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RECENT GLACIER DISTRIBUTION AND PRESENT CLIMATE IN THE CENTRAL ANDES OF SOUTH AMERICA

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With 4 figures and 1 map supplement

SUMMARY

The uniform triangulation of the whole glacierized area of the Eastern Cordillera of Bolivia provided the first comparable geometric basis for an accurate photogrammetric height evaluation of glaciers in the mountain range from the far south up to the Peruvian border.

A total of 1775 glaciers, larger than 0.1 ha, were recorded in 16 mountain ranges of the Eastern Cordillera. Snow lines in the outer tropics can now be analysed with an accuracy of European standards. In spite of the widemeshed network of meteorological stations this allows a more precise climatic differentiation to be made, particularly at high altitude sites. The methods and results of the analysis are described. Because of these results it becomes necessary to revise and refine previous concepts of the spatial distribution of climatic phenomena.

Characteristics of glaciers in the Bolivian Cordillera obviously depend on the NE to SW decline in precipitation. The snow lines which are found at an altitude of 4500 m on the northeastern slope directed towards the Yungas climb up to 5200 m on the lee slope towards the Altiplano. The N to S increase in snowline elevation is not as significant as expected. With some reservation a 100 m fall in the snowline elevation in the Bolivian Cordillera can be explained by an increase in precipitation of about 50 mm.

DIE REZENTE GLETSCHERVERTEILUNG UND DAS HEUTIGE KLIMA IN DEN ZENTRALEN ANDEN SÜDAMERIKAS

ZUSAMMENFASSUNG

Für die gesamte vergletscherte Ostkordillere Boliviens wurde durch eine erstmalige und einheitliche Aerotriangulation eine vergleichbare geometrische Grundlage geschaffen, die photogrammetrische Höhenbestimmungen aus Luftbildern mit Genauigkeiten von wenigen Metern über die gesamte Kordillerenlängserstreckung von den südlichsten tropischen Gletschern bis über die nördliche Landesgrenze nach Peru hinein zulassen.

In der Ostkordillere gibt es 1775 Gletscher von mehr als 0,1 ha Eisausdehnung bei insgesamt 577,4 km^2 Gesamtfläche, die sich auf 16 Gebirgskomplexe verteilen.

Es besteht damit für den randtropischen Gletscherbereich die Möglichkeit, Aussagen über Grenzlinienverläufe mit europäischem Genauigkeitsstandard zu treffen, die bei dem weitmaschigen Klimastationsnetz dieser Gebirgsregion eine genauere klimatische Differenzierung besonders der Höhenbereiche zuläßt. Die Methoden und Ergebnisse der Bearbeitung werden dargelegt. Nach dieser Analyse ist eine Revision und Verfeinerung bisher bestehender Vorstellungen der räumlichen Verteilung von Klimaerscheinungen und der Zusammenhänge mit Gletschermerkmalen in der bolivianischen Ostkordillere notwendig, die eine eindeutige Abhängigkeit vom NO—SW-gerichteten Niederschlagsgefälle zeigen.

Die bis auf 4500 m tief liegenden Schneegrenzen am NO-Abfall zu den Yungas steigen auf über 5200 m im Lee zum Altiplano hinauf, während sich der großräumig vom Äquator zu den Wendekreisen erwartete Anstieg im N—S-Verlauf überraschenderweise nicht so signifikant ausprägt. Mit einigem Vorbehalt werden etwa 100 m Schneegrenzabsenkung in der bolivianischen Ostkordillere auf eine Niederschlagserhöhung von ca. 50 mm zurückgeführt.

LA DISTRIBUCIÓN DE GLACIARES RECIENTES Y EL CLIMA ACTUAL EN LOS ANDES CENTRALES DE SUDAMÉRICA

RESUMEN

Se elabaró una base geométrica comparable por la primera y homogénea triangulación aérea de toda la Cordillera Oriental de Bolivia cubierta de glaciares, la cual permite la determinación fotogramétrica de la altura de fotos aéreas con una exactitud de pocos metros sobre toda la extensión de la cordillera del límite sur de la distribución de glaciares en las zonas trópicas hasta más allá de la frontiera con el Perú.

Del análisis de todos los glaciares de Bolivia resultó que en la Cordillera Oriental existen 1775 glaciares de más de 0,1 hectáreas de extensión de hielo de una superficie total de 577,4 km^2, distribuidos en 16 macizos de montañas.

