Monitoring the Regional and Temporal Variability of Winter Snowfall in the Arid Andes Using Digital NOAA/AVHRR Data

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Abstract

This paper deals with the spatial distribution and the temporal variability of snowfall in the most arid part of the Andes (18° - 28°S) during southern hemisphere winter (May-September). As the official precipitation data is of poor quality, analyses were carried out by means of digital image processing techniques, using NOAA/AVHRR satellite-data. Through analysis of 24 different snowfall events from six winters, a previously unknown spatial and temporal precipitation pattern in this remote and unexplored area was revealed. Snowfall is most abundant in the southernmost part of the research area and on the western side of the Andes, indicating the Pacific origin of the snowfall.

Nevertheless, the typical snowfall pattern is modified during different periods of the winter. Three typical time periods could be defined and distinguished from one another. Each of these three periods is characterized by typical weather conditions (cold fronts and "cut-offs") leading to a distinct snowfall pattern.

As this study is part of a broader paleoclimatic project, the results will serve as a basis for paleoclimatic reconstruction of past climate. Only by knowing the modern circulation and precipitation patterns is it possible to interpret paleoclimatic signals and archives found in the study area (e.g. paleosol, moraines) correctly.

Introduction

The present study is part of the interdisciplinary project "Climate Change in the Andean dry diagonal of South America", which focuses on the reconstruction of past climate and environmental conditions, including changes in atmospheric circulation during the last 20,000 years. Such a goal can only by successful if knowledge of present-day atmospheric circulation and precipitation patterns is expanded. Therefore, the aim of this paper is to investigate the regional and temporal snowfall patterns in the most arid zone of the Andes, between 18° and 28° S (Figure 1). The results of this study can help to enhance knowledge about present-day circulation and precipitation patterns during southern hemisphere winter (May - September) in this remote and unexplored area of Northern Chile, Northwestern Argentina and Southern Bolivia. This knowledge is a basic prerequisite for a better understanding and paleoclimatic interpretation of different paleoarchives such as lake sediments, paleosols, moraines, pollen and archeological sites found in this area (Grosjean, 1994; Grosjean & Nuñez, 1994; Grosjean *et al.*, 1995; Messerli *et al.*, 1993).

The study area lies in a very dry zone, between the tropical circulation in the North, dominated by convective summer precipitation, and the west wind zone with its frontal winter precipitation regime towards the South. These two different circulation zones can be clearly identified in the Meteosat-satellite image in Figure 1. The aridity in this area is caused by subsiding dry air masses from the Southeast Pacific Anticyclone, the cooling effect of the cold Humboldt current near the Pacific coast, and the blocking effect of the high mountain range, leading to extremely dry conditions on the western side of the Andes. The Atacama desert on the Chilean slope of the Andes is considered to be the driest place on earth, with precipitation rates below 10 mm/year. In higher areas at 4500 m, 215-230 mm/year might be an appropriate value in the region near the tropic of Capricorn (Vuille, 1996). Nevertheless, aridity is still extreme, leading to the unique phenomenon that even the highest volcanoes at 6700 m a.s.l. are lacking glaciers under current climatic conditions. Due to the seasonal shifts of the circulation belts, both precipitation regimes are able to penetrate into this arid zone and produce rain or snowfall in the Andes. But the climatic data base for this region is full of gaps and the available data is of poor quality. Therefore precipitation records, which indicate that only summer precipitation is relevant, are questionable. Even though there are some very important studies dealing with atmospheric circulation and the origin of precipitation over this part of the Andes (Aceituno, 1989; Aravena *et al.*, 1989; Berbery & Nuñez, 1989; Chu, 1985; Horel *et al.*, 1989; Jacobeit, 1992; Nishizawa & Tanaka, 1983; Rutllant & Fuenzalida, 1991;

