CURRENT LARGE-SCALE CLIMATIC CONDITIONS IN SOUTHERN PERU AND THEIR INFLUENCE ON SNOWLINE ALTITUDES

With 6 figures and 1 table

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Zusammenfassung: Gegenwärtige großräumige klimatische Bedingungen in Südperu und ihr Einfluß auf die Höhenlage der Schneegrenze

Auf der Grundlage von öffentlich zugänglichen Daten wurde eine Karte des mittleren Jahresniederschlages erarbeitet. Diese Karte zeigt für den Großteil der Gebiete oberhalb 4000 m Höhe Niederschläge von mehr als 600 mm/Jahr, wobei weite Gebiete sogar mehr als 800 mm/Jahr erhalten. Diese Niederschlagsmengen liegen um 200–500 mm/Jahr über den Angaben, die in Niederschlagskarten in der Literatur gegeben werden, und deuten auf wesentlich feuchtere Bedingungen als bisher angenommen hin. Das generelle Niederschlagsverteilungsmuster, wie es frühere Niederschlagskarten zeigen, konnte jedoch bestätigt werden: Hohe Niederschläge am Ostrand der Anden nehmen zum Pazifik hin ab und innerhalb der Westkordillere reduziert sich der Niederschlag von Nord nach Süd. Eine Korrelation zwischen den jährlichen Ablußmengen von Flüssen, die im Pazifik münden und Angaben über die El Niño Southern Oscillation (ENSO) konnte nur für Teile des Zeitraumes 1926 bis 1971 gefunden werden, was die Frage eines direkten Einflusses von ENSO auf die Niederschläge in der Westkordillere Südperus unbeantwortet läßt. Ausgehend von den Jahresmitteltemperaturen für 35 Stationen in Höhen über 3000 m wurde die Höhenlage der 0 °C Jahresisotherme für jede dieser Stationen berechnet, die danach in der Ostkordillere oberhalb 5000–5100 m und in der Westkordillere unterhalb 4900–4800 m liegt. Basierend auf Angaben für 931 Gletscher aus dem Peruanischen Gletscherinventar zur Höhe der Höhenlinie, die die Gletscherfläche halbiert und somit einer *accumulation area ratio* (AAR) von 0,5 entspricht, wurde eine Karte der Schneegrenzhöhen erstellt. Sie zeigt die tiefsten Schneegrenzlagen mit 4900–5000 m in der Ostkordillere und die höchsten mit 5600 m in der Westkordillere. Außerdem ist zu erkennen, daß die 5200 m- und 5300 m-Schneegrenzisohypsen die Anden von der Ostkordillere zur Westkordillere queren, was trotz geringerer Niederschläge in der Westkordillere zu ähnlichen Schneegrenzhöhen am Nevado Sara Sara in der Westkordillere, wie in Bereichen der Ostkordillere führt. Durch das Konzept der ‚normalisierten Schneegrenzhöhe' kann der Einfluß der Niederschlagsveränderungen als Einzelfaktor auf die Schneegrenzhöhe demonstriert werden. Da die festgestellten Niederschlagsunterschiede zu größeren Schneegrenzhöhenunterschieden zwischen Ost- und Westkordillere führen sollten, als sie in der Schneegrenzhöhenkarte dargestellt sind, muß ein zweiter Faktor in die Überlegungen einer klimatischen Interpretation der Schneegrenzhöhen miteinbezogen werden, der in der Lage ist, die abnehmenden Niederschläge zu kompensieren. Dieser Faktor ist die Höhe der 0 °C Jahresisotherme.

Summary: Based on detailed and publicly available data, a map of annual precipitation has been constructed. This map indicates for most of the area above 4000 m altitude precipitation exceeding 600 mm/yr, with many areas receiving even more than 800 mm/yr. These values exceed the precipitation data given in maps in the literature by 200–500 mm/yr and indicate considerably wetter conditions than have so far been assumed. However, the general pattern shown in previous precipitation maps was confirmed: high precipitation at the eastern edge of the Andes decreases towards the Pacific, and precipitation in the Western Cordillera decreases from north to south. A correlation between the annual river discharge of rivers flowing into the Pacific and records for the El Niño Southern Oscillation (ENSO) was found only for parts of the period 1926 to 1971, leaving the question of a direct influence of ENSO on the precipitation in the Western Cordillera of Southern Peru unanswered. From annual mean temperatures for thirty-five stations above 3000 m, the altitude of the 0 °C isotherm above each station was calculated, locating it above 5000–5100 m in the Eastern Cordillera and below 4900–4800 m in the Western Cordillera. A snowline altitude map was constructed from data for the contour line altitude that halves the glacier area, representing the accumulation area ratio (AAR) of 0.5 for 931 glaciers from the Peruvian glacier inventory. It shows the lowest snowlines at 4900–5000 m in the Eastern Cordillera and the highest snowlines at 5600 m in the Western Cordillera, but it also indicates that the 5200 m and 5300 m snowline contours cross the Andes from the Eastern to the Western Cordillera, leading to similar snowline altitudes at the Nevado Sara Sara in the Western Cordillera as in parts of the Eastern Cordillera, despite lower amounts of annual precipitation. With the concept of a 'normalised snowline altitude' the influence of precipitation differences as a single factor on the snowline altitude can be demonstrated. Because the observed precipitation differences should lead to larger snowline altitude differences between the Eastern and Western Cordillera than seen in the snowline altitude map, a second factor has to be taken into consideration for the climatic interpretation of the snowline altitude that is able to compensate the decreasing precipitation. This factor is the altitude of the annual 0 °C isotherm.

1 Introduction

To evaluate past climatic change from a comparison between Pleistocene and current snowline altitudes, detailed information was needed on the current snowline altitude and its determining climatic conditions for Southern Peru. The availability of more detailed data than hitherto used in the literature on current annual precipitation, annual cloud cover, annual mean temperatures, and snowline altitudes provided the basis for a new assessment of the present climatic conditions and their influence on the present snowline altitude. First, the climatic conditions in Southern Peru are described, followed by a compilation of the current snowline altitudes and their interpretation based on the climatic conditions.

2 Current climate

The term 'current climate' relates to the mean conditions during the periods for which data were available, generally the late 1960s. The data sets used in this study were taken from publicly available sources, mainly the volumes of the 'Oficina Nacional de Evaluacion de Recursos Naturales' (ONERN various years) in Lima. Precipitation sums were available for individual years for sixty stations, of which for fifteen stations the data had to be measured from diagrams. For an additional thirty-four stations only mean values were given for a certain observation period. Annual mean temperatures for individual years could be obtained for fourteen stations above 3000 m altitude and annual mean temperatures for certain observation periods were available for another eighteen stations. Details about methods of data collection and processing were largely lacking and so a statistical assessment of the data quality was not possible. However, positive and negative deviations from the mean occurred simultaneously in nearly all of the stations for which there were data on an annual basis and the means of neighbouring stations did not vary unreasonably, so that a good overall data quality can be assumed.

