REGIONAL SNOWFALL PATTERNS IN THE HIGH, ARID ANDES

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Abstract. Since 1990 the project 'Climate Change in the Arid Andes' has been focusing on past climate and environmental conditions in the high mountain range of the north Chilean Andes (18° S–28° S). The extreme aridity of this region is shown by the absence of glaciers, even at the highest altitudes above 6700 m a.s.l. More knowledge of the present climatic situation is needed to interpret the proxy data of different paleoarchives in this transition belt between tropical and extratropical circulation.

Precipitation events in this arid region are mainly registered during southern hemisphere summer, when the ITCZ reaches its southernmost position. Winter precipitation (snowfall) has so far not been considered an important factor in the hydrologic system of the area, because snow is seldom accurately registered by climatic stations. To fill this gap in our information, winter snowfall activity was analysed for a period of 6 years using digital NOAA/AVHRR satellite data. The results show that snowfall during winter (May–September) is a quite regular phenomenon, mainly linked to northward displacements or cut-offs of cold air-masses from the Pacific. The areal distribution of snowfall is determined by the synoptic situation that produces precipitation. During cold frontal events, snowfall is most frequent in the southernmost part of the research area and on the western Chilean side of the Andes. Cold air that has been cut off from the westerlies often interacts with warmer and more humid air over the continent and therefore gives rise to a different snowfall distribution, with the greatest snowfall frequency between 23° S–25° S, decreasing polewards as well as towards the equator. These two winter snowfall patterns show that reconstruction of paleoclimate has to take into account the different mechanisms that may cause precipitation in the research area. Intensification of winter precipitation (e.g., the west wind zone) can induce largely different precipitation patterns, depending on which mechanisms (cut-offs, cold-fronts or both) within the west wind zone are strengthened.

Introduction

This study is part of a broader interdisciplinary project on climate change in the arid Andes of Northern Chile, focusing on past climate and environmental conditions in the high mountain range of the Andes between 18° S–28° S during the last 20,000 years.

The study area lies between the tropical circulation zone in the north and the west wind belt with its cyclonic activity in the south (Figure 1). This arid part of the Andes is an excellent place to study past climatic changes because any variation or shift in circulation zones in the past would have left tracks in different paleoarchives (paleosols, moraines, lacustrine sediments, etc.) that are found in the area (Grosjean, 1994; Messerli et al., 1993, forthcoming).

Under present conditions the precipitation systems of both circulation zones penetrate into this area due to the seasonal shifts of these zones, but precipitation is nevertheless very scarce. The whole area is presently an extremely dry zone, mainly

Climatic Change **36:** 413–423, 1997.

