Bull. Inst. fr. études andines
1995, 24 (3): 671-681

SOME NOTES ON THE BEHAVIOUR OF TROPICAL GLACIERS

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Abstract

The fact of a relatively immediate inference of tropical glacier fluctuations on a climate originating from relatively homogenous air masses makes glaciological investigations in the tropics particularly important. One peculiarity of tropical climate is the lack of any appreciable thermal seasonality. Under this general aspect, two characteristic features of the glacier - climate relationship, (a) the sensitivity of the equilibrium line altitude (ELA) on climatic perturbations and (b) the corresponding reaction of glacier tongues are discussed in comparison to the Alpine conditions. The discussion is based on a modelled vertical budget gradient (VBG). Compared to midlatitude glaciers, the ELA reacts generally less sensitively, but more strongly if forced by a change in temperature. The tongues as well as small glaciers react sensitively on increasing ablation. The reaction on long term dynamic forcing is weak.

Key words: *Tropical glaciers, tropical climate, equilibrium line, mass balance.*

OBSERVACIONES SOBRE EL COMPORTAMIENTO DE LOS GLACIARES TROPICALES

Resumen

El hecho de que se pueda llegar en los Trópicos a una conclusión casi inmediata sobre la evolución climática a partir de las fluctuaciones glaciares, debido al carácter relativamente homogéneo de las masas de aire, confiere a los estudios glaciológicos en esas regiones una grande importancia. Una de las características del clima tropical es la ausencia de variación térmica estacional significativa. Bajo este aspecto general, se trata de dos aspectos de la relación clima-glaciar: a) la sensibilidad de la altitud de la línea de equilibrio glaciar (ELA) a cambios climáticos y b) la reacción correspondiente de la lenguas glaciares. Ambos aspectos son discutidos en comparación con las condiciones existentes en los Alpes. Se establece la discussión sobre un modelo de gradiente vertical del balance de masa (VBG). Comparada con los glaciares de las latitudes medias, la ELA reacciona en general de una manera menos sensible, pero responde más fuertemente a cambios de temperaturas. Las lenguas así como los glaciares pequeños reaccionan de una manera sensible a una ablación creciente. La respuesta a las influencias dinámicas de largo plazo son poco significativas.

Palabras claves: *Glaciares tropicales, clima tropical, línea de equilibrio, balance de masa.*

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QUELQUES OBSERVATIONS SUR LE COMPORTEMENT DES GLACIERS TROPICAUX

Résumé

Le fait qu'il soit possible sous les Tropiques de tirer des conclusions quasi immédiates sur le climat à partir des fluctuations des glaciers, en raison du caractère relativement homogène des masses d'air, rend les recherches glaciologiques dans ces régions particulièrement importantes. Une des caractéristiques du climat tropical est l'absence de variations thermiques saisonnières significatives. En tenant compte de ce fait, on évoque la relation climat-glacier sous deux de ses aspects : a) la sensibilité de la ligne d'équilibre (ELA) aux variations climatiques, et b) la réponse correspondante des langues glaciaires. On discute de ces aspects par comparaison avec les conditions rencontrées dans les Alpes. La discussion est fondée sur un modèle de gradient vertical du bilan de masse (VGB). Comparée avec les glaciers des latitudes moyennes, la ELA réagit généralement de façon moins sensible, mais cependant plus fortement à un changement de température. Les langues, comme les petits glaciers réagissent de façon sensible à une ablation croissante. Les réponses à des influences dynamiques à long terme sont peu significatives.