2.1 Precipitation

An annual precipitation map represents the mean situation for the period for which data were available. In the case of this study, most of the precipitation stations used were in operation only during the period 1964 to 1970. This short period of time may feature a climatic extreme situation that is not representative for a longer one, especially in an area of the world that is characterised by large precipitation deviations in relation to the El Niño Southern Oscillation (ENSO). Therefore, precipitation data for longer periods were needed to assure that the resulting precipitation map represents the mean situation for a much longer period. These data could only be obtained for five stations before 1964 and four stations after 1970 (ONERN various years, FNDE 1971, WWR 1991 and individual data from the Servicio National de Meteorologia y Hidrologia in Lima (SENAMHI)), so that a proxy record for annual precipitation was needed. This was assumed to be provided by the annual discharges of rivers on the Pacific slope of the Andes (ONERN various years) which should represent annual precipitation in the catchment area above 2800 m, because precipitation below 2800 m is negligible (ONERN various years), leading to desert conditions that reach up to this altitude (ABELE 1992). To establish whether discharge data can be used as a proxy for the precipitation, both data sets were converted into units of standard deviation to allow for comparison. The discharge data for four rivers (location in Fig. 1) out of the eight available (ONERN various years, additional rivers were the Rios San Juan, Pisco, Grande and Yauca) are shown in Fig. 2 together with the mean of the standard deviation for up to fifty-five out of sixty precipitation stations (ONERN various years, FNDE 1971 and WWR 1991). There is a very good agreement between these two data

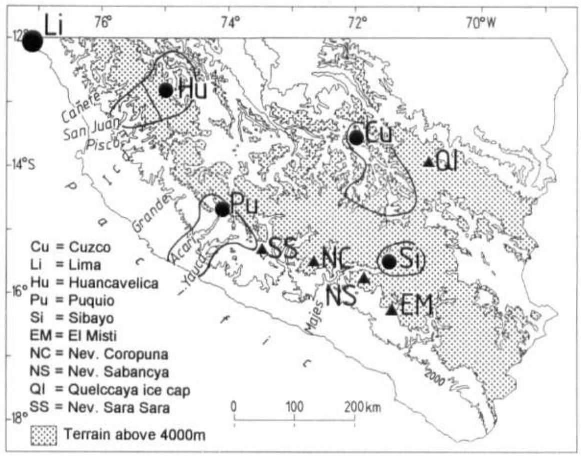

Fig. 1: General topography of Southern Peru with the location of rivers, towns and mountains mentioned in the text. Areas delimited by thick lines are areas for which annual mean temperatures were available

Topographischer Überblick von Südperu mit der Lage von Flüssen, Orten und Bergen, die im Text erwähnt werden. Bereiche, die durch eine dicke Linie begrenzet werden, kennzeichnen Gebiete, für die Jahresmitteltemperaturwerte vorlagen

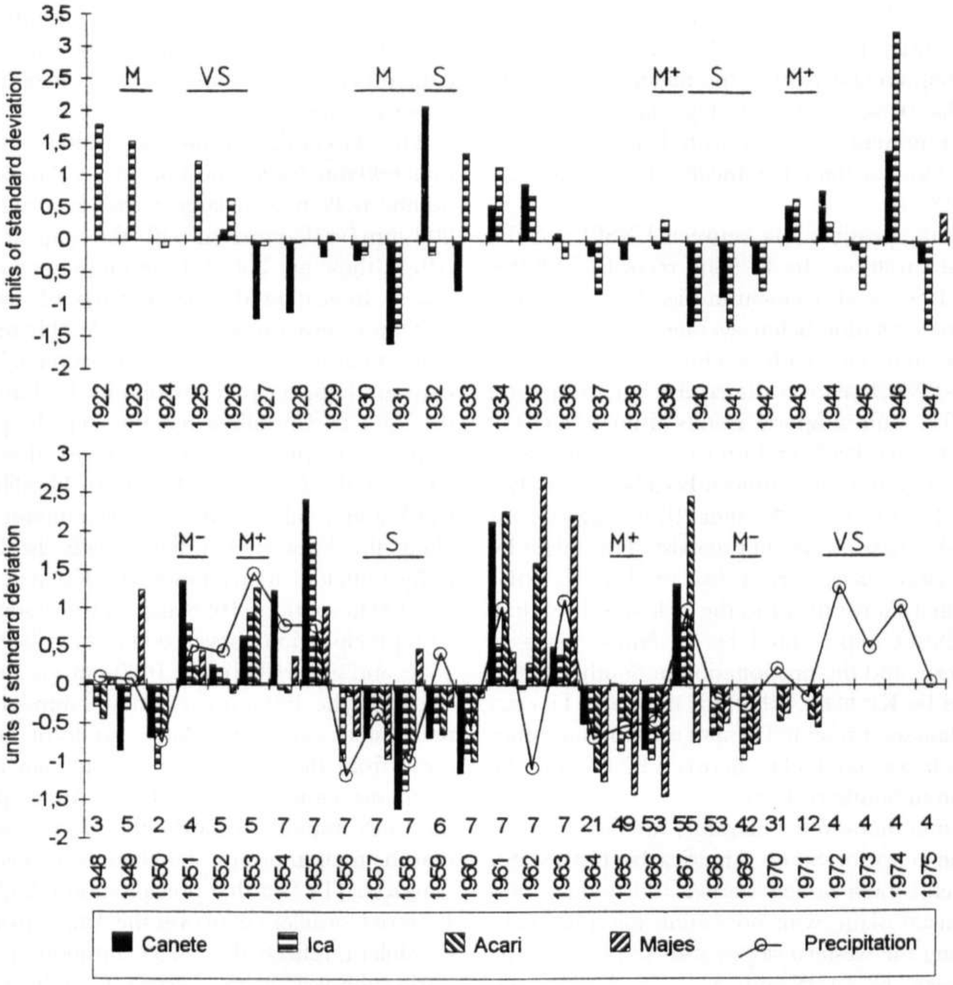

Fig. 2: Standard deviation of annual river discharges and mean annual precipitation. The line in the lower part of the graphic represents the averaged standard deviation for the mean annual precipitation of up to fifty-five out of sixty precipitation stations (the number of stations used for each year is given above the year). Letters indicate El Niño events from QUINN and NEAL (1992), where M indicates moderate (M^+ somewhat above and M^- somewhat below moderate), S strong and VS very strong events. Sources for the river data: ONERN (1970, 1971a, 1973, 1975), sources for precipitation data: ONERN (various years), FNDE (1971) and WWR (1991)

Standardabweichungen der jährlichen Abflußmengen und des Jahresniederschlages. Die Linie im unteren Teil der Grafik stellt die mittlere Standardabweichung des mittleren Jahresniederschlages von bis zu 55 von insgesamt 60 Niederschlagsstationen dar (die Anzahl der herangezogenen Stationen steht über den Jahreszahlen). Buchstaben markieren El Niño Ereignisse aus QUINN und NEAL (1992), wobei M für mittelstarke (M^+ etwas stärker und M^- etwas schwächer), S für starke und VS für sehr starke Ereignisse steht. Quellen der Abflußdaten: ONERN (1970, 1971a, 1973, 1975), Quellen der Niederschlagsdaten: ONERN (verschiedene Jahre), FNDE (1971) und WWR (1991)

sets (r = 0,76 (N = 24) between the mean of the four river discharges and the mean of the precipitation stations) allowing for the river discharges to be used as a proxy data set for annual precipitation in the upper parts of the Andes. Apparently, interannual variability of the precipitation in southern Peru is large, with one standard deviation exceeding 50% of the mean at several stations, while the mean standard deviation for all stations is 35%. The same amount of inter-annual variation applies to the river discharges. For each of the precipitation stations with recording periods exceeding the period 1964–70 and for each of the eight river discharges, means were calculated for the periods 1948–63 and 1964–70 for the precipitation stations and for the periods 1926–63 and 1964–70 for the river discharges. Differences in the means for the years before and after 1964 indicate that the period 1964–70 was 10–20% drier than the preceding periods. The precipitation map compiled from the mean precipitation data for the period 1964-70 (Fig. 3a) is therefore assumed to represent a situation with slightly lower precipitation amounts than the mean situation for the period ~1926–70.

To assess the possible link between ENSO and the inter-annual variation, the El Niño record of QUINN and NEAL (1992) is also shown in Fig. 2. A pattern of years with precipitation below average coinciding with ENSO years and years with precipitation above average in anti-ENSO years is discernible for the period 1955 to 1971 and supports results from LECOMTE (1983), ACEITUNO (1988) and QUINN and NEAL (1992) about drier conditions in southern Peru before or after an El Niño. Prior to 1955 and after 1971 an agreement of the two databases seems not to exist. This might be due to the close succession of two or three El Niño events within a short time or to the lack of a direct link between ENSO, represented by El Niño events in northern Peru, and the precipitation in Southern Peru as indicated by KESSLER (1990) for the Lake Titicaca area. The data sets presented cannot substantiate either of the hypotheses about a link between ENSO and the precipitation in Southern Peru.