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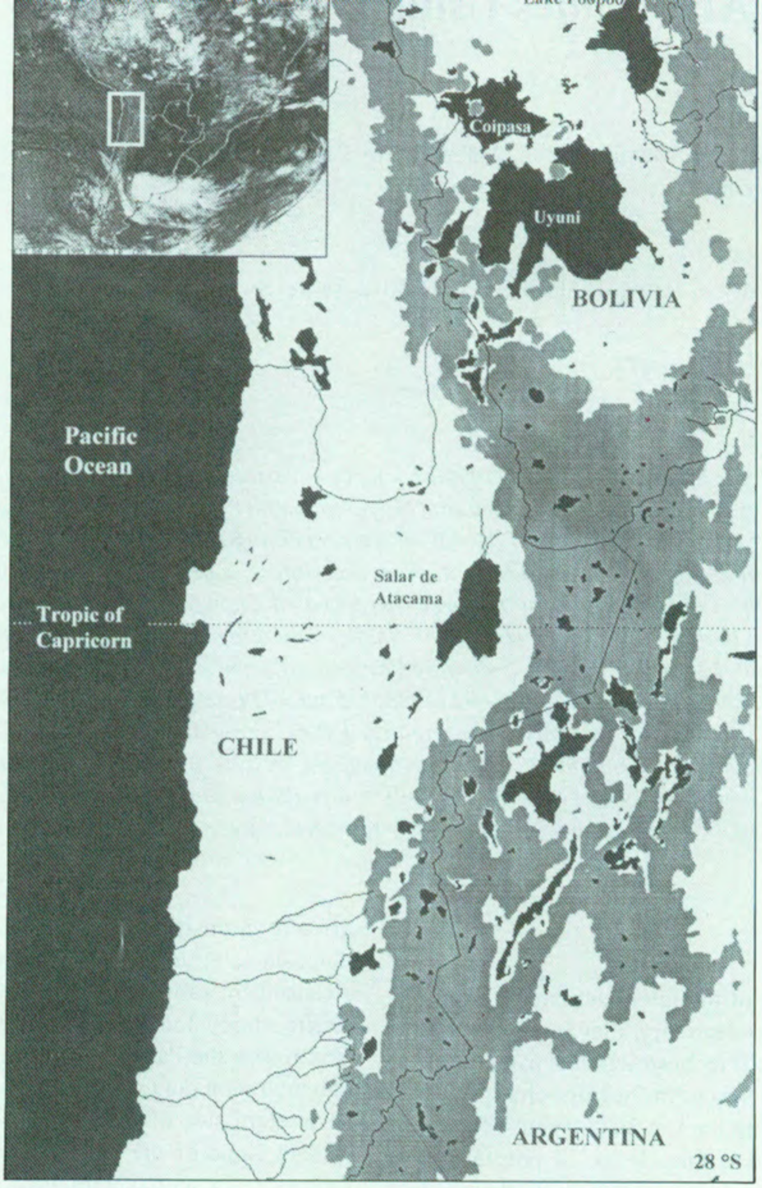

Figure 1 The location of the study area (white rectangle in a Meteosat-image) is shown in the inset (upper left), whereas the map represents a section of the Andes (areas above 4000 m a.s.l. are shaded in light grey; the Pacific ocean, international frontiers, lakes and salars (salt pans) are displayed in black).

Virji, 1981; Walsh, 1994), no investigation of the role, importance and frequency of winter precipitation has been undertaken so far. The final aim of this study is to make up for this lack of information. Special emphasis will be given to the analysis of the frequency and the regional distribution of snowfall during different periods of the winter season.

Methods and Data

Due to the very unreliable precipitation data available, digital NOAA/AVHRR satellite data were used to monitor the frequency and extent of winter snowfall. This inaccessible and remote region with very few climate stations and extremely low cloud cover frequency is an excellent place for such remote sensing applications. This has already been shown in earlier studies in this region (Vuille & Grosjean, 1991; Vuille & Baumgartner, 1993). Nevertheless, the NOAA/AVHRR satellite sensors detect only snow, not rainfall. Therefore, the study area was limited to the higher Andean regions. The lower areas, where rainfall might appear, are beyond the scope of this study.

As mentioned, the main focus is on winter precipitation events between May and September. 24 different snowfalls were analysed for the years 1984, 1986, and 1990 - 1993.

Table 1 shows the number of analysed events per month and year. Even though not every year was analysed in detail, two-thirds of all snowfall events were monitored. The six years represent the wide range of climatic variability in this region, including the El-Niño event of 1991/92. The results of this investigation can therefore be considered as fully representative for this area.

Table 1 Number of snowfalls analysed per month and year (number of recorded events in brackets).

	1984	1986	1990	1991	1992	1993	**Total**
May	-(-)	1(2)	1(2)	-(-)	1(1)	1(1)	**4 (6)**
June	1(2)	1(1)	3(3)	1(2)	2(2)	-(1)	**8 (11)**
July	-(1)	-(2)	2(2)	1(2)	-(1)	2(2)	**5 (10)**
August	-(1)	1(2)	1(1)	-(-)	-(1)	3(3)	**5 (8)**
September	-(-)	-(-)	1(1)	1(1)	-(-)	-(-)	**2 (2)**
Total	**1(4)**	**3(7)**	**8(9)**	**3(5)**	**3(5)**	**6(7)**	**24(37)**

Table 2 lists all snowfall events, the recording date of the NOAA/AVHRR data analysed, and the satellite system used.

Analyses were carried out on a microcomputer using a Maximum-Likelihood classification algorithm, including NOAA/AVHRR bands 1-4 in the visible, near-infrared, middle and thermal infrared range of the electromagnetic spectrum. To control classification accuracy, a parallel snow classification was carried out at two selected test sites, using high-resolution Landsat-MSS data (56 m * 79 m instead of 1.1 km * 1.1 km when using NOAA/AVHRR). Earlier studies have shown that such a control can help to prevent systematic classification errors when using coarse resolution satellite systems (Baumgartner *et al.*, 1987; Baumgartner & Seidel, 1988). The control classifications showed that the classification accuracy with NOAA/AVHRR data was very reliable and no corrections had to be made. Afterwards, each classification was geometrically corrected by a third-degree transformation, using a Digital Terrain Model (DTM) of the study area as a grid base. Resampling was done by the Nearest-Neighbour method in order to keep the original classification values.