Mots-clés : *Glaciers tropicaux, climat tropical, ligne d'équilibre, bilan de masse.*

INTRODUCTION

While climate in the midlatitudes is an average of travelling synoptic patterns of different air masses, climate in the tropics is determined by homogenous air mass characteristics, and this allows more immediate inferences of glacier fluctuations on climate. Thus, the study of tropical glaciers is of particular interest within the context of global change. Out of a number of differently defined climatological delimitations for the tropical regions, the lines where the amplitudes of diurnal and annual range of temperatures are equal (Troll, 1943) emphasize one peculiarity of tropical climate: the lack of any appreciable thermal seasonality. These lines encompass, of course, approximately the Tropics of Cancer and Capricorn. The seasonal shifting of the Intertropical Convergence Zone (ITCZ) is responsible for the tropical hygric conditions featuring precipitation all year round with a tendency for double peaks in the annual cycle, whereas in the outer tropics a pronounced dry season is characteristic (Kaser *et al.*, 1995b).

Glaciers still exist in Irian Jaya, East Africa, on the Mexican volcanoes and in the South American Andes. Their total area is estimated at about 2,5 10^3 km^2 (Kaser *et al.*, 1995b), corresponding to 4,6% of the mountain glaciers and to 0,16% of the total ice cover of the world (WGMS, 1989). More than 70% of this is found in the Peruvian Andes.

The tropical climatic setting has the following consequences for the glacier mass budget: (a) accumulation is concentrated in the wet season; (b) accumulation occurs only above the approximately constant limit of snowfall; (c) ablation persists throughout the year; (d) ablation occurs mainly in the (annual mean) ablation zone. In contrast to the clear separation between the accumulation and ablation seasons in the Alps, in the tropics ablation occurs during the entire year, while accumulation may be either confined to one wet season in the outer tropics or continue throughout the year in the inner tropics (Kaser *et al.*, 1995b).

Under these general aspects two characteristic features of the glacier - climate relationship, the sensitivity of the equilibrium line altitude (ELA) to climatic perturbations and the corresponding reaction of glacier tongues shall be discussed in comparison to the well studied Alpine conditions in order to explain observed peculiarities of tropical glaciers. Whereas the position of the ELA is an immediate result of the mass budget and, therefore, of the weather and climatic situation, the extent and the position of a glacier tongue is caused by both the mass budget and the ice dynamics. Both aspects will be discussed by means of the vertical budget gradient VBG.

1. HOW DIFFERENT ARE TROPICAL FROM ALPINE GLACIERS?

Our knowledge of the behaviour of tropical glaciers is very limited compared with that of the midlatitude mountain glaciers in the Alps. Therefore, the possibilities for comparisons are limited.

Studies of the mass balance have a long series only on Lewis Glacier, Mt. Kenya (Hastenrath, 1984; 1991) and some short-time investigations have been done in different tropical mountain regions (Bergstrom, 1955; Whittow *et al.*, 1963; Hope *et al.*, 1976; Hastenrath, 1978; Kaser *et al.*, 1990; Hastenrath & Ames, 1995; Francou *et al.*, 1995a; 1995b; Kaser *et al.*, 1995b). Table 1 compares the specific mass balances of Lewis Glacier (0,25 km^2) with those of Hintereisferner (9,05 km^2) in the Austrian Alps. The year to year values are, of course, not synchronous but vary within the same order of magnitude with a tendency to higher values in both directions at the much smaller Lewis Glacier.

Table 1 - Specific mass balances in [mm we] of Lewis Glacier (L.G.), Mt. Kenya (Hastenrath, 1984; 1991) and of Hintereisferner (HEF), Austrian Alps (data base: Meteorological Inst., Univ. Innsbruck).

	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87	87-88	88-89	89-90	90-91	mean
L.G.	-70	-1750	-1210	-370	-720	-900	-950	-680	-770	-2300	770	-1010	-810	-828
HEF	-219	-50	-173	-1240	-581	320	-574	-731	-717	-946	-636	-996	-1325	-605

Generaly, long-term fluctuations of tropical glaciers were more or less synchronous with those of the midlatitude glaciers of both the northern and the southern hemisphere including the maximum extensions in the middle of the 19th and the beginning of the 20th century (*e.g.*: Messerli, 1980; Hastenrath, 1984; Grove, 1988). This tendency has also been proved for historical times by reconstructed and measured fluctuations of Lewis Glacier, Mt. Kenya (Patzelt *et al.*, 1984). Signs of thickening of the upper Lewis Glacier between 1963 and 1974 (Bhatt *et al.*, 1988) as well as small advances and stagnation of Ruwenzori glaciers in the 60s (Temple, 1968) and of glaciers in the Cordillera Blanca in the 70s (Kaser *et al.*, 1990) suggest even a certain synchronism with the last small advances of midlatitude glaciers.