Precipitation maps in the literature are based on the precipitation map for South America by HOFFMANN (1975), which is built on few stations (thirty-three outside the coastal plain) with no station for more than 500 km along the western slopes and Altiplano of the Andes between 76°–71°W and 15°–13°S . For the construction of the precipitation map in Fig. 3, data were available for the ninety-four stations mentioned in part 2 (mainly for the 1960s, ONERN various years), and from isohyet maps for smaller parts of Southern Peru, which are probably also based on precipitation data from the late 1960s (FNDE 1971, HOFFMANN 1975, RICHTER 1981, INAF 1982 and ONERN 1984, Fig. 3b and 3c). The mean precipitation values for each station, together with these isohyets, were marked in a general topographic map. Isohyets with an interval of 200 mm/yr were then interpolated linearly between the individual stations and joined with the existing isohyets, taking into consideration the degree of completeness of the 1964–70 record at each station and the topographic situation, thus modifying the linear interpolation. Precipitation values exceeding 1200 mm/yr were not differentiated owing to the steep gradient at the flank of the Eastern Cordillera down to the Andean foothills (compare HOFFMANN 1975) and to their lack of influence on snowline altitudes. No isohyets were drawn immediately south of 12°S between ~72° and ~74° W due to a lack of data, and because the isohyets from HOFFMANN (1975) could not be linked up with the data from the other sources as was possible in the north-eastern corner.

The map in Fig. 3a shows precipitation values larger than 600 mm/yr for most of the area above 4000 m in Southern Peru with large parts receiving more than 800 mm/yr. Compared with the map in HOFFMANN (1975), these are 200–500 mm more per year in most places, indicating that large parts of terrain above 4000 m receive on average considerably more precipitation than has previously been assumed. The general pattern of higher precipitation in the Eastern than in the Western Cordillera remains, but the precipitation changes are primarily concentrated along the outer edges of the Eastern and Western Cordillera. Southwards a gradual reduction in precipitation can be seen along the Western Cordillera with the 200 mm/yr isohyet situated at an altitude of 2000 m at 13°S, rising to 4000 m south of 16°S and on the eastern Altiplano with precipitation above 1000 mm/yr between 12° to 13°S and generally below 1000 mm/yr further south. Similarly, the 400 mm/yr and 600 mm/yr isohyets on the western side of the Andes are to be found further away from the coast in the south than at 13–14°S. From the eastern slopes of the Andes precipitation increases rapidly towards the northeast indicating that the main moisture source for Southern Peru is the Amazon. The fact that precipitation is higher over the Eastern Cordillera than over the Altiplano and Western Cordillera, reflects the longer duration of cloud cover during the year in the Eastern Cordillera, as demonstrated by GRAF (1986) and WARREN et al. (1986). The high amounts of annual precipitation on the Altiplano support assumptions made by KISTEMANN and LAUER (1990) about high precipitation from intense convection near the valley heads of large rivers due to airflow along the deeply incised valleys from the Amazonian and Pacific sides on to the Altiplano. This circulation has recently been modelled numerically by DAPOZZO (1995).

2.2 Temperature

Differences in the duration of the annual cloud cover and in the annual amount of precipitation may lead to different annual mean air temperatures for stations at the same altitude in the Eastern and Western Cordillera owing to differences in incoming and outgoing radiation or different amounts of latent heat released. Data on the annual mean temperatures were taken from ONERN (various years) providing mainly mean values for a given time period, generally for more than

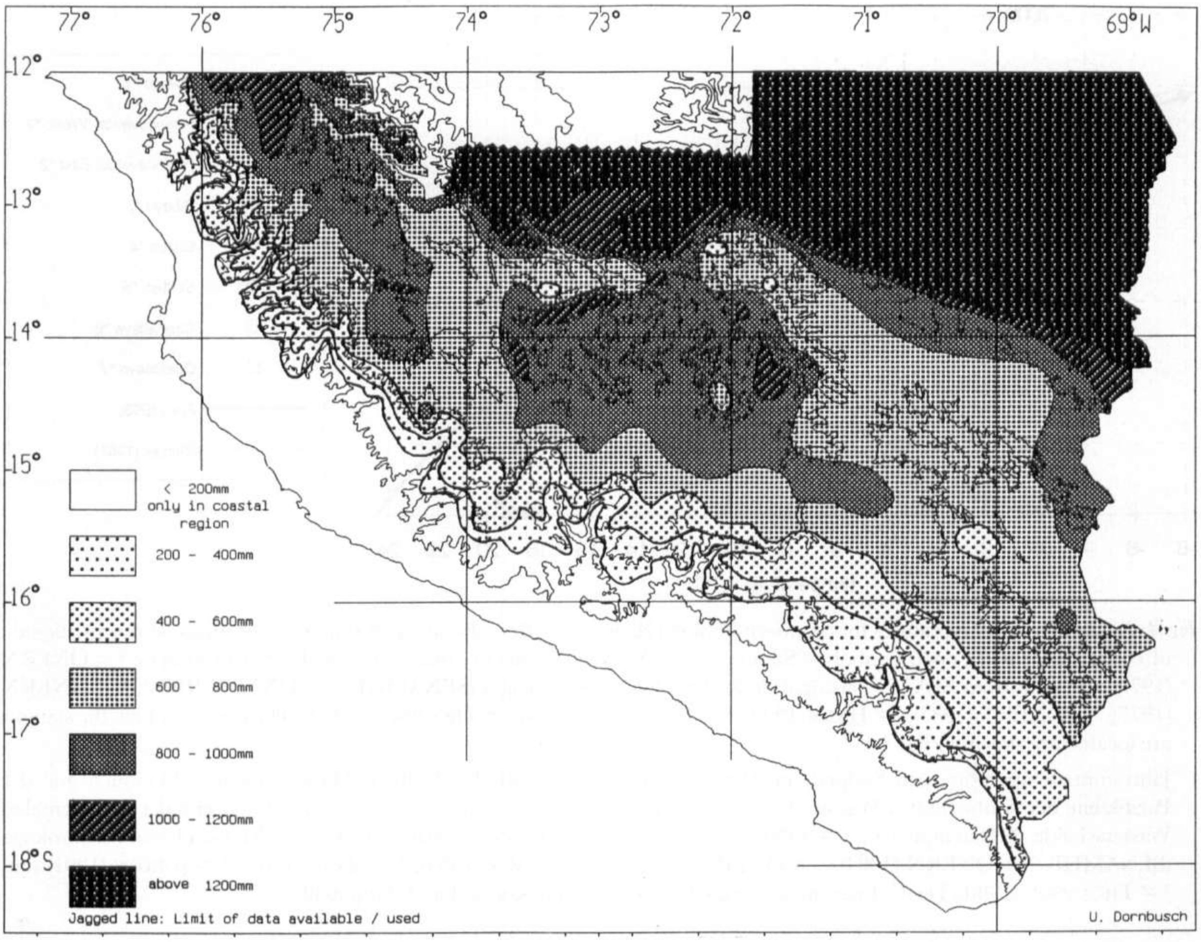

Fig. 3a: Mean annual precipitation in Southern Peru

Mittlerer Jahresniederschlag in Südperu

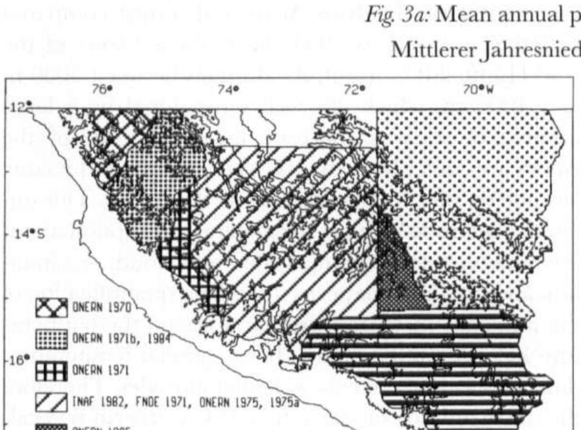

Fig. 3b: Location of the areas covered by the sources. Isohyets were provided by INAF (1982), HOFFMANN (1975) and RICHTER (1981)

