

Pleistocene and modern snowlines in the Central Andes (24-28°S)

By

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Abstract

Despite summit elevations of 5000 m to more than 6700 m, few of the peaks on the Puna and northern Sierras Pampeanas of the central Andes Mountains (24-28°S) presently support glaciers even though they occur well above the 0°C mean annual isotherm (4600 m). On an east to west transect, the average modern snowline rises from 5100 m in the Sierra Aconquija to more than 6000 m in the western Puna as a result of a westward decrease in precipitation from about 2500 to less than 100 mm/yr. During the Pleistocene, the region experienced at least three episodes of cirque and valley glaciation. These glaciations have been traditionally explained by increased precipitation derived from westerly winds associated with a northward shift of the South Pacific anticyclone, which would depress the snowline to the west. However, late Pleistocene cirque floor altitudes rise westward from about 4300 m in the Sierra Aconquija to about 5500 m in the western Puna, and glaciation occurred predominantly on east-facing slopes. Glacial age snowline depression was not uniform, but averaged 600 m in the Sierras Pampeanas and only 300 m in the western Puna between 26 and 28°S. The unequal late Pleistocene snowline depression reflects an increase in effective precipitation in the Sierras Pampeanas relative to the Puna. Late Pleistocene atmospheric circulation patterns in the central Andes (24-28°S) were similar to those of today, with precipitation derived from Atlantic rather than Pacific air masses.

Resumen

A pesar de que la parte norte de las Sierras Pampeanas y los Andes Centrales alcanzan alturas de 5000 a 6700 m y se encuentran sobre la isoterma de 0°C (4600 m), bajo las condiciones actuales se encuentran apenas cubiertas de glaciares. A causa de una fuerte reducción de las precipitaciones en dirección oeste, de 2500 a menos de 100 mm/a, asciende la línea de nieve de 5100 m en la Sierra de Aconquija a más de 6000 m en la Puna Occidental. Durante el Pleistoceno fue cubierta esta región alta por lo menos tres veces de glaciares. Hasta ahora ha sido interpretado esto como resultado del traslado hacia el norte del Anticiclón Sudpacífico y su asociado aumento en la cantidad de precipitación que ocasiona una depresión de la línea de nieve hacia el oeste. Sin embargo nuestra investigación muestra englaciamiento preferencial en los vertientes orientales y un incremento de la línea de nieve pleistocena de 4300 m en las Sierras Pampeanas hasta aproximadamente 5500 m en la Puna Occidental. La depresión de la línea de nieve en el Pleistoceno no fue uniforme. Mientras que en las Sierras Pampeanas llegó hasta los 600 m en el sector entre 26 y 28°S de latitud, en la Puna Occidental, llegó solo hasta los 300 m. Esto indica un incremento de la precipitación efectiva en las Sierras Pampeanas en comparación con la Puna Occidental. El esquema de circulación atmosférica en el Pleistoceno

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tardío en los Andes Centrales (24-28°S) correspondió a las condiciones recientes y fue determinado por masas de aire del Atlántico y no del Pacífico.

Kurzfassung

Obwohl die nördlichen Sierras Pampeanas und die zentralen Anden (24-28°S) Höhen von 5000 m bis über 6700 m erreichen und höher als die 0°C Isotherme (4600 m) liegen, sind diese Gebiete unter heutigen Bedingungen nur geringfügig vergletschert. Aufgrund einer starken Abnahme der Niederschläge in westlicher Richtung von 2500 mm auf <100 mm/a steigt die rezente Schneegrenze von 5100 m in der Sierra Aconquija (E) auf >6000 m in der westlichen Puna. Während des Pleistozäns wurden diese Hochgebiete mindestens dreimal vergletschert; dies wurde bisher mit der nördlichen Verlagerung der südpazifischen Antizyklone und damit verknüpften erhöhten Niederschlagsmengen mit entsprechend stärkerer Schneegrenzdepression im Westen erklärt. Allerdings zeigen unsere Untersuchungen bevorzugte Vergletscherung auf Osthängen und ein Ansteigen der pleistozänen Schneegrenze von 4300 m in der Sierra Aconquija (E) auf etwa 5500 m in der westlichen Puna. Die pleistozäne Schneegrenzdepression war nicht uniform in den zentralen Anden, sondern betrug 600 m in den Sierras Pampeanas und nur 300 m in der westlichen Puna im Bereich zwischen 26 und 28°. Dies deutet auf einen Anstieg des effektiven Niederschlags in den Sierras Pampeanas im Vergleich zur Puna hin. Das spätleistozäne atmosphärische Zirkulationsgefüge in den zentralen Anden (24-28°S) entsprach den rezenten Bedingungen und war durch atlantische und nicht durch pazifische Luftmassen geprägt.