Table 2 compares the relative recession in surface area of tropical and Alpine glaciers since the last maximum extents in the middle of the 19th and the beginning of the 20th century.

In the Cordillera Blanca (Perú) the smallest glaciers show a clearly stronger recession whereas the biggest glaciers lost much less area than Alpine glaciers of a comparable size. The reasons for the latter might be debris covered tongues and the difficulties to make out death ice on the airphotographs. The recession of Lewis Glacier, Mt. Kenya (East Africa) compares well with Alpine glaciers, the Irian Jaya (Indonesia) glaciers suffered from a generally higher recession, the recessions of Ruwenzori glaciers (East Africa) refer to a different period but indicate similar behaviour.

Table 2 - Relative loss of glacier surface area of tropical glaciers and the glaciers of the Austrian Alps.

classes[1] [km²]	*ÖA (n)[a] 1850-1969 [%]*	IJ (n)[b] 1850-1972 [%]	Lewis (n)[c] 1850-1974 [%]	*ÖA[a] 1920-1969 [%]*	CB (n)[d] 1920-1970 [%]	Lewis (n)[c] 1920-1974 [%]	RU (n)[e] 1906-1955 [%]
-0.15	*67.8 (85)*	78.2 (2)		*45.3*	73.4 (4)		58.0 (1)
-0.30	*60.3 (70)*	75.3 (2)		*41.5*	50.2 (3)		20.6 (1)
-0.50	*55.5 (52)*			*36.8*	35.7 (1)		14.8 (1)
-1.00	*52.4 (76)*	64.0 (1)	53.3 (1)	*35.1*	35.0 (4)	47.9 (1)	
-1.50	*44.4 (25)*			*29.8*	22.8 (2)		
-2.00	*42.6 (17)*	62.7 (1)		*28.1*			
-3.00	*40.2 (14)*			*26.4*	18.7 (6)		
-5.00	*33.9 (23)*	60.4 (1)		*22.4*	20.8 (3)		
-9.00	*29.2 (6)*			*20.4*	8.2 (4)		
>9,00	*23.0 (6)*			*14.1*			
total	*40.8 (374)*	64.2 (7)		*26.2*	18.0 (27)		

[1] most recent extension, i.e. ca. 1970; (n) number of glaciers; [a] Austrian Alps (Gross, 1987); [b] Irian Jaya (Allison, 1976); [c] Lewis Glacier, Mt Kenya (Patzelt *et al.*, 1984); [d] Cordillera Blanca, Huascarán - Chopicalqui massif (Kaser *et al.*, 1995a); [e] Moore, Elena and Speke Glacier, Ruwenzori (Kaser & Noggler, 1995).

Figure 1, showing the altitudinal extent between highest and lowest points of glaciers within three different tropical mountain ranges and one central Alpine catchment basin, draws the attention to a distinct difference between tropical and midlatitude glaciers.

Whereas Alpine glaciers show a clear symmetry between highest and lowest points, in the tropical Huascarán - Chopicalqui massif the different altitudes of glacier origins have almost no effect on the altitudes of the tongues. They end more or less all at the same elevation. Glaciers with small altitudinal extent (*i.e.* of course all small but also markedly flat glaciers like the two major Irian Jaya ice bodies) in both, the Alps and the tropics, scatter without any general trend. They reflect predominating local effects of relief, exposition and climate as discussed for example by Kruss & Hastenrath (1990) or Kaser & Noggler (1991).