Lage der Bereiche, die durch die verschiedenen Quellen abgedeckt werden. Isohyetendarstellungen stammen aus INAF (1982), HOFFMANN (1975) und RICHTER (1981)

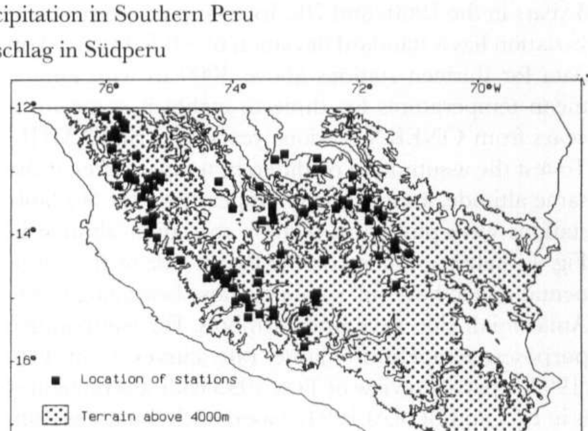

Fig. 3c: Location of individual stations used for the precipitation map. Fig. 3a, 3b and 3c feature 2000 m and 4000 m topographic contour lines

Lage der einzelnen Stationen, die für die Niederschlagskarte herangezogen wurden. Fig. 3a, 3b und 3c beinhalten die 2000 m und 4000 m Isohypsen

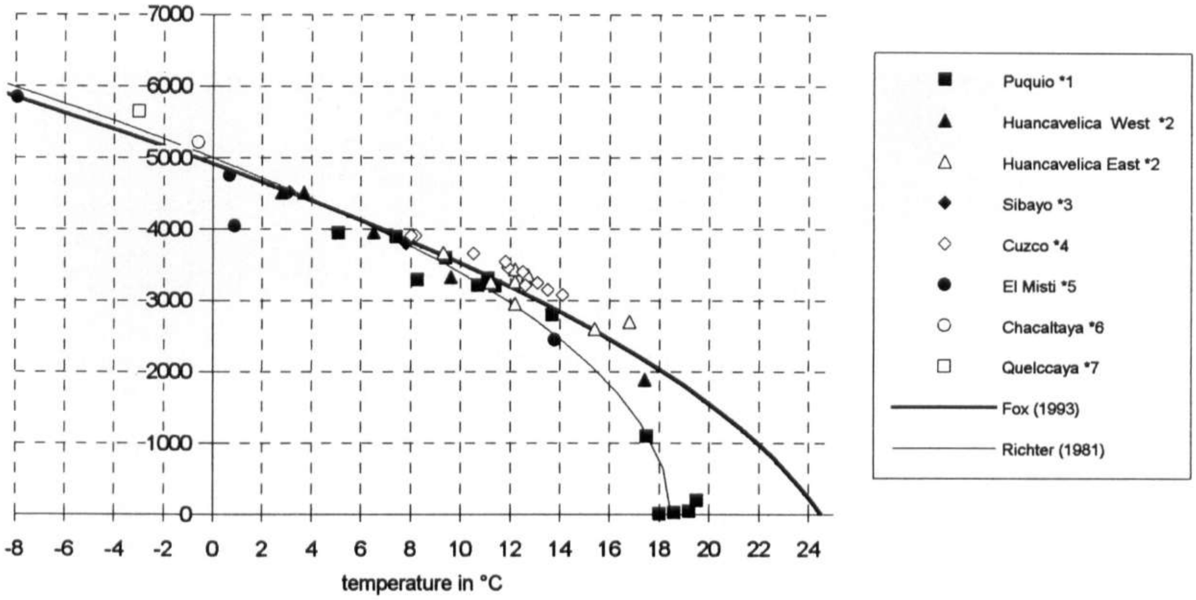

Fig. 4: Annual mean temperatures for Southern Peru in relation to station altitude. Full symbols = Stations on the Pacific side of continental divide, open symbols = Station on the Amazonian side of continental divide. * Data sources: [1] = ONERN (1975) and data from Servicio Nacional de Meteorologia y Hidrologia (SENAMHI), [2] = ONERN (1984), [3] = ONERN (1977), [4] = ONERN (1985), [5] = HANN (1909), [6] = JORDAN (1991) and [7] = THOMPSON (1980). The areas in which the stations are located are shown in Fig. 1

Jahresmitteltemperaturen in Südperu in Abhängigkeit zur Stationshöhe. Gefüllte Markierungen = Stationen auf der Pazifikseite der kontinentalen Wasserscheide, hohle Markierungen = Stationen auf der Amazonasseite der kontinentalen Wasserscheide. * Datenquellen: [1] = ONERN (1975) und Daten des Servicio Nacional de Meteorologia y Hidrologia (SENAMHI), [2] = ONERN (1984), [3] = ONERN (1977), [4] = ONERN (1985), [5] = HANN (1909), [6] = JORDAN (1991) und [7] = THOMPSON (1980). Die Gebiete, in denen die Stationen liegen, sind in Fig. 1 dargestellt

5 years in the 1960s and 70s. Inter-annual temperature variation has a standard deviation of ~0.5 °C (tested on data for thirteen stations above 3000 m with annual mean temperatures for three to eighteen consecutive years from ONERN (various years) and SENAMHI). To test the assumption of different temperatures at the same altitude, annual mean temperatures for available stations were plotted in relation to station altitude in Fig. 4. Stations situated on the Pacific side of the continental divide have full symbols, those belonging to the Amazonian side have open symbols. For comparative purposes, temperature lapse rate curves from FOX (1993, a partial review of FOX 1993 with several figures is in FOX and BLOOM 1994), based on 206 stations from the whole of Peru and from RICHTER (1981) for fifty-two stations in the department of Arequipa in the southern corner of Peru (compare Fig. 3b) are also shown in Fig. 4. Annual mean temperatures on the Pacific side of the Andes (full symbols, curve from RICHTER 1981) are cooler than on the Amazonian side (open symbols) or compared with an average for stations from all over Peru (FOX 1993). At sea-level the difference is largest (Richter 1981 and the stations at the mouths of the Rios Acari and Yauca compared with the curve in FOX 1993) due to the influence of the cold Humboldt Current. At altitudes between 3000 m and 4000 m, which are well represented by a large number of stations, those on the Pacific side of the Andes are cooler by up to 4°C than stations in the same altitude on the Amazonian side of the Andes. This difference seems to support the general assumption about the relation between temperature and cloud, precipitation and insolation patterns though no quantification of the influence of these three variables on the temperature has been attempted. These regional temperature differences must also exist at higher altitudes. Therefore the mean altitude of the annual 0°C isotherm was calculated for the thirty stations above 3000 m in Fig. 4 along the temperature gradient curve from FOX (1993). The standard deviation of 0.5 °C for the annual mean temperatures amounts to a deviation of ±65 m. Because HANN (1909) provides an altitude for the 0°C isotherm on El Misti the three altitudes supplied by him were not considered. The spatial distribution of the thirty-three temperature stations (Fig. 1) does not allow for the interpolation of a contour line map for the alti-

