Changes of the equilibrium line altitude in the tropical Cordillera Blanca (Perú) between 1930 and 1950 and their spatial variations.

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Abstract

As on all Peruvian Cordilleras, the glaciers on the eastern slopes of the Cordillera Blanca extend to generally lower elevations than those on the western slopes. The mountain range of Santa Cruz - Pucahirca possesses the largest E-W extension within the Cordillera Blanca. A significant retreat of the glaciers between two quasistationary situations around 1930 and around 1950 was reconstructed from air photographs. The derived ELAs as well as the $\Delta ELA_{(1930 - 1950)}$ show spatial diversities. The pattern of the ELAs is caused by differences in both accumulation and effective global radiation. The change in $ELAs_{(1930-1950)}$ is partly due to a spatially uniform increase in air temperature. The remaining rise of the equilibrium line, which varies within different parts of the investigation area, has to be related to changes in precipitation and effective global radiation. Both correspond to changes in air humidity which is suggested to be an important factor on tropical glacier fluctuations. A model of superposed typical tropical circulation patterns of different scales and ELA-climate model based approaches is presented.

Introduction

The tropical Cordillera Blanca stretches 130 km from 8°30´ to 10° S and reaches the 6000 m level at several summits. The highest mountain is Nevado Huascarán Sur with 6768 m (Fig. 1).

The climate is typical for the outer tropics. It is characterized by relatively small seasonal, but large daily temperature variations and the alternation of a pronounced dry season (May - September) and a wet season (October - April). The wet season brings 70 to 80 % of the annual precipitation (Johnson, 1976; Kaser, Ames and Zamora, 1990; Niedertscheider, 1990). The hygric seasonality is caused by the oscillation of the Intertropical Convergence Zone ITCZ. As typical for the tropics, the precipitation processes are characterised by the combination of a large scale advection of humid air from the East (i.e. the Amazon river basin) and locally induced convective cells. The Cordillera Blanca is, in any case, a significant barrier in the easterly - southeasterly atmospheric circulation of tropical South America.

As on all Peruvian Cordilleras, the glaciers on the eastern slopes of the Cordillera Blanca extend to generally lower elevations than those on the western slopes. Kinzl (1942) was the first to suggest higher precipitation amounts in the east as a reason for lower snow lines. Modern snow lines or equilibrium line altitudes (ELAs) have never been studied. The present paper concentrates on the following problems across the Cordillera Blanca:

- How large are the spatial differences of the equilibrium line altitudes (ELAs)?
- How are the spatial differences of eventual fluctuations of the equilibrium line altitude (ΔELA)?
- What are the climatic causes for the spatial pattern of ELA and ΔELA?

For these investigations the massif of Santa Cruz - Alpamayo - Pucahirca was chosen. It is situated in the northern part of the Cordillera Blanca and its main ridge shows the largest E-W extension within the Cordillera Blanca (Fig. 1). Three short S-N running ridges subdivide the mountain group into six glacierized basins, i.e. Pucahirca East and West, Alpamayo East and West and Santa Cruz East and West (Table 1 and Fig. 2).

As a data base for this study a set of vertical air photographs taken in 1948 and 1950, respectively, (SAN project 2524) are available. They cover the entire massif under clear sky conditions, whereas more recent vertical air photographs from 1962 and 1970 respectively suffer from gaps in the chosen area. The glacier extent in 1948/50 as well as one indicated by the youngest moraines was drawn onto a 1:25000 contour line map (Dirección Generál de Reforma Agraria y Asentiamiento Rurál, 1972: map sheets Nevado Alpamayo, Yanacollpa, Nevado Pucaraju and Huaripampa) and analysed by using a Geographical Information System. The ELAs were obtained using the accumulation area ratio (AAR) method.

Climatic records are not available from the wet eastern side of the Cordillera Blanca and those of the western Rio Santa catchment basin only date back to 1949. Thus, climatological interpretations are made on the basis of an ELA - climate model.