Typical Winter Snowfall Patterns

By adding all snowfall events analysed, and by considering that only two-thirds of the snowfalls were investigated, a mean annual snowfall frequency map was established (Figure 2). The different colour layers indicating different snowfall frequencies and NOAA/AVHRR channels 1 and 2 (visible and near-infrared) were superimposed on the DTM. The Figure shows the whole study area frown 18° - 28 °S. The

Table 2 Date of snowfall, NOAA/AVHRR data analysed, and satellite system

Period of snowfall in the research area	Date and recording time (UTC) of NOAA/AVHRR data analysed	NOAA satellite system
21.-26. 06.1984	28.06.1984 (20:10:39)	NOAA-7
29. 05.-03.06.1986	01.06.1986 (20:27:30)	NOAA-9
28.-30.06.1986	30.06.1986 (20:05:59)	NOAA-9
17.-20.08.1986	24.08.1986 (20:32:35); 25.08.1986 (20:21:58); 27.08.1986 (20:00:28)	NOAA-9
29.05.1990	01.06.1990 (18:44:25)	NOAA-11
30.05.-01.06.1990	02.06.1990 (18:33:24) 03.06.1990 (18:22:26)	NOAA-11
03.-04.06.1990	07.06.1990 (19:19:35)	NOAA-11
07.-11.06.1990	15.06.1990 (19:32:58)	NOAA-11
07.-09.07.1990	13.07.1990 (19:29:08)	NOAA-11
15.07.1990	16.07.1990 (18:56:19)	NOAA-11
17.-18.08.1990	20.08.1990 (19:15:50)	NOAA-11
05.-06.09.1990	10.09.1990 (18:46:38)	NOAA-11
16.-19.06.1991	20.06.1991 (19:33:55); 22.06.1991 (19:10:55)	NOAA-11
27.-30.07.1991	30.07.1991 (20:17:22); 01.08.1991 (19:54:20)	NOAA-11
29.09.1991	02.10.1991 (19:42:25); 04.10.1991 (19:19:02)	NOAA-11
27.-29.05.1992	31.05.1992 (20:41:41)	NOAA-11
02.-09.06.1992	06.06.1992 (19:29:38); 09.06.1992 (20:34:22)	NOAA-11
25.06.-01.07.1992	02.07.1992 (21:00:03); 03.07.1992 (20:48:21)	NOAA-11
27.-30.05.1993	31.05.1993 (21:01:09); 04.06.1993 (20:12:17)	NOAA-11
04.-06.07.1993	07.07.1993 (20:12:45)	NOAA-11
15.-17.07.1993	17.07.1993 (21:32:17)	NOAA-11
02.08.1993	05.08.1993 (21:01:50)	NOAA-11
10.-13.08.1993	13.08.1993 (21:04:53); 14.08.1993 (20:52:39)	NOAA-11
16.-21.08.1993	23.08.1993 (20:43:23)	NOAA-11

