annual course of ablation and of accumulation appear reasonable in fig. 8. The main ablation processes and the main accumulation processes are coinciding in time. The amount of the annual ablation at equilibrium line altitude was estimated as 480 mm and the accumulation as 510 mm.

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MASS BALANCE PROFILES ON TROPICAL GLACIERS

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With 3 figures

ABSTRACT

The total surface area of tropical glaciers is estimated at about 2,5 10^3 km^2, corresponding to 4.6 % of the mountain glaciers and to 0.16 % of the total ice cover of the World. The tropical climate is determined by homogeneous air masses, the missing of any appreciable thermal seasonality and a hygric seasonality, changing from precipitation all year round with a tendency for double peaks in the annual cycle in the inner tropics to a pronounced dry season in the outer tropics. Under these general aspects and drawing on a limited observational evidence, the paper discusses a typical tropical vertical net balance profile (VNBP), which represents the climatic forcing function for the ice flow dynamics and changes in the long-term functioning of a glacier. A continuously constant sensible heat flux and the almost constant positions of 0 °C-line and snowfall-line all year round are the foremost causes for the typical shape of the tropical VNBP and, therefore, for the high sensitivity of tropical glaciers to temperature increase.

MASSENBILANZPROFILE AUF TROPISCHEN GLETSCHERN

ZUSAMMENFASSUNG

Die Vergletscherung in den Tropen wird auf eine Fläche von ca. 2,5 10^3 km^2 und damit auf rund 4,6 % der gesamten Gebirgsgletscher und auf 0,16 der gesamten vergletscherten Fläche der Erde geschätzt. Das tropische Klima ist von homogenen Luftmassen, dem Fehlen thermischer Jahreszeiten und einem hygrischen Zyklus bestimmt, der von weitgehend feuchten Verhältnissen mit zwei jährlichen Niederschlagsspitzen in den inneren Tropen bis zu einer ausgeprägten Trockenzeit in den äußeren Tropen reicht. Unter diesen generellen Gesichtspunkten und gestützt auf eine limitierte Datengrundlage diskutiert die Arbeit ein für die Tropen typisches Vertikalprofil der Nettomassenbilanz (VNBP) als Ausdruck der Klima – Gletscher-Beziehung. Ein über das Jahr anhaltender fühlbarer Wärmestrom, eine ebenso konstante 0 °C Grenze und damit verbunden eine gleichbleibende Schneefallgrenze sind die dominanten Ursachen für die typische Form des tropischen VNBP und damit für die hohe Empfindlichkeit, mit der tropische Gletscher auf Temperaturerhöhungen reagieren.

INTRODUCTION

The glaciers in the high mountains of the tropics are particularly sensitive components of the environment and merit attention in the context of global change. Glaciers still exist in Irian Jaya, East Africa, on the Mexican vulcanoes and in the South American Andes. Their total area is estimated at about 2.5 10^3 km^2, corresponding to 4.6 % of the mountain glaciers and to 0.16 % of the total ice cover of the World (WGMS, 1989). The greater part of this is found in the Peruvian Andes (Tab. 1).

Out of a number of differently defined climatological delimitations for the tropical regions, the lines where the amplitudes of diurnal and annual range of temperature are equal

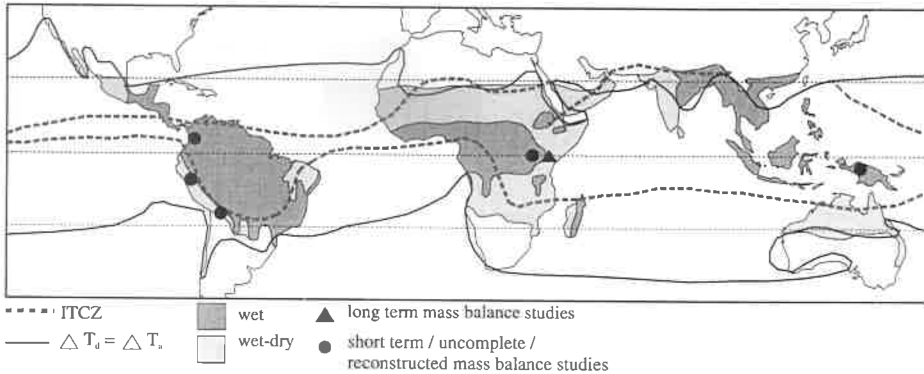
Table 1: Surface area of tropical glaciers after Jordan (1991); updated.