INTRODUCTION

The northern Sierras Pampeanas and Puna Plateau dominate the relief of the semi-arid to arid Andean region between 24-28°S latitude (Fig.1). Despite maximum elevations of more than 6700 m, the region lacks modern glaciers. During the late Pleistocene several of these high peaks were glaciated by cirque and small valley glaciers. The glacial chronology is known only in a general and qualitative way (PENCK 1920; TAPIA 1925; ROHMEDEY 1943; STRECKER 1987).

Although uplift of the Andes has probably occurred throughout the late Cenozoic (STRECKER 1987), early investigators of Andean glacial history such as SCHMIEDER (1922), TROLL (1937), MACHATSCHKE (1944), HEIM (1951), and KLAMMER (1957) questioned whether the mountains were high enough during the early Quaternary to permit glaciation. Moraine sequences visible on aerial photos and satellite imagery clearly show, however, that several glaciations have occurred in the study region. Multiple glaciations occurred in the southern Andes since late Miocene/early Pliocene times (MERCER & SUTTER 1981). Glaciogenic materials older than 3.27 m.y. were also reported from the Bolivian Altiplano (CLAPPERTON 1979). In addition to these deposits, even older tills in Patagonia (MERCER 1978) led CLAPPERTON (1983) to propose a model of Andean glaciations with the assumption that the necessary mountainous relief had been established by the end of the Miocene and thus could support glaciers during the many subsequent glacial episodes.

Recent work in the northern Sierras Pampeanas, however, demonstrated that Sierra Aconquija, now more than 5000 m high, existed only in the form of subdued hills, and that the Santa Maria Valley region (Fig.1) was still a lowland prior to the Quaternary with braided-river channels and a semi-humid climate similar to the present Argentine Chaco located to the east (STRECKER 1987; STRECKER

et al. 1987; STRECKER et al. 1989). Principal uplift of the Sierras Aconquija and Cumbres Calchaquies ranges started after 3.4 m.y. and culminated after 2.9 m.y. (PASCUAL 1984; STRECKER 1987; STRECKER et al. 1989). Even if uplift rates had been extremely high, the altitude of these two ranges was probably not sufficient in the early Pleistocene to permit glaciation. The detailed uplift history of the adjacent Puna is not known, but both the Puna and Sierras Pampeanas were high enough to be glaciated during the late Pleistocene. TAPIA (1925) found evidence for three recessional moraine systems, and ROHMEDEK (1941) suggested that they were formed during the last Andean glaciation.

The central Andes (24–28°S) presently lie in the arid transition zone between two wind and precipitation systems, the tropical easterlies and the mid-latitude westerlies. Moisture-bearing northeasterly and easterly winds develop in response to the summer low pressure system over the Argentine Chaco region in the Andean foreland, and dry westerly winds strengthen during the winter months when the South Pacific anticyclone moves north to about 25°S latitude from its summer location at about 32°S (WILHELMY & ROHMEDEK 1963; PROHASKA 1976). HASTENRATH (1971) proposed that the glacial-age South Pacific anticyclone and its associated moist westerly wind system may have maintained its position as far north as 25°S, mirroring the reported equatorward shift of the North Atlantic and North Pacific anticyclones in the northern hemisphere. Alternatively, PASKOFF (1977) hypothesized that the Andes between 27 and 30°S may have been in an arid corridor during glacial intervals because, like today, of their transitional position between the two planetary wind systems.

In this paper geomorphic evidence for mountain glaciation and snowline depression in the central Andes (24–28°S) is examined synoptically in order to better constrain the regional atmospheric circulation pattern during the Pleistocene and improve our understanding of late Quaternary climate change. The term snowline as used here refers to the lower limit of perennial snow on mountain slopes averaged over many years, which is also known as the regional or climatic snowline (FLINT 1971). A snowline is really a three-dimensional surface having complex undulations determined by local variations in temperature, precipitation, and topography. Modern snowline elevations are based on field observations and examination of aerial photos and space imagery. Cirque floor altitudes are used as proxy for late Pleistocene snowline elevations (see HASTENRATH 1971; NOGAMI 1976; SELTZER 1987). Variations in precipitation resulting from the interaction of regional atmospheric circulation and topography control the direction of snowline rise (i.e. windward to leeward). North of about 28°S, the modern Andes are primarily influenced by easterly winds and have a westward rising snowline, whereas the regions south of about 28°S are dominated by precipitation from westerly winds and have an eastward rising snowline. Horizontal precipitation gradients control the magnitude of snowline gradients, with high precipitation gradients producing high snowline gradients.