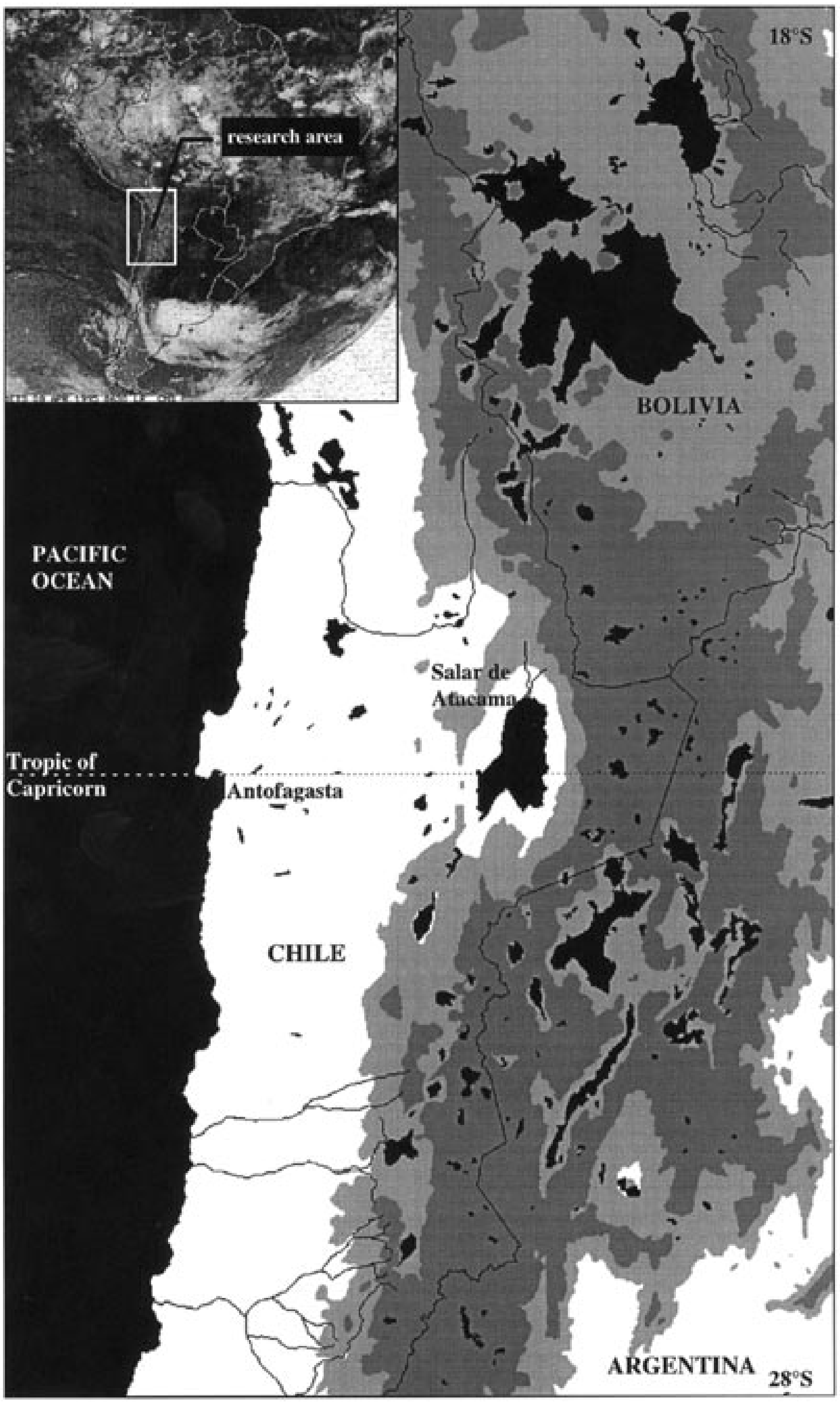

Figure 1. Position of the research area (18° S–28° S) and altitudinal zonation of the Andes (areas above 3000 m are shown in light gray, areas above 4000 m in dark gray, Pacific ocean, lakes and salars (salt pans) in black).

under the influence of subsiding dry air masses associated with the south Pacific anticyclone. The driest desert on earth, the Atacama Desert in the lower altitudes on the Chilean side of the Andes, and the lack of glaciers even on the highest volcanoes above 6700 m demonstrate this aridity. Near the Tropic of Capricorn at an altitude of about 4000 m a.s.l., the few climatic stations register less than 180 mm annual precipitation.

Many studies on actual climatic conditions and the circulation mechanisms leading to precipitation in this part of the Andes have been carried out to date. But nearly all these studies concentrate on convective summer precipitation, initiated by a southward expansion of the inter-tropical convergence zone (ITCZ) and the heating effect of the Altiplano (Aceituno and Montecinos, 1993; Chu, 1985; Gutman and Schwerdtfeger, 1965; Horel et al., 1989; Jacobeit, 1992; Rao and Erdogan, 1989; Virji, 1981). Winter precipitation, resulting from northward incursions of the west wind zone has been neglected so far, except for a very few case studies on its isotopic composition or wind trajectories (Aravena et al., 1989; Fuenzalida and Rutllant, 1986; Rutllant and Aceituno, 1991). This leads to serious problems, because reconstruction of past climate and atmospheric circulation must be based on knowledge of the present circulation and precipitation patterns. Without knowing the winter precipitation pattern, interpretation of proxy data from paleoarchives becomes extremely difficult. Thus, modern climatic patterns have to be evaluated to find a climatic match with environmental data from the past.

