

# ON THE MASS BALANCE OF LOW LATITUDE GLACIERS WITH PARTICULAR CONSIDERATION OF THE PERUVIAN CORDILLERA BLANCA

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*Kaser, G. and Georges, Ch., 1999: On the mass balance of low latitude glaciers with particular consideration of the Peruvian Cordillera Blanca. Geogr. Ann., 81 A (4): 643–651.*

**ABSTRACT.** Glacier mass balance studies in the low latitudes are rare and glaciological methods and terminology are basically adapted from mid- and high latitude conditions. The low latitudes are considered to be the tropics and, to some extent, the adjoining dry subtropics. The outer tropics are proposed as an intermediate zone with tropical character during the humid season and subtropical character during the dry season. Delimitations as well as respective climate and glacier regimes are discussed in order to distinguish them from each other and from the mid-latitudes. Different sensitivities of the glaciers can be expected and promise, in turn, a complex climatological interpretation of glacier fluctuations. For this, detailed mass balance studies on low latitude glaciers are required. The respective discussion is concentrated on the Peruvian Cordillera Blanca whose topographical setting provides both spatial and temporal subdivisions in humid and dry regimes in one region. However, theoretical considerations and field experience show problems for the determination of mass balance variables in the Cordillera Blanca and the low latitudes in general. The absence of annual temperature variations hinders the development of impermeable layers which can be identified as annual reference layers and which prevent meltwater from percolating into the firn body. Thus, a combination of ablation measurements and the application of the flux divergence method for the determination of accumulation is proposed.

*Key words:* glacier mass balance, low latitudes, methods

## Introduction

Glaciers in the mid- and high latitudes have always been objects of intensive classical and modern scientific investigation. The development of glaciological methods and terminology have been based on them (e.g. Meier 1962; Hoinkes 1970; Østrem and Brugman 1991; Paterson 1994). In contrast, glaciers on low latitude high mountains are rarely studied (Kaser 1995, 1999; Kaser *et al.* 1996a), though they are sensitive indicators of the environment on a regional as well as a global scale (e.g. Hastenrath 1984, 1995; Thompson *et al.* 1995; Kaser *et al.* 1996a; Kaser 1996, 1999; Wagnon

1999). They also have an important impact on the regional water balance (Kaser 1996). The aim of this article is to outline the particular interest in mass balance studies on low latitude glaciers, to mention the methodological difficulties, and to propose possible solutions. The low latitudes are prevalently considered to be the tropics and, to some extent, the adjoining subtropics. Their delimitations as well as their climatological and glaciological characteristics will be discussed in order to distinguish them from those in higher latitudes.

Mass balance studies, in particular, on tropical glaciers are rare. A long-term record of mass balance variations only exists for the Lewis Glacier on Mount Kenya (Hastenrath 1984, 1991; Haeberli *et al.* 1996) showing that this East African glacier corresponds to the global trend of strong recession. Various analyses have been made (e.g. Hastenrath and Kruss 1992; Hastenrath 1995). Short-term studies have been carried out on the Elena Glacier in the Rwenzori mountains (Bergstrøm 1955, Whitow *et al.* 1963) in Irian Jaya (Hope *et al.* 1976) and on the Quelccaya Ice Cap in Southern Perú (Hastenrath 1978). Measurements, basically limited to the ablation zones, have been conducted on some relatively small glaciers in the Cordillera Blanca, Perú, for about a decade (Ames 1985; Kaser *et al.* 1990). Mass balance measurements have begun on the Zongo Glacier in Bolivia, (Francou *et al.* 1995) and on the Antisana Glacier in Equador (B. Francou, personal communication) in the last few years.