MODERN CLIMATE

A recent analysis of the relationship between climate and snowline elevation in the central Andes (FOX in press) demonstrates that mean annual temperature and precipitation are the primary climatic factors controlling regional snowline elevation, with higher precipitation corresponding to a lower

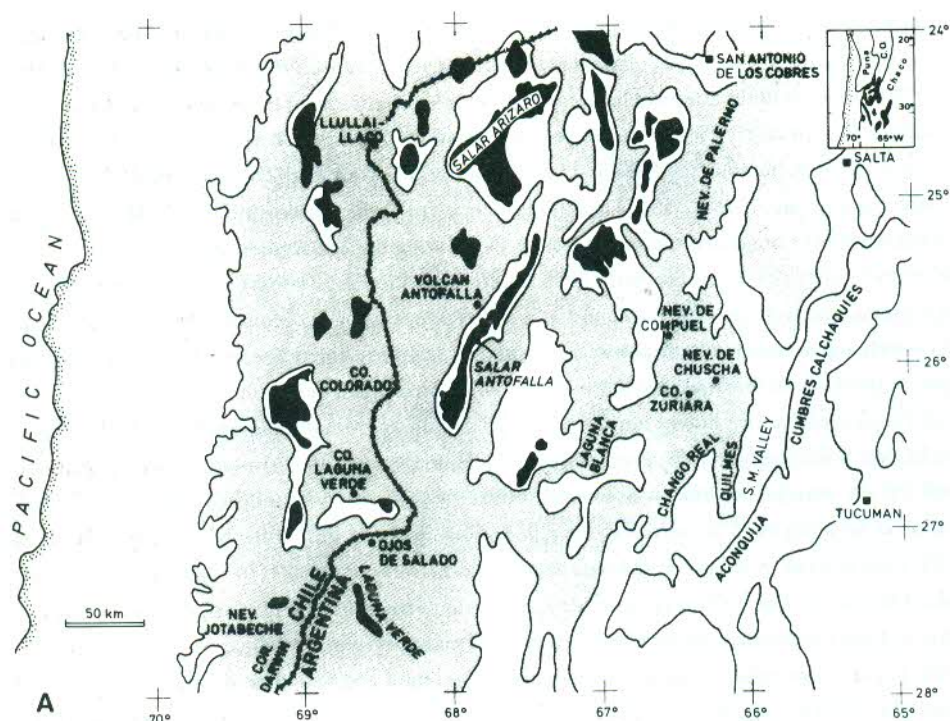


Fig.1A: Map of studied locations in the central Andes (14-29°S). Discussed locations that are not shown are indicated in the text by their longitude and latitude. Index map depicts the location of important geologic provinces, the area shown in black corresponds to the Sierras Pampeanas, C.O. corresponds to the region of the Cordillera Oriental and the adjacent Sierras Subandinas

snowline. Secondary controlling variables, such as evaporation and sublimation, are also locally important processes but cannot be adequately quantified because of the lack of data, and may not influence the regional snowline trend differentially since they are a function of temperature and precipitation. Precipitation and temperature data are sparse for the high Andes compared with sites at lower elevations, although geomorphic and vegetational evidence suggest that climate is relatively uniform on the Puna. The greatest variation in climate occurs between the mountain ranges of the Sierras Pampeanas located to the east (Fig.1).

The precipitation pattern for the study region is dominated by an east-west gradient across the eastern margin of the Andean Cordillera. Most of the precipitation falls during the summer months and is related to easterly and northeasterly winds, while the winter months are dry in most of the study region (WMO, UNESCO 1975). Another source of summer precipitation are convective thunderstorms that occur on the extensive Puna plateau (PROHASKA 1976). Most of the total precipitation in the Chilean part of the Andes falls during the winter and is, therefore, related to occasional incursions of westwind related storms which are also responsible for precipitation in the southern Andes (MILLER 1976). These occasional winter incursions (viento blanco) account for limited snowfall in the Puna.