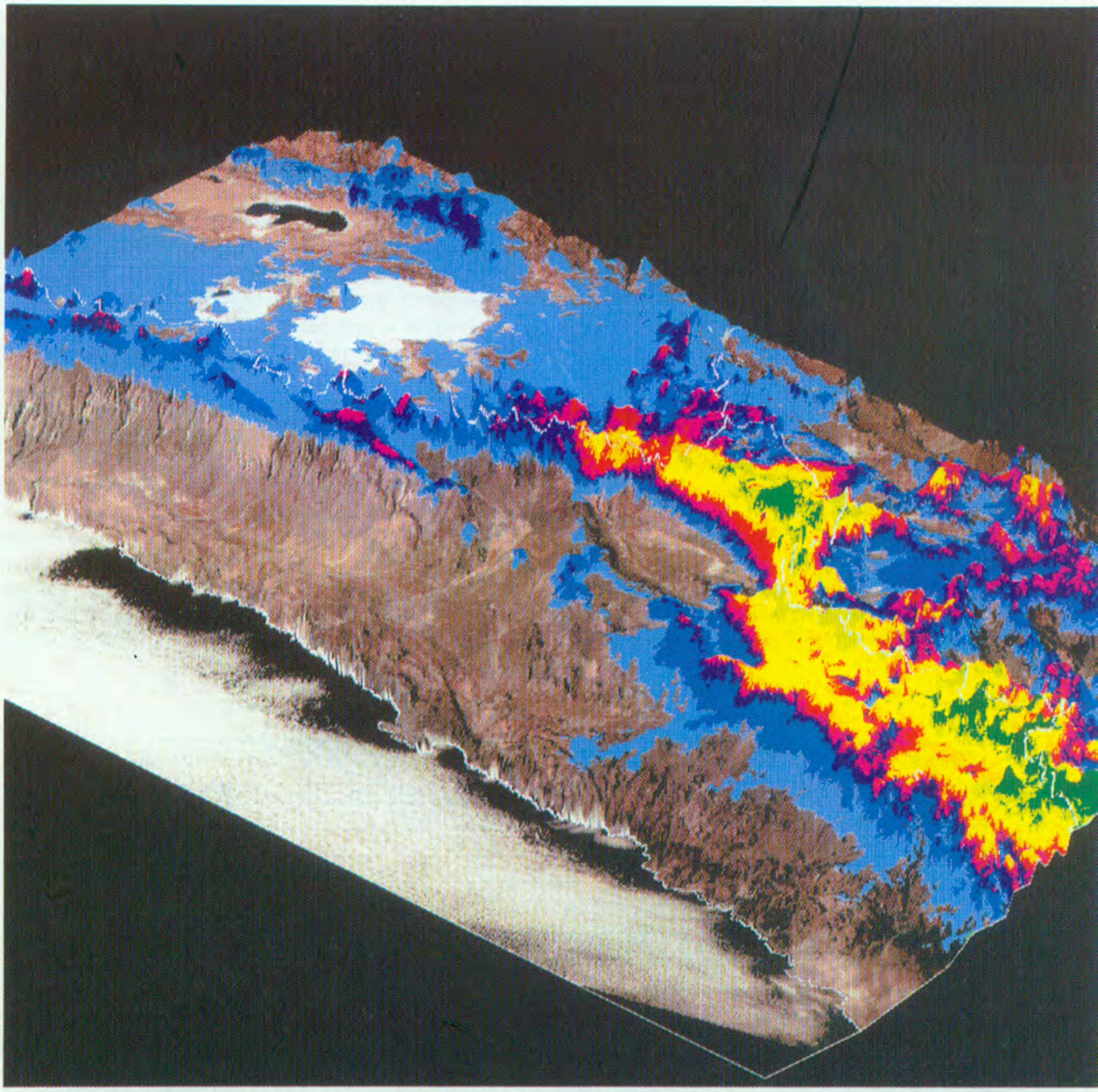

Figure 2 Mean number of snowfalls per winter in the study area (18° - 28°S), seen from South-West (bottom) to North-East (top): light blue < 0.5, blue 0.5 - 1, dark blue 1 - 1.5, violet 1.5 - 2, red 2 - 2.5, orange 2.5 - 3, yellow 3 - 3.5, light green 3.5 - 4, green 4 - 4.5, dark green > 4.5. The white areas in the foreground represent cold fog (known as Camanchaca), the white plains in the northern part belong to the Bolivian salars (salt pans) Uyuni and Coipasa. Lake Poopoo appears in the North-East

view is from the southwest (bottom) to the northeast (top). The white or greyish areas in the foreground represent the cold fog (called Camanchaca) lying over the Pacific along the Chilean Coast. To the northeast, the great Bolivian salars Uyuni and Coipasa (great white areas) and lake Poopoo (black area in the northermost part) are clearly visible. The basin of the Salar de Atacama is less striking due to the brownish color of the surface. Nevertheless, it appears as a snowfree basin, surrounded by higher areas that are affected by snowfall.

As indicated by the different colours, snowfall frequency is obviously highest in the southernmost part of the study area near 28 °S. Towards the North, snowfall probability decreases with a strong gradient near 22° - 23 °S, North of the Salar de Atacama. North of 22 °S, snowfall is registered only once or twice every winter, while three to five events are normal further South at a similar elevation. However, this South-North gradient doesn't represent a constant decrease. To the East of the Salar do Atacama, near the Tropic of Capricorn, a significant secondary maximum appears. As the snowfall frequency decreases towards the North, the lowest detected snowline rises from South to North. While snowfall occurred even at an altitude of 1500 m near 28 °S, no snowfall was registered below 3500 m a.s.l. at 18 °S. Furthermore, the Pacific origin of the snowfall and the moisture-blocking effect of the Andes leads to a very pronounced East-West contrast in the southern part of the region under investigation. The high Andean ridge (up to 6800 m) prevents the penetration of moisture into the south-eastern part of the region, leading to very rare snowfalls on the Argentinian slope of the Andes.

One goal of this investigation was to analyse whether the frequency and the regional distribution of snowfall change during the different periods of the winter season. A first attempt comparing the different months failed, because this temporal split did not consider precipitation fluctuations during winter. In Figure 3 the frequency of daily snowfall in the region under investigation, as well as a running mean (9-day average), is shown from May through September. Three different time periods can easily be distinguished (see dotted lines in Figure 3). Each period is characterized by a maximum precipitation frequency and an interval with low frequency values. The three periods were separated so that each of them included 32 days. Period l runs from 20 May - 20 June; period 2 from 21 June - 22 July; and period 3 from 23 July - 23 August. The month of September was not used for further investigations because snowfall activity is very low and hence its influence is negligible. Snowfall frequency in the three winter periods from May to August is rather uniform, with 12 events registered in period 1, 11 in period 2, and 1 0 in period 3. Nevertheless, it seems that snowfall frequency in the region under investigation is highest at the end of May and the beginning of June (Figure 3).