## Climatic regimes and mass balance processes

It has been suggested that tropical glaciers can be specified by the following delimitations (Kaser 1995; Kaser *et al.* 1996a). They must be within: (i) the astronomical tropics (radiative delimitation); (ii) the area where the daily temperature variation

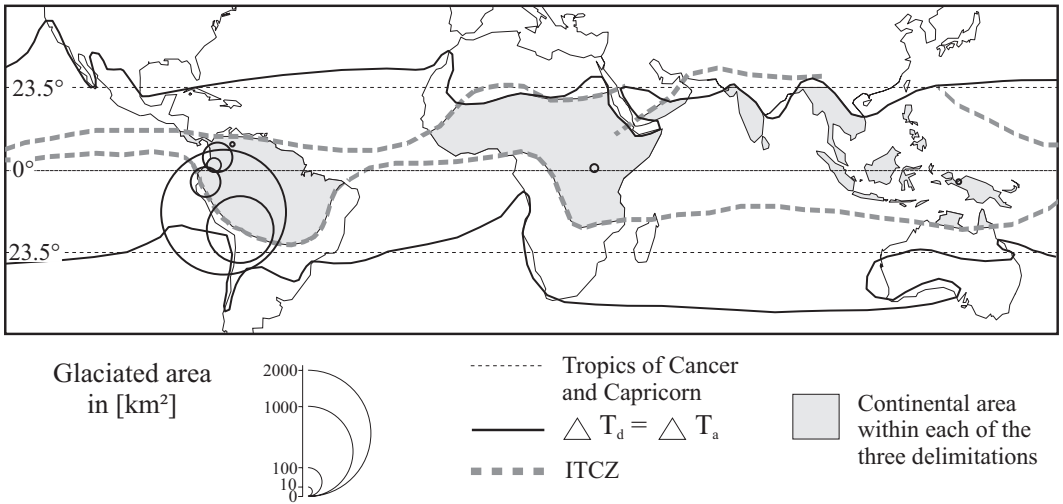


Fig. 1. The tropics and their delimitations from a glaciological point of view, and the distribution of the glacier areas by country. ITCZ = Inter Tropical Convergence Zone (after Kaser 1995 and Kaser *et al.* 1996a).

exceeds the annual temperature variation (thermal delimitation); and (iii) the oscillation area of the Inter Tropical Convergence Zone (ITCZ) (hygric delimitation). The three delimitations and the distribution of the tropical glacier areas according to countries are shown in Fig. 1. Within these boundaries outer tropical conditions with one wet and one dry season may be distinguished from the inner tropical conditions with more or less continuous precipitation. Towards higher latitudes, the outer tropics are adjoined by the subtropics, which, in general, gain no humidity and precipitation either from the ITCZ or from the frontal activities of the west wind circulation system in the mid-latitudes. Thus, extremely dry conditions lead to a glacier regime which is clearly different from both the one in the mid-latitudes and the one in the tropics. Due to the seasonal oscillation of the ITCZ, the outer tropics, in fact, are characterized by tropical conditions during their humid season and by subtropical conditions during their dry season. The schematic glacial regimes of the inner and the outer tropics are compared to that of the mid-latitudes in Fig. 2 (according to Kaser *et al.* 1996a).

In mid- and high latitudes, seasonal variations in accumulation and ablation are dominated by seasonal variations in temperature. In contrast, seasonal mass balance variations are controlled by the course of the rainy seasons in the tropics. There, the absence of any major thermal seasonality, includ-