The aim of this study is to reveal the actual temporal and regional precipitation patterns in this part of the Andes. Very generally, precipitation can be divided into tropical summer precipitation, due to the heating effect of the elevated Altiplano (Gutman and Schwerdtfeger, 1965; Rao and Erdogan, 1989), and winter precipitation originating in the west wind zone (Miller, 1976). As the mechanisms of tropical summer precipitation are already quite well known, this study deals with the origin and spatial distribution of winter precipitation. During winter, precipitation falls as snow at higher altitudes due to lower temperatures, and is therefore hardly ever correctly registered. Furthermore, climatic stations are quite rare in this remote part of the Andes. Therefore, an interpretation of the few and qualitatively poor climatic records leads to the general misconception that the whole area is predominantly influenced by summer rainfall at present, although this is certainly not correct. Field measurements in 1993 during southern hemisphere winter and water equivalent computations for the years 1990–1992 by means of satellite snowcover monitoring show, that a mean annual amount of 50–80 mm of snow (mm water equivalent) can be expected at 4500 m at 23°45′ S (Vuille, 1996).

Methods and Data

The results presented here are based on an analysis of data from six different southern hemisphere winters (May–September). The years 1984, 1986 and 1990–

1993 were chosen because they represent rather wet (1984, 1992) as well as rather dry (1990) years. The climatic variability was analysed in earlier studies using digital Landsat satellite data (Vuille and Baumgartner, 1993) and climatic data from two automatic weather stations installed in the centre of the study region in 1990 at 4400 m and 5000 m a.s.l. at 23°45′ S (Vuille, 1996). Such a variability analysis is crucial, in order to be sure of getting significant results in an area of very high temporal and regional precipitation variability. Even though the analysis of a longer data set would have been desirable, this article presents a first case study towards a better understanding of the climate in this region. During the six winters, 37 different precipitation events were registered by climatic stations in the research area. Out of the 37 events, 24 were selected for this study and analysed using weather charts (surface, 500 hpa and 200 hpa), radio soundings from Antofagasta (Figure 1), GOES satellite data and the records from the official Chilean climate stations. The other 13 events were not analysed due to missing data sets. The main criteria for this synoptic analysis were the pressure fields and the radiosonde soundings from Antofagasta. Analysis of these data resulted in a preliminary classification of the different events into typical synoptic situations which produce precipitation in the research area. A better and final separation resulted by integrating the vertical temperature distribution and the horizontal temperature and wind fields. A detailed description of this synoptic analysis is given in Ammann (1996).

It is quite difficult to monitor the regional extent of precipitation as the official climatic stations are very rare and unevenly spread over the research area. Furthermore, it seems that at least winter snowfall is not always correctly registered by these stations. Therefore, satellite data were chosen as a basis for this study, as such data had already been applied successfully in earlier studies in this area (Vuille and Baumgartner, 1993). During winter, precipitation falls as snow at higher altitudes, so satellite data offer a unique opportunity to monitor the extent and frequency of snowfall. Digital NOAA/AVHRR data were used to separate snow-covered areas from bare soil. The NOAA/AVHRR satellite sensor was chosen because its spatial resolution of 1 km^2 allows snow classification on a regional scale (Rango et al., 1983; Baumgartner and Seidel, 1988) and the whole study area can be covered in one image. Moreover, many authors have shown that if a multispectral classification algorithm is used, the different satellite sensors (channels) allow snow-covered areas to be accurately separated from their surroundings (Allen et al., 1990; Kidder and Wu, 1987; Lucas and Harrison, 1990). In this study snow discrimination was done by using NOAA/AVHRR channel 1–4 and applying a Maximum Likelihood Classification algorithm (Duda and Hart, 1973). During the winter of 1993 a field verification was carried out in order to detect classification errors and to exclude light snowfalls without any contribution to the hydrological cycle, that might still show up as snow cover in the satellite imagery. Typical snow depths at 4400 m, 23°45′ S for single snowfall events are 5 cm–20 cm, depending on slope and aspect (Vuille, 1996). Furthermore, all scenes were geometrically corrected and resampled using a Nearest Neighbour Resampling method. Finally, all scenes were matched to a Digital Terrain Model to be able to detect the temporary snowline and the snow-covered area in different elevation zones.