Modern glacier fluctuations in the Cordillera Blanca

For many centuries, human activities in the Cordillera Blanca have been strongly linked to the glaciers both - in a useful (e.g. Kinzl, 1944) and a threatening (e.g. Lliboutry, Morales, Pautre and Schneider, 1977; Patzelt, 1983) way. Nevertheless, with the exception of a few descriptive reports glaciological investigations started not until the 1930s. Even then the investigations were frequently interrupted, mainly for political and economic reasons (a comprehensive overview of the glaciological investigations is given by Ames and Francou, 1995). The last survey of the entire glacial extent dates back to 1970 when air photographs were taken in the sequel of the destructive earthquake of 30.5.1970 (Patzelt, 1983). With a surface area of approximately 720 km^2 (glacier inventory 1970 by Ames et al., 1988), the glaciers of the Peruvian Cordillera Blanca represent more than 25 % of all tropical glaciers (Kaser, Hastenrath and Ames, 1995).

The knowledge of modern glacier fluctuations in the Cordillera Blanca is poor compared to the mid latitudes. The approximative variations of the glacial extent in the Cordillera Blanca are shown in Fig. 3. A Little Ice Age extent is marked by prominent moraines. The retreat from it began in the 1870s and accelerated after 1890 (Spann, 1948). A short readvance in the 1920s is reported by Kinzl (1942), Broggi (1943) and Spann (1948). It is indicated by fresh and small moraines in the 1948/50 air photographs. Only some limited observations were made by miners at Glaciar Atlante (Kinzl, 1942). After the advance it remained in its position between 1924 and 1927 and then started to retreat. In the Huascarán massif (Figure 1) the retreat began in 1931 (Broggi, 1943). In that massif the areal loss since the 1920s advance was determined by Kaser, Georges and Ames (1995). It amounts to -16% (59 km^2 versus 71 km^2) in 1950 and only additional -1.8% (58 km^2) in

1970 (1950 extension: Kaser and Georges, unpublished data). The glacier extent in 1962 as shown on the air photographs cannot be distinguished from that in 1970. After 1970 the measured variations of selected tongues give the only information about the most recent glacial fluctuations. Two of them, Glaciar Yanamarey and Glaciar Uruashraju in the southern Cordillera Blanca (Figure 1), show a minor advance between 1974 and 1979, Glaciar Broggi a halt in retreat. After 1979 all of them were retreating markedly (Kaser, Ames and Zamora, 1990; Ames and Francou, 1995).

Both glacier extents (1930 and 1950) which were determined for the Santa Cruz - Pucahirca range represent quasistationary situations and make, therefore, a climatological interpretation possible. The earlier one is characterized by a short advance ending around 1930. Assuming similar behaviour as on Huascarán, the later one was reached around 1950 and dit not change markedly until the 1980s. The areal loss in the Santa Cruz - Pucahirca massif amounted to -10 % from 93.7 km^2 in 1930 to 84.2 km^2 in 1950 (Table 1).

The principal behaviour of tropical glaciers

The mass balance regime of outer tropical glaciers is described by Kaser, Hastenrath and Ames (1995). Mass accumulation takes place only during the wet season and predominantly in the upper parts of the glaciers, whereas ablation occurs throughout the whole year. Thus, the vertical budget gradient is much stronger on tropical tongues than on those in the mid latitudes (Lliboutry, Morales and Schneider, 1977; Kaser, Hastenrath and Ames, 1995). Consequently, under equilibrium conditions, tropical ablation areas are markedly smaller and the accumulation area ratio AAR has to be considered larger than in the mid latitudes (Kaser, 1995). Since detailed studies on low latitude AARs are missing, we assume a mean value of AAR = 0.75 for the Cordillera Blanca.

Little is known about the response time of Cordillera Blanca glaciers. However, compared with mid latitude glaciers, the strong vertical budget gradients cause a quite immediate reaction of glacier tongues to a rise of the ELA (Kaser, 1995).