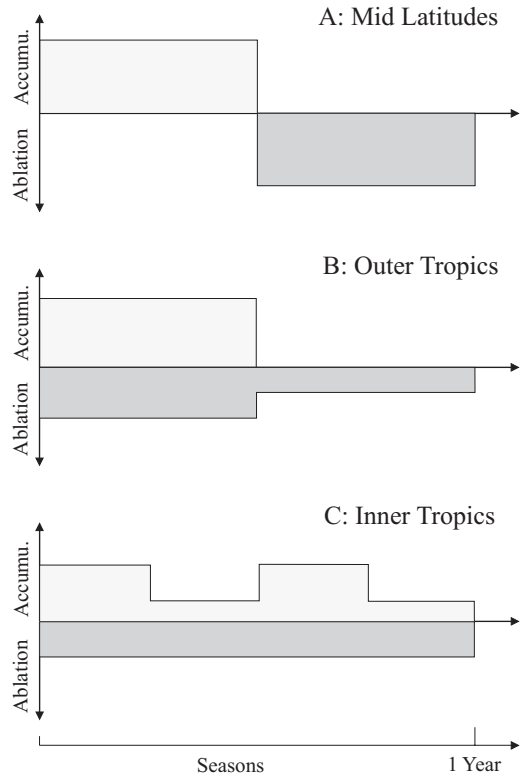


Fig. 2. A schematic comparison of inner tropical and outer tropical glacier regimes with those of the mid-latitudes (after Kaser 1995 and Kaser *et al.* 1996a).

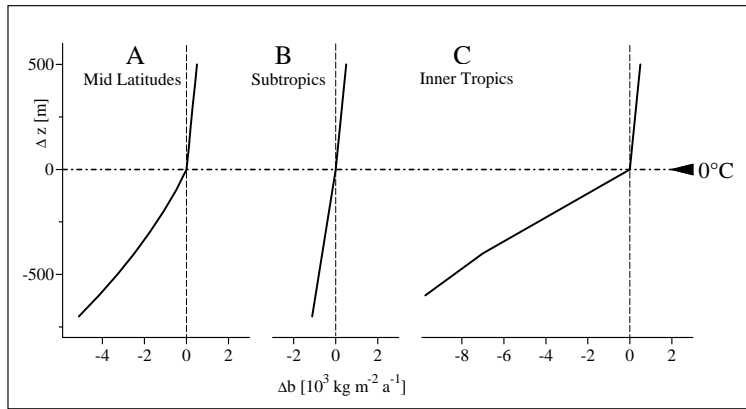


Fig. 3. Modelled mass balance profiles for (A) mid-latitude, (B) subtropical and (C) tropical conditions. Note that at the x-axis changes of mass balance  $\Delta b$  in respect to the mass balance at the  $0^{\circ}\text{C}$  level are depicted. The figure does not show equilibrium line altitudes which might differ to various extents from the  $0^{\circ}\text{C}$  level.

ing a fairly constant height of the  $0^{\circ}\text{C}$  isotherm, causes ablation throughout the whole year. Accumulation, on the other hand, is limited to periods of precipitation and to the high areas of the glaciers. In the humid inner tropics, in addition to thermal homogeneity, more or less constant humid conditions also lead to mass balance conditions which change little throughout the year. Such conditions can be expected on the Rwenzori mountains, East Africa, and on Irian Jaya, New Guinea (Kaser *et al.* 1996a). In the outer tropics, these conditions only appear during the wet season. During the dry season there is no accumulation, and the ablation is reduced as well. Because of the dry air conditions, much of the still available energy is consumed by sublimation and, therefore, less remains for melting. This has been shown by Kaser *et al.* (1990) through analysis of ablation measurements from Cordillera Blanca glaciers and by Wagnon *et al.* (1999) through energy balance investigations on the Zongo Glacier in Bolivia.

The differences in the glacier regimes lead, above all, to different vertical mass balance profiles which are the result of the complex impact of climate on the glaciers (e.g. Kuhn 1984; Oerlemans and Hoogendoorn 1989). In turn, these profiles characterize the sensitivity of a glacier to climate disturbances or changes. A typical profile for the mid-latitudes (Fig. 3A) has been modelled by Kaser (1995) and, in an improved version, by Kaser *et al.* (1996a), making simplifying assumptions which, among others, neglect ablation above the  $0^{\circ}\text{C}$  isotherm, assume constant melting conditions on the tongues throughout the ablation period, and reducing the vertical variations of climatic parameters to those of air temperature and accumula-