The mean rise of the equilibrium line altitude in the Austrian Alps between 1850 and 1969 was $\Delta ELA = 94$ m (Gross, 1987). For the Huascarán - Chopicalqui massif a mean rise of $\Delta ELA = 95 \pm 5$ m between 1920 and 1970 was determined (Kaser *et al.*, 1995a). These values are well comparable since in the Cordillera Blanca the advance at the beginning of our century reached almost the same extension as the next previous maximum in the 19th century (Kinzl, 1942). Whereas these values were obtained by the accumulation area ratio (AAR) method, Allison & Kruss (1977) determined a well comparable value of $\Delta ELA = 96$ m between the maximum neoglacial extent (ca. 1850) and the 1970s for Carstenz Glacier, Irian Jaya, by numerical modelling.

However, the general fluctuations of tropical glaciers are not essentially different from those of Alpine glaciers, but in the tropics the tongues as well as the small glaciers and / or glaciers with a small altitudinal extension behave particularly different.

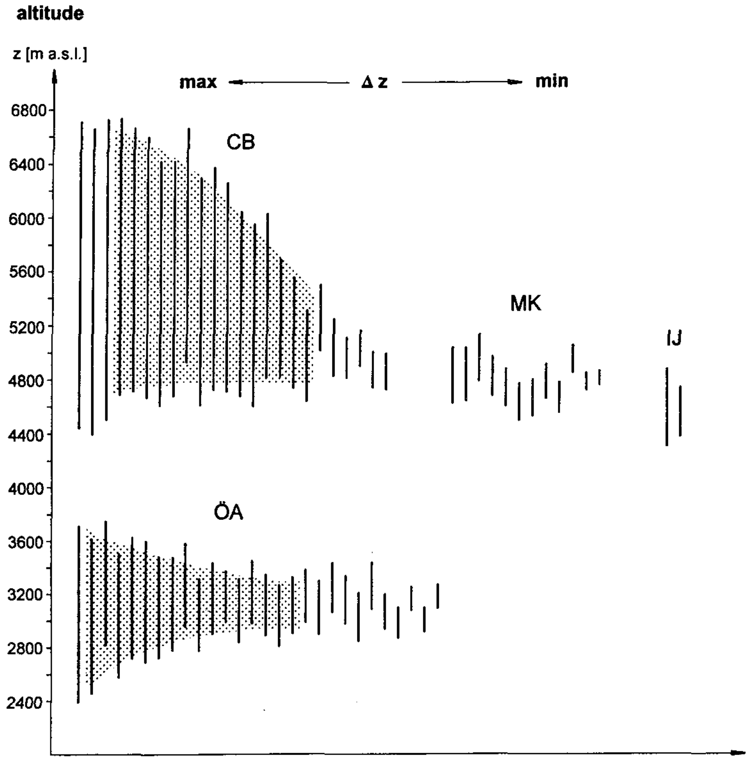

Fig. 1 - The altitudinal extension of glaciers between highest and lowest points within three different tropical mountain ranges [CB = Huascarán - Chopicalqui massif, Cordillera Blanca in 1970 (own analysis); MK = Mt. Kenya in 1963 (Hastenrath *et al.*, 1989); IJ = Meren and Carstensz Glacier, Irian Jaya in 1972 (Allison, 1976)] and a central Alpine catchment basin [ÖA = Niedertal- and Rofenache, Ötztal Alps in 1969 (Austrian glacier inventory, 1969)]. The altitudinal extensions of the single glaciers are arranged from the highest values on the left to the smallest on the right.

2. THE VERTICAL BUDGET GRADIENT (VBG)

Characteristic are much stronger vertical budget gradients (VBG = db/dz [mm we m^{-1}]) for tropical glaciers than for mid- and highlatitude glaciers (Kuhn, 1979; 1984). This can also be seen from the measured VBGs of the Alpine Hintereisferner and of three tropical glaciers in Figure 2.