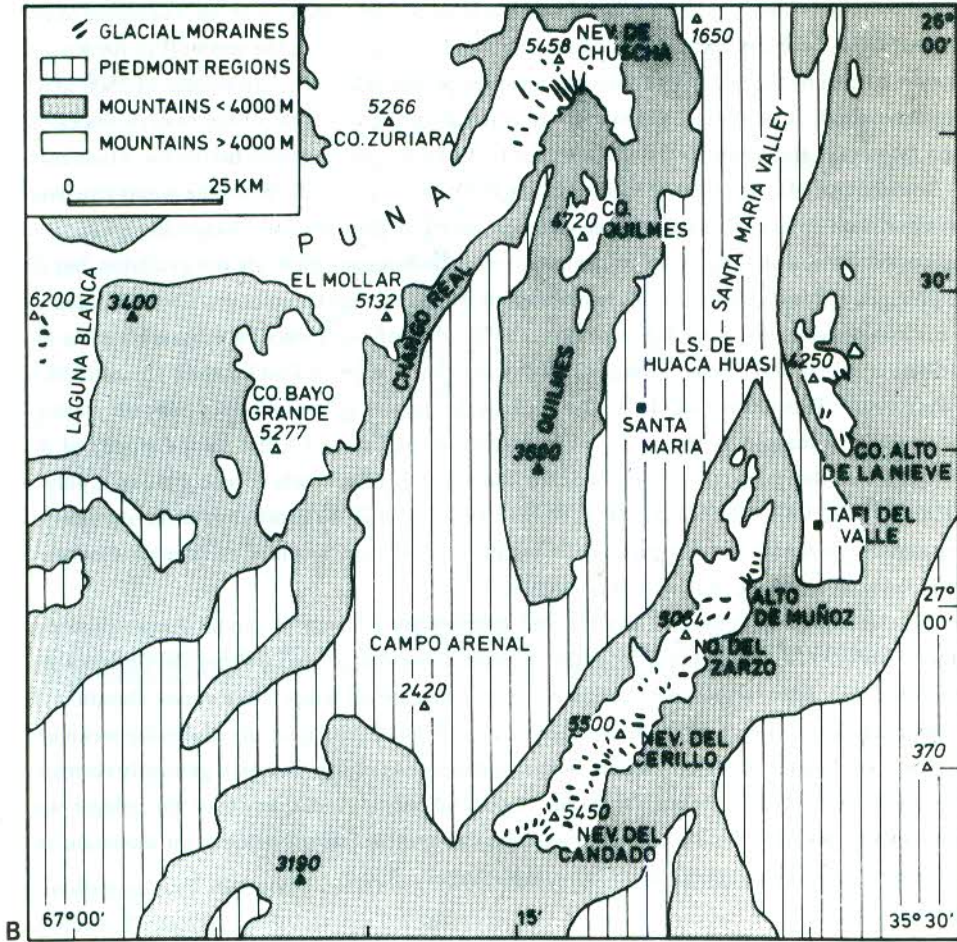


Fig.1B: Simplified map of the northern Sierras Pampeanas and the Puna Plateau, spot elevations are in meters

The predominant wind direction on the Puna is from the west. The frequency and intensity of westerly winds increase slightly during the dry winter, whereas during the summer, moist easterly incursions are more common. Despite their relative scarcity, easterlies account for 88-96% of the annual precipitation in the area (HALLOY 1982). In summary, the Puna region receives its precipitation primarily during the summer, with amounts generally decreasing to the west. Rates of potential evapotranspiration (PET) as high as several cm/day result from extremely low atmospheric humidity, high daily insolation, and surface temperatures (KANTER 1937).

Orographic precipitation from the dominant easterly and northeasterly winds is produced along the high, steep eastern slopes of the north-south oriented Sierras Pampeanas. Climate stations report a

range of persistent moist summer wind directions from southwesterly (S.M. de Tucumán) to northeasterly (Salta), with dry northerlies common at both localities during the winter (PROHASKA 1976). Moisture carried by the easterlies condenses and precipitates primarily at an altitude of 2500 m where precipitation values of about 2500 mm/yr are reached during its ascent of the eastern slopes of the Sierra Aconquija and Cumbres Calchaquies, the first significant orographic barrier the winds encounter (ROHMEDER 1943; WILHELMY & ROHMEDER 1963; WERNER 1972). When the winds rise over the next significant orographic barrier to the west (ex. Sierra de Quilmes and Chango Real, Fig.1), additional condensation and precipitation occur. Direct measurements there are not available, but effective precipitation is probably low, as inferred from the sparse vegetation cover. Cloud buildup along the eastern slopes of the Sierras Pampeanas, and the dramatic influence of orographic rains on the distribution and abrupt change in vegetation density can be observed on Landsat Thematic Mapper (TM) imagery. This change can be appreciated on the ground by driving west from the subtropical rainforests of Tucumán to the grass-covered highland at Tafi del Valle on the slopes of Sierra Aconquija, and down into the semi-arid Santa María Valley (Fig.1) where precipitation is only 145-230 mm/yr (GALVAN 1981; GARLEFF & STINGL 1983). During summer storms the mountains are often cloud-covered and receive precipitation in the form of snow and hail, an infrequent occurrence during the cold and normally dry winter months.

The close relationship between elevation and temperature in the arid central Andes produces an isotherm pattern that is symmetric about the crestline of the Andes, which forms the Chile-Argentina border. A simple linear regression of climate station mean annual temperature versus elevation yields a temperature lapse rate of $-5^{\circ}\text{C}/\text{km}$. A linear extrapolation of this lapse rate places the mean annual 0°C isotherm at an elevation of 4600 m. In humid regions, snowline elevation generally corresponds to the elevation of the 0°C annual isotherm. In the arid central Andes, however, the coldest parts of the mountains are also the driest, which explains the present lack of glaciers on mountain slopes located well above the level of the 0°C annual isotherm.

