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Late Quaternary Glacier response to humidity changes in the arid Andes of Chile (18–29°S)

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Abstract

Today, no glaciers exist between 18°30′S and 27°S, even on mountains much higher than 6000 m. These dry high-mountain environments are very sensitive to changes in climatic boundary conditions, particularly humidity since temperatures are far below freezing. Here we present a reconstruction of climatic changes since the Last Glacial Maximum for the Chilean dry Andes of the southern hemisphere. We reconstructed regional equilibrium line altitudes (ELA) for three different moraine stages, representing extensive past glaciations in this currently unglaciated region. Comparison of the regional pattern of the ELA with modern climate conditions allows us to draw implications about the paleoclimatic conditions during the best preserved 'moraine stage II' glaciations in the northern as well as in the southern part of the research area. Our results suggest humid conditions in the northern part (18–24°S) during Late Glacial times, with strongly increased convective precipitation during austral summer. The temporal-coincidence of glaciers in the mountains and high lake levels on the Altiplano (Tauca Phase) is evident. To the south, no simple shift of the Westerlies is implied by our glacier reconstructions. The northern limit of effective moisture for glacier formation did not shift significantly, but stayed in the area of the present day northernmost glaciers of the Westerlies at about 27°S. But further south, precipitation increased significantly, accompanied by at least 2–3°C colder conditions. The age of this glaciation is uncertain, but probably of Late Glacial or Last Glacial Maximum (LGM) times. Overall, glaciers in the dry Andes of South America clearly responded to large changes in the humidity, not primarily the temperature regime, with all its consequences on the environment (hydrology, vegetation, etc.), illustrating the different regional responses to global climatic change.

Keywords: Altiplano; Climatic controls; Glacial extent; Last glacial maximum; Moraines; Paleoclimatology

1. Introduction

Recently, Quaternary climate research has increased its focus on the low latitudes to resolve contentious issues about temperature and precipitation change during the last maximal extent of continental ice sheets (referred to as the Last Glacial Maximum, LGM) some 19,000–21,000 cal yr BP, and the following transition to the Holocene (e.g. CLIMAP, 1976; Rind and Peteet, 1985; Broecker, 1995; Bard et al., 1997; Beck et al., 1997; Curry and Oppo, 1997; Miller et al., 1997). In South America, proxy data from the tropical oceans (Broecker, 1986; Curry and Oppo, 1997; Guilderson et al., 1994; Webb

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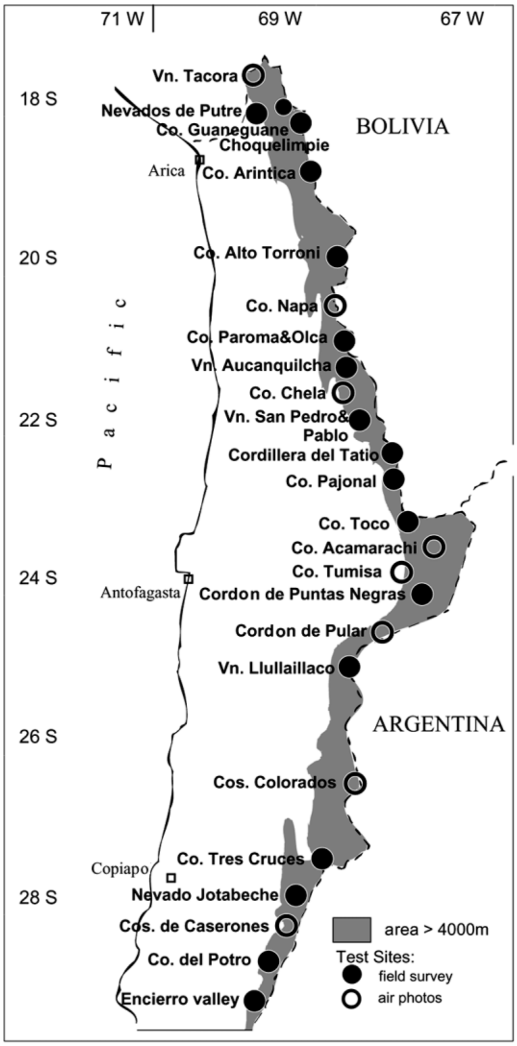


Fig. 1. Overview of the research area in northern Chile, with locations of test sites for former ELA reconstructions. Most of the test sites were studied in the field (bold circles), although some were investigated only using air-photographs (open circles). Details can be found in Table 1.

et al., 1997), Amazon lowland (Van der Hammen and Absy, 1994; Stute et al., 1995; Colinvaux et al., 1996) and the Andes (e.g. Grosjean, 1994; Hooghiemstra and Ran, 1994; Thompson et al., 1995, 1998; Clayton and Clapperton, 1997; Sylvestre et al., 1999; Klein et al., 1999) are used to reconstruct former environmental conditions.