tion. A tropical profile (Fig 3C) has been derived from the mid-latitude one by solely extending the ablation period from 100 days per year, as a mean, to 365 days. The modelled profiles fit well with the measured ones (Kaser 1995, 1996; Kaser *et al.* 1996a). A recent confirmation of the suitability of the model has been provided by Klein *et al.* (1999). In addition to these mass balance profiles, the mass balance profile for a subtropical glacier (Fig. 3B) is calculated from profile in Fig. 3C under the assumption that the entire available energy is consumed by sublimation. The profiles in Fig. 3 depict the change of mass balance with altitude in respect to the  $0^{\circ}\text{C}$  level. Thus, they show neither absolute values of mass balances nor equilibrium line altitudes, but concentrate on the shape of the profiles. Again, it has to be emphasized that these profiles are modelled, making idealized assumptions. In the subtropics, two probable deviations from the model assumptions compensate each other: (i) the ablation period, which decreases with increasing latitude, steepens the profile; and (ii) any occurrence of melting has the opposite effect. However, the difference between tropical and subtropical mass balance profiles is fundamental as is the difference between the two seasonal regimes on outer tropical glaciers. Wagnon (1999) prove this with measured vertical profiles of specific mass balance from the Zongo Glacier in the Cordillera Real in Bolivia.

### The benefits of mass balance studies on low latitude glaciers

The mass balance of glaciers has, of course, a direct impact on the hydrological budget of the respective

region. Corresponding to the seasonal variations of the tropical glacier regimes (Fig. 2), the annual variation of the runoff is, in contrast to the mid-latitudes, smoothed by the glaciers. In the outer tropics, the contribution from glaciers is the principal runoff during the dry season (Kaser 1996). Major changes in the glaciation would incisively affect the runoff regime causing economic consequences, such as on the water supply in the populated and cultivated valleys and foothills and on the use of hydraulic power. This is of great importance mainly in the South American Andes. Combined studies of the energy and mass balance on glaciers would give important information on the role of the glaciers in the water cycle.

Considering tropical glaciers as highly sensitive indicators of the global climate, the study of their mass balances can considerably improve our respective understanding. Compared to the mid-latitudes, tropical climate is mainly characterized by homogeneous thermal conditions where frontal activities are, on average, insignificant. As a result, the fluctuations of tropical glaciers can be related more directly to variations of simple climate parameters. Most recent discussions propose humidity changes as a major reason for sudden climate jumps and focus, in fact, on the tropical high mountain environments as key areas where, among others, glaciological studies provide considerable evidence (Broecker 1997). Kaser (1999) summarizes probable reasons for the modern fluctuations of tropical glaciers as reported by different authors, showing that changes in air humidity and in the related variables predominate. For example, for the northern Cordillera Blanca, Perú, Kaser and Georges (1997) have shown that the main reason for a greater glacier retreat, beginning in the 1920s and slowing around 1950, was a decrease in air humidity rather than a rise in air temperature. Hastenrath and Kruss (1992) assign the retreat of the Lewis Glacier on Mount Kenya, between 1963 and 1987, to an increase of both air temperature and air humidity, and Wagnon (1999) shows, from recent energy and mass balance studies on the Zongo Glacier, that an extremely negative mass balance during the El Niño year 1997/98 was due to decreased precipitation during the humid season and increased air humidity during the dry season. Obviously, the effects of changes in air humidity are manifold and depend decisively on the given starting conditions. Generally, the effects have opposite signs under dry conditions than under humid conditions. Thus, detailed mass balance and climate

studies on outer tropical glaciers promise highly interesting information. They can also contribute to the interpretation of palaeoglaciological evidence (Thompson 1995; Thompson *et al.* 1995) and, therefore, to the understanding of tropical climate and its variability in the context of global change.