The tongues of tropical glaciers suffer from by far higher ablation amounts, and the weak inclinations of the tropical VBGs indicate, in a first view, little sensitivity of the ELA on climatic perturbations. The main reasons for the differences in the shape of midlatitude and tropical VBGs are shown by Kaser *et al.* (1995b) in a simple model (Figure 2). The synthetic VBG of Hintereisferner - which is based on mean climatologiacal values assuming that the ablation at the summer 0°C-line occurs during 100 days per year - was shifted into simplified tropical conditions, *i.e.*: (a) the 0°C-line has no annual variations, and, therefore, (b) the ablation period lasts the whole year round *i.e.* 365 days per year; (c) the continuous ablation occurs on the entire ablation zone; (d) exclusively solid precipitation occurs only above the

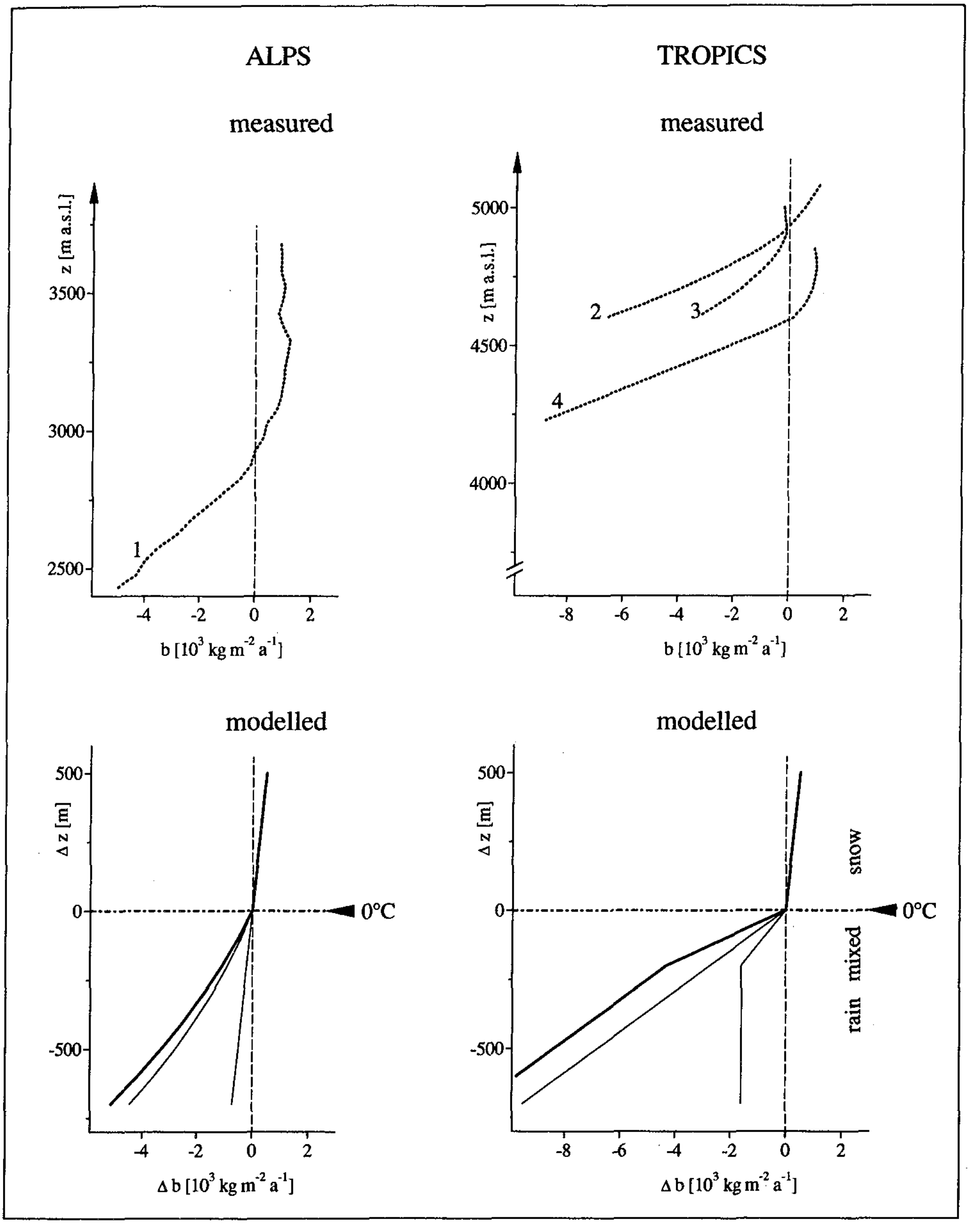

Fig. 2 - Measured and modelled vertical profiles of accumulation and ablation (thin lines) and the resulting vertical budget gradient (VBG) (thick line) of midlatitude (Alps) and tropical glaciers. 1 = Hintereisferner, Austrian Alps [1966/1967: mean specific net balance = + 20 kg m-2 (Kuhn *et al.*, 1979)]; 2 =: Glaciar Yanamarey, Cordillera Blanca [1977 - 1988 (Hastenrath & Ames, 1995)]; 3 = Lewis Glacier, Mt. Kenya [1978 - 1986 (Hastenrath, 1989)]; 4 = Punjak Jaya, Irian Jaya [1972 (Allison, 1976)]. Details of calculation are given in the text and by Kaser *et al.* (1995b).

0 °C-line, while (e) mixed precipitation with a decreasing solid part is assumed until 200 m below the 0°C-line; (f) below all precipitation is liquid.