tude of the 0 °C isotherm but, nevertheless, a regional pattern can be observed. In the Cuzco area (Fig. 1), the 0 °C isotherm altitude ranges between 4990 m and 5160 m for eleven stations (mean = 5077 m), in the Huancavelica East area between 4770 m and 5170 m for eight stations (mean = 4992 m), in the Huancavelica West area between 4700 m and 4880 for four stations (mean = 4810), in the Puquio area between 4520 m and 4900 m for six stations (mean = 4762 m) and in the Sibayo area from 4880 m to 4920 m with a mean of 4900 m for two stations. For the station at Chacaltaya in the Eastern Cordillera of Bolivia (16°19'S, 68°10'W, 5220 m), JORDAN (1991) reports an annual mean temperature of –0.6°C, yielding an altitude of 5150 m for the 0°C isotherm. An annual mean temperature of ~–4.8°C can be inferred from data in THOMPSON (1980) for the top of the Quelccaya ice cap (13°56'S, 70°50'W, 5650 m, Fig. 1), corresponding to an altitude of 5085 m for the 0 °C isotherm. HANN (1909) presents an altitude of 4600 m for the 0 °C isotherm on El Misti (Fig. 1), though from the summit value of –7.9°C (Fig. 4) and the gradient curve given by FOX (1993) the altitude would be 4920 m. The evolving pattern indicates altitudes of the 0°C isotherm in the Eastern Cordillera of >5000–5100 m and in the Western Cordillera of <4900–4800 m. The lowest values at the western edge of the Western Cordillera are close to the altitude of 4760 m for the free atmosphere, calculated for the latitude of 15 °S from radiosonde data over Lima and Antofagasta quoted by SCHWERDTFEGER (1961).

3 *Current snowline altitude*

Detailed data on current glaciers in Southern Peru can be found in the Peruvian glacier inventory (AMES et al. 1988). They provide the basis for comparing snowline altitudes between different areas in Southern Peru. Though no period or point of time for which this glacier information is valid is provided explicitly in the inventory, the term 'current', as used for the snowlines in this study, probably refers to the years 1955 and 1962 because the air photo identification numbers on which each glacier can be found are given in the inventory and refer to the flight projects from 1955 and 1962. The national topographic maps at scales of 1:100,000 and 1:50,000 edited by the Instituto Geografico Nacional are primarily based on air photos from 1955 and are also mentioned as sources for the glacier data. Therefore the glacier inventory represents the glacier situation of about forty years ago and some of the smaller glaciers may have disappeared already, considering the rapid glacier retreat at the Quelccaya Ice cap in the 1980s shown in THOMPSON et al. (1993). For Peru south of 12 °S, 1401 glaciers or perennial snow fields larger than 0.005 km^2 are listed in the inventory in accordance with the criteria for the 'World Glacier Inventory' (MÜLLER et al. 1977). The data set for each glacier includes details on its location, size and orientation. For 900 glaciers "The elevation of the contour line that divides the surface area of the glacier into two equal parts" (AMES et al. 1988, 17) is given, representing an accumulation-area-ratio (AAR) of 0.5. This altitude is from now on referred to as the 'line that halves the glacier area (LHGA)'. It is not possible to determine how individual LHGAs relate to the equilibrium line altitude (ELA) of each glacier owing to the lack of mass balance studies in Southern Peru during the period 1955–1962. However, according to JORDAN (1991) an AAR of 0.5 provides for glaciers in the Bolivian Andes a close approximation to the mean equilibrium line altitude for glaciers <0.5 km^2. This relationship is assumed to be valid for the Peruvian Andes too. In the Austrian Alps GROSS et al. (1977) found that for glaciers of up to ~3 km^2 an AAR of 0.5 results in snowline altitudes that are on average 38±18 m higher than those based on an AAR of 0.67 that approximates the ELA more closely. Of the 900 glaciers 62% are smaller than 0.5 km^2, 18.5% are between 0.5–1 km^2, 10.5% are between 1–2 km^2, 7% are between 2–5 km^2 and only 2% are larger than 5 km^2. This size distribution, together with the statements of JORDAN (1991) and GROSS et al. (1977) led me to assume that the LHGA is representative for the long term mean ELA for the great majority of the 900 glaciers for the period of air photo coverage. Initially, the LHGA data were arranged into ten cordillera groups following the classification in the glacier inventory. In cases where the individual cordillera covered a large area (e. g. Cordillera Vilcanota), smaller subsets were taken to allow for a better spatial resolution and altitudinal differentiation, resulting in nineteen groups altogether (Table 1) with the number of glaciers in these groups ranging from 7 to 201 with a mean of fifty-two. In each of the nineteen groups the LHGAs were then subdivided into eight glacier expositions. The mean of all LHGAs in each of the eight expositions is seen as the average exposition snowline altitude (AESA) in a certain cordillera. The mean of all eight AESAs produced a value that represents the 'climatic' snowline altitude. Only in the south-western part of the Cordillera Carabaya glacier data were lacking for four expositions (NW, NE, E and SE); hence the value for the climatic snowline is too low and is therefore given in brackets in Fig. 5 (5080 m). Though the climatic snowline cannot be

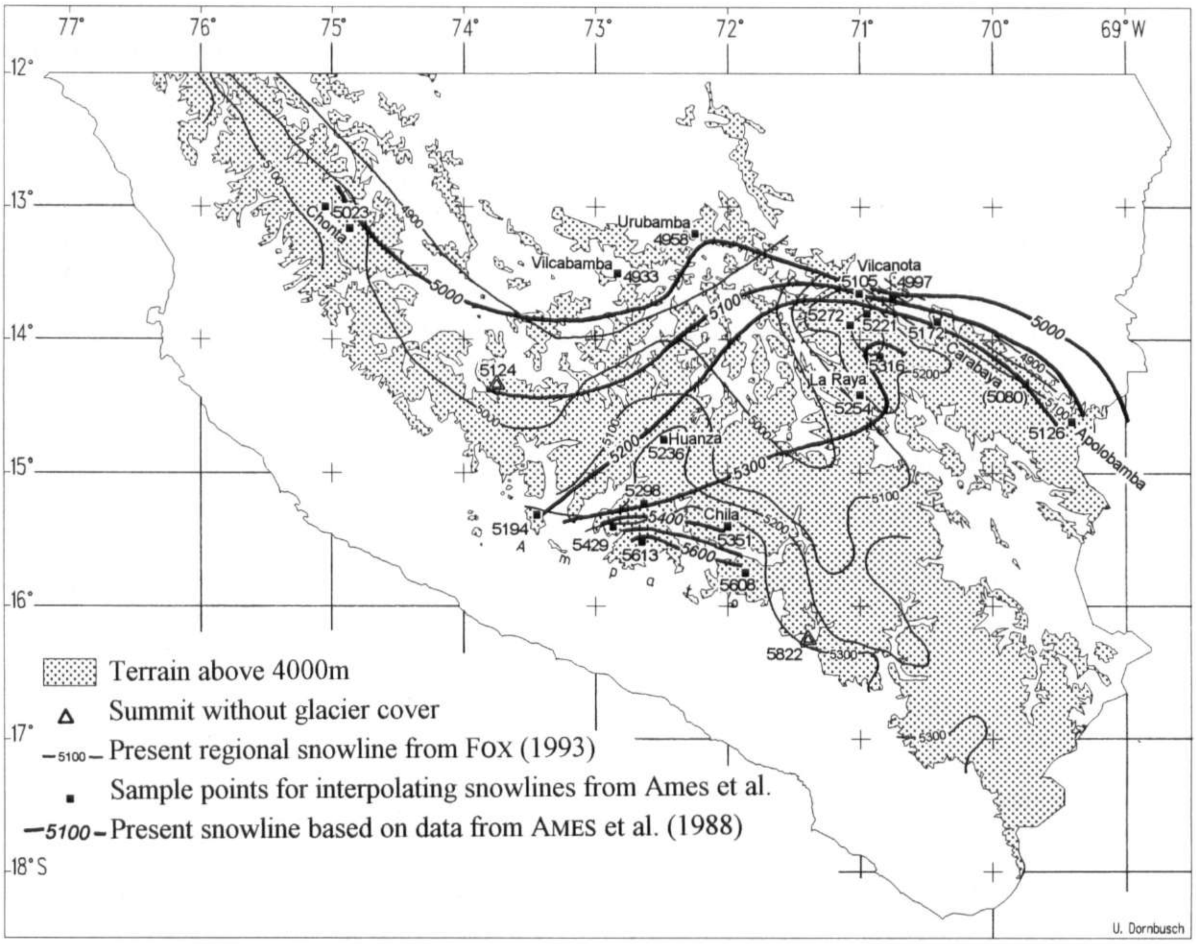

Fig. 5: Map of the altitude of the current snowline in Southern Peru based on 900 glaciers from AMES et al. (1988). For a comparison the 'present regional snowline' from FOX (1993) is also shown