SNOWLINE OBSERVATIONS

Mountain peaks in the central Andes ($24-28^{\circ}\text{S}$) were examined for evidence of modern and late Pleistocene snowlines (Fig.2). The data were derived from TM imagery for the entire region (30 m resolution), stereoscopic air photo analysis (1:50 000 scale), published observations (PENCK 1920; TAPIA 1925; ROHMEDER 1941; HASTENRATH 1971; NOGAMI 1976) and personal field observations in the Sierra Aconquija, Sierra de Quilmes, and Cumbres Calchaquies. Incomplete coverage by topographic maps, however, made it difficult to determine accurate elevations for some of the cirques and modern snow cover identified on TM imagery. There are discrepancies between modern snowline elevations reported in the literature at different times for the same mountain, which represent the normal interannual variation in orographic snowline altitude. However, since we are more concerned with average regional snowline trends, all available data were included in our analysis except for those observations that we could confidently reject. A computer algorithm was used to interpolate

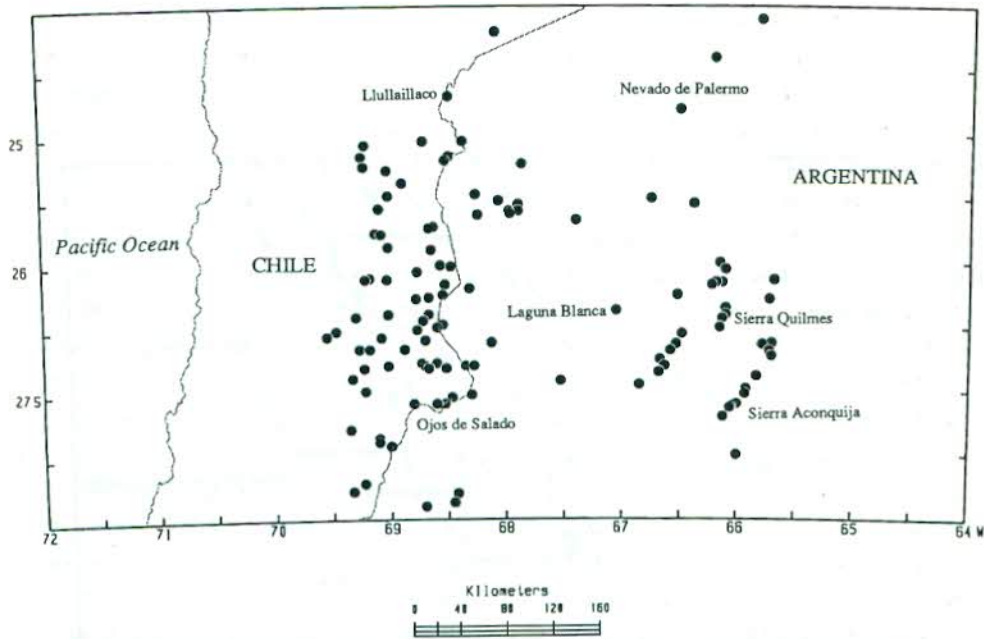


Figure 2. Location of available snowline observations and higher mountain peaks below present and/or late Pleistocene glacial age snowline (ie. provides minimum snowline elevation value).

three-dimensional surfaces representing the regional modern and late Pleistocene glacial age snowlines. Figures 3 and 4 show the calculated isoglacihypses (snowline contours) and perennially snow-covered surfaces.

Modern snowlines

West of Tucumán, the modern snowline passes through the summits of the Sierra Aconquija at an altitude of about 5100 m (Fig.1; ROHMEDEY 1941; 1943). The peaks of Sierra Cumbres Calchaquies are lower in elevation farther north and are located below the snowline. Modern snowline is at an elevation of 5200 m on Nevados de Chuscha of the Sierra Quilmes range. The highest peaks in Sierra Chango Real to the southwest, however, are located below the modern snowline even though they reach altitudes of 5132 m (El Mollar; 26.55, 66.48)¹ and 5277 m (Cerro Bayo Grande; 26.75, 66.67).

¹ All locations are indicated with decimals according to 1:1,000,000 Operational Navigation Charts

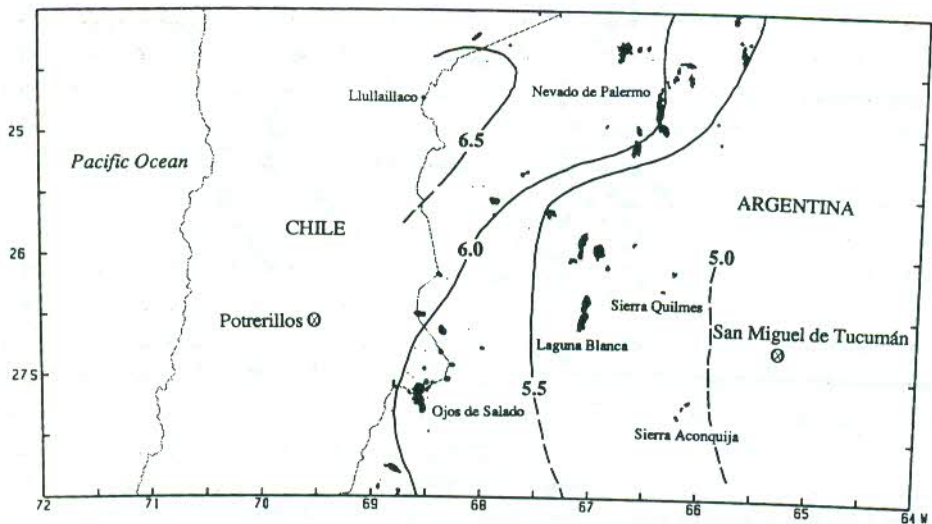


Figure 3. Modern snowline elevations (km) and perennially snow-covered slopes (black fill). Dotted lines are the coast and international border.