The resulting VBG is in good agreement with the general shape of the measured tropical gradients. Those of inner tropical Irian Jaya and Lewis Glacier show even clearly the bend toward the accumulation zone, whereas marked evaporation/ sublimation amounts and, therefore, less ablation as well as a pronounced vertical gradient of solid precipitation could explain the smoothed VBG at Glaciar Yanamarey of the outer tropical Cordillera Blanca. The strong gradient below the 0 °C isotherm results from the sensible heat transfer supposedly occuring 365 days per year plus the all year round constant transition from the solid into the mixed and fluid precipitation zone. The absolute position was not the aim. Nevertheless, the lack of a thermal seasonality causes mainly the characteristic shape of tropical VBGs.

3. THE SENSITIVITY OF TROPICAL ELA ON CLIMATIC PERTURBATIONS

Although the cause of a shift of the mean ELA has to be understood as an interactive combination of all climatic parameters involved, the sensitivity of ELA on separated single parameters can be discussed. A shifting of the equilibrium line along the synthetic Alpine VBG of ΔELA = 100 m could be caused by either a perturbation in accumulation of dc = - 430 kg m-2 a^{-1} or in radiation balance of dR = 1.44 MJ m^{-2} d^{-1} or in air temperature of dT_a = + 0.9 K. The sensitivity of ELA on climatic perturbations at tropical glaciers is twofold. If there is ELA $\leq$ 0 °C-line - as it can be assumed for the tropical regions (Kuhn, 1980) - the above mentioned perturbations would cause ΔELA (dc) = 35 m, ΔELA (dR) = 50 m but ΔELA (dT_a) = 120 m. Whereas the little sensitive reaction of ELA on dc and dR is obvious from the small inclination of the lower VBG, the increased reaction of ELA on dT_a is caused by the combination of its immediate effect on ablation and the effect on accumulation due to the implied shift of the 0 °C-line. In the seasonally dry outer tropics, as supposedly also in the Cordillera Blanca, there is ELA > 0 °C-line. Therefore, its sensitivity on climatic perturbations is related to the upper VBG which depends mainly on the vertical gradient of accumulation.