### **The outer tropical Cordillera Blanca as a favourable area for glacier mass balance studies**

Compared to other tropical mountain ranges, the Cordillera Blanca is by far the most glaciated, covered by about 700 km<sup>2</sup> of glacier surface which amounts to one-quarter of all tropical glaciers (Kaser *et al.* 1996a; Kaser 1999). As part of the South American Andes, the Cordillera Blanca stretches over about 180 km from 8°30'S to 10°S. Twenty-seven peaks reach elevations of over 6000 m a.s.l., and more than 200 peaks extend over 5000 m a.s.l. The highest peak has an elevation of 6768 m a.s.l. at the Nevado Huascarán Sur (Fig. 4). The shape and setting of the Cordillera Blanca make it a pronounced barrier to the easterly dominated atmospheric currents and it separates the dry Pacific side from the humid Amazon side. Marked windward and lee-side effects are the result (Kinzl 1942; Fliri 1968; Kaser *et al.* 1990; Kaser and Georges 1997). In fact, the relatively densely populated and intensively cultivated valley floor of the Callejón de Huaylas receives little rain. Precipitation amounts reach from 158 mm at the Hidroelectra station (1386 m a.s.l.) and 180 mm in Caraz (2286 m a.s.l.), up to a maximum of 750 mm in Ticapampa (3480 m a.s.l.) (long-term annual mean values; Niedertscheider 1990). In contrast, the eastern slopes of the Cordillera collect more than 3000 mm per year (Johnson 1976). Nevertheless, the precipitation is concentrated from October to May over the entire region with up to 90% of the annual amount. This assigns the Cordillera Blanca clearly to the outer tropics.

Because the pronounced hygric seasonality meets with a well pronounced spatial gradient in air humidity across the mountain range, the Cordillera Blanca is highly suitable for glacier climate research. Within short distances, almost ideal humid tropical conditions prevail on the eastern slopes during the wet season, and subtropical conditions on the western side during the dry months. The existence of such basically different mass balance regimes within one mountain range provided a rea-

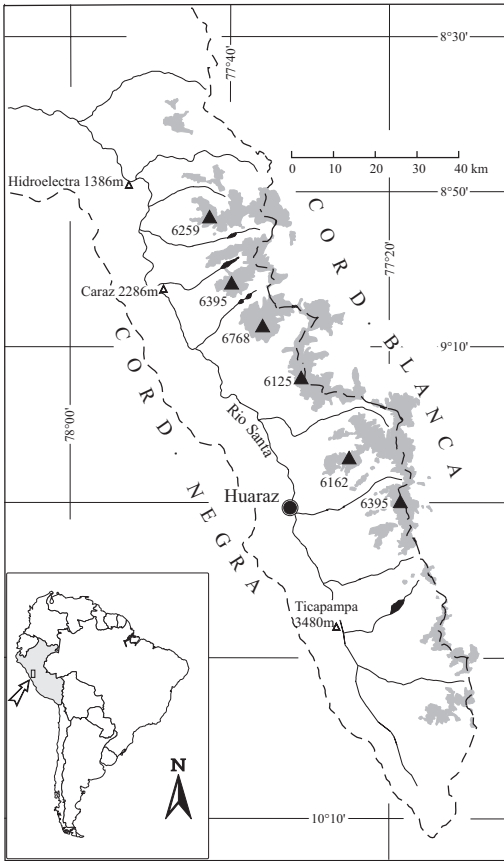


Fig. 4. The Cordillera Blanca and the catchment area of the Rio Santa. Shading represents glaciation corresponding to its extension in 1970 (Ames *et al.* 1989). The broken line delimits the catchment area of the Rio Santa. The full triangles show the range of the highest peaks. The open triangles show the precipitation gauges mentioned in the text.

son for the investigation by Kaser *et al.* (1996b), Georges (1996), and Kaser and Georges (1997), which have determined mean equilibrium line altitudes (ELAs) for different glaciated areas along a west-east cross-section in the northern Cordillera Blanca. The different ELAs, as well as their different shifts between the 1920s and 1950s, were analysed and possible climatic reasons for the marked retreat which took place during this period were discussed. It was shown that only about one-third of the glacier retreat can be attributed to a rise in temperature. The main part was caused by a decrease in air humidity and the respective complex

changes in the mass and energy balance variables which depend on it. Such studies may be extended to the postglacial period since the knowledge of respective glacier fluctuations is gradually increasing (e.g. Thompson *et al.* 1995). However, the mentioned investigations still had to be derived from mid-latitude-based general assumptions about glacier behaviour. Obviously, results can be improved using detailed knowledge on the mass and energy balance regimes. Respective attempts have only been partially successful so far.