Con esto existe la posibilidad de determinas las lineas de nieve de la región glacial de los márgenes de los trópicos con un standard de exactitud europeo, la cual permite una exacta diferenciación climática especialmente de las zonas altas bajo la condición de una red de estaciones climáticas muy amplia en esa región montañosa. Los métodos y resultados del trabajo son explicados. A base de eso es necesario una revisión y un perfeccionamiento de las ideas existentes hasta ahora de la propagación regional de fenómenos climáticos y sus relaciones con síntomas glaciales en la Cordillera Oriental boliviana los cuales tienen una dependencia clara de la disminución de precipitaciones dirigidas de noreste a suroeste.

Las lineas de la nieve estando situados hasta 4500 metros en el declive noreste hacia las yungas suben hasta más de 5200 metros en el sotavento hacia el altiplano, mientras la esperada ascención de grandes espacios del ecuador hasta el trópico no es tan significante. Con unas reservas se puede decir que aproximadamente 100 metros de descenso del límite de las nieves en la Cordillera Oriental boliviana son causados por un aumento de precipitaciones de más o menos 50 milímetros.

1. INTRODUCTION

The Central Andes of Bolivia, where the shift from abundant glaciation in the outer tropics to its total absence in the subtropics takes place under constant orographic conditions, are used for an investigation of the correlation between recent glaciation and climatic features. The only reason for glacial retreat in this zone is the reduction in cloudiness and precipitation, whereas the latitudinal change of insolation is not significant and should cause lower temperatures and, therefore, greater glaciation in the south (see fig. 1).

The literature about tropical glaciers shows that existing regional comparisons in the Andes, based on data of barometric accuracy and varying reference standards, lead to unsatisfying and often almost speculative interpretations (Jordan 1982). Also previous records of glaciers for practical use (e. g. potable water, industrial water, and power production; Jordan 1978, 1978/79, 1983), and previous examinations of glacier extent as a function of climatic conditions are quite frequently useless. An attempt was made therefore to draw up an inventory of the Bolivian glaciers as a more precise basis for further investigations (Jordan et al. 1980). In this context, the rapid progress of

