summit. No long-range transport or upper air advection of humidity occurred. These patterns are characteristic of strong convection processes over the Altiplano and moist air advection in lower levels. With regard to the stable isotope composition of the snow, a strongly depleted signal seems most likely as the humid air masses must have experienced significant precipitation and reevaporation processes, associated with loss of heavy isotopes during a slow transport toward Sajama. The main difference between groups A and B is the somewhat extended area toward the southeast during situation B (Figure 8b), suggesting some enhanced moisture influx from this area in upper levels. The transit time plots for groups C and D, however, reveal a very different situation. Figure 8c shows the strong easterly upper level flow, with the 90% isoline extending across subtropical South America toward the Atlantic Ocean. A significant and fast moisture influx from remote regions must have occurred during these events, transporting air particles from the tropical South Atlantic toward Sajama within 5 days. Such rapid transport mechanisms from source to receptor within a few days could result in quite a different stable isotope signal, even though precipitation during transport might have occurred. In general a significantly higher $\delta^{18}O$ value would be expected in the snow layers related to these events. The same is true for the single event N1, forming group D (Figure 8d). Again, a transport over several thousand kilometers occurs at the 400 hPa level during the last 5 days before arrival on Sajama. However, the northerly flow and the convergence of winds from the NE and the NW over the central Andes (Figure 7h) further complicate the story. Single 5 day back trajectories at the 400 hPa level (not shown) suggest influx from the NW during the first few days, then switching toward the NE during the second half of the event. In addition to influencing the isotopic composition, differences in atmospheric circulation during these events will also produce variability in the chemistry and particulate concentration of the snow.

These analyses demonstrate that all snowfall events except N1 can be characterized by the relative deviation of the maximum of geopotential height in the 400 hPa level. While the Bolivian High was located over the Altiplano during the events belonging to group A (December 1996, end of January and middle of March 1997), it was displaced toward the southwest during mid-January 1997 (group B) and toward the south during February and the beginning and end of March (group C). A comparison of the position of the Bolivian High with its long-term mean reveals these rather unusual dislocations (Figure 9). As shown, these southern and southwestern positions are very favorable for the development of precipitation events over the Altiplano and provide the main explanation for the unusually wet 1996/1997 rainy season.

6. Summary and Conclusion

In order to improve the calibration of an ice core recently recovered from Sajama ice cap, Bolivia, this study reveals the main atmospheric features related to precipitation events on the Altiplano during the southern hemisphere summer. On the basis of the analysis of midtropospheric circulation associated with 17 precipitation events recorded on the Sajama volcano during the 1996/1997 summer season, four major synoptic situations were distinguished. While highly convective situations prevailed during most of December and January, significant moisture influx from remote areas, particularly to the east, occurred during February and most of March, as indicated by transit time analysis at the 400 hPa level. The different synoptic situations can best be distinguished by the change in the position of the maximum geopotential height in the 400 hPa level (Bolivian High). The unusual position of this high-pressure system is the main reason for the anomalously high precipitation amounts over most of the Altiplano.

The varying transport history of air particles before their arrival on Sajama influences the geochemical and stable isotope composition of snow, accumulating on the ice cap. It is therefore a prerequisite to analyze the transport mechanisms involved in order to establish a sound relationship. This study provides evidence that highly variable conditions can attribute to snowfall on Sajama during the summer months; analysis on the basis of single events is therefore necessary. Accordingly, earlier model attempts assuming constant and similar atmospheric conditions associated with summer snowfall in the tropical Andes may not be applicable to the Sajama region. As this study continues and will include winter snowfall events and additional years, even more circulation patterns associated with snowfall on Sajama might be revealed. Together with the geochemical analysis of snow layers associated with these events, a more accurate ice core calibration will then be possible.

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References

Aceituno, P., and A. Montecinos, Circulation anomalies associated with dry and wet periods in the South American Altiplano (Preprints), *in Fourth International Conference on Southern Hemisphere Meteorology and Oceanography*, Am. Meteorol. Soc., Boston, Mass., 1993.

Aravena, R., H. Peña, A. Grilli, O. Suzuki, and M. Mordeckai, Evolución isotopica de las lluvias y origen de las masas de aire en el Altiplano chileno (Isotope hydrology investigations in Latin America), *IAEA-TECDOC, 502*, 127-142, 1989.

Bradley, R.S., Are there optimum sites for global paleotemperature reconstruction?, *NATO ASI Ser. I, 41*, 603-624, 1996.

Chu, P.-S., A contribution to the upper-air climatology of tropical South America, *J. Climatol., 5*, 403-416, 1985.

Davidson, C.I., J-L. Jaffrezo, M. J. Small, P. W. Summers, M. P. Olson, and R. D. Borys, Trajectory analysis of source regions influencing the south Greenland ice sheet during the Dye 3 gas and areosol sampling program, *Atmos. Environ., 27A*(17/18), 2739-2749, 1993.

Dorling, S.R., T. D. Davies, and C. E. Pierce, Cluster analysis: A technique for estimating the synoptic meteorological controls on air and precipitation chemistry-Method and applications, *Atmos. Environ., 26A*(14), 2575-2581, 1992.

Figueroa, S.N., P. Satyamurty, and P. L. Da Silva Dias, Simulations of the summer circulation over the South American region with an Eta coordinate model, *J. Atmos. Sci., 52*(10), 1573-1584, 1995.

Fuenzalida, H.P., and J. Ruttlant, Origen del vapor de agua que precipita en el Altiplano de Chile, in *Anales del II Congreso Interamericano de Meteorologia*, Buenos Aires, Argentina, 1987.