**Problems related to mass balance studies and possible solutions.**

In the 1970s, members of the *Unidad de Glaciología e Hidrología-Electroperú* (Huaraz, Perú) started a mass balance programme in the Cordillera Blanca (Ames 1985). But only very few and relatively small glaciers at the southern edge of the range were found to be suitable for traditional glaciological mass balance investigation. The reason was that, due to the relatively steep slopes of the geologically young mountains, most of the glaciers are thin, heavily fissured and fed from steep sides (Fig. 5). Avalanche activities in the upper regions, as well as many extensive serac zones and ice falls, prevent a reasonable delimitation of accumulation and ablation areas and make most of the areas inaccessible. However, Ames *et al.* (1989) have classified 61 valley glaciers that are mostly heavily covered with debris, and thus unsuitable for mass balance studies.

Besides these adverse circumstances, which are typical not only for the Cordillera Blanca but for many parts of the Andes, another phenomenon complicates accumulation measurements on tropical glaciers. It is attributed to the lack of thermic seasons in the tropics which causes the snow cover and the firn body to be isothermal. Most accumulation areas of tropical glaciers barely reach far above the 0°C isotherm, and thus the snow and firn cover is isothermal at 0°C and slightly below. Annual dirt and frozen layers, which can be recognized quite clearly in the mid-latitudes, cannot develop in the tropical regions. Furthermore, the isothermal structure also leads to a lack of a vapour pressure gradient within the snow cover. Thus, the decomposing (isothermal) metamorphosis and the regelation processes dominate in the metamorphosis of the snow crystals. The firn grains become more rounded and more uniform than those in the mid-latitudes. This reduces the possibility of any

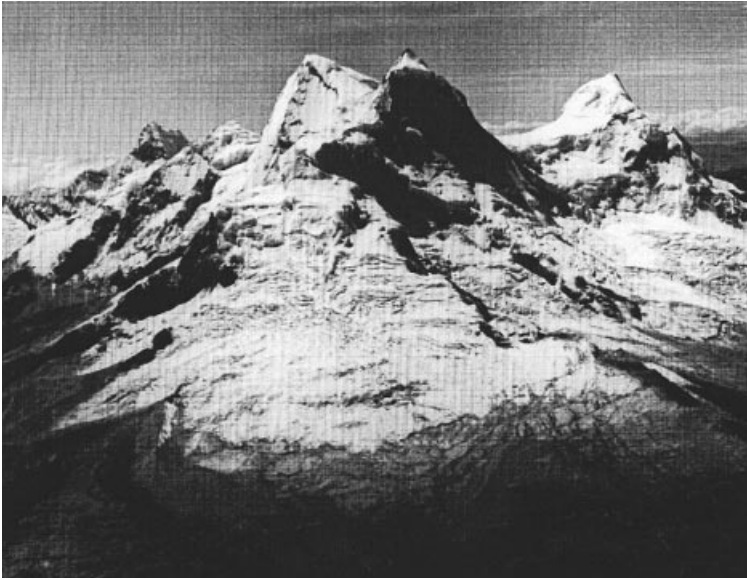


Fig. 5. The Huandoy (6395 m a.s.l.) massif in the central Cordillera Blanca, Perú. Oblique air photograph: L. Ortenburger 1952 (Archive Inst. f. Geogr. Innsbruck).

stratigraphic evaluation. But, even if annual layers are shown by large dust particles, these are never impermeable and meltwater percolates through several of them, preventing a reasonable determination of seasonal or annual accumulation from snow pits or drill cores.