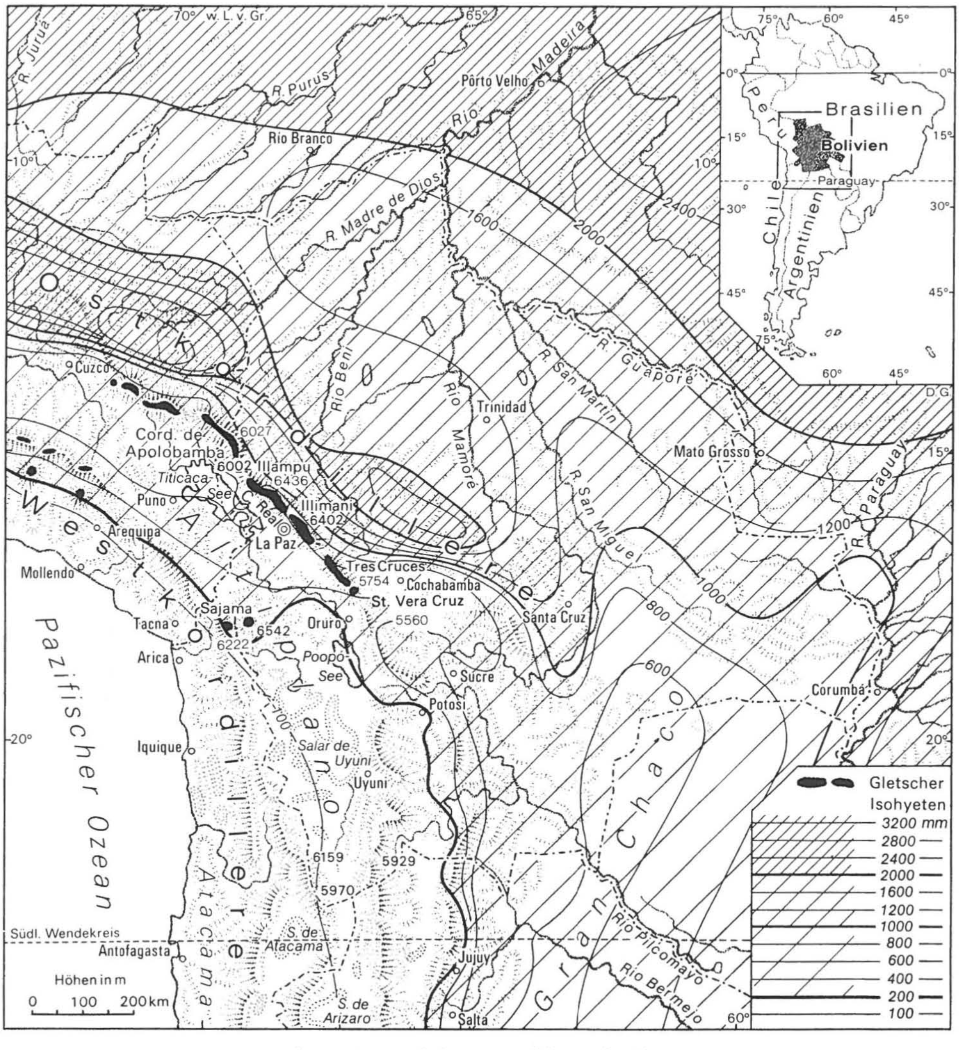

Fig. 1: Map of the area of investigation

photogrammetry and especially aerotriangulation, during the last decade opened up new possibilities, particularly in impassable terrain.

2. METHODS

In collaboration with Dr. Ing. Jacobsen (Institute for Geodesy, Hannover) the geometrical basis for a precise survey of aerial photographs for the entire Eastern Cordillera of Bolivia was set up (Jacobsen 1980), technical details of which are given by Jordan and Kresse (1981), Mohl (1982), Schwebel (1984), Schwebel and Mohl (1984).

Table 1: The Glacier Areas of the Southern Central Andes as of June 1984

Locality		Latitude (S)	Longitude (W)	Area (km²)	Number of Glaciers	Highest Elevation (m)	Lowest Glacier Tongue (m)
1.	Cordillera Oriental	14° 37′—17° 04′	67° 13′—69° 14′	577.412	1775	6436	4311
1.1	Cordillera de Apolobamba	14° 37′—15° 04′	68° 58′—69° 14′	220.696	651	6027	4311
	Chaupi Orco Region	14° 40′	69° 10′	132.914	350	6027	4365
	Cololo Region	14° 50′	69° 06′	41.815	126	5774	4311
	Ulla Khaya Region	15° 00′	69° 03′	45.967	175	5669	4435
1.2	Cordillera de Muñecas	15° 20′—15° 38′	68° 33′—68° 55′	0.684	9	5237	4828
	Amarete Region	15° 20′	68° 55′	0.148	6	5156	4828
	Chuchu Region	15° 38′	68° 33′	0.536	3	5237	4886
1.3	Cordillera Real	15° 45′—16° 40′	67° 40′—68° 34′	317.162	919	6436	4420
1.3.1	Northern Cordillera Real	15° 45′—16° 20′	68° 01′—68° 34′	260.206	749	6436	4420
	Illampu-Ancohuma Region	15° 50′	68° 33′	102.814	150	6436	4620
	Calzada-Chachacomani Region	16° 00′	68° 20′	94.189	251	6127	4676
	Nigruni-Condoriri Region	16° 08′	68° 13′	36.716	164	5648	4420
	Saltuni-Huayna Potosi Region	16° 15′	68° 08′	14.279	50	6088	4804
	Chacaltaya-Zongo-Cumbre Region	16° 18′	68° 05′	12.208	134	5519	4578
1.3.2	Southern Cordillera Real	16° 18′—16° 40′	67° 40′—67° 58′	56.956	170	6402	4499
	Hampaturi-Taquesi Region	16° 26′	67° 52′	11.694	70	5546	4723
	Mururata Region	16° 30′	67° 47′	15.939	70	5869	4637
	Illimani Region	16° 38′	67° 44′	29.323	30	6402	4499
1.4	Tres Cruces (Quimsa Cruz)	16° 47′—16° 59′	67° 22′—67° 32′	36.645	180	5754	4708
	Choquetanga Region	16° 52′	67° 25′	6.580	22	5541	4812
	Main region of Tres Cruces	16° 54′	67° 27′	30.065	158	5754	4708
1.5	Santa Vera Cruz	17° 03′—17° 04′	67° 13′—67° 14′	2.225	16	5560	4853
2.	Cordillera Occidental	18° 03′—18° 25′	68° 53′—69° 09′	13		6542	5100
2.1	Nevado Condoriri	18° 03′	69° 05′	2		5762	5300
2.2	Sajama	18° 06′	68° 53′	4		6542	5100
2.3	Nevados Payachata	18° 09′	69° 09′	5		6222	5300
2.4	Nevado Quimsa Chata	18° 23′	69° 03′	2		6032	5300