In Figure 4-6, the areal distribution of the mean snowfall frequency is shown for every period in the same manner as in Figure 2 (note that the different colours do not indicate the same frequencies as in Figure 2).

The most striking feature during the first period of the winter (20 May - 20 June) is the extremely low elevation of the snowline along the southern part of the western Andean range, which can't be observed in the later winter periods (Figure 4). There is an obvious and significant increase in the elevation of the snowline during wintertime in this region. Another interesting aspect of the snowfall pattern in period 1 is the very high snowfall frequency East of the Salar de Atacama, near the Tropic of Capricorn. This value is higher than in the southernmost part of the region under investigation and is not recorded in the later winter periods.

The second period (21 June - 22 July) is characterized by snowfall frequency that is still very low in the northernmost part of the region under investigation, and especially in the Bolivian part of the Andes (Figure 5). On the other hand, in the Argentinian part of the study area, the snowfall frequency is surprisingly high, and the snowline is much lower than during the other periods.

The third period (23 July - 23 August) is the only one where snowfall appears in the whole northern part of the study area, between the western Chilean and the eastern Bolivian range of the Andes (Figure 6). Snowfall frequency is obviously higher in this area than earlier in the winter. In the central and southern part of the study area, the snowline is very high, and to the west of the Salar de Atacama no snowfall was detected. Furthermore, the snowfall frequency is generally lower than during the two earlier periods. Only in the southernmost part up to 1.5 snowfall events can be expected in this late winter phase.

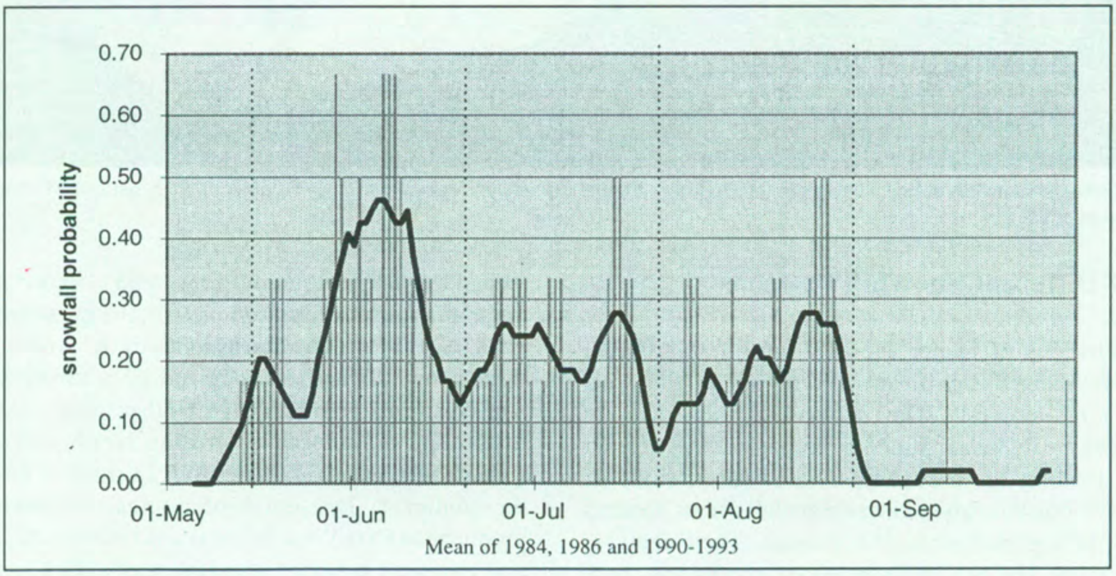

Figure 3 Probability of daily snowfall from May through September (moving 9-day average), determined for 1984, 1986 and 1990-1993, showing the three main precipitation periods (dotted lines): 20 May - 20 June, 21 June - 22 July, 23 July - 23 August (source: Dirección General de Aguas DGA, Santiago de Chile).