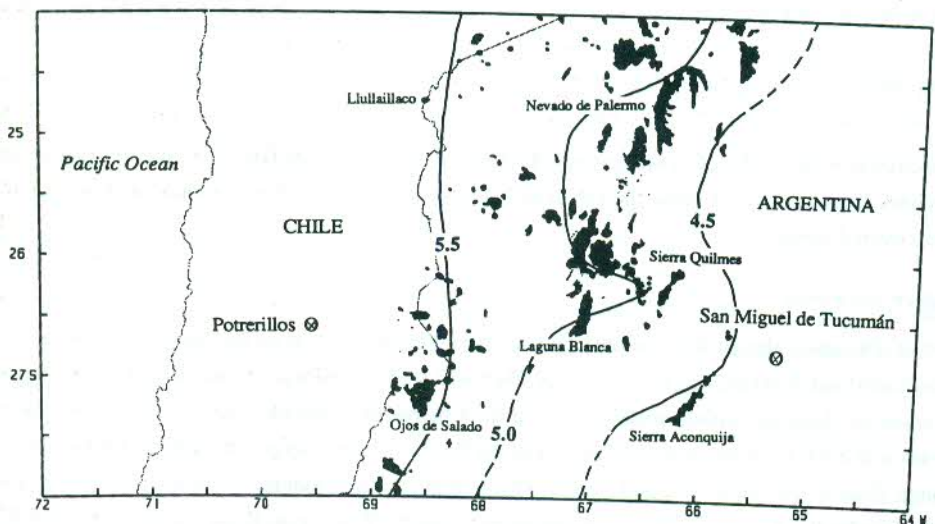


Figure 4. Late Pleistocene glacial age snowline elevations (km) and perennially snow-covered slopes (black fill). Dotted lines are the coast and international border.

Similarly, Cerro Cenizo (5262 m; 27.87, 68.45) and Cerro Azul (5000 m; 26.92, 67.53) on the southern edge of the Puna are located below the modern snowline, with only ephemeral snow associated with summer precipitation visible on a TM image acquired in December, 1984.

The modern snowline rises progressively westward from about 5100 m in the Sierras Pampeanas onto the Argentine Puna, where it is located at 5200 m on Cerro Zuriara, 5300 m on Sierra Laguna Blanca, and at 5500 m on Cerro Calalaste (Figs.1, 3). The snowline continues to rise to the west across the Puna towards the Chile-Argentina border. Cerro Peinado (5740 m; 26.62, 68.13) is free of perennial snow, but other higher peaks in the Salar de Antofalla (Fig.1) region are snow-covered. On Volcán Antofalla (6100 m; 25.55, 67.90), for example, the snowline is above 5750 m, with adjacent lower peaks such as Cerro Cajero (5700 m; 25.60, 67.98) and Cerro de la Aguada (5750 m) located below the modern snowline.

The westward rise of the modern snowline continues into Chile, where there is very little perennial snow cover (Figs.1, 3). Prominent peaks such as Nevado de León Muerto (5793 m; 26.17, 68.53) have only minor accumulations of perennial snow. In contrast, the adjacent Cos. Colorados (6049 m) are snow-covered, with the snowline located at an altitude of about 5800 m. This elevation is confirmed by the lack of perennial snow on adjacent lower peaks such as Pico Wheelwright (5650 m; 26.78, 68.73) and Cerro Laguna Verde (5830 m; 26.82, 68.52) located to the south. Higher peaks such as Cerro de la Linea (5870 m; 26.80, 68.35) and Cerro Dos Conos (5900 m; 26.80, 68.28) do, however, have perennial snow cover.

In the region south of Cerro Laguna Verde (Figs.1, 3), several volcanic peaks higher than 6000 m have perennial snow accumulations on slopes above 5800 m. The only existing glaciers of the Argentine Puna occur in the Ojos de Salado (6885 m) region, one at 6600 m and another at 5800 m. The glaciers are small and appear to be in equilibrium (LLIBOUTRY et al. 1957). The altitude of the modern snowline west of 69°W longitude is not precisely known, although it must be higher than 5880 m since no perennial snow is detected on Nevado Jotabeche (5880 m) in the southern Cordillera de Darwin. Only temporary summer snow accumulation is visible there on a December 1984 TM image, which confirms earlier observations by SEGERSTROM (1964) and C. MPODOZIS (pers. comm., 1986). To the north, the highest peak in the study region (Volcán Llullaillaco, 24°43'S, 68°30'W, 6739 m) may also have the highest snowline, with three published values ranging from 5600 m to 6723 m (NOGAMI 1976).