	km^2	%	year	source of updating
Ruwenzori	2.6	0.09	1990	Noggler (1992)
Mt. Kenya	0.5	0.02	1987	Hastenrath et al. (1989)
Kilimanjaro	4.9	0.18	1970's	Hastenrath (1984)
Africa	8.0	0.29		
Irian Jaya	3.0	0.11	1988	Peterson & Peterson (1995)
Mexico	11.4	0.41	1960's	
Colombia	108.5	3.90	1950's	
Venezuela	2.7	0.10	1950's	
Ecuador	112.8	4.05	1970's	
Perú	1972,0	70.82	1970	
Bolivia	562.0	20.18	1980's	
Chile	4.0	0.14	?	
S-America	2762.0	99.20	1950's–1980's	
total	2784.4	100	1950's–1990	
estimated total surface area for 1990			$> 2.5\ 10^3\ km^2$	

($\Delta T_d = \Delta T_a$), emphasize one peculiarity of tropical climate: the missing of any appreciable thermal seasonality (Paffen, 1967). These lines encompass, of course, approximately the tropics of Cancer and Capricorn (Figure 1). The continental depression zones and the seasonal shifting of the Intertropical Convergence Zone (ITCZ) are 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 (Figure 1). While climate in the midlatitudes is an average of travelling synoptic patterns of different air masses, climate in the tropics is determined by homogeneous air mass characteristics, and this allows more immediate inferences from mass balance studies on climate.

Mass budget studies on tropical glaciers are rare, as is also illustrated in Figure 1. A series, now spanning 17 years, is being maintained on Lewis Glacier, Mount Kenya (Hastenrath, 1984; 1991). Measurements have been conducted on glaciers in the North Peruvian Andes for about a decade, but have been discontinued (Kaser et al., 1990; Hastenrath and Ames, 1995a, b). Short-period field studies have been performed on the Ruwenzori glaciers (Bergstrøm, 1955; Whittow et al., 1963), in Irian Jaya (Hope et al., 1976) and on the Quelccaya Ice Cap in Southern Perú (Hastenrath, 1978). Very recently, a mass balance monitoring program has been initiated on Glaciar Zongo in the Cordillera Real of Bolivia (Francou et al., 1995) and similar programs are being considered for the Glaciar Artesonraju in the Cordillera Blanca of Perú and on a glacier of Antisana in Ecuador (Francou, 1994).

Of particular interest is the vertical profile of net mass balance (VNBP = b(z)), because this represents the climatic forcing function for the ice flow dynamics and changes in the longterm functioning of the glacier. Drawing on a limited observational evidence, the paper discusses the typical tropical VNBP in the context of the climatic characteristics.



sources: Lauer (1975), Liljequist and Cehak (1984), Paffen (1967), Weischet (1988)

Fig. 1: The tropical belt, some of its climatological features and sites of mass balance studies. ΔT_d a[...] ΔT_a are the amplitudes of diurnal and annual range of temperature

GENERAL CHARACTERISTICS OF TROPICAL GLACIER REGIMES

Pertinent climatic characteristics of the tropics are (a) the negligible annual range of te[...] perature and (b) the marked seasonality of precipitation, with the prevalence of double peaks [...] the year-round precipitation activity in the equatorial belt as compared to a single wet seas[...] and pronounced dry season in the outer tropics. This climatic setting has the following cons[...] quences for the glacier mass budget: (a) accumulation occurs only above the approximate[...] constant limit of snowfall; (b) accumulation is concentrated in the wet season; (c) ablation p[...] sists throughout the year; (d) ablation occurs mainly in the (annual mean) ablation zone; (e) t[...] mass budget year should be counted from the end of the most pronounced dry season.

The resultant tropical characteristics from the mass budget regime are illustrated in Fi[...] ure 2 in comparison with conditions in the Alps. In contrast to the clear-cut separation b[...] tween the accumulation and ablation seasons in the Alps (Figure 2a), in the tropics ablati[...] covers the whole year (Figures 2b and 2c), while accumulation may be either confined to [...] wet season in the outer tropics (Figure 2b) or continue throughout the year in the inn[...] tropics (Figure 2c). As type sites, Perú's Cordillera Blanca, where during the dry seas[...] even ablation is reduced by high evaporation/sublimation (Kaser et al., 1990), may corr[...] spond to Figure 2b, the Ruwenzori glaciers to Figure 2c.

Under these general aspects the characteristics of the vertical net balance profile sh[...] be discussed.

THE VERTICAL NET BALANCE PROFILE (VNBP)

The shape of the vertical net mass balance profile (VNBP = b(z)) and its climatic inte[...] pretation was comprehensively discussed by Kuhn (1980 and 1984). Characteristic a[...] much larger vertical gradients for tropical glaciers than for mid- and highlatitude glacie[...] The purpose of this section is to highlight the prominent differences between midlatitud[...] and tropics (Figure 3) when the mean VNBP of an Alpine glacier (Hintereisferner, Austri[...] Alps) is shifted into tropical conditions.