In the high mountain environments of the tropical and subtropical Andes, extended areas with large moraine-systems suggest an eventful climate history (Hastenrath, 1971; Messerli et al., 1992; Clapperton, 1993). Unfortunately, dating is difficult and too rare to entirely disentangle the different glacial advances (Clapperton, 1993). In this paper, we investigate the former glaciation of the modern dry Andes. Two approaches to merge the glacial history of this region into a global scale are used, here called the 'cold' and the 'humid hypothesis'. In the first one, Broecker and Denton (1989) used snowline reconstructions of glaciers in a transect from the high northern latitudes along the west coast of North and South America to the high southern latitudes. Based on the general coincidence of temperature depression and glacial advances, they show an overall maximum reduction of the snowline of 900 m, and estimate a general temperature decrease of about 4.5–6.5°C during the (global) Last Glacial Maximum (LGM). For the central Andes, some regional studies of glacial and periglacial environments (e.g. Fox and Strecker, 1991) describe extensive glacial advances with these significantly reduced temperatures during the global LGM. The 'humid hypothesis' relates the last large glacier extensions in the dry Andes to a much more humid (and probably warmer) period of the late Pleistocene, around 13,000 ^{14}C yr BP (e.g. Hastenrath and Kutzbach, 1985; Messerli et al., 1992; Seltzer, 1992; Clapperton, 1993; Seltzer, 1994; Servant et al., 1995; Clayton and Clapperton, 1997). In this view, glacial expansion was suppressed during the cold LGM due to a lack of humidity.

We present data from the dry subtropical Andes between 18 and 29°S (Fig. 1). At these latitudes, the eastern and western Cordillera enclose the high intramontane plateau of the Altiplano with an elevation of about 4000 m. Full desert conditions extend from the Pacific coast (Atacama desert) to the summits of the Western Cordillera. Although the highest peaks often exceed 6000 m, no glaciers are present between 19 and 27°S (not taking into account the semi-permanent snow, firn or ice fields, e.g. on Volcano Llullaillaco, described by Lliboutry (1956) and observed by members of the Swiss NSF project since 1988). Climatically, the arid Andes are located in the transition zone between the tropics (mainly summer precipitation) and the westerly wind belt (mainly winter precipitation). Both large-scale circulation systems

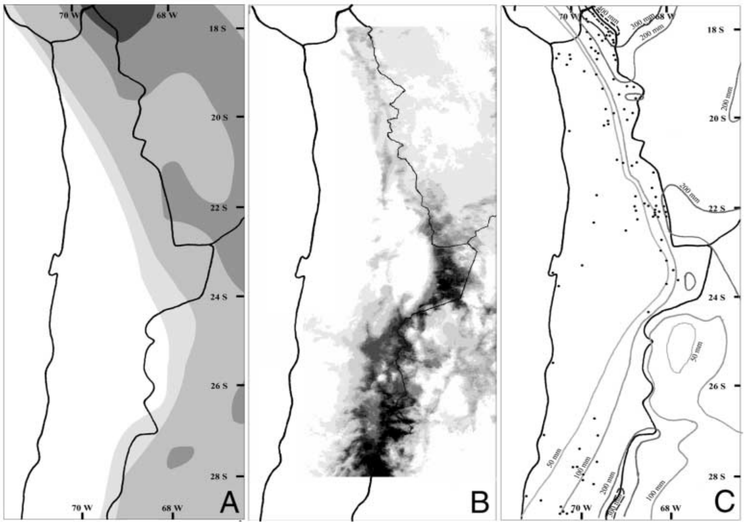


Fig. 2. Precipitation estimates: (a) Summer convective cloud cover frequency obtained from 96 GOES infrared satellite images during summer in late afternoon from October 1993 to March 1994. Gray shaded areas represent convective cloud occurrence (from light to dark shades) in 6–10, 10–30, 31–50 and >50% of days. (b) Mean winter snowfall frequency ranging from 0 to 8 events (ranging from white to darker grays) after Vuille (1996). The most frequent snow events are found to the south, with a secondary maximum at 23–24°S resulting from cut-off events. (c) Mean annual precipitation derived from summer convective cloud cover and winter snow occurrence (Ammann, 1996). The Andean Dry Diagonal is crossing the mountain range between 25 and 26°S. Black dots represent Chilean climate stations.

extend into the dry area, where they overlap. Between 18 and 29°S, the South American Dry Diagonal (Eriksen, 1983) crosses the Andes from NW to SE, tracing the rain shadow of the high mountain ridges to the prevailing airflow. Since the dry mountain environments are highly sensitive to changes in boundary conditions, they offer considerable potential for detecting patterns of regional change. Changes in either circulation system have specific impacts on the climate of the area. Their imprints with a typical spatial pattern help to link the changed environmental conditions to the source of the change.

Little is known about Late Quaternary climates of the arid Andes. Here we present evidence from former glaciations to identify past climatic conditions and outline the changes in environmental conditions in this dry transition zone. In earlier works, present day climatic conditions of this area were analyzed using convective cloud cover distribution for the summer, and snowfall frequency for the winter season (Ammann, 1996; Vuille and Ammann, 1997). The seasonal precipitation distribution showed distinct patterns: During summer (Fig. 2a), humid air from the eastern lowlands reaches the Altiplano, where the topography modifies the distribution of convective clouds and rain. The precipitation is at maximum in the north at 18°S. At a lower level, it then remains almost constant to about 23°S, from where it quickly decreases and around 25°S almost vanishes. In winter (Fig. 2b), frontal systems of the Westerlies sometimes penetrate into the area. South of 27°S the number of frontal passes with snowfall is high. Less frequent events are recorded further north, although not absent. Cold air pockets in the middle troposphere, cut-off from the strong westerly flow (cut-off cells), lead to a slight secondary maximum of snowfall events at 23–24°S. Further north only few events are found each year. These distinct seasonal patterns explain well the modern glaciation. This observation raises the interesting question, if we can find similar explanatory climate and circulation patterns for the late Pleistocene glaciation. First, we discuss the method of reconstructing late Quaternary equilibrium line altitudes (ELA) of glaciers with the Accumulation Area Ratio (AAR) method. Second, we compare the spatial distribution of the late Quaternary ELAs with modern precipitation fields and reveal their strong relationship. This allows us to draw implications about the late Quaternary environment and the climatic conditions during the last major glaciation in the Chilean dry Andes.