Karte der Höhenlage der heutigen Schneegrenze in Südperu auf der Basis von 900 Gletschern aus AMES et al. (1988). Zum Vergleich ist die 'present regional snowline' von FOX (1993) eingezeichnet

identified in the field (GROSS et al. 1977), it is a necessary abstraction to compare snowline altitudes between the nineteen groups and to compare the results from this study with those in the literature. The average of the AESAs was used instead of a simple average of all LHGAs in each cordillera because in many of the cordilleras greater numbers of glaciers exist in southern and western than in other expositions, leading to the general mean being up to 141m higher than the AESA mean. The difference in the number of glaciers per sector has the same cause as the difference in the AESA between the N to E and S to W expositions (Table 1), representing a local asymmetry induced by differential shielding from solar radiation through clouds (TROLL and WIEN 1949).

The climatic snowlines for individual areas, calculated from the data from the glacier inventory, were compared with snowline estimations in the literature. MERCER and PALACIOS (1977) estimated a snowline altitude of 5100 m for the northern side of the Cordillera Vilcanota and of 5300 m for the western side of the Quelccaya ice cap, while, on the basis of field observations, THOMPSON (1980) gives a snowline altitude of 5250 m for the whole of the Quelccaya ice cap. These altitudes correspond well with the climatic snowlines of 5105 m for the northern part of the Cordillera Vilcanota and 5272 m for the southern part, which includes the Quelccaya ice cap. On the level of individual glaciers, a comparison was possible between the LHGAs and the 'approximated ELA' given by JORDAN (1991) for thirty glaciers in the Cordillera Apolobamba along the Peruvian-Bolivian border. Although the LHGA data are based on air photos dating from 1962 and the data by JORDAN (1991) on air photos from the mid-1970s the difference between the means of the two data sets is only about one metre with a correlation of

Table 1: Mean LHGA-altitude of the lowest and highest sector in nineteen cordillera subgroups with the sector exposition following. Last column is the mean altitude of the sector means representing the climatic snowline altitude with the number of glaciers in each group in brackets. Numbers and letters behind the cordillera names indicate the map quadrangles of the topographic map 1:100,000 of Peru in which this cordillera subgroup is located. All heights in metres

Gemittlelte Höhe der Linie, die die Gletscherfläche halbiert für den niedrigsten und höchsten Sektor für 19 Kordilleren-untergruppen mit dem Sektorenaspekt dahinter. In der letzten Spalte die gemittelten Sektorenmittel, die der klimatischen Schneegrenze entsprechen mit der Anzahl der Gletscher jeder Gruppe in Klammern. Die Ziffern- und Buchstaben-kombinationen hinter den Kordillerenbezeichnungen weisen auf die Planquadrate der Topographischen Karte 1:100 000 von Peru hin, in denen die Kordillerenuntergruppen liegen. Alle Höhen in Metern

Cordillera subgroups	Sector min.	Sector max.	Sector mean
C. Apolobamaba	5102 NW	5242 E	5126 (34)
C. Carabaya (28u4+u1)	4891 S	5060 N	4997 (84)
C. Carabaya (28v3)	5040 SW	5258 NW	5172 (39)
C. Carabaya (29x)	5045 SW	5125 N	5080 (34)
C. Chila	5273 SW	5387 E	5351 (28)
C. Chonta	4988 SW	5060 N	5023 (66)
C. Huanza	5187 SW	5285 N	5236 (64)
C. La Raya	5184 S	5350 N	5254 (38)
C. Urubamba	4840 S	5025 N	4985 (47)
C. Vilcabamba	4843 S	5034 NE	4933 (47)
C. Vilcanota (28t1, 28u4)	5010 S	5222 NE	5105 (134)
C. Vilcanota (28t2, t3, u3)	5224 W	5312 E	5272 (201)
C. Vilcanota (29u4)	5200 S	5400 E	5316 (16)
C. Vilcanota (total)	5192 W	5282 E	5221 (351)
N. Coropuna	5450 W	5850 N	5613 (15)
N. Fiura	5250 SW	5350 NE	5295 (7)
N. Sabancaya	5525 NW	5850 NE	5608 (11)
N. Sara Sara	5112 S	5350 E	5194 (7)
N. Solimana	5240 S	5587 N	5429 (28)

r = 0.86. These comparisons indicate that the individual data from the glacier inventory together with the averaging processes provide a good basis for the construction of a snowline altitude map for Southern Peru.

The values of the climatic snowlines for each of the nineteen areas were plotted into a general topographic map at the centre of the region it represents and contour lines were interpolated linearly at intervals of 100 m (Fig. 5). Snowlines are lowest at the outer edge of the Eastern Cordillera with ~5000 m in the Cordilleras Apolobamba and Vilcanota and between 4900–5000 m in the Cordilleras Urubamba and Vilcabamba. The absence of glaciers, according to the glacier inventory, on the 5124 m high Nevado Ccarhuaraso (14°20′S, 73°46′W, Fig. 5) together with a snow signature that generally reaches down to 4800 m in the 1:100,000 topographic map indicate a climatic snowline of about 5100 m leading to the snowline contours being displaced southwards from the Cordillera Urubamba. The snowline altitude of 5023 m in the Cordillera Chonta means that the contour line trends NW again following the eastern side of the closed terrain above 4000 m. From their low position at the eastern edge, snowlines rise to ~5300 m towards the interior of the Eastern Cordillera. For a wide stretch of the Altiplano between the Cordilleras La Raya, Huanza and Chila no glaciers are reported in the glacier inventory. Snowline altitudes in the Cordillera Ampato range from 5194 m at the Nevado Sara Sara in the West to above 5600 m at the Nevados Coropuna and Sabancaya. Further to the southeast, at the El Misti volcano, the snowline altitude must be above the summit of 5822 m as only snow fields and not glaciers are reported from it (Knoch 1938, Hastenrath 1967, Silva and Francis 1991). The general picture displayed in Fig. 5 is therefore one of low snowlines in the Eastern Cordillera and higher snowlines in the Western Cordillera. It is disturbed by the 5200 m and 5300 m snowline contours crossing the Andes from the Eastern to the Western Cordillera.