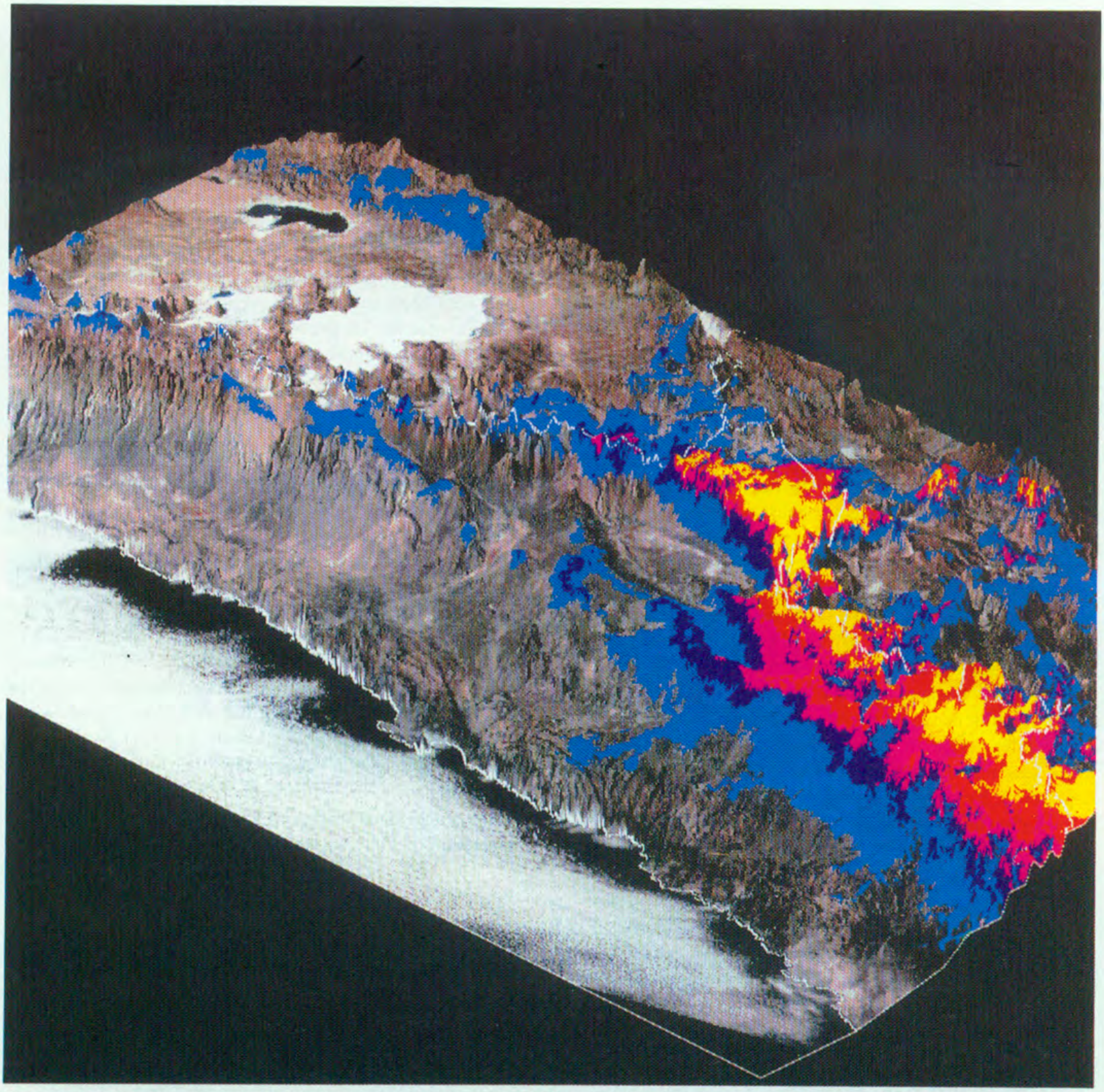

Figure 4 Number of snowfalls during winter period 1 (20 May - 20 June): Blue < 0.5, dark blue 0.5 - 0.75, violet 0.75 - 1, red 1 - 1.25, orange 1.25 - 1.5, yellow > 1.5

Origin of Different Snowfall Patterns

The subdivision of winter snowfall into three different time periods showed significant differences in the areal distribution of snowfall. The reason for this different behaviour can easily be explained by looking at the weather conditions leading to these winter snowfalls. Vuille & Ammann (1997) have analysed these snowfall events, looking at their origin and meteorological genesis. Their analyses show that there are two main weather conditions, both originating in the Pacific, which cause snowfall in the region under investigation. Northward displacements of cold fronts, embedded in the west wind zone, lead to snowfall mainly in the southern part of the region, with the greatest frequencies at 28° S and on the western slopes of the Andes. Therefore, these snowfalls are characterized by a strong South-North and West-East gradient. On the other hand, cold air masses in the upper troposphere, drifting North as isolated cells ("cut-offs"), can lead to an uplift of tropical moist air over the continent. This uplift of tropical air produces a less pronounced East-West difference in the snowfall distribution and therefore a higher snowfall probability in the eastern part of the Andes, in Argentina and Bolivia. Moreover, during these cut-off events, the maximum snowfall frequency