1. Synoptic Situation During Winter Snowfall Episodes

The synoptic analysis of precipitation events in the research area during southern hemisphere winter led to a weather classification, in which events with different synoptic situations were separated. The results show that there are only two main categories of weather conditions producing snowfall in the area during winter. Of course there are many variations within these two categories, but they are of no relevance when looking at the spatial distribution of snowfall in the research area. This conclusion results from the analysis of the final snowfall patterns which are very homogeneous within each category.

The first category consists of snowfall from cold front events originating in the Pacific. Normally cold fronts cross the Andes further south (Miller, 1976; Van Husen, 1967), but sometimes they reach far north and can penetrate into the research area. Such events are often combined with blocking episodes in the South Pacific leading to a northward displacement of cold polar air masses and precipitation in northern and central Chile (Berbery and Nuñez, 1989; Rutllant and Fuenzalida, 1991). Figure 2 (left side) shows such an event in June 1990 which produced heavy snowfall in the arid Andes. The low pressure trough belonging to the cold front is easily detectable at the 500 hpa level.

The second category also represents moisture advection from the Pacific, but it is composed of polar air that has been cut off and wanders north along the Chilean coast as an isolated cell rather than a typical cold front. Figure 2 (right side) shows such an outbreak of cold air at the 500 hpa level in August 1993. The GOES data in Figure 3 belong to the same event and show the cold air drop over the Pacific (left side) as well as the uplifted more humid, tropical air lying over the Altiplano one day later (right side). The interaction between cold Pacific air and warmer tropical air over the arid Andes, generating a large cloud cluster in Figure 3 (in the image on the right) has already been reported by Aravena et al. (1989) and by Fuenzalida and Rutllant (1986) and seems to be quite a regular phenomenon.

Both weather conditions appear with nearly the same frequency. The 24 events analysed were classified into 13 snowfalls originating from cold fronts and 11 from cut-offs.

2. Present Snowfall Patterns

To be able to interpret proxy data from the paleoarchives, it is important to know the present areal distribution of snowfall associated with the different synoptic situations. Therefore, the snowfall events belonging to each category were analysed

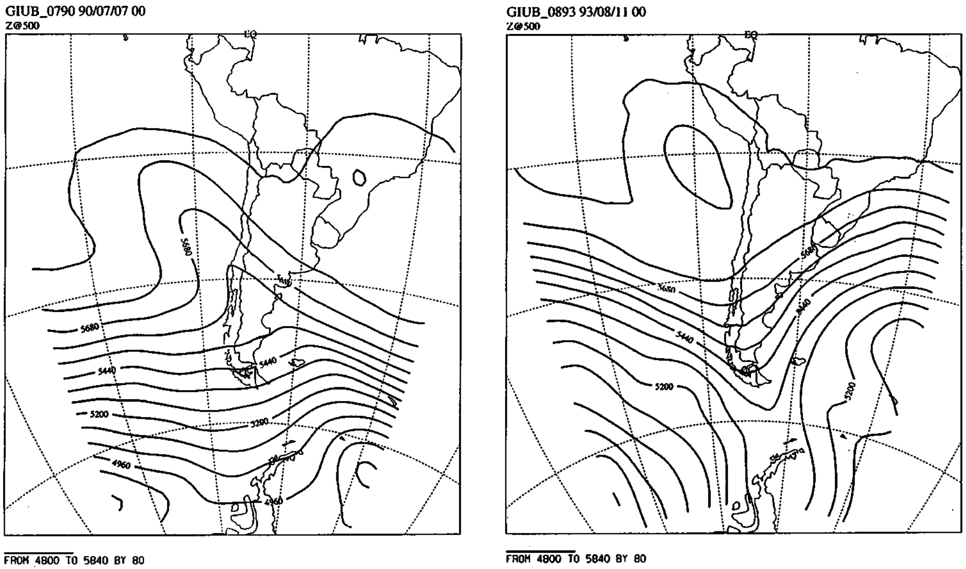

Figure 2. Synoptic weather charts (500 hpa) showing typical circulation patterns leading to snowfall in the research area. Left side: cold front event in June 1990, right side: cut-off event in August 1993 (Source: European Weather Forecast Center, Reading, UK, by permission of D. Luethi, ETH-Zuerich).