4. THE REACTION OF GLACIER TONGUES ON CLIMATIC PERTURBATIONS

The position of the end of a glacier tongue is given where the downward increasing net ablation equals the downward decreasing mass flux from the upper glacier. The schematic model in Figure 3 points out the general characteristics of a tongue reaction on climatic perturbations as well as the respective differences between a tropical and a midlatitude situation. The inclination of the midlatitude VBGm was chosen arbitrarily. The tropical VBG_t is subsequently 3,65 times the VBG_m. The available mass per unit area AM at any point of the glacier tongue is the result of the mass flux and the local mass budget. Its vertical gradient VGM = dAM/dz was again chosen arbitrarily and was assumed to be equal for both the tropical and the Alpine glacier. Moreover, all gradients are assumed to be linear. All values have to be taken per horizontal square unit.

For a first equilibrium situation with ELA1, the terminus elevation TE is much higher in the tropics than in the midlatitudes. Then, the equilibrium line is moved into a higher position ELA_2. Subsequently the balance curves rise parallel to their former position and

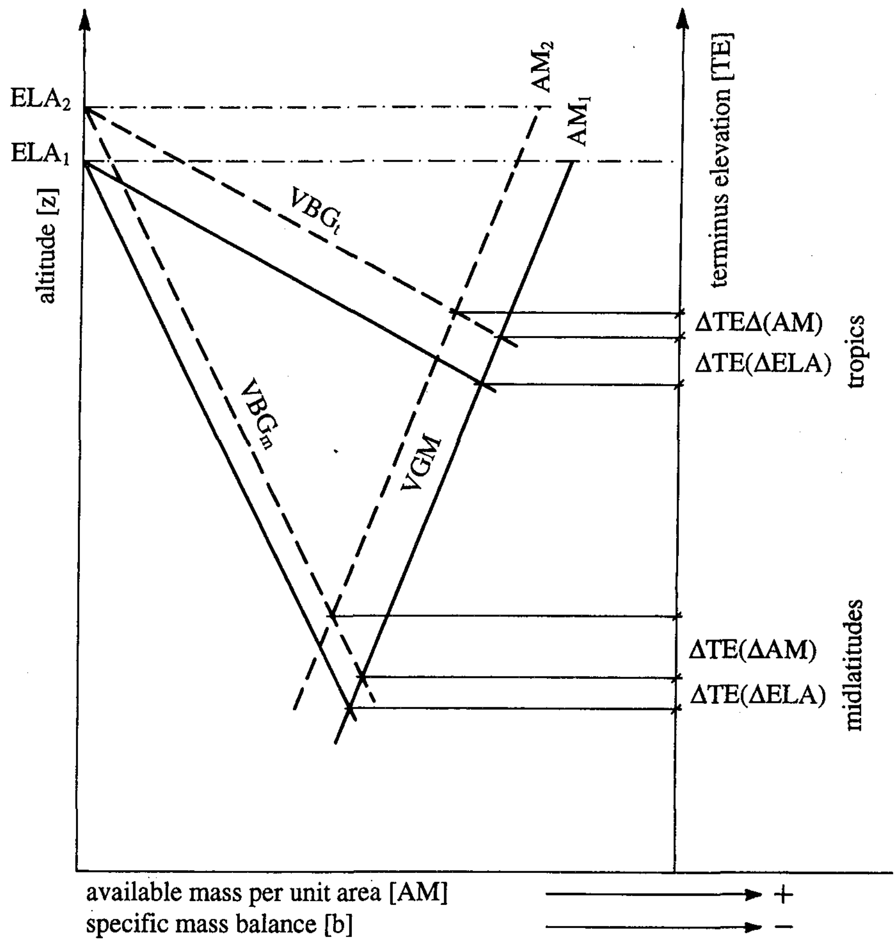

Fig. 3 - A simplified model of the vertical gradients of specific net mass balance VBG and available mass per unit area VGM in order to determin the elevation of a glacier terminus TE under different conditions. ELA = equilibrium line altitude, AM = available mass per unit area. The index t stands for tropics, $_m$ for midlatitudes, $_1$ for a first equilibrium condition and $_2$ for a second one.

cross the VGM in new elevations. The resulting rise of the terminus is obviously more sensitive in the tropics. Certainly, if the tropical VGM is assumed to be stronger than the midlatitude one, the differences in ΔTE (ΔELA) will become less and would disappear if the tropical VGM_t becomes 3,65 times the midlatitude VGM_m. In the same way ΔTE (ΔELA) would also have the same values for both cases if VGM = 0. These two cases are assumed to be the theoretical limiting values.