2. Methods

2.1. Glacial morphology

Glacial systems respond quickly to changes in the climate. Many authors reconstruct past glacier–climate relationships including both climatic and geomorphologic parameters (e.g. Gross et al., 1978; Maisch, 1988; Kerschner, 1990). Our goal was to reconstruct former equilibrium line altitudes (ELA). This altitude is a sensitive indicator for climate conditions because it is primarily controlled by summer temperature and precipitation (Gross et al., 1978; Kerschner, 1990). Some topographic features (e.g. aspect) also have an indirect influence on a local scale. Many striations and moraines throughout most of the area show that the glaciers in the dry Andes were mainly temperate (exhibiting basal sliding) and therefore an ELA can be calculated in two ways. The primary method applied in this study to estimate former ELAs is the AAR method (Gross et al., 1978), which uses the proportion of accumulation to ablation area. Secondly, an area-independent estimate of the ELA can also be obtained through the maximum altitude of lateral moraines, which only form at or below the ELA, when the ice flowlines are pointing upward, out of the glacier body. Throughout the research area, the altitude of lateral moraines confirmed the — at first — surprising AAR of 2:1, implying temperate glacier conditions. Using the limits of cirques and glacial deposits established by field mapping or the stereoscopic study of vertical air photographs, former glacier beds were reconstructed. ELAs were then calculated for a large number of mountains and aspects along a N–S-transect in the Western Cordillera between 18 and 29°S. The locations are indicated in Fig. 1 and calculated ELAs are summarized in Table 1.

2.2. Climate

During the summer season, precipitation generally emerges from convective activity over the Altiplano, due to influx of warm and humid tropical air masses (Schwerdtfeger, 1961; Miller, 1976; Romero, 1985; Messerli et al., 1992). We use new precipitation estimates derived from systematically mapped convective cloud cover from GOES-infrared satellite images as described in Ammann (1996). After considering the large elevation changes, the frequency of convective cloud cover presented in Fig. 2a shows good agreement with precipitation as measured at climate stations and offers a higher spatial resolution and more reliable coverage of areas without regular station measurements.

To estimate winter precipitation, snowfall frequency observations (Fig. 2b, from Vuille, 1996) were merged with available climate station data. Due to a complete lack of snow accumulation measurements in the high mountain area of the southern part of the research area, extrapolations from field measurements during the season of 1993 in El Laco (23°50′S/67°30′W) were derived from the mean snowfall frequency of Vuille (1996).

Both methods are described in more detail in Ammann (1996) and Vuille and Ammann (1997). Finally, Fig. 2c presents combined summer and winter precipitation as derived from convective cloud cover and snowfall frequency.

3. Late Quaternary glaciation

Several glacial stages indicate that most of the dry region of Northern Chile was glaciated in the late Pleistocene. Dating of these glaciations is very difficult (Clapperton, 1993). Detailed morphological mapping allows us to correlate the major moraine-stages in the northern part of the area (18–25°S) from mountain to mountain. In the central region (25–27°S), air photos reveal only weak indications of possible glacial deposits, and only very reduced field assessment could be done. At 27°S, moraines appear again, and one major stage can be correlated southward to 29°S. Because of the gap in the central region, the glacial stages of the northern and southern regions cannot be morphologically and therefore, temporally correlated. Hence, the two regions are discussed separately. A detailed description of all investigated test areas and compiled maps are presented in Jenny and Kammer (1996).

Table 1
Overview of test areas with calculated equilibrium line altitudes of stages N-II and S-II. Moraines in additional locations were mapped and morphologically correlated to N-II and S-II, but no ELAs were calculated. Note, not all test areas were mapped in all aspects. More detailed information is compiled in Jenny and Kammer (1996)