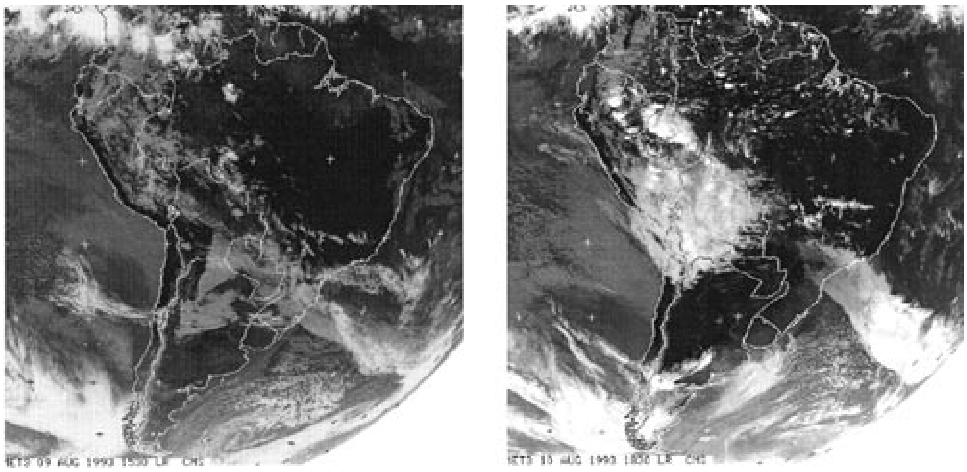

Figure 3. GOES satellite data from August 9th and 10th 1993, showing development of a typical cut-off event over the arid Andes (Source: Dept. of Geography, Univ. of Berne).

separately and then combined into a 'cold front-snowfall pattern' and a 'cut off-snowfall pattern'. The results show that there are significant and relevant differences in the spatial pattern of the two categories due to the different synoptic situation (Figures 4 and 5).

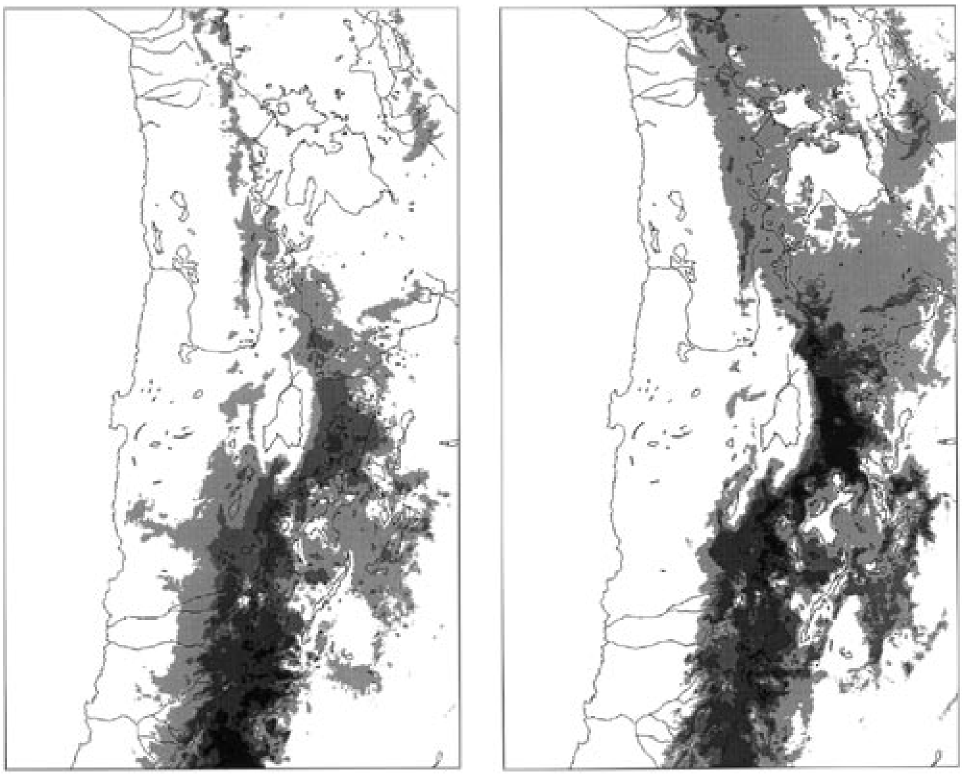

Figure 4. Snowfall probability patterns in the research area during cold front (left side) and cut-off events (right side). Snowfall probability: light gray $< 20\%$, gray: $< 40\%$, dark gray: $< 70\%$, black: $> 70\%$.