In summary, the westward rise in modern snowline from about 5100 m in the Sierra Aconquija to more than 6500 m on Volcán Llullaillaco along the Chile-Argentina border clearly demonstrates the importance of precipitation derived from moist easterly winds. A similar westward rise in modern snowline has also been reported for the Argentine Puna north of 24°S and the Andes of Peru and Bolivia by WRIGHT (1983) and JORDAN (1985). Minor precipitation resulting from occasional incursions of westerly storms into the study area does not depress the regional snowline in a westward direction. Although vientos blancos may contribute to snow cover on the highest peaks, summer precipitation is more significant for maintaining perennial snow cover. If westwind-derived precipitation were important, many more peaks of the Chilean Cordillera would be snow-covered, and a permanent eastward rise in snowline would be observed.

Late Pleistocene glacial age snowlines

A cooler and effectively wetter climate depressed the snowline during late Pleistocene glacial episodes relative to its position during warmer interglacials. Unlike the modern snowline, the late Pleistocene snowline passed well below the peaks of Sierra Cumbres Calchaquies allowing limited glaciation in the southern part of the range (Figs.1, 4). Glacial landforms occur as low as 4250 m at the Quebrada del Matadero and rise to about 4700 m on Cerro Alto de la Mina in the Laguna Huaca Huasi area. Cirque and valley glaciers commonly had southerly and southeasterly aspects along shadowed slopes protecting them from melting and sublimation due to intense daily insolation. Small south-facing cirques at Cerro El Negrito (26.68, 65.72) and Cerro Alto de la Nieve (26.72, 65.70) illustrate this preferred aspect.

To the south, cirques are found at 4200 m on east- and northeast-facing slopes of the Sierra Aconquija between Alto de Muñoz (4437 m; 26.88, 65.83) and Morro del Zarzo (5064 m; 26.98, 65.92). The lowest reported cirque elevation in the region was 3800 m by ROHMEDER (1941) on the eastern slope of Cuesta de Medanito of Sierra Aconquija, but could not be located on TM imagery and air photos. The average regional late Pleistocene snowline determined from cirque floor altitudes on the eastern slopes of Sierra Aconquija was about 4300 m, even though cirques as low as 4000 m were observed. South of Morro del Zarzo (Fig.1B) (26.98, 65.92) the number of west-facing cirques on Sierra Aconquija increases. In comparison to cirque floor altitudes on east-facing slopes, most west-facing cirques are located at higher elevations and occur between 4400 and 4600 m (TAPIA 1925). For example, a cirque was observed in the upper Río Pajanguillo at an elevation of 4600 m, and is floored by partly barren and polished basement rock surfaces with glacial striae. The glacier formerly filling that cirque extended downstream to an elevation of 3800 m and left high-standing moraines. These moraines may be contemporaneous with the moraines on Sierra Cumbres Calchaquies, since they occur at similar elevations. The interpretation of a late Pleistocene age for these moraines is supported by the occurrence of a tephra layer within a glaciofluvial outwash terrace in front of the Río Pajanguillo moraine. The terrace can be traced downstream into the piedmont region and correlated with other fluvial terraces in the Santa María Valley that are either late Pleistocene or early Holocene in age (STRECKER et al. 1984). Evidence for older glacial episodes is lacking.

Evidence for late Pleistocene glaciation is found only on peaks higher than 4720 m in the Sierra Quilmes (Figs.1, 4), despite topographic relief and orientation similar to the Sierra Aconquija located to the east. Cirques were identified at an elevation of about 4800 m on Nevados de Chuscha (5468 m) in the field, on TM imagery, and on air photos. The east-facing slopes of Sierra Quilmes were glaciated more extensively than west-facing slopes, reflecting the importance of an easterly moisture source. Although there is ample evidence for at least three stages of glaciation on Sierra Quilmes, there are only two known morphologic and stratigraphic descriptions of the moraines (GALVAN 1981; STRECKER 1987).

Similar in trend to the modern snowline, the late Pleistocene snowline rose from an average of about 4300 m in the Sierras Pampeanas to about 5500 m in the Chilean Cordillera to the west (Fig.4). Glacial landforms have been observed on Cerro Zuriara (26.25, 66.52), the Nevados de Compuel

(25.54, 66.38), and Sierra Laguna Blanca where PENCK (1920) identified Pleistocene cirque floors at 5000 m. Evidence of more extensive glaciation on east-facing slopes is even more pronounced on the Puna than in the Sierras Pampeanas. Glaciers developed only on the east-facing slopes of Sierra Laguna Blanca (Fig.1B), although dissected terrain favorable for cirque glaciation also existed on the western slopes. The same situation is found on the eastern edge of the Puna at Nevados de Palermo (Figs.1, 4), where glacial landforms are absent on west-facing slopes, but occur on east- and southeast-facing slopes at about 5000 m (TURNER 1964).