Test area	Latitude longitude	Moraine (stage II) (in m)	ELA (stage II) (in m)	Max. altitude of lat. moraine (in m)	Aspect
Cerro Guane Guane	18°08′S	4650	4750		SE
	69°07′S	4500	4700		S
Nev. Putre/ Larancagua	18°05′S	4550	4700		S
	69°30′S	4550	4700		SW
		4250	4800		W
		4550	4750	4800–4850	NW
Massif Choquelimpie	18°17′S	4550	4800	4800	N
	69°12′W	4550–4650	4800–4850	4750–4800	NE
		4550	4750		E
		4500	4700	4750	SE
		4480	4700		S
		4450–4600	4700–4800	4800	W
		4550	4750		NW
Co. Arintica	18°50′S	4500	4850		NE
	69°W	4550	4750		E
		4450	4750		SE
		4350	4700		S
		4400	4700		W
Co. Alto Toroni	19°45′S	4400–4550	4700–4850		N
	68°40′W				
		4250–4450	4650–4850		E
		4300	4750–4850		S
		4450	4850		NW
Co. Napa	20°30′S	4250–4300	4500–4600		SW
	68°40′W	4400	4550		W
		4500	4650	4750	NW
Co. Paroma	20°56′S	4550	4700		NE
	68°25′W	4350	4650		SE
		4400	4600		S
Volcan Aucanquilcha	21°13′S	4500		4750–4800	N
	68°28′W	4350–4500	4750	4800–4850	E
		4200	4650	4700	SE
		4200		4700	S
		4750		4850	SW
		4450–4600	4750–4800	4750–4850	NW
Co. Chela	21°24′S	4250	4600		S
	68°30′W	4400	4650		SW
		4300	4650		W
		4450	4700	4800	NW
V. San Pedro and Pablo	21°53′S	4000	4600		S
	68°23′W				
Cord. del Tatio	22°15′S	4100	4600		SW
	68°W	4450	4650		W
		4400–4450	4700–4750	4800	NW
Co. Pajonal	22°30′S	4000	4600		S
	67°54′W	4550	4650		W
Co. Acamarachi	23°17′S	4500		5000	NW
	67°37′W	4700		5000	S

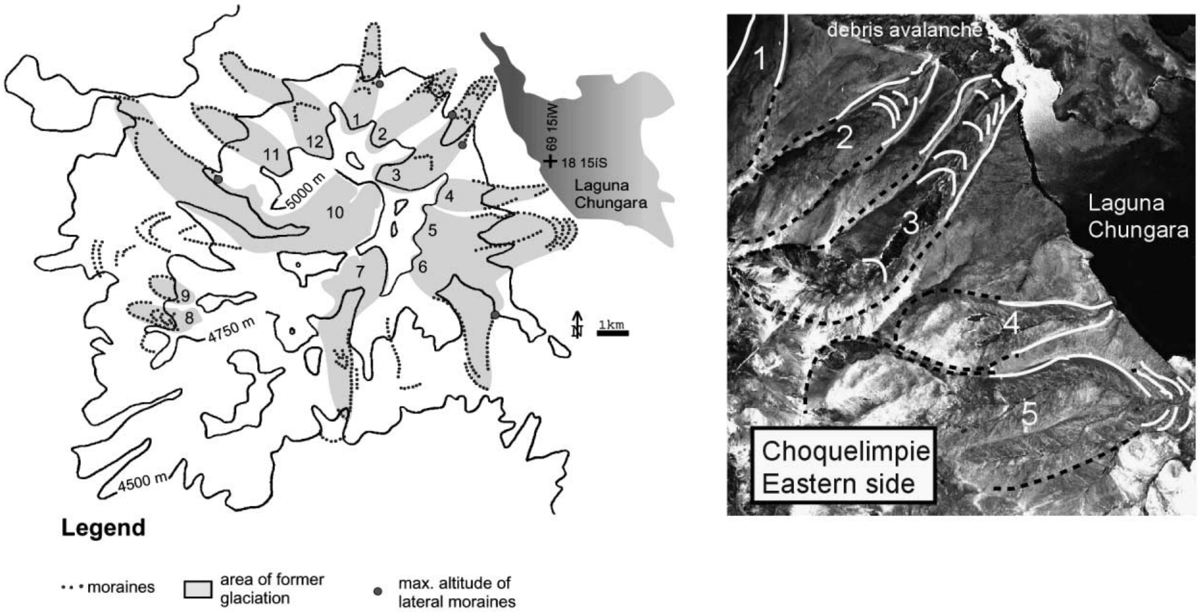
Table 1 (*continued*)

Test area	Latitude longitude	Moraine (stage II) (in m)	ELA (stage II) (in m)	Max. altitude of lat. moraine (in m)	Aspect
Cord. Puntas Negras	23°30′–50′S	4500–4700			NE
	67°30′–45′W	4300		4900	S
Cord. Pular	24°11′S	4750	5100–5150		NE
	68°03′W	4400–4650	5000–5050	5000	SE
		4600	5000–5050		S
		4500–4750	5050	5000	NW
Co. Colorados	26°10′S	5000–5150	5300–5450	(5400)	NE
	68°23′W	5250	(5500)		SW
Tres Cruces	27°06′S 68°47′W	4550	5300		SW
Nev. Jotabeche	27°42′S	4300	4750		N
	69°13′W	4550	4750	4750	SE
		4350	4700	4750	W
Co. Caserones Sur	28°12′S 69°30′W	3900	4350		NNE
Co. Potro	28°23′S	3650–4350	4300–4500		N
	69°38′W	4100	4350	4350	S
Encierro Valley	29°11′S	3500–4050	3900–4250		NE
	69°57′W	4000	4250		E
		3850–4000	4050–4150		SE
		4000	4150	4150	SSE
		3950	4200	4200	W
		4150	4250	4250	NW

3.1. The northern region (18–25°S)

In the northern part of our research area, three main moraine stages are distinguishable: The oldest, least preserved glacial deposits (Moraine-Stage-North I, hereafter referred to as N-I) reach the level of the Altiplano. These moraines are extensively eroded. Moraine-Stage-North II (N-II) showing large and sharp lateral moraines (Fig. 3a) must be significantly younger. These generally well preserved moraines are prominent as far south as 25°S, and can easily be correlated morphologically. We concentrated the calculation of the ELA mainly on this stage. Additionally, a youngest well-preserved moraine stage (N-III)

Fig. 3. (a) Massif Choquelimpie (18°17′S/69°15′W) with well preserved lateral moraine systems to the north and north-west. (b) Volcano Parinacota, immediately north of Massif Choquelimpie, with present glaciation on southern slopes.