After almost 10 years of work, 1775 glaciers, each more than 0.1 ha in 16 mountain ranges were recorded in the Eastern Cordillera with a total surface of 577.4 km^2 (see table 1).

In comparison with European glacier inventories (Patzelt 1980, Gross 1983, Müller et al. 1976, Vivian 1975, Vivian and Edouard 1978) considerably smaller glaciers are predominant, which is not a consequence of climatic conditions, but of the terrain. The ratio of the number of glaciers to total glacier surface increases from the Western Alps with 1.36 to the Eastern Alps (1.71) to the Central Andes (2.4). This emphasises the predominance of small glaciers in the outer tropics.

The strong effect of surface features on glacier formations in the Andes has to be taken into consideration in any climatic interpretations of the data from these tropical glaciers. This had already been pointed out by Kinzl (1935a, 1935b, 1937, 1942, 1949, 1968) for Peru and was recently confirmed by Kuhn (1981).

Considering the papers of Hoinkes (1970), Gross et al. (1977), Slupetzky (1974), and Heuberger (1980), the application of the snowline or average equilibrium line, as a characteristic parameter for indicating the present climate, surely need not be justified for the tropics as well. Nevertheless, the determination of this equilibrium line in the Central Andes turns out to be much more difficult: Although fig. 2 shows subdivision of several years between the firnline and the firn edge at a glacier in the marginal tropics as perfectly as the ablation patterns known from the Alps (Slupetzky 1971), this originated only from rare meteorological circumstances and therefore does not show a

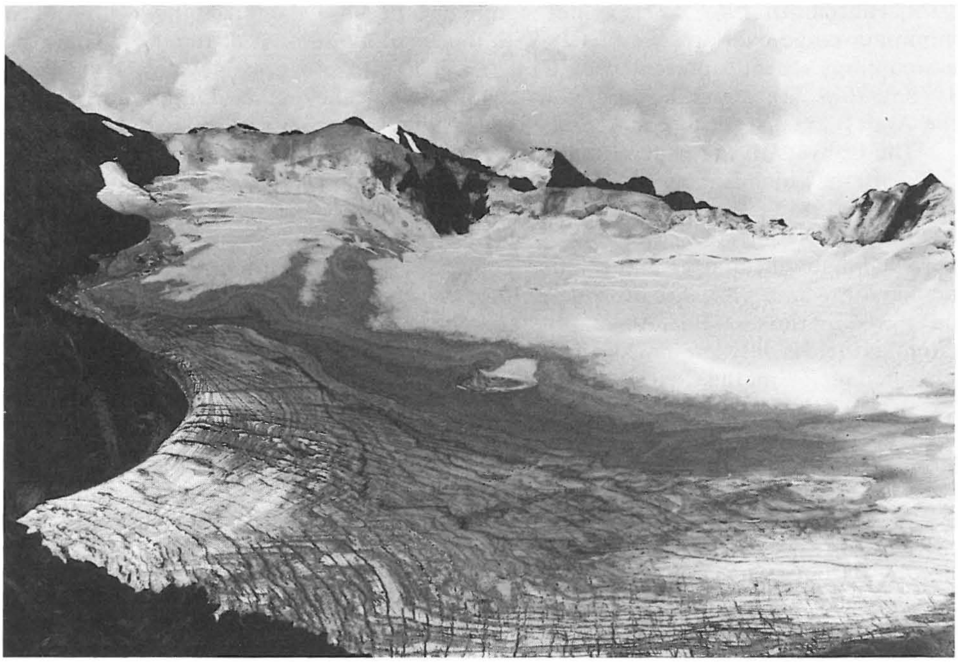

Fig. 2: Ablation patterns of a west-facing glacier at the Huayna Potosi (UTM N-8202000, E-589000, 68° 10′ W, 16° 15′30″ S). Photo: E. Jordan, 22-12-1980, about 5400 m altitude

state of ablation occurring every year. The acyclic regime of glaciers in the marginal tropics has already been mentioned (Jordan 1979). It presents great difficulties for the planning of aerophotographic flights and causes considerable restrictions on the interpretation of the material.