The field evidence of various authors on different tropical glaciers proves this consideration, although they have not always been taken into account in the respective analyses:

- The Peruvian glaciologists, in fact, have attempted to define clear horizons in the snow pits for years, but without success (A. Ames, personal communication). The measurements had to be limited to the ablation zone.
- Allison (1976) reports that, in 1972, following examinations at the Meren Glacier and the Carstensz Glacier in Irian Jaya, no stratigraphy worth mentioning was seen in 10 m deep drill holes in the firn areas of the two glaciers. He attributes the isothermia measured in the firn bodies to the extremely low annual fluctuation of air temperature. There is no discussion about considering these observations when determining the accumulation on the gauging poles.
- Platt (1966) reports from the Lewis Glacier at Mt Kenya, where the annual mass balance has been determined since 1978 (e.g. Hastenrath 1984 1991), that melting occurred daily during

a measuring period in the long rainy season despite predominant accumulation at the glacier surface. The possible consequences for the determination of the mass balance are not reported.

In July 1995, field work on the Artesonraju Glacier in the Cordillera Blanca brought similar results (Kaser 1996). Up to 11 m deep drill cores were obtained with a hand drill (SIPRE) at four sites between 4950 and 5350 m a.s.l. (Fig. 6) (the measurements were performed by B. Francou, P. Wagnon, W. Tamayo, J. Gómez, B. Noggler and G. Kaser). The only recognizable changes in the stratigraphy were a few slight differences in the size of the firn grains and a few thin ice lamellae, but little change in density was found. Furthermore, the cores were wet from top to bottom from percolating meltwater. Not a single dust layer could be found. Only in the lowest core (4950 m a.s.l.), which reached glacier ice, was this impermeable glacier ice covered with a dirt layer which had probably accumulated over several years. In comparison, density profiles and dust layers in a 20 m deep pit in the firn area of the Ötztal Kesselwandferner (3240 m a.s.l.) show clear autumn horizons. In Fig. 6, the top 11 m have been entered from Ambach and Eisner (1966).

On the whole, it has to be realized that accumulation measurements by traditional methods must fail on Cordillera Blanca glaciers as well as on oth-