Nr.	aspect	altitude of end moraine	maximum altitude of lateral moraine	ELA (AAR=0.67)	Nr.	aspect	altitude of end moraine	maximum altitude of lateral moraine	ELA (AAR=0.67)
1	N	4550 m	4800 m	4800 m	7	S	4480 m		4700 m
2	NE	4650 m		4850 m	8	W	4550 m		4700 m
3	NE	4550 m	4750,4800 m	4800 m	9	W	4600 m		4750 m
4	E	4550 m		4750 m	10	W	4450 m	4800 m	4800 m
5	E	4550 m		4750 m	11	NW	4450 m		4750 m
6	SE	4500 m	4750 m	4700 m	12	NNW	4550 m	4750 m	4750 m

Fig. 4. Late quaternary glaciation of Massif Choquelimpie showing the N-II ELA with different aspects and the former extension of the glaciers. An accumulation to ablation area ratio (AAR) of 2:1 was used to estimate the ELA for each ice lobe. Some lateral moraines still show well-preserved upper limits, allowing independent control of the ELA. Glacial systems 1–5 on the eastern side of Massif Choquelimpie indicated in an air photograph. Only the main moraines are shown.

is found in most of the investigated test areas. These features are significantly smaller.

As an example, we present the Massif Choquelimpie (5327 m, 18°17′S/69°15′W). Its close location to several glaciated mountains (e.g. Volcanoes Parinacota, Pomerape and Guallatire, 18–19°S) allows direct comparison of former and present climatic conditions (Fig. 3a and b). The estimate of the N-II ELA of Massif Choquelimpie is considered to be good, as lateral moraines and cirques clearly determine the former glacier catchments (Fig. 4). The ELA corresponding to N-II varies between 4700 and 4850 m, depending on aspect. This former glaciation at Massif Choquelimpie can be directly compared to the present glaciation of neighboring Volcano Parinacota, whose glacier tongues reach down to 5000 m (Fig. 3b). Today, the ELA of this ice cap lies between 5500 and 5700 m (although this is quite problematic to calculate, because there is no clear separation in accumulation and ablation zones). Jordan (1991) indicates a modern ELA of the nearby Volcano Sajama (Bolivia) between 5400 and 5700 m. Therefore, a late-Pleistocene ELA depression of about 700–1000 m must be considered. A debris avalanche from Volcano Parinacota, that crossed N-II moraines on the northern side of Massif Choquelimpie, permits some age control. From a pond within the debris avalanche deposits (Laguna Seca), bottom sediments yielded a radiocarbon age of 12,040 ± 270 ^{14}C yr BP (Geyh, pers. comm., 1997). This is a minimum age for the