The application of the AAR method

Under certain conditions a mean ELA of a stationary glacier or a glaciated area can be determined by the application of an accumulation area ratio to the hypsographic curve (Kerschner, 1990). Within the altitudinal range of possible ELAs (a) the growth of surface area with altitude must have its maximum and (b) the hypsographic curve must be linear. This is rarely the case on single glaciers, but if one looks at a glaciated basin or an entire mountain massif as a whole, the boundary conditions are met quite well. This is the case in all six glacierized basins of the Santa Cruz - Pucahirca range (Fig. 4). Deviations from the above mentioned AAR of 0.75 may affect the absolute positions of the ELAs to a certain extent, but have only a minor effect on the determination of their vertical shift (ΔELA) between two stationary situations. The ELAs for 1930 and 1950 as well as the vertical shift $\Delta ELA_{(1930-1950)}$ for the six basins are shown in Table 2.

The spatial variation of the ELAs

The spacial pattern of the ELAs (Table. 1 and Fig. 5) shows for both situations (1930 and 1950) that:

- the ELA´s are lowest on Nevado Pucahirca and highest on Nevado Santa Cruz; but,
- Alpamayo as well as Santa Cruz have the higher ELAs on their eastern slopes.

The reasons for this ELA pattern can be explained by peculiarities to the atmospheric circulations in the tropics:

(a) Humid air is almost exclusively advected from the east and thus, convective activity decreases to the West (Fig. 6). Consequently, the accumulation decreases from the East to the West as well and is, therefore, one reason for the tendency of ELAs to rise from the east to the west. Precipitation measurements from the inner Cordillera Blanca and their eastern slopes are missing, but large scale gradients hold to be true. The gradient between Tingo Maria (φ = 09°08´S, λ = 75°57´W) and Chiclayo (6°47´S, 79°50´W) is more than 3000 mm (Johnson, 1976).

(b) A superposed diurnal convective circulation system - where convective clouds are better developed in the afternoon - causes a zonal asymmetry in the radiation balance on these mountains and, therefore, also in the ablation conditions of its glaciers (Fig. 7). This leads to generally higher ELAs on eastern slopes of these mountains and lower positions on the western slopes. This is also typical for other tropical mountains (Troll, 1942; Troll and Wien, 1949; Hastenrath, 1991).

The influence of (a) decreases from the East to the West giving more and more weight to the influence of the daily circulation (b). Whereas (a) explains the rise of the ELAs from the East to the West in general as well as on the easternmost Nevado Pucahirca, (b) is responsible for the inverse asymmetry on the Nevados Alpamayo and Santa Cruz in the western part of the massif.

Due to missing climatic records these hypotheses cannot be directly checked. Therfore, an approximation shall be made by estimating values of climatological variables which could explain the respective spatial differences of the ELA. The ELA-climate model by Kuhn (1989) is used to calculate alternative simplified climatic changes compatible with the observed fluctuation of ELA. The particular constants and variables for the Cordillera Blanca are discussed in Kaser, Georges and Ames (1995). The results obtained for 1930 are shown in Table 3.

The required differences in accumulation of up to almost 3000 mm seem obviously too high. Annual precipitation on the western slopes of Cordillera Blanca at 5000 m a.s.l. is estimated to approximately 1200 mm (Niedertscheider, 1990), the highest values east of the Cordilleras reach approximately 3000 mm (Tingo Maria, 665 m a.s.l.: 3072 mm; Johnson, 1976).

Additionally, differences in effective global radiation mainly due to different degrees of cloudiness can be taken into account. If we consider a mean daily effective global radiation of approximately 15 MJ m^{-2} d^{-1} (Wagner, 1979) which is the July mean value for Hintereisferner, Austria, the 2.7 MJ m^{-2} d^{-1} required for Santa Cruz East are 18% of that value. The altitude of the sun at Hintereisferner (47°N) in July is close to the mean value for the dry season in the Cordillera Blanca (9°S). The combination of these two variables, precipitation and effective global radiation, can explain both the pattern and the amount of spatial differences of ELAs.