Because of the strong influence of topography on glaciation, the accumulation area ratio of 0.66, determined for the Eastern Alps, rarely applies in the Central Andes. For the same reason the application of the approach adopted by Lichtenecker raises problems, which are even more difficult to solve as the outcome of the lateral moraines often depends on the insolation and may differ considerably for a single glacier — differences in altitude of about 500 m at larger glaciers are no exception.

In order to compare the regional course of the glacier snowline and to derive the best approximation of the equilibrium line, only smaller glaciers with lesser vertical extent have been chosen to record the mean glacier elevation within the meaning of center of gravity (Müller 1977, Müller 1978). On the other hand, the distribution of smaller glaciers is extremely dependent on terrain and exposition. Hence, other parameters were taken into consideration such as azimuth and elevation angle of the shadowing, which are easily recorded with the help of the stereoanalyser.

3. RESULTS

The present evaluation showed unexpectedly that the southward increase in the snowline deviation in the Eastern Cordillera (Herzog 1931, Hermes 1965, Heuberger 1974, Hastenrath 1967, 1971) is not significant, because the variability within each mountain range overlaps completely with the small meridional differences. Thus, the assumptions recently presented by Graf (1975, 1981 p. 67), and Nogami (1968, 1970, 1972, 1976 p. 72), cannot be verified by any glaciological evidence. Orographic rains at the Andes' knee seem to counterbalance the inland position of the Santa Vera Cruz.

The isohyets in the general map (fig. 1), reflect only roughly the actual precipitation pattern, which is determined by summer NE to E winds (Kessler 1963, 1974, 1981; Monheim 1981). Because of missing or unreliable meteorological stations (Sheriff 1979), a precise differentiation can only be achieved by phytogeographical studies. As macroclimatic differences in insolation and temperature are directly related to cloudiness and precipitation, it is possible to infer the small scale precipitation pattern from an analysis of the snowline. Absolute values of precipitation, however, can only be speculative, as there is only one meteorological station with a 6-years precipitation record in the glaciated region on the Chacaltaya, at an altitude of 5220 m (Jordan 1979 p. 307).

Because of the extent of the Eastern Cordillera's glaciation and the wealth of data only one characteristic mountain group will be selected (see map 1), which demonstrates the correlations with general validity. Table 1 and map 1 may give an overall view of the distribution of glaciers in Bolivia.

All the wider mountain systems show a clear ascent in the snowline elevation from the Yungas up to the Altiplano, which means from NE to SW, modified only by the terrain. At the Cololo the change is about 700 m in a distance of 15 km. The ascent does not take place abruptly at the main divide, although it is more pronounced there. In addition, irregularities are evidently connected with higher frequency of cloud cover which tends to lower the snow line. In the case of the Cololo, one pass which is oriented towards the equator is free of ice, whereas another pass at almost the same altitude, but experiencing greater cloudiness is glacierized (fig. 3).

Fig. 3: Northern part of the Cololo Massif in the Cordillera Apolobamba, looking toward the NE. The gentle slopes in the foreground are orientated towards the Altiplano. In the background the steep, deep-shaped tributary valleys of the Amazon; here the Pelechuco Valley. Photo released by the IGM, La Paz, Bolivia. Trimetrogon-flight by USAF, 10 August 1948. Position: UTM N-8358000/E-485000, 14° 50′ S, 69° 06′ W

4. CONCLUSIONS

With these facts the concept of glaciers ending at greater altitude in the east than in the west, which had originally been put forward by Hauthal (1911, p. 117/118), and later supported by Herzog (1913a, 1913b, p. 194/195), and Troll (1929b, 1940, 1942, 1949) seems to be no longer tenable. Nevertheless, a slight modification and more precise definition of terms would maintain their concept, if they referred not to galciers on the eastern slope, but to glaciers with an easterly aspect. In relation to their neighbourhood these glaciers actually show higher snowlines, but given the impassable terrain, Hauthal, Herzog and Troll only could achieve these comparative observations. These conditions of almost glacier-free slopes (fig. 4), are the result of a mutual reinforcement of two factors.