All these features of the current snowline distribution can be found in maps for the 'present regional snowline' from Fox (1993), also shown in Fig. 5, and for the 'modern snowline altitude' from Klein et al. (1995). All three maps are an advance in displaying snowline altitudes in space compared with presentations of meridional transects by HASTENRATH (1971), HEINE (1977), NOGAMI (1982), BROECKER and DENTON (1990), CLAPPERTON (1991), ABELE (1992) or SCHULZ (1994), because meridional transects cannot be representative in an area like Southern Peru, where snowline data between 13° and 15°S are provided by glaciers from the Eastern Cordillera and between 15° and 16°S by glaciers from the Western Cordillera, indicating a southward rise of the snowline of 300 to 600 m (see references above) that is in reality a rise between the Eastern and Western Cordilleras. Compared with the first snowline contour map by NOGAMI (1982), the three maps display more detail, with contour line intervals of 100 m compared with 500 m in NOGAMI's (1982) map. Though the general patterns of snowline contours are similar on all three maps, the absolute contour line altitudes of both FOX (1993) and KLEIN et al. (1995) are considerably lower than those presented in this study based on the glacier inventory data. Values given by FOX (1993) range from 4900 m in the Eastern Cordillera to 5300 m in the Western Cordillera with a differing contour line pattern on the Altiplano (Fig. 5), while KLEIN et al. (1995) report lowest snowlines for the Eastern Cordillera at 4700 m and for the Western Cordillera at 5200 m with a similar pattern to that of the present study on the Altiplano. The snowline altitudes in FOX (1993) are based on data obtained from the series of 1:100,000 topographic maps of Peru (s.o.), drawn from air photos taken in 1955 and 1962, which show snow-covered areas with blue contour lines. GRAF (1981) pointed out that the snow-covered areas in the topographic maps of Bolivia are more extensive than the actual glacier cover, i. e. snowline estimations are at least 100 m too low. As the topographic maps of Bolivia and Peru were compiled in a very similar way, GRAF's comment may also apply to the Peruvian maps. Furthermore, FOX (1993) sampled altitudes of the perimeter of the snow-covered areas at horizontal intervals of about 1km and then averaged all perimeter altitudes lying within a grid square of 20 × 20 km to obtain a snowline value for the contour lines shown in Fig. 5. Assuming the presence of a young, perfectly formed volcanic cone covered by an ice cap, thus minimising the topographic control (JORDAN 1983), the arbitrarily sampled perimeter of this area, even if it were ice and not snow, would always give altitude measurements below the mean ELA or below an AAR of 0.5, because the vertical glacier extent is not taken into consideration. A perimeter altitude of, for instance, 5200 m can relate to a mean ELA of 5300 m or 5800 m depending on the altitude of the accumulation area. These considerations together with the map critique by GRAF (1981) can only lead to the altitudes calculated by FOX (1993), which bear no relation to the snowline, being several hundred metres lower than the snowlines compiled in this study based on the glacier area and an AAR of 0.5.

KLEIN et al. (1995) used the data by FOX (1993) for areas north of 15°S and topographic maps and Landsat TM images for the areas south of 15°S (KLEIN pers. comm.). The method of measuring the perimeter altitudes around snow-covered areas remained the same as in FOX (1993), leading to the similar altitudes for the 'snowline'.

From this discussion of the snowline maps of FOX (1993) and KLEIN et al. (1995) it becomes clear that the snowline altitude map compiled in this study provides the more realistic picture of the aerially averaged mean ELA in Southern Peru.

4 *Climatic interpretation of the snowline pattern*

Differences in current snowline altitudes or even the presence/absence (Cordillera Blanca/Negra) of recent glaciers on the eastern flank of the Andes compared with the interior or the western flank have often been reported (e. g. JORDAN 1985 and 1991 for Bolivia, WRIGHT 1983 for central Peru and RODBELL 1992 for northern Peru). They have been attributed to differences in annual precipitation and differences in cloud cover (JORDAN 1985, FOX 1991). Because precipitation and cloud cover influence temperature, the altitude of the 0°C isotherm has also been taken into consideration in this study. To assess the influence of temperature and precipitation on the snowline altitude, they have to be considered separately. Because the formation of ice depends on subfreezing temperatures, they are the main limiting factor for the existence of glaciers. Given sub-freezing conditions, precipitation is the second limiting factor, as can be seen in Chile where the Llullaillaco volcano (6739 m, 24°43'S) reaches ~1700 m above the annual 0°C isotherm, but does not feature any glaciers (MESSERLI et al. 1992). To isolate the influence of precipitation, FOX (1993) introduced the term 'normalised snowline altitude' "as the difference between the regional snowline altitude and altitude of the annual 0°C isotherm" (FOX 1993, 9). For three regions in Southern Peru (Nevado Sara Sara (Fig. 5) / Puquio area (Fig. 1), Cordillera Chonta / Huancavelica area and the Cordilleras Vilcanota and La Raya / Cuzco area), snowline altitudes, the altitude of the annual 0°C isotherm and annual precipitation were determined from data provided in this study (Fig. 3 and Fig. 5). The altitude of the annual 0°C isotherm for the Nevados Sabancaya and Coropuna

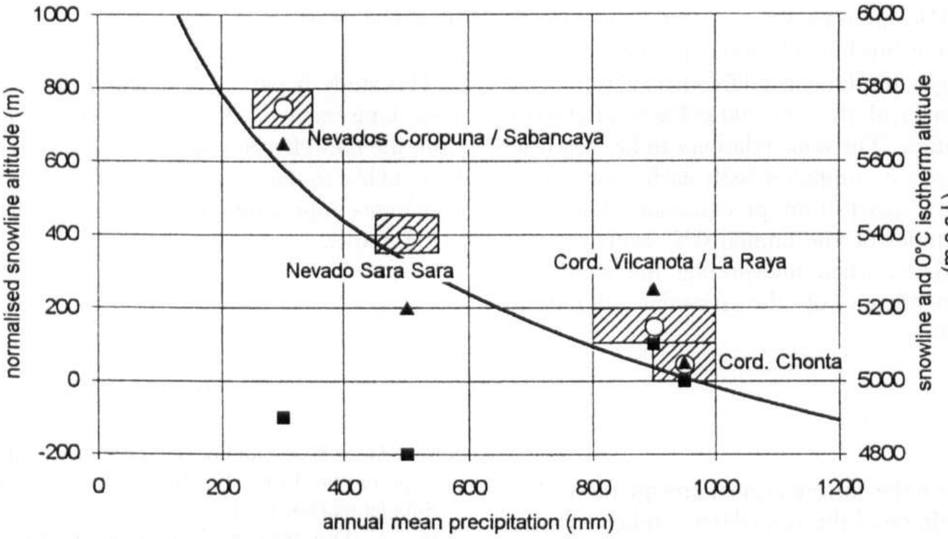

Fig. 6: Normalised snowline altitude, snowline altitude and alitude of the annual 0°C isotherm in relation to the mean annual precipitation for four areas in Southern Peru. Black squares are altitudes of the annual 0°C isotherm and triangles represent snowline altitudes (both belong to the right-hand scale). Circles represent the normalised snowline altitudes (left-hand scale) in their relation to annual mean precipitation with the surrounding hatched areas indicating the probable range of deviation in estimating the normalised snowline and annual precipitation. The solid line represents the curve y = 3748–1264 × log(x) in FOX (1993), with y being the mean annual precipitation and x the normalised snowline altitude

Normalisierte Schneegrenzhöhe, Höhenlage der Schneegrenze und Höhenlage der 0°C Jahresisotherme in Abhängigkeit zum mittleren Jahresniederschlag in vier Gebieten Südperus. Schwarze Quadrate sind die Höhen der 0°C Jahresisotherme und schwarze Dreiecke sind die Schneegrenzhöhen (beide Angaben gehören zur rechten Höhenskala). Offene Kreise sind die normalisierten Schneegrenzhöhen (linke Höhenskala) in Relation zum mittleren Jahresniederschlag. Die umgebenden schraffierten Bereiche markieren die möglichen Abweichungen in der Abschätzung der Höhenlage der normalisierten Schneegrenzhöhe und des mittleren Jahresniederschlages. Die dicke durchgezogenen Linie stellt die Kurve y = 3748–1264 × log(x) aus FOX (1993) dar mit y = mittlerer Jahresniederschlag und x = normalisierte Schneegrenzhöhe

had to be estimated from data for the Puquio area and El Misti, thus providing a fourth region. The data for the snowline altitude, altitude of the annual 0°C isotherm and calculated normalised snowline altitudes for these four regions are shown in Fig. 6 in relation to the annual precipitation. For comparative purposes Fig. 6 also shows a curve for the normalised snowline altitudes from FOX (1993, 47) based on data from Peru. Although FOX (1993) used lower snowlines, lower precipitation values (he took them from HOFFMANN 1975) and a uniform 0°C isotherm altitude (4920 m), his curve and the data from the four regions show a good agreement in that they indicate a logarithmic relationship where the influence of decreasing precipitation becomes more pronounced in drier than in wetter regions. In the Eastern Cordillera snowline altitudes are close to the level of the annual 0°C isotherm due to precipitation of 800–1000 mm/yr. With decreasing annual precipitation, as in the Western Cordillera, the normalised snowline altitude rises above the level of the annual 0°C isotherm by ~400 m at the Nevado Sara Sara to 700–800 m at the Nevados Coropuna and Sabancaya. Considering the situation on El Misti with precipitation of only ~200 mm/yr and a snowline altitude above the summit, the normalised snowline altitude is at >900 m, extending the curve further. However, this extension may be questionable with regard to a 'hygric' glacier limit proposed by JORDAN (1991) for Bolivia, according to which no glaciers can exist at annual precipitation values below 300 mm.