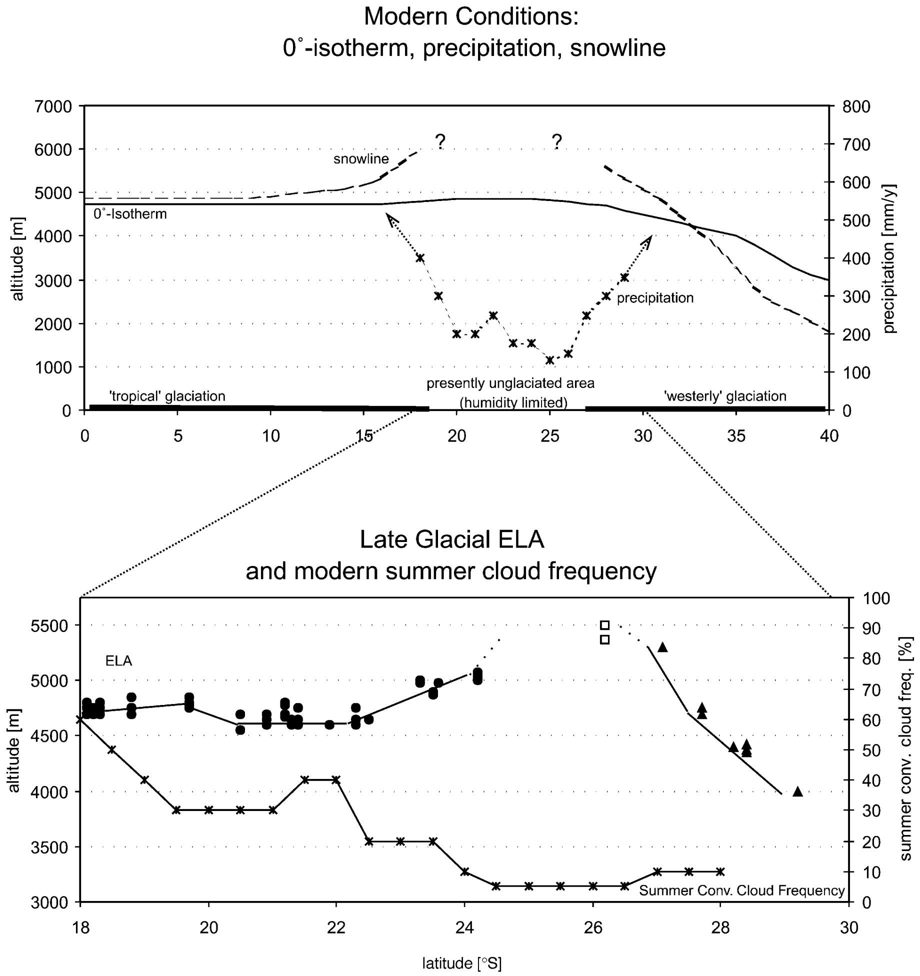


Fig. 5. Top panel: Modern climate conditions with 0°-isotherm, annual precipitation (18–29°S) and snowline in a transect from the Equator to 40°S (after Kuhn, 1981). The area where glaciers are sensitive to humidity is marked, as the snowline rises significantly above the annual 0°-isotherm and is even absent in the area of the South American Arid Diagonal. Bottom panel: Course of the former ELA based on the well-preserved moraine stage N-II and S-II with corresponding glacier catchments (AAR of 0.67), and the maximum altitude of lateral moraines. Shown are all estimates of ELAs. ELAs at the same latitude correspond to the same mountain, but to different aspects. The ELA of the northern (circles) and the southern region (triangles) cannot necessarily be considered to represent synchronous events. For the ELA of the central part (unfilled squares), it is not possible to tell if it corresponds with the northern or the southern part.

debris avalanche and therefore for N-II as well. This date is in agreement with a previously published radiocarbon age of 13,500 ^{14}C yr BP from peat samples underlying the debris avalanche (Francis and Wells, 1988). Hence, the moraine stage N-II was not developed during the Holocene but in the Late Glacial.

Many ELA calculations on N-II moraines were done along a transect from 18 to 25°S (see Fig. 5 and Table 1). It is important to note that the altitude of the reconstructed equilibrium line did not change significantly between 18 and 23°S, and there may even be a slight decrease in ELA. Within this northern region, the influence of aspect on the ELA is shown at several mountains in 100–150 m higher elevations on slopes exposed to NW, N and E (Fig. 4, Table 1). Between 23 and 24°S, the reconstructed late Pleistocene ELA abruptly rises southward by about 300 m

Fig. 6. Lateral moraines of extensive valley glaciation S-II in Encierro Valley (29°11′S/69°38′W).

and disappears further south (not yet fully verified in the field).

3.2. The southern region (27–29°S)

At 27°S, the Altiplano with its individual volcanic cones ends, and large mountain chains and deep valleys dominate southward. This also implies a general change in glacial characteristics towards valley glaciers and comparison with the northern area requires caution. All test areas show very old, smooth moraines, indicating extended glaciation (Moraine-Stage-South I, S-I). Again, an intermediate, younger moraine stage (S-II) with very well preserved moraines can be correlated within the southern area (27–29°S). The calculation of the ELA concentrates on this stage. Several smaller stages at higher elevation represent younger advances (S-III + IV, see Jenny and Kammer, 1996).

The Encierro Valley (29°11′ S/69°38′W) is a representative example (Fig. 6). Other locations are indicated in Fig. 1 and Table 1. Veit (1994) gave a first description of the Encierro Valley. The main tongue of the former glacier sat in a NE-facing valley, additionally fed by small glaciers from hanging side valleys. Several glacial stages can be noted. The terminal moraines of the very old S-I end at 3450 m, representing a lobe length of about 20 km. The much better preserved S-II moraines reach down to about 3650 m (Fig. 6). They sharply delineate a former ice stream of approximately 15 km in length with a corresponding ELA of about 4000 m. Many younger moraine systems (S-III-IV) are found higher up in the valley.

At 27°S, south of the Andean Dry Diagonal, the former ELA descends quickly towards 29°S (Fig. 5). Today, glaciation in the southern region is very limited. The northernmost glaciers in the Westerly belt are the small glaciers or ice-fields in the area of Nevado Tres Cruces (27°06′S/68°47′W). Cerro Potro (28°23′S/69°38′W) shows the largest glacier of the area (about 11 km^2). Despite the low 0°-isotherm at 4300–4500 m (Veit, 1994), the present ELA at this location is estimated between 5200 m and 5400 m (Jenny and Kammer, 1996). For Moraine-Stage S-II ELA depressions exceed 1000 m at 29°S.

4. Discussion

4.1. The northern region (18–25°S)

The pattern of late Pleistocene N-II ELA resembles closely modern summertime precipitation pattern (Fig. 2a). The general features of the present distribution of precipitation during summer can also be seen in the late Pleistocene ELA of the northern part of the research area. The modern precipitation in Northern Chile is highest at 18°S, remains constant between 19 and 22°S, like the former ELA, and diminishes quickly further south while the former ELA rises.

Today, the glacier development is strongly limited by the lack of humidity: the annual 0°-isotherm lies far below the summits (Hastenrath, 1971; Messerli et al., 1992; Ammann, 1996) and the 'thermal readiness' (Messerli, 1967) is present. Between 18 and 23°S, the N-II ELA is at about the same altitude as the modern 0°-isotherm. Hence, no temperature reduction was necessary in order to produce glacial advances during glacial stage N-II. Because heating of the Altiplano and the Cordilleras drives the summer time plateau circulation and convection, strongly reduced temperatures would not necessarily support an increase in precipitation. Additionally, reduced temperatures would further decrease the transport capacity of the air (Clausius–Clapeyron equation, e.g. Peixoto and Oort, 1992), a limiting factor today. Therefore, much cooler conditions would not support an extensive glaciation as seen in N-II.