During cold front events (Figure 4, left side) snowfall frequency is obviously greatest in the southernmost part of the research area at 28° S, decreasing constantly towards the equator. This is also evident considering the snowfall probability along a transect on the western Chilean range from 18° S–28° S at 4500 m a.s.l. (Figure 5). While snowfall occurred during more than 80% of all analysed cold front events at 28° S, only about 10% of these events reached as far north as 18° S. Another phenomenon typical of this snowfall pattern is the great difference between the western and the eastern slopes of the Andes. Figure 6 shows a cross-section through the Andes at 27.5° S from the Pacific coast to the Argentinian lowlands. The black bars indicate the snowfall frequency along this cross-section during cold front events. Obviously, snowfall is much more frequent on the western side, showing that the Andes act as a moisture-blocking ridge. Snowfall hardly ever occurs on the Argentinian side. All these indicators show very clearly that moisture comes from the Pacific during cold front events and therefore mainly influences the southern part of the research area and the western range of the Andes.

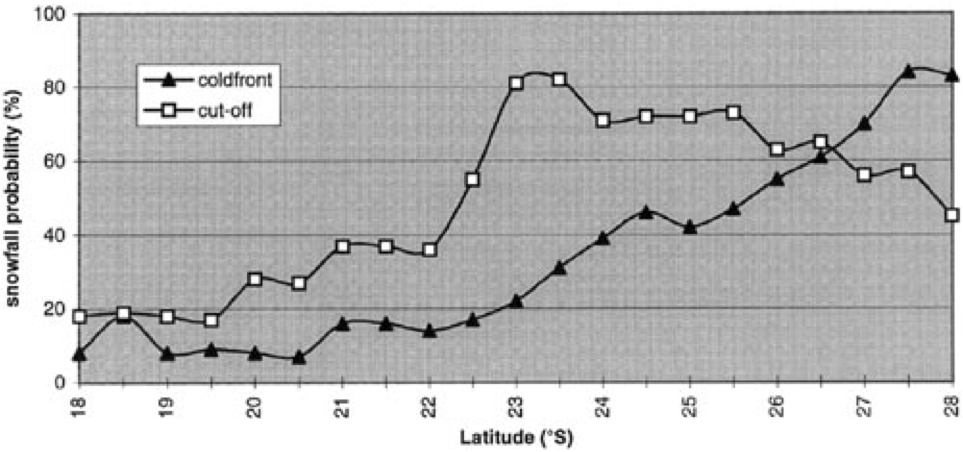

Figure 5. Snowfall probability along a transect on the western Andean range from 18° S–28° S at 4500 m a.s.l. during cold front and cut-off events.

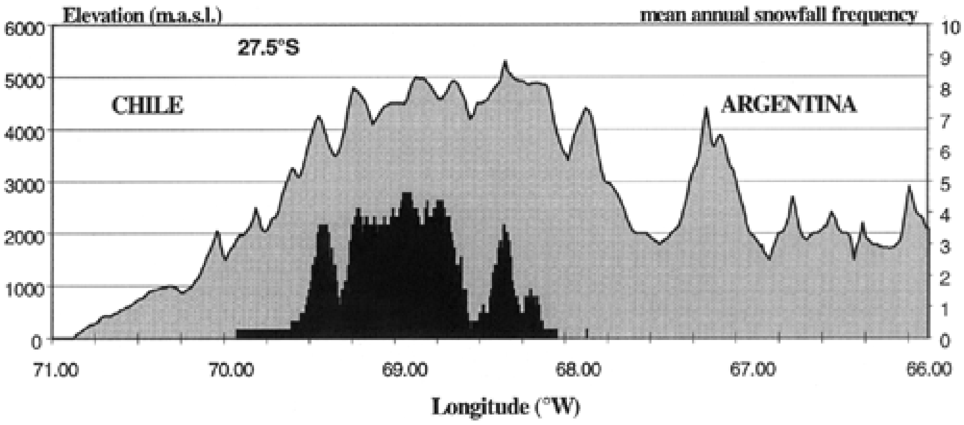

Figure 6. Cross-section through the Andes at 27.5° S from the Pacific coast (71° W) to the Argentinian lowlands (66° W). The gray surface represents the topography of the Andes, the black bars indicate the mean annual snowfall frequency across the Andes during cold front events.