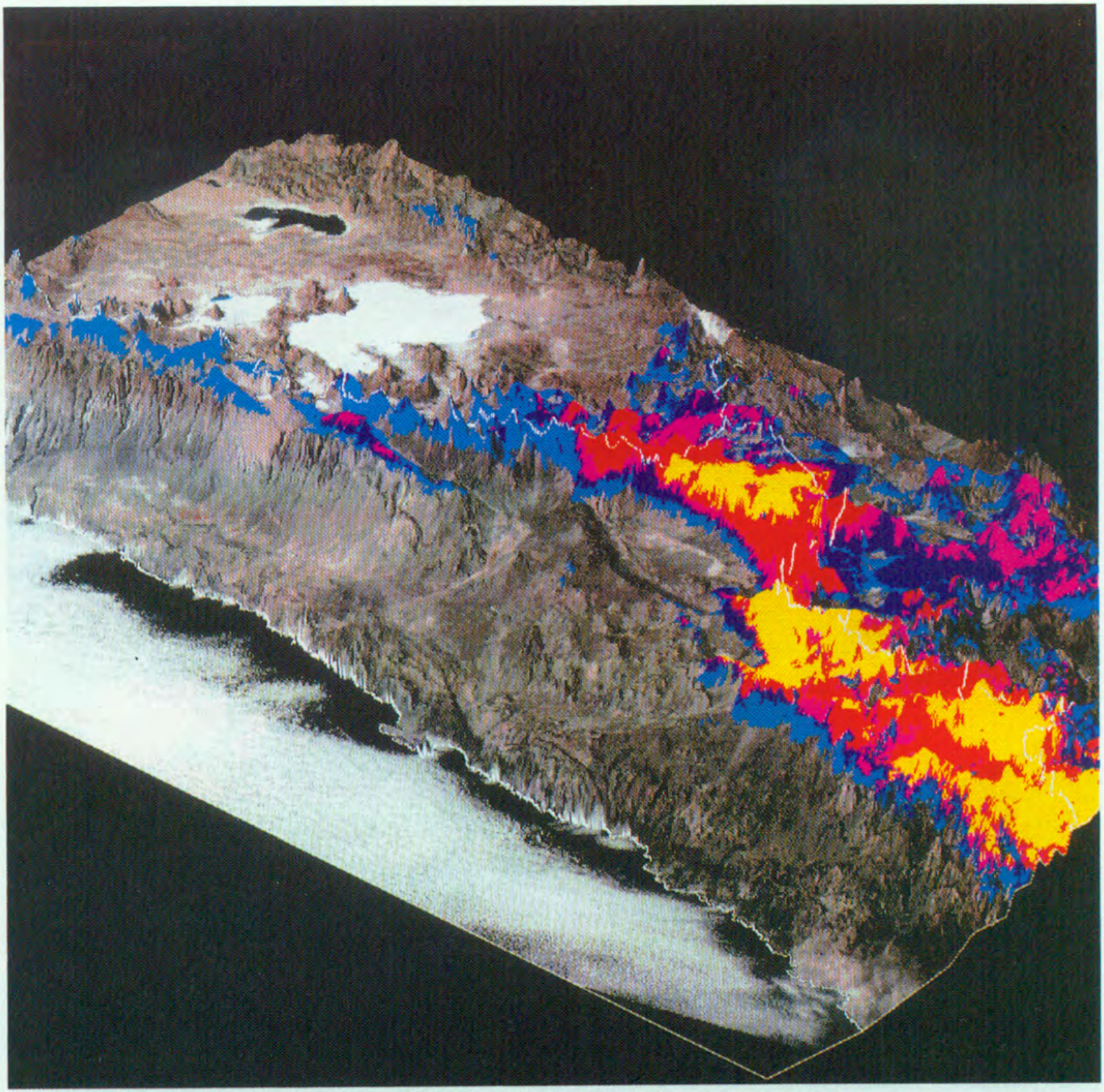

Figure 5 Number of snowfalls during winter period 2 (21 June - 22 July): same legend as in Figure 4.

occurs near the Tropic of Capricorn, to the East of the Salar de Atacama (Vuille & Ammann, 1997). This is a further contrast with snowfall originating from cold fronts, when snowfall frequency is highest in the southernmost part of the region at 28°S. The spatial precipitation patterns produced by the different meteorological boundary conditions help to interpret the snowfall distribution in the three winter periods. The frequency of cold frontal events decreases during the winter, leading to the observed increase of the elevation of the snowline from period 1 to period 2 and 3. The reason for this decrease of cold frontal events is a progressive stabilization of the zonal circulation of the westerlies during winter, preventing most cold fronts from reaching so far North in late winter. On the other hand, no change in the amount and intensity of cut-offs drifting toward the study area was detected, implying their growing importance in the second and third winter period. This fact matches well with the snowfall pattern of period 2 and 3, with higher snowfall probabilities in the eastern part of the Andes, in Argentina (Figure 5) and Bolivia (Figure 6).