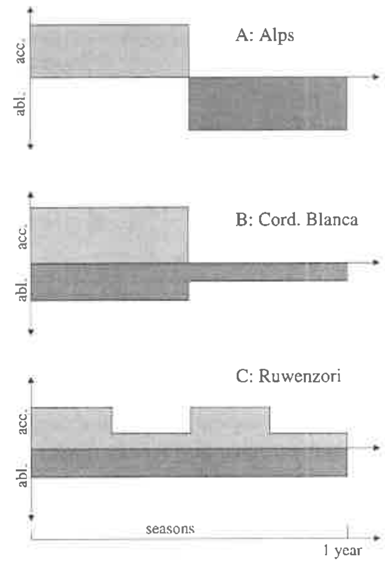


Fig. 2: Schematic diagrams of the annual cycles of accumulation (light dot raster) and ablation (dark raster). From top: midlatitudes (Alps), outer tropical region with pronounced dry season (Cordillera Blanca) and inner tropical humid regions with double wet season peaks (Ruwenzori)

Figure 3a portraying the Hintereisferner is constructed from the following specifications (Kuhn et al., 1979; Kuhn, 1979, 1980):

- the reference point is the zero degree line (0C-line) of summer temperature (June–September),
- the duration of the ablation period at the hight of the summer 0 °C-line is τ=100 d a^{-1},
- the change of the duration of the ablation season with altitude is $d\tau/dz = -0,1$ d m^{-1} a^{-1},
- the accumulation gradient with altitude is $dc/dz = 1$ kg m^{-2} m^{-1} a^{-1},
- the mean laps rate of air temperature is $dt_a/dz = -0,0065$ °C m^{-1},
- the heat transfer coefficient as an integrative term for turbulent exchange in the boundary layer and for the heat conductivity between glacier surface and air is $\alpha = 1,5$ MJ m^{-2} d^{-1} °C^{-1},
- the entire glacier surface is assumed to be continuously under melting conditions during the whole ablation season.
- all altitude gradients of the remaining energy balance terms are neglected. Therefore, they do not influence the shape of VNBP.

Figure 3A shows the vertical profiles of accumulation, ablation and net balance for the range of altitude of foremost interest between 400 m above and 600 m below the summer 0 °C isothermal surface. The shape of VNBP thus synthesized compares well with the observed conditions depicted in Figure 3C. The previously neglected terms of the energy balance (i.e. those without or negligible vertical gradients) would shift the entire VNBP-line in an even realistic position where ELA is drawn closer to the 0 °C-line.