The next step simulates the lagging reaction of a decrease in mass flux ($AM2 < AM_1$) which follows, consequently, a persistent higher ELA_2. The resulting ΔTE (ΔAM) is in the tropics markedly smaller than ΔTE (ΔELA) and would become smallest with $VGM_t = 3{,}65\ VGM_m$. It would also remain smaller under the other limiting situation of VGM = 0. Moreover, exponential gradients within realistic values, too, would show the same tendency of (a) a higher sensitivity of tropical tongues on ΔELA compared to midlatitude tongues, (b) a markedly less sensitivity of tropical tongues on ΔAM than on ΔELA and (c) a less total response of tropical than of midlatitude tongues. If glaciers with a small altitudinal extension lose most or all of their accumulation area and the dynamic mass flux becomes stagnant, the recession of tropical glaciers is more pronounced due to a net ablation rate up to 3,65 times the midlatitude one.

This holds for recession conditions, whereas advances are in any case dominated by the dynamic forcing and, therefore, less sensitive in the tropics.

5. CONCLUSIONS

Pertinent climatic characteristics of the tropics are (a) the negligible annual range of temperatures and (b) the marked seasonality of precipitation, with the prevalence of double peaks in the year-round precipitation activity in the equatorial belt as compared to a single wet season and a pronounced dry season in the outer tropics.

The simple synthesized VBG of a midlatitude Alpine glacier and its shifting into tropical conditions demonstrates clearly that the shape of the tropical VBG is mainly related to the missing thermal seasons. A continuously constant sensible heat flux and a decreasing portion of solid precipitation below the 0 °C line cause a strong gradient of the VBG in the ablation zone. The position of the 0 °C-line marks a more or less sharp bend toward a weak VBG in the accumulation zone which is mainly controlled by the vertical gradient of solid precipitation. As a consequence, the sensitivity of the tropical ELA on climatic perturbations depends on its position relative to the 0°C-line, being more or less sensitive above, but generally weak on or below it. Yet, a perturbation in air temperature affects the ablation as well as the accumulation by a shift of the snowfall line in order to intensify the reaction of a tropical ELA 1,2 times that of a midlatitude ELA. Due to the ablation which is persistent all year round, the tropical tongues are kept much closer to the ELA which makes assume that the accumulation area ratio is in any case higher in the tropics than in the midlatitudes.

Compared to midlatitude glaciers, in summary, it has do be assumed that the response of tropical glaciers on climatic perturbations is more pronounced (a) in ΔELA if it is caused by a change in air temperature and (b) in immediate short-term tongue and, therefore, surface area reactions on disadvantageous climatic changes. This is most pronounced if the ELA shifts toward the top of small glaciers or glaciers with a small altitudinal extension. Thus, their sharp reaction as well as the "cutted" tongues of the huge Cordillera Blanca glaciers can be explained. Moreover, (c) the whole year round ablation reduces also the effectivity of the long-term dynamic forcing and predominates therefore the total reaction toward a smaller sensitivity. (This corresponds well with the simulated results which Kruss (1984) obtained for the Lewis Glacier, showing long term tongue reactions being independent on the amplitude of the applied mass balance fluctuation.) Since advances are predominated by the dynamic forcing they are subsequently weaker in the tropics. In detail, local peculiarities of the energy balance can overlay the general regime causing particular reactions which are most obvious on small glaciers.

However, the comparatively scarce field evidence and the fact of a relatively immediate inference of tropical glacier fluctuations on a climate which originates from relatively homogenous air masses makes glaciological investigations in the tropics particularly important.

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