The $\Delta ELA_{(1930-1950)}$, its spatial variations and possible causes

Table 1 and Figure 5 also show the shift of the mean ELA between the two quasistationary situations ($\Delta ELA_{1930 - 1950}$). The shift is again not homogeneous and shows spatial differences similar to those of the ELAs:

- the values increase generally from the East to the West;
- on Alpamayo and on Santa Cruz the ΔELA is larger on their eastern slopes.

Assuming that possible secular changes in air temperature on a mesoclimatological scale are widely homogeneous in space, they cannot hold for the explanation in this case.

It is suggested that a reduction in air humidity and ist effect on the above mentioned atmospheric circulation system is the main reason for the determined retreat of the glaciers between 1930 and 1950. It influences the mass balance in various respects. It causes a general reduction of precipitation amounts mainly during the wet season and therefore a decrease in accumulation. A reduction of the convective clouds increases the incoming global radiation and, consequently, the ablation mainly in the afternoon and, therefore, on the western slopes. This effect is most significant during the dry season, and obviously the basins which are already drier, react more sensitively to a disturbance in air humidity (Table 2). Even more complex feedbacks to sublimation and lapse rates may be expected, but cannot be quantified.

Again, climatological records for proving the cause for different $\Delta ELAs_{(1930-1950)}$ are not available and only a quantitative approximation can be offered (Table 4). The rise of the ELA due to a change in air temperature has to be considered uniform in space. This is esecially valid for the climate in the tropics which is, in contrast to the mid latitudes with the travelling synoptic patterns of different air masses, determined by homogeneous air mass characteristics. Thus, only a „basis“ value of the obtained $\Delta ELAs_{(1930-1950)}$ - i.e. the lowest value on Pucahirca east (25 m) as a maximum - can be related to a change in air temperature. Following the ELA-climate model by Kuhn (1989), this would have to be 0.12°C which, in fact, corresponds well with the observed secular rise of 0.15°C in the tropics of the southern hemisphere between 1920 and 1945 (Hansen and Lebedev, 1987). The remaining part of $\Delta ELA_{(1930-1950)}$ is quite different for each of the six basins and has, therefore, to be forced by climatic parameters which can vary markedly within the investigation area. This is the fact with precipitation, global radiation, and sublimation which are all related to the air humidity. A quantitative estimation is shown for one example: 40% of the maximum value of $\Delta ELAs_{(1930-1950)}$ = 70 m at Santa Cruz east can be explained by the „basis“ rise due to an increase in air temperature of 0.15°C. An increase in effective global radiation of 0,375 MJ m^{-2} d^{-1} which is 2,5% of 15 MJ m^{-2} d^{-1} (approximate daily average, see above) plus a decrease in accumulation of 114 mm a^{-1}. This is less than 10% of the 1200 mm a^{-1} precipitation in 5000 m a.s.l. on the western slopes of Cordillera Blanca (Niedertscheider, 1990).

The quantitative approach proposes realistic values of a combination of changes in precipitation and effective global radiation. Eventual changes in sublimation, albedo of the glacier surface, and atmospheric lapse rate due to changes in air humidity are neglected. The highly significant correlation between global radiation and the retreat of Mt. Kenya glaciers (Kruss and Hastenrath, 1990) as well as the differential retreat of Speke glacier on Ruwenzori (Kaser and Noggler, 1991) indicate that changes in air humidity are generally important factors for tropical glacier fluctuations.

Conclusions

- As suggested before the ELA is lowest in the East of Pucahirca and increases generally towards the West (Kinzl, 1942) whereas the ELAs of of Santa Cruz and Alpamayo in the western part of the massif show an opposing trend. An E-W accumulation gradient and different amounts of effective global radiation are the probable causes. A superposition of a tropical diurnal circulation to the general advection of humidity from the Amazon river basin can explain this.

- A marked recession from one quasistationary situation around 1930 to a second one which started around 1950 took place.

- The rise of the equilibrium line $\Delta ELA_{(1930-1950)}$ shows different values across the Santa Cruz - Pucahirca massif. A combination of a spatially uniform rise in air temperature and a decrease in air humidity with spatially different effects has to be taken into account as a cause for the glacier retreat between 1930 and 1950.