Gandu, A.W., and J. E. Geisler, A primitive equations model study on the effect of topography on the summer circulation over tropical South America, *J. Atmos. Sci., 48*(16), 1822-1836, 1991.

Garreaud, R. D., and J. M. Wallace, The diurnal march of convective cloudiness over the Americas, *Mon. Weather Rev., 125*, 3157-3171, 1997.

Grootes, P.M., M. Stuiver, L. G. Thompson, and E. Mosley-Thompson, Oxygen isotope changes in tropical ice, Quelccaya, Peru, *J. Geophys. Res., 94*, 1187-1194, 1989.

Haagenson, P.L., Y.-H. Kuo, and M. Skumanich, Tracer verification of trajectory models, *J. Clim. Appl. Meteorol., 26*, 410-426, 1987.

Harris, J.M, and J. D. Kahl, A descriptive atmospheric transport climatology for the Mauna Loa Observatory, using clustered trajectories, *J. Geophys. Res., 95*,13,651-13,667, 1990.

Hastenrath, S., Annual cycle of upper air circulation and convective activity over the tropical Americas, *J. Geophys. Res., 102*, 4267-4274, 1997.

Horel, J.D., A. N. Hahmann, and J. E. Geisler, An investigation of the annual cycle of convective activity over the tropical Americas, *J. Clim., 2*, 1388-1403, 1989.

Jacobeit, J., Die grossräumige Höhenströmung in der Hauptregenzeit feuchter und trockener Jahre über dem südamerikanischen Altiplano, *Meteorol. Zeitschrift, 1*(6), 276-284, 1992.

Kahl, J.D., A cautionary note on the use of air trajectories in interpreting atmospheric chemistry measurements, *Atmos. Environ., 27A*(17/18), 3037-3038, 1993.

Kahl, J.D., and P. Samson, Uncertainty in estimating boundary layer transport during highly convective conditions, *J. Appl. Meteorol., 27*, 1024-1035, 1988.

Kahl, J.D., D. A. Martinez, H. Kuhns, C. Davidson, J-L. Jaffrezo, and J. M. Harris, Air mass trajectories to Summit, Greenland: A 44-year climatology and some episodic events, *J. Geophys. Res., 102*, 26,861-26,875, 1997.

Kleeman, R., A modelling study of the effect of the Andes on the summertime circulation of tropical South America, *J. Atmos. Sci., 46*(21), 3344-3362, 1989.

Kousky, V.E., and M. T. Kayano, Principal modes of outgoing long-wave radiation and 250 mb circulation for the South American sector, *J. Clim., 7*, 1131-1143, 1994.

Lenters, J.D., and K. H. Cook, On the origin of the Bolivian High and related circulation features of the South American climate, *J. Atmos. Sci., 54*, 656-677, 1997.

Moody, J.L., and P. J. Samson, The influence of atmospheric transport on precipitation chemistry at two sites in the midwestern United States, *Atmos. Environ., 23*(10), 2117-2132, 1989.

Nishizawa, T., and M. Tanaka, The annual change in the tropospheric circulation and the rainfall in South America. *Arch. Meteorol. Geophys. Bioklimatol., Ser. B, 33*, 107-116, 1983.

Nogués-Paegle, J., and K. C. Mo, Alternating wet and dry conditions over South America during summer, *Mon. Weather Rev., 125*, 279-291, 1997.

Rao, G. V., and S. Erdogan, The atmospheric heat source over the Bolivian Plateau for a mean January, *Boundary Layer Meteorol., 46*, 13-33, 1989.

Rao, V.B., I. F. A. Cavalcanti, and K. Hada, Annual variation of rainfall over Brazil and water vapor characteristics over South America, *J. Geophys. Res., 101*, 26,539-26,551, 1996.

Schwerdtfeger, W., Strömungs- und Temperaturfeld der freien Atmosphäre über den Anden, *Meteorol. Rundsch., 14*(1), 1-6, 1961.

Silva Dias, P.L., W. H. Schubert, and M. DeMaria, Large-scale response of the tropical atmosphere to transient convection, *J. Atmos. Sci., 40*, 2689-2707, 1983.

Thompson, L., E. Mosley-Thompson, and B. J. Arnao, El Niño-Southern Oscillation events recorded in the stratigraphy of the tropical Quelccaya Ice Cap, Peru, *Science, 226*, 50-52, 1984.

Thompson, L.G., E. Mosley-Thompson, W. Dansgaard, and P. M. Grootes, The Little Ice Age as recorded in the stratigraphy of the Tropical Quelccaya Ice Cap, *Science, 234*, 361-364, 1986.

Thompson, L.G., M. E. Davis, E. Mosley-Thompson, and K.-B. Liu, Pre-Incan agricultural activity recorded in dust layers in two tropical ice cores, *Nature, 336* (22/29), 763-765, 1988.

Thompson, L.G., E. Mosley-Thompson, M. E. Davis, P.-N. Lin, K. A. Henderson, J. Cole-Dai, J. F. Bolzan, and K.-B. Liu, Late Glacial stage and Holocene tropical ice core records from Huascaran, Peru, *Science, 269*, 46-50, 1995.

Trenberth, K.E., and J. G. Olson, An evaluation and intercomparison of global analyses from the National Meteorological Center and the European Centre for Medium Range Weather Forecasts, *Bull. Am. Meteorol. Soc., 69*(9), 1047-1057, 1988.

Virji, H., A preliminary study of summertime tropospheric circulation over South America estimated from cloud winds, *Mon. Weather Rev.*, *109*, 599-610, 1981.
Vuille, M., and C. Ammann, Regional snowfall patterns in the high arid Andes, *Clim. Change*, *36*(3-4), 413-423, 1997.

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