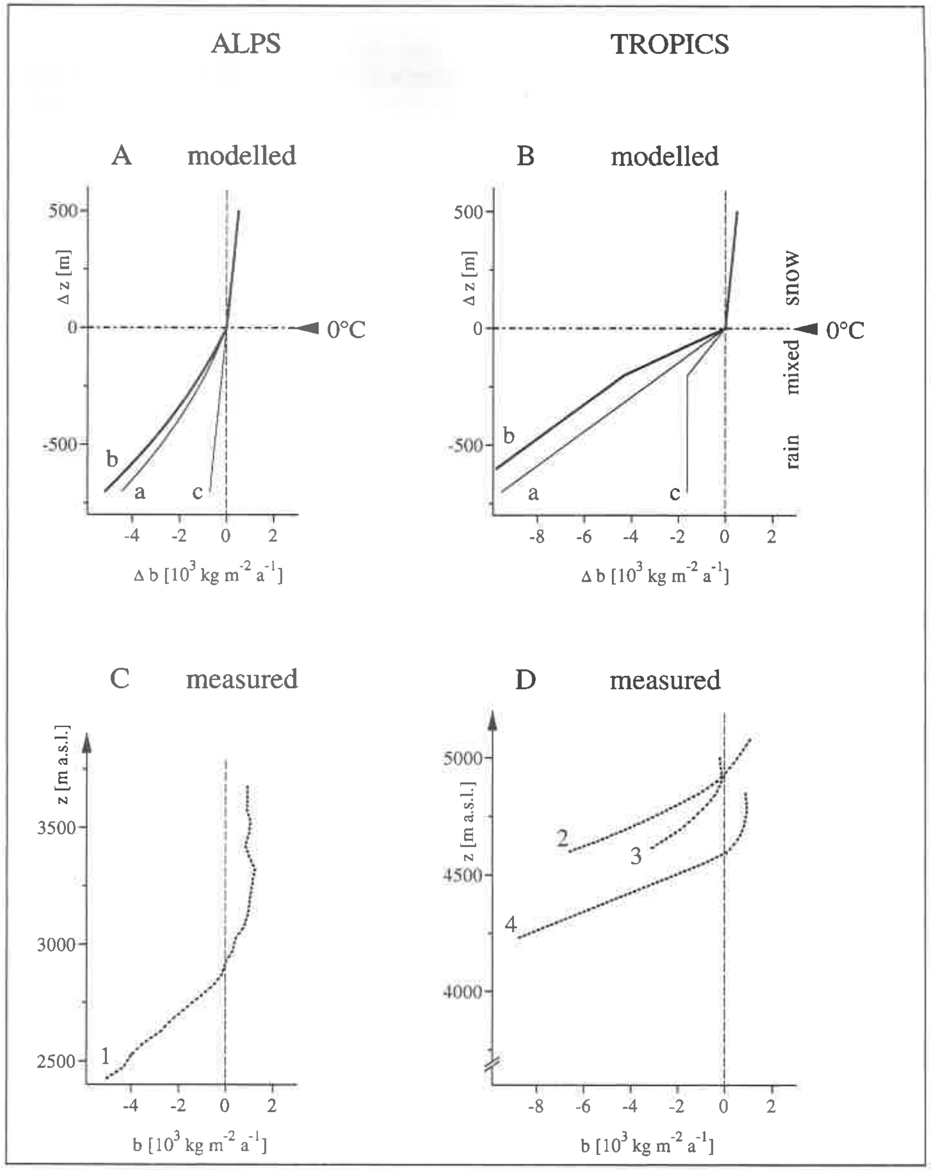


Fig. 3: Calculated vertical profiles of accumulation c and ablation a (thin lines) and the resulting net mass balance b (VNBP) (thick line) of Hintereisferner, Austrian Alps (A) and for a tropical glacier (B). Details of calculation are given in the text. C: The measured vertical net balance for a balanced year at Hintereisferner (1) (1966/67: mean specific net balance = + 20 kg m^{-2}). D: The measured vertical net balance for three tropical glaciers: 2: Glaciar Yanamarey – Cordillera Blanca, 1977–88 (Hastenrath and Ames, 1995b); 3: Lewis Glacier – Mt. Kenya, 1978–86 (Hastenrath, 1989); 4: Punjak Jaya – Irian Jaya, 1972 (Hope et al., 1976)

Turning now to the tropics, Figure 3B offers a picture corresponding to the following specifications:

- the 0 °C-line has no annual variations and therefore,
- the ablation period lasts the whole year round with $\tau_o = 365$ d a^{-1},
- the continuous ablation occurs on the entire ablation zone causing $d\tau/dz = 0$ d m^{-1} a^{-1},
- exclusively solid precipitation occurs only above the 0 °C-line, while
- mixed precipitation with a decreasing solid part is assumed down to 200 m below the 0 °C-line,
- below that level all precipitation is liquid,
- this leads, together with the assumtion of a mean accumulation of $c_0 = 1600$ kg m^{-2} a^{-1} at the 0 °C-line to an accumulation gradient of $(dc/dz)_a = 8$ kg m^{-2} m^{-1} a^{-1} within the 200 m zone of mixed precipitation.
- as a best guess, the heat transfer coefficient is assumed to be the same as in the Alps.
- all other assumptions remain the same as for the alpine glacier.

Figure 3B shows the resulting accumulation and ablation gradients as well as the VNBP which has a weak gradient above the 0 °C-line and changes rapidly into a very strong gradient within the zone of mixed precipitation, marking a distinct kink of the curve near the 0 °C isotherm. The still strong gradient in the lower ablation zone results from the sensible heat transfer supposedly appearing 365 days per year. This synthesized VNBP is compared with three measured profiles in Figure 3D. Again, the absolute position was not the aim. That would have to include additional energy balance terms and better knowledge of the actual accumulation amounts. However, there is good agreement in the general shape of the VNBP. All measured VNBPs show the small inclination in the lower part, those of inner tropical Punjak Jaya and Lewis Glacier show also clearly the bend toward the accumulation zone. Markedly higher evaporation/sublimation amounts in the outer tropics can explain the diversity of VNBP at Glaciar Yanamarey of the Cordillera Blanca.

CONCLUSIONS

The simply synthesized VNBPs of a midlatitude Alpine glacier and its shifting into tropical conditions demonstrate clearly that the shape of the VNBP of tropical glaciers is mainly related to the missing thermal seasons. A continuously positive sensible heat flux causes a strong gradient of the VNBP in the ablation zone, the position of the 0 °C-line marks a more or less sharp bend to a weak VNBP in the accumulation zone. This indicates a high sensitivity of tropical glaciers to increasing temperature because larger parts of the glacier are exposed immediately to much stronger ablation conditions.

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