There are additional arguments relating the N-II glaciation to a synchronous humid period. Clayton and Clapperton (1997) found 5 major advances at Cerro Azanaques (19°50′S, 67°40′W) on the Bolivian Altiplano. Their 'advance 3' is delimited by morphologically sharp moraines. Based on the morphology and comparable ELA, this advance corresponds most probably to the same glacial expansion as our well-preserved N-II. Radiocarbon dating on peat at the base of the terminal moraine shows that 'advance 3' culminated after ca. 13,300 ^{14}C yr BP (Clayton and Clapperton, 1997) and preliminary ^{36}Cl cosmogenic exposure ages obtained by Sharma et al. (1995) indicate an age in the range of 14,000–12,000 yr BP. These values clearly suggest a synchronous glaciation and high lake stand (Tauca), when high-lake-levels formed on the Altiplano due to significantly higher precipitation rates than today (Hastenrath and Kutzbach, 1985; Grosjean et al., 1995; Servant et al., 1995; Wirrmann and Mourguiart, 1995). Clayton and Clapperton (1997) estimate a possible increase in precipitation of up to 600 mm (their scenario 3) from the present 350 mm. During our N-II, much higher precipitation rates than at present must have also reached the Western Cordillera between 18 and 23°S, and the minimum age of 12,040 ± 270 ^{14}C yr BP (Geyh, pers. comm. 1997) for N-II at Cerro Choquelimpie suggests a similar timing to the Tauca phase. In fact, the constant ELA between 18 and 23°S not only mirrors present day precipitation distribution, but high lake levels on the Altiplano immediately to the east of the Western Cordillera would further support an even level of the ELA.

Much higher precipitation than today is also suggested by the AAR of 2:1 (0.67). We expected ratios of 3:1 or 4:1 in these dry environments. The AAR obtained is usually found in climates with no significant limitation in humidity (Gross et al., 1978; Maisch, 1988). We conclude therefore, that N-II glaciers of Northern Chile were most probably not synchronous with the worldwide LGM (21,000 yr BP), when both temperature and humidity were minimal, but during a much more humid and not necessarily much colder climate than today.

Other indications for the connection to summer precipitation are frequent aspect-related differences in ELA. A lower ELA in SW aspect compared to the N aspect is easily explained by lower radiation, but a generally lower value in the W compared to the E calls for another explanation. Lower western ELAs support summer convective cloud activity with clear sky in the morning and, therefore, stronger radiation on E-facing slopes, but common cloud cover in the afternoon and less radiation in W-facing slopes. Additionally, local diurnal wind systems could enhance the effect through rising motion along the western slopes followed by downward descent onto the Altiplano to the east. The influence of winter snowfall is small, otherwise there would be a significant increase in precipitation southward. But the lack of clear glacial features in the Dry Diagonal excludes frontal systems as a significant factor. At most, cut-off lows might have partly contributed to the low ELA around 22–24°S, but were not sufficient in their own right to cause this extended glaciation. Additionally, the similarity in present and past snowline gradient between the Western and Eastern Cordillera across the Altiplano (Hastenrath, 1971) lend further support to a comparable to present, but intensified summer precipitation regime.

South of 23°S, precipitation decreased rapidly, similar to today (see Fig. 5). Since (1) there are only weak glacial features in the area of the Dry Diagonal (25–27°S), (2) the pattern of the increasing ELAs compares well to the modern summer precipitation distribution, (3) the AAR of 2:1, (4) the distinct differences in ELA with different aspects and (5) the comparable east–west gradient in present and past ELAs, we favor not a shift of the precipitation belt but an intensification of the summer precipitation field over the Altiplano during the time of glaciation.

4.2. The southern region (27–29°S)

Today, the number of frontal systems per year decreases quickly north of 27°S, but some rare events reach lower latitudes as far north as the Peruvian border (Vuille, 1996). The northernmost modern glaciers under westerly influence are found at 27°S, the same latitude as the first well-preserved moraines (Fig. 5). At this latitude, the present 0°-isotherm lies far below the modern and late Pleistocene ELA. The limiting factor for glaciers is exclusively the lack of humidity, not temperature. The situation is different at 29°S, where the reconstructed ELA of 4000 m for S-II drops significantly below the present day ELA

(5250–5400 m) and annual 0°-isotherm (4300–4500 m; Veit, 1994). Therefore, at 29°S, not only an increase in precipitation must be postulated, but also a reduction in temperature of at least 2–3°C (considering a lapse rate of 0.7°C/100 m).

Today, precipitation from the Westerlies increases quickly from 27°S southward (Fig. 2b), allowing glaciers to exist. Because during S-II, the glaciers fed by Westerlies were limited at about the same latitude as present (27°S), an even steeper decrease of S-II ELA than present is found between 27 and 29°S (Fig. 5). Increased influence from the Westerlies south of 27°S is consistent with the snowline transects in east–west direction presented by Hastenrath (1971). Yet, the even faster increase in precipitation for the extensive glaciation of S-II south of 27°S, and the required temperature depression at 29°S cannot be easily explained by a simple shift of the whole Westerly Storm Track. Although at 29°S both temperature decreased and humidity increased, surprisingly, the northern limit of glacier growth due to precipitation from the Westerlies did not change at all (see also Veit (1996) for evidence from soil development). Therefore, compared to today, an even further intensified gradient existed at the southern end of the 'Andean Dry Diagonal'.