The differences of the normalised snowlines between the Eastern and Western Cordilleras, resulting from precipitation differences, are larger than the differences in the snowline values shown in Fig. 5 and Fig. 6 (triangles). While the normalised snowline at Nevado Sara Sara is 200–300 m higher than in the Cordilleras Vilcanota/La Raya, the absolute snowline altitude is similar or even 0–100 m lower despite reduced annual precipitation. This difference between the normalised and absolute snowline altitude of 200–400 m compares well with the 300 m difference in the altitude of the annual 0°C isotherm between the two areas (squares in Fig. 6). Similarly, the difference between the Nevados Coropuna/Sabancaya and the

Cordilleras Vilcanota/La Raya is 500–700 m for the normalised snowline but only 400 m for the snowline in Fig. 5 and Fig. 6, resulting in a difference of 100–300 m that agrees well with the 200–300 m lower annual 0 °C isotherm altitude. The same relation can be seen when all four areas are compared with each other, which indicates that, apart from precipitation differences, differing altitudes of the annual 0 °C isotherm have to be considered when interpreting the large scale climatic dependency of the snowline altitude in Southern Peru.

5 Conclusion

New data on the current annual precipitation, cloud cover, and altitude of the annual 0 °C isotherm make it possible to explain the snowline altitude distribution seen in Southern Peru as it can be constructed from data from the Peruvian glacier inventory. The snowline altitude distribution and its determining climatic conditions provide a climatic reference situation for estimating climate change from the altitude difference between current and paleo-snowlines. From the situation in the Eastern Cordillera where, owing to high annual precipitation, the snowline is located close to the annual 0 °C isotherm, it can be inferred that a snowline depression can only be the result of a temperature depression because an increase in precipitation cannot lower the snowline considerably. The situation in the Western Cordillera is different. Here the snowline is located ~400 m (at Nevado Sara Sara) to up to ~800 m (at Nevados Coropuna and Sabancaya) above the annual 0 °C isotherm due to low annual precipitation. A snowline depression can therefore result from a temperature depression or a precipitation increase or a combination of both. Similar Pleistocene snowline depressions in the Eastern and Western Cordillera, assuming their simultaneity, would therefore indicate a temperature depression as their cause while the general atmospheric circulation and precipitation pattern must have been similar than today. Lesser snowline depressions in the Western Cordillera than in the Eastern Cordillera would indicate increased aridity in the Western Cordillera i.e. a greater precipitation gradient between Eastern and Western Cordillera as proposed e.g. by Fox (1993). However, a larger snowline depression in the Western Cordillera than in the Eastern Cordillera may also be possible, indicating wetter conditions in the Western Cordillera that would have to be explained by moisture transport from the Pacific, requiring a different circulation pattern from the present.

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BERICHTE UND MITTEILUNGEN

BODENTEMPERATUREN INNERHALB UND AUSSERHALB BEWALDETER UND UNBEWALDETER BLOCKHALDEN IN DEN BOLIVIANISCHEN HOCHANDEN

Ein Test der Hypothese von WALTER und MEDINA (1969)

Mit 4 Abbildungen, 2 Photos und 1 Tabelle

MICHAEL KESSLER und STEFAN HOHNWALD

Summary: Soil temperatures inside and outside forested and treeless boulder slopes in the Bolivian high Andes. A test of the hypothesis of WALTER and MEDINA (1969)

In the northern and central Andes, isolated forest patches dominated by *Polylepis* (Rosaceae) occur at elevations of up to 1000 m above the closed timberline, in many cases growing on boulder slopes. WALTER and MEDINA (1969) proposed (a) that soil temperature determines the upper timberline in tropical mountains and (b) that boulder slopes have higher soil temperatures than fine-grained soils because the open structure of the boulder slope permits warm air to penetrate deeper into the soil, thus allowing trees to grow there. We tested these hypotheses by measuring soil temperatures in 5 cm and 12,5–17,5 cm depth at three sites in forested and treeless boulder areas and in adjacent unforested fine-grained soil at 4050 m a.s.l. in the Zongo Valley, La Paz, Bolivia, in 1995 and 1996. We found that minimum, maximum and average soil temperatures are about 2°C lower within the forested boulder slope and about 1°C lower within the unforested boulder slope than in adjacent fine-grained soil, thus rejecting the hypothesis of WALTER and MEDINA. This suggests that the restriction of *Polylepis* patches to boulder slopes above the present-day forestline is due to anthropo-zoogenic causes (burning and grazing). While our results do not provide decisive data to judge whether soil temperature is the limiting factor at the Andean timberline, they show that forest can grow at average soil temperatures of 4–5°C (and less than 3°C over periods of several months), which are lower than the limiting value of 7–8°C proposed by WALTER and MEDINA.

Zusammenfassung: In den nördlichen und zentralen Anden finden sich bis zu 1000 m oberhalb der geschlossenen Waldgrenze von *Polylepis* (Rosaceae) dominierte Wäldchen, die häufig auf Blockhalden stocken. WALTER u. MEDINA (1969) vermuteten (a), daß Bodentemperaturen die Waldgrenze in den tropischen Anden bestimmen und (b), daß Blockhalden höhere Bodentemperaturen als feinkörnige Böden haben, da ihre offene Struktur das Eindringen von warmer Luft bis in größere Bodentiefen und somit das Baumwachstum ermöglichen. Wir haben diese Hypothesen durch Messungen der Bodentemperatur in 5 und 12,5–17,5 cm Bodentiefe an drei Stellen in bewaldeten und unbewaldeten Blockhalden sowie in angrenzendem Feinboden auf 4050 m üNN im Zongo-Tal, La Paz, Bolivien, getestet. Unsere Ergebnisse zeigen, daß Mittel-, Maximum- und Minimumtemperaturen in bewaldeten Blockhalden ca. 2°C, jene in unbewaldeten Blockhalden ca. 1°C unter denen des unbewaldeten Feinbodens lagen. Dies widerlegt die Hypothese der thermischen Begünstigung von Blockhalden von WALTER u. MEDINA und deutet darauf hin, daß die Beschränkung von *Polylepis*-Gehölzen auf Blockhalden v. a. auf anthropo-zoogene Faktoren (Brand und Beweidung) zurückzuführen ist. Zur Hypothese der Bodentemperatur als begrenzendem Faktor an der andinen Waldgrenze konnte keine abschließende Aussage gemacht werden.

1 Einleitung

Aus allen tropischen Gebirgen sind oberhalb der geschlossenen Waldgrenze isolierte, von Páramo- oder Puna-Grasland umgebene Gehölze bekannt (TROLL 1959; MIEHE u. MIEHE 1994; ELLENBERG 1996). In den nördlichen und zentralen Anden reichen diese meist durch *Polylepis* (Rosaceae) gebildeten Wäldchen bis auf über 5000 m üNN hinauf (JORDAN 1983). Das auffällige Vorkommen dieser „höchststeigenden Bäume und Gehölze der Welt" (TROLL 1959) in den ansonsten oberhalb von 3500 (3000–3800) m üNN baumfreien Gebirgsregionen hat seit jeher Botaniker und Geographen vor die Frage nach den Ursachen für das isolierte Vorkommen dieser Waldstücke gestellt.