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Tables

Table 1: The galciated surface area of the Santa Cruz - Pucahirca ridge in 1930 and in 1950 respectively.

	Santa Cruz		**Alpamayo**		**Pucahirca**	
	West	**East**	**West**	**East**	**West**	**East**
1930 [km^2]	16.0	8.7	12.1	11.0	20.3	25.8
1950 [km^2]	13.5	6.8	11.2	9.5	18.4	24.8

Table 2: The equilibrium line altitudes (ELAs) in 1930 and in 1950 and their shift ($\Delta ELA_{1930-1950}$) across Santa Cruz - Pucahirca ridge, Cordillera Blanca, Perú under the aspect of exposure [m].

	Nev.Santa Cruz		Nev. Alpamayo		Nev. Pucahirca	
ELA$_{1930}$	5051		5015		4894	
ELA$_{1950}$	5109		5056		4928	
ΔELA_{30-50}	*58*		*41*		*34*	
	West	East	West	East	West	East
ELA$_{1930}$	5014	5118	4981	5053	4911	4882
ELA$_{1950}$	5068	5189	5019	5099	4958	4905
ΔELA_{30-50}	*54*	*71*	*38*	*46*	*47*	*23*

Table 3: Spatial differences in ELA$_{1930}$ *refering to Pucahirca east and alternatively requested values for differences in accumulation (*δc*) and effective global radiation (*δG*).*

	Santa Cruz		Alpamayo		Pucahirca	
	West	**East**	**West**	**East**	**West**	**East**
d ELA$_{(1930)}$ [m]	132	236	99	171	29	*0*
δc [mm a^{-1}]	-1634	-2921	-1225	-2116	-359	*0*
δG [MJ m^{-2} d^{-1}]	+1,49	+2,67	+1,12	+1,94	+0,33	*0*

Table 4: Spatial differences in ΔELA$_{1930-1950}$ *refering to Pucahirca east and alternatively requested values for differences in air temperature (*δt_a*) accumulation (*δc*), and effective global radiation (*δG*).*

	Santa Cruz		Alpamayo		Pucahirca		observed
	West	**East**	**West**	**East**	**West**	**East**	
ΔELA$_{(1930-50)}$ [m]	54	**71**	38	46	47	*23*	
δt_a [°C]	+0,29	**+0,38**	+0,20	+0,25	+0,25	*+0,12*	+0,15*
δc [mm a^{-1}]	-668	**-879**	-470	-269	-582	*-285*	
δG [MJ m^{-2} d^{-1}]	+0,61	**+0,80**	+0,43	+0,52	+0,53	*+0,26*	

** Hansen and Lebedeff (1987)*

Figure captions

Fig. 1: Index map of the Cordillera Blanca. Broken lines indicate the watershed of the Rio Santa basin, dotted areas indicate the glacier extension. A solid line surrounds the Santa Cruz - Pucahirca glaciers. Triangles show the chain of the highest summits. Circles indicate glaciers which the paper refers to.

Fig. 2: The six glacierized areas in Santa Cruz - Pucahirca range. Highest peaks are indicated. The cross section follows the line in the map.

Fig. 3: A qualitative approximation of the modern glacier fluctuations in the Cordillera Blanca. Arrows indicate two different quasistationary situations (after Georges, 1996).

Fig. 4: The hypsographic curves for the glacier extent in each basin and for the two quasistationary situations in 1930 and in 1950. Vertical broken lines mark the AAR = 0.75.

Fig. 5: ELAs in 1930 and 1950 and $\Delta \text{ELAs}_{(1930\text{-}1950)}$ in the six basins of the Santa Cruz - Pucahirca range.

Fig. 6: Schematic model of the superposition of advective and convective processes over the tropical Cordillera Blanca.

Fig. 7: Diurnal variations of cloudiness and the resulting asymmetry of the glacier extension on a tropical mountain (after Troll and Wien, 1949).