The age of S-II is unknown. Veit (1994) proposes a late glacial age of about 15,000 yr ^{14}C BP, synchronous with high lake levels on the Argentinean side of the Andes. Around this time (14,890–13,900 yr ^{14}C BP), Lowell et al. (1995) found glacial advances in the Chilean Lake District (42°S). But the maximum glacial extension at these southern latitudes was reached at 21,000 yr ^{14}C BP (Lowell et al., 1995).

Finally, an important addition to this scenario is the surprisingly young age of peat incorporated into an S-III-IV moraine in the upper Encierro Valley. Grosjean et al. (1998) found a maximum age for this glacial advance of 2620 ± 45 ^{14}C yr BP (29°11′S). It is important to note, that this glacial advance, with a corresponding S-III-IV ELA of about 4300 m, indicates an increase in humidity during the late Holocene, but does not require cooler temperatures. Further to the south, in the upper Elqui-Valley (29°40′S), Veit (1996) also dated a glacial advance younger than 3360 ± 255 yr BP, confirming late Holocene glaciation in the southern part of the dry Andes. Comparable young dates for the northern part of the research area are not available, but for the Cordillera Blanca, Peru, the Neoglacial is well dated (e.g. Rodbell, 1992; Rodbell, pers. comm., 1999).

5. Conclusions

Under current climatic conditions, no glaciers can exist in the high Andes of the Western Cordillera between 19 and 27°S. The annual mean temperatures in the highest peaks are far below freezing, but the extremely dry conditions make any glacial development impossible. With increasing summer precipitation towards the tropics, persistent snowfields are more frequent, and at 18°30′S, the first glacier appears (Volcano Guallatiri). In the southern region, first glaciers appear under sharply increased wintertime precipitation south of 27°S. Between these two regimes, the South American Dry Diagonal crosses the Andes from the northwest to the southeast.

Detailed field analysis in the dry Andes of Northern Chile reveals a spatial pattern of Pleistocene glaciations in the transition zone between the tropics and extra-tropics of South America. In much of the N–S-transect, glaciation was widespread. As today, the central area (24–27°S) stayed significantly drier. The reconstructed ELA in the northern (moraine stages N-II) and in the southern region (moraine stages S-II) are compared with 'spatial fingerprints' of the circulation systems, which are responsible for the precipitation. Because there are no dates available to reliably link the reconstructed ELA rising from the south, and from the north towards the dry center, the former ELA depressions are not necessarily synchronous.

In the northern region, the ELA calculated from N-II lies higher or close to the modern annual 0°-isotherm. No temperature reduction is therefore needed for this glaciation (but this does not necessarily exclude it), but significant increases in precipitation made the glaciation possible. The spatial pattern of the reconstructed ELA follows the areas of preferred cloud development during today's summer. Because cloud development is mainly guided by humidity transport from the east as well as regional topography, strongly intensified summer precipitation would still exhibit similar overall spatial patterns towards the dry central area. This process was probably further supported by the existence of extensive lakes on the Altiplano (Tauca Phase). The humidity for the glaciation between 18 and 25°S comes from a significant intensification of summer convective rainfall, pushing the boundary of humidity limitation for glacial development further south.

The reconstructed S-II ELA south of the dry center reflects an even steeper gradient than present. North of 27°S, no clear glacial features could be found so that extreme limitations in humidity must have prevailed. To the south, a distinct increase in precipitation is needed to depress the ELA. No temperature depression is required around 27°S, since the ELA remained above the altitude of the modern annual 0°C-isotherm. But at 29°S, finally, the reconstructed S-II ELA of large valley glaciers drops below the modern 0°-isotherm. Here, a temperature depression of at least 2–3°C is required. This change from a mainly humidity-limited environment in the north to a temperature-limited glaciation to the south is not much different from today. The postulation of a simple shift of the entire westerly belt cannot be supported, since the northern limit of the late Pleistocene glaciation did not significantly exceed the present boundary at 27°S. Nevertheless, the required increase in precipitation south of 27°S together with lower temperatures at 29°S suggests at least an intensification of the Westerlies.

A reliable chronology of the glaciations is still a matter of debate. In adjacent areas of southern Bolivia, broad synchrony of Late Glacial glacier advances and high paleolakes of the Tauca Phase is documented. The glacial advances in Northern Chile (18–25°S) are not well dated, but we note a constant former N-II ELA in the Western Cordillera at the western limits of the Tauca paleolakes. The ELA rises quickly southward as the Tauca signal of paleolakes disappears. For the southern region (27–29°S), it is unclear if the large glacial extension is synchronous with the maximum glacier advance during the (global) LGM or the well documented advance at 14,000 ^{14}C yr BP in the Chilean Lake District. This question cannot be answered until the dating problems are solved.

This study demonstrates the high sensitivity of dry mountain areas and the differences in environmental response to changes in climatic conditions. In the dry Andes, it is not mainly a temperature depression causing a glaciation, but a change in humidity. This strongly emphasizes the importance and need for a better understanding of the climatic variability in the tropics, where large humidity fluctuations have taken place since the last (global) glacial maximum.

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