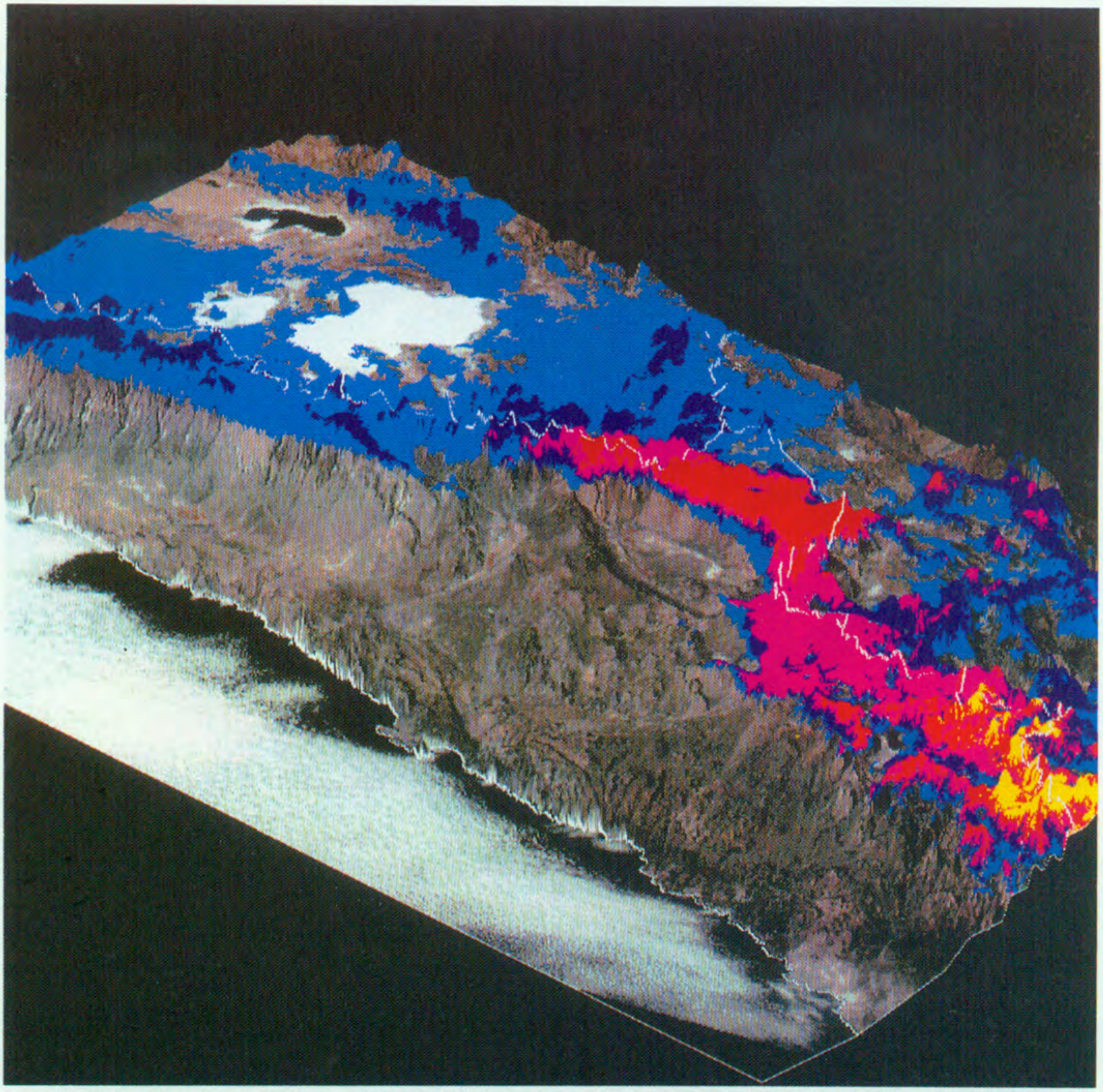

Figure 6 Number of snowballs during winter period 3 (23 July - 23 August): same legend as in Figure 4.

Summary and Conclusions

This study has revealed previously unknown winter precipitation patterns in the most arid part of the Andes. Monitoring of these snowfall patterns showed that the spatial distribution of precipitation is a function of the meteorological boundary conditions producing precipitation. As these weather conditions appear with changing frequency during the winter, the snowfall patterns for different time periodes of the winter obviously change as well. Frequent cold frontal events lead to snowfall in the southern part of the region, mainly on the western slopes of the Andes during the early winter (May and June). In mid and late winter (July and August), these events become less frequent. Snowfall is then mainly triggered by cut-offs leading to the uplift of tropical, moist air. Such events are characterized by a higher snowfall probability in the central and northern part of the region and on the eastern slope of the Andes (Argentina and Bolivia).

These snowfall patterns will serve as a basis for further studies within the project. The present-day areal distribution of precipitation in southern hemisphere winter will be compared with the areal distribution of the different paleoarchives found in the study area. Only by knowing the spatial extent and variability of winter precipitation in this remote and unexplored area, a reliable interpretation of past climate and atmospheric circulation can be made.

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