Obviously the situation looks quite different during cut-off events. (Figure 4, right). The main snowfall activity in the Andes occurs east of the Salar de Atacama, near the Tropic of Capricorn between 23° S and 24° S, decreasing both equatorwards and polewards. This becomes even more evident when we consider the snowfall frequency on the same north–south transect along the western Andean range. Figure 5 shows that the highest snowfall frequency ($> 80\%$) is observed between 23° S–24° S, decreasing polewards (45% at 28° S) and towards the equator (20% at 18° S). Furthermore, the differences between the eastern and the western sides of the Andes are less pronounced because these cut-offs often interact with humid tropical air lying over the continent in the upper troposphere.

The question of why the main snowfall activity occurs only in the area east of the Salar de Atacama is still under discussion. Probably this zone is often frequented by the cut-off tracks, but the number of analysed events is still too small for definite conclusions. Furthermore, the role of Andean topography during phases of cold air advection is not yet clear. Therefore, the orographic effect of the high mass elevation east of the large Salar de Atacama must be analysed more precisely.

3. Paleoclimatic Implications and Conclusions

Proxy data from the paleoarchives (moraines, lacustrine sediments, paleosols, etc.) indicate that more humid conditions during the late glacial and the early holocene in the research area are probably due to an intensification and southward extension of tropical summer precipitation (Grosjean, 1994; Grosjean et al., 1995; Hastenrath and Kutzbach, 1985; Messerli et al., 1993, forthcoming). These findings are consistent with the reported expansion of Bolivian Altiplano lakes during this Tauca phase (Wirrmann and Mourguiart, 1995) and tropical moisture advection producing a lower late pleistocene equilibrium line on the eastern slope of the Andes (Fox and Strecker, 1991).

Nevertheless, the two typical present-day precipitation patterns during southern hemisphere winter in the arid Andes have clear implications for climatic interpretation of paleoarchives in the research area. They show that an intensification of the westerlies can have different effects, depending on whether cold fronts, cut-off lows or both are intensified within the west wind zone. In any case, it would be a dangerous simplification to compare an intensification of the westerlies with a simple and continuous northward shift of more humid conditions. If an intensified west wind zone was accompanied by a higher cut-off frequency, reconstruction of a former precipitation pattern becomes difficult. It is not yet clear whether the snowfall maximum near the Tropic of Capricorn is significant even for longer time periods, or if it is a random effect due to the small number of analysed events. If this distribution is produced by topographic effects, it can be concluded that a similar pattern should have been active in the past, as topography has remained the same over the last 20,000 years. Even though all proxy data from paleoarchives suggest a tropical moisture source to be the origin of the more humid conditions, the precipitation pattern derived from cut-off events shows that it is theoretically possible to explain such conditions in the central and also in the northern part of the study area even without intensified tropical circulation. This has to be kept in mind when interpreting moisture signals from paleoarchives.

We must emphasize, that it is not satisfactory to analyse past climate by shifting or intensifying entire circulation belts. The processes within a circulation zone leading to different precipitation patterns have to be analysed and understood. By changing intensity and the frequency of the synoptic situation, many more possible paleoclimatic interpretations become available.

Finally, this study has led to a better understanding of the present atmospheric circulation in winter over the research area during precipitation episodes, and contributed to the discovery of previously unknown precipitation patterns in the arid Andes. It is obvious that the snowfall frequency has been highly underestimated so far, due to the lack of climatic records in the area (no data or data of very poor quality). Satellite data have proven to be an excellent tool for such purposes.

Acknowledgements

This article is part of the Swiss National Science Foundation Project 'Climate Change in the Arid Andes' (NF 20-36382.92). Special thanks are owed to B. Messerli and M. F. Baumgartner (Dept. of Geography, Univ. of Berne) and all other members of our team, each of whom contributed to this study.

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(Received 22 February 1996; in revised form 30 October 1996)