In the western Puna, late Pleistocene snowlines rise to about 5500 m, and the lack of Pleistocene glacial landforms along the present Chile-Argentina border has been noted by SEGERSTROM (1964), MORTIMER (1973), and MERCADO (1982). Only fossil rock glaciers are reported from Nevado Jotabeche and Cerro Cadillal in the southern Cordillera Darwin (SEGERSTROM 1964; C. MPODOZIS, pers. comm. 1986).

PENCK (1920) reported east-facing cirques at an elevation of 5500 m on Nevado Tres Cruces (6330 m) and Volcán Bonete (6850 m; 27.43, 69.00) (Figs.1A, 4). As previously mentioned, Ojos de Salado (6885 m) is the only modern glacier-supporting peak in the region (LLIBOUTRY et al. 1957), but the elevation of the Pleistocene snowline is not precisely known. Glacial age snowline depression on the neighboring peaks suggests, however, that the late Pleistocene snowline may have been above an altitude of 5500 m. NOGAMI (1976) reported an elevation of 4900 m for cirque floors in the Laguna del Negro Francisco area (27°15'-27°30'S and 69°00'-69°15'W), but was not confirmed during this study or by earlier work (MERCADO 1982).

CONCLUSIONS

Both the modern and late Pleistocene snowlines in the study area rise in elevation to the west (Fig.5). The late Pleistocene glacial age snowline was determined using only cirque floor altitudes of cirques on east-facing slopes between 26 and 28°S latitude in order to reduce the amount of bias introduced by different slope aspects and the north-south variation in the regional snowline gradient. The similarity between the snowline gradients clearly demonstrates the primary importance of an easterly moisture source both during late Pleistocene glacial and modern interglacial times. A large scale shift of the South Pacific anticyclone and associated westerlies as far north as 25°S did not occur during late Pleistocene glacial ages as proposed by HASTENRATH (1971) because moist westerlies did not significantly influence the snowline gradient north of 28°S. If there had been a northward migration of the westerly wind system and associated precipitation, the late Pleistocene snowline gradient would be opposite of the modern gradient and rise to the east.

PORTER (1964) and FLINT (1971) suggested that a uniform regional decrease in temperature with no change in total precipitation was primarily responsible for glaciation in areas where glacial age snowlines were depressed parallel to the modern snowline. Since late Pleistocene snowline depression was not uniform in the central Andes (26-28°S), but was an average of 300 m on the Argentine Puna and as much as 1000 m in the Sierra Cumbres Calchaquies and Aconquija, mountain glaciation in

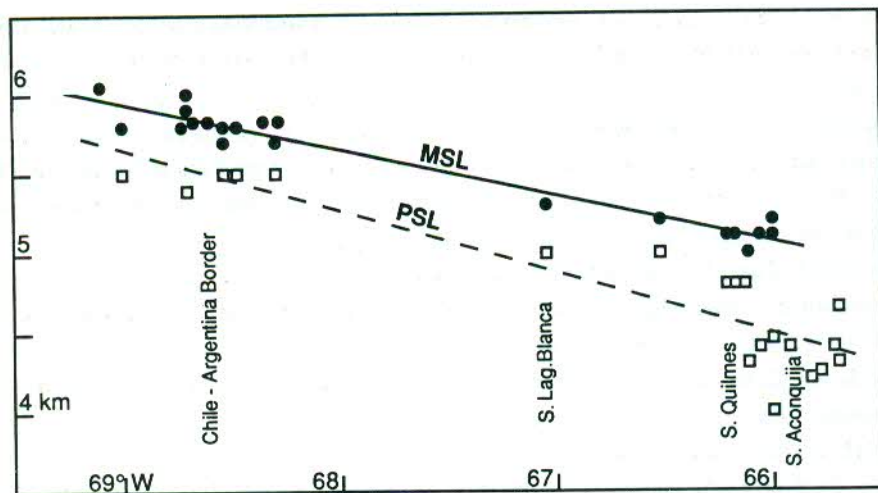


Figure 5. East-west modern (filled circles) and late Pleistocene glacial age (open squares) snowline elevation profiles through the central Andes (26-28°S). Glacial age snowline data are cirque floor altitudes of east-facing cirques only.

these regions did not result solely from a uniform decrease in temperature. Instead, the greater glacial age snowline depression in the Sierras Pampeanas primarily reflects an increase in effective, not necessarily total, precipitation from the Atlantic Ocean along the eastern margin of the Andean Cordillera where high, north-south oriented mountains form an effective moisture trap.

Acknowledgments

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