1. The astronomical conditions of the sun: between 15° and 17° S the incidence of solar rays is from the north for ten months and from the south for only about 60 days. Additionally, the angle of incidence is very steep in the southern position which occurs at the time of the summer rains and the densest cloudiness of the year. In the course of the year therefore, places with a northern aspect receive the greatest amount of insolation.

Fig. 4: A mountain range at the Cumbre of the Cordillera Real in the NE of La Paz
Running from east to west the mountain chain between Unduavi Valley and Pajchiri Valley demonstrates the differences of glaciation determined by exposition in the marginal tropics. While the southern slopes are considerably glacierized, slopes facing north and north-east are almost free of snow and ice. Photo released by IGM, La Paz, Bolivia. Trimetrogon-flight by USAF, 10 July 1945. Position: UTM N-8195000, E-605000, 68° 01′ W, 16° 21′ S

2. The daily course of the sun, in connection with the development of cloudiness and generally steepest slopes in the NE towards the Yungas. The upper limit of clouds is regularly lowered to a little less than 4000 m during the night and only rises well after sun up (Troll 1929b, 1952, 1959). At the same time, the clouds in the deeply notched transverse valleys move in the direction of the lower passes of the Cordillera towards the Altiplano and cover the glacierized mountain tops. The particular time and the extension of cloudiness seem to depend on the relative humidity and clouds seem to appear earlier and be denser the greater the humidity in the eastern Yungas.

For slopes with an eastern to northern aspect this means high insolation at high altitude occurs just after sunrise — whereas in a north-westerly aspect it means a cover of clouds screening off insolation when the sun would be in a most favourable position. Slopes with southerly aspect also suffer from a loss of insolation through shadowing. This means a strong energetic disadvantage for the shade, as with increasing height above sea level the diffuse radiation diminishes (Weischet 1980, p. 93). Troll (1975, p. 193), already quoted a fraction of 5 % of diffuse radiation at an altitude of 4355 m for Mt. Evans/Colorado in contrast to 15—20 % at sea level. The level of the Bolivian glaciers is 1000 m higher.

Hence, for the glacierized regions of Bolivia, the following phenomena have to be distinguished clearly: On the one hand the development of glaciers which depends on the daily course of cloudiness, with highest snowlines in places with a NE aspect and lowest levels in places with a SW aspect, and on the other hand the course of snowlines, which by contrast show lowest levels in the NE towards the Yungas where rainfall amounts are highest whereas in the lee, towards the Altiplano (inland situation), less rainfall results in comparatively high glacier snowlines (cf. map 2).

Before closing this brief synopsis, the correlation of precipitation with snowline elevation in the tropics will be discussed: In the East and West of the Cololo we have data from a 5-year survey at our disposal, performed by one weather station each (Servicio National de Meteorologia e Hidrologia). Pelechuco, at the foot of the easternmost glaciers shows an average of 785 mm precipitation at an altitude of 3300 m, whereas Ulla Ulla, near the westernmost glaciers, has about 440 mm at an altitude of 4460 m. A direct correlation with the varying positions of the snowline suggests that an increase in precipitation of 50 mm is accompanied by a snowline depression of 100 m.

Following the pattern of precipitation at different altitudes in the tropics (after Weischet 1965 and 1969), this deduction seems realistic, at least in its order of magnitude. Results of a cross profile further south near the Chacaltaya, where at least one high altitude station can be included in the calculation, are quite similar.

Great variability in precipitation is characteristic of the semi-arid, seasonally humid tropics (cf. Mensching 1983a, 1983b). As Kessler has pointed out concerning the fluctuation in the level of Lake Titicaca, a period of dry years is often followed by a series of years with high precipitation. The mass balance of glaciers seems to experience similar fluctuations. Thus, with a glacier regime as dependent on precipitation as is the case here, the demand for an increase in rainfall of more than 30 % during the latest glacial high-level period of the Lake Tauca (12,500—11,000 BP) easily can be met (Kessler 1985, this volume). In addition these results are in good agreement with the findings by Stingl and Garleff (1985, this volume), concerning changes of precipitation at glaciers at the southern border of the subtropical arid belt.

The consequence of these results for Holocene and present-day glacial flow will be shown in a continuation of this paper (Jordan 1984b).

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