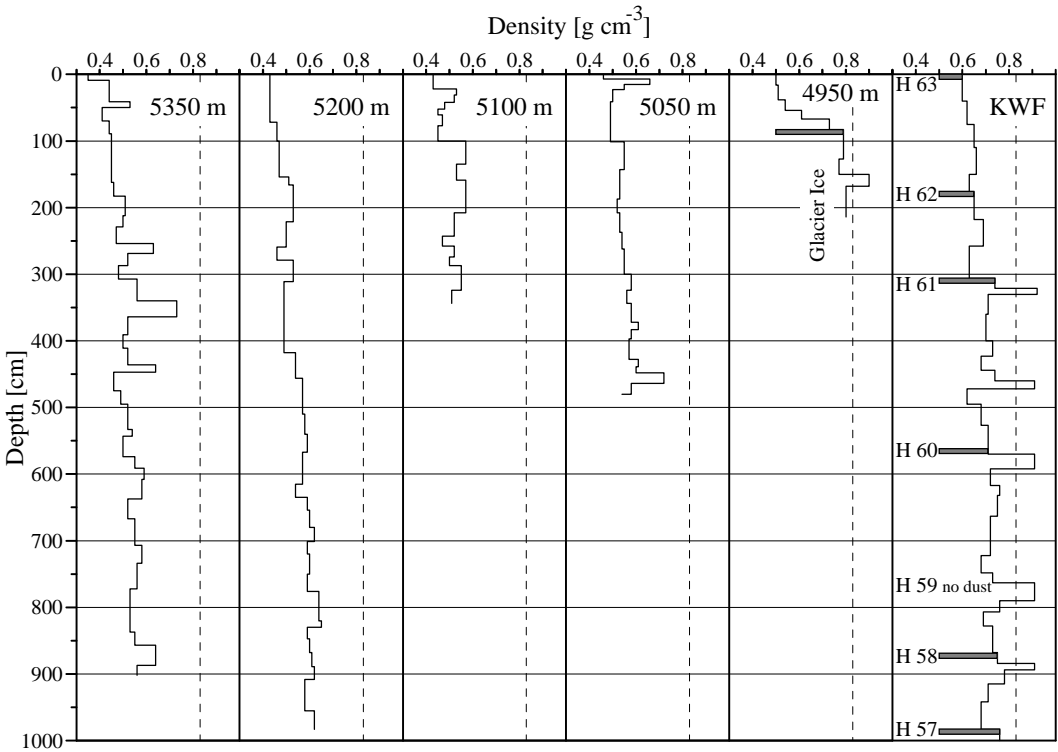


Fig. 6. The density distribution in the drill cores from the firn area of the Glaciar Artesonraju. It is compared to the density profile of a pit in the firn area of the Kesselwandferner (KWF; Ambach and Eisner 1966). The transition density from firn to ice ( $\rho = 0.83$ ; Paterson 1994), the dirt layers (dark bars) and the annual horizons are shown.

er tropical glaciers. Under the given circumstances, it is suggested that stake measurements in the ablation zone be combined with the application of the flux divergence method (Kuhn *et al.* 1999) in order to determine accumulation. The flux divergence method relates the mass flux through the cross-section under the equilibrium line to the mass balance of the accumulation area. This only holds true for a steady-state glacier and was basically described by Finsterwalder (1897). The application of the method requires the determination of the mean equilibrium line altitude, the corresponding cross-sectional area, and the respective surface velocity. The assumption of negligible lateral divergency and a maximum ice velocity at the equilibrium line altitude have to be proved in each case. However, Kuhn *et al.* (1999) show clearly that this method can only give limited information, especially if the glacier is out of balance. Nevertheless, if carefully applied, the method can provide a rough knowledge of the accumulation volume. Ablation and

mass balance profiles can be determined by stake measurements over the ablation zone even if heavily crevassed zones and ice falls may challenge obstacles. If two to four index glaciers can be selected in order to present east side and west side conditions, and if measurements can be made separately for the dry and for the humid season, highly valuable and important data for climate change investigations can be obtained. A respective research project has been approved by the Austrian Science Foundation and has started in September 1999.

**Summary**

Glacier melt in the low latitudes, in contrast to the mid-latitudes, smooths the seasonal runoff variations in the respective catchment basins. Especially during the dry season, it can be the principal contributor. Thus, special attention is given to the behaviour of glaciers which requires mass balance studies. In turn, such studies provide knowledge

on the climate of the low latitudes. Increasing attention is paid to tropical high mountain environments as sensitive indicators of global climate fluctuations. Glaciers are thought to provide valuable information. Although glacier regimes in the low latitudes are basically characterized by the thermally homogeneous tropical atmosphere, they are distinctly different from each other. The inner tropical climate provides humid conditions with accumulation and melting at the same time all year round, whereas small precipitation amounts and the high energy consuming sublimation govern subtropical glaciers. In the outer tropics tropical conditions prevail during the humid season and subtropical conditions during the dry season. In particular, changes in air humidity and their related climate variables interfere with the respective glacier mass balances with different effects. Thus, combined glacier mass and energy balance studies on low latitude glaciers promise valuable knowledge on the tropical and global climate. The outer tropical Cordillera Blanca, also being a distinct barrier to the predominating eastern humid air currents, offers the possibility within short distances of studying both inner tropical conditions on its humid side during the rainy season, and subtropical conditions on its western side during the pronounced dry season.

However, the thermic homogeneity of the tropical atmosphere also causes obstacles for the application of traditional methods to determine the accumulation. In the Cordillera Blanca, the steep slope angles cause additional challenges for field work. A combination of both ablation measurements from stakes in the ablation area and the application of the flux divergence method for the determination of the mass input to the glacier is proposed. In respect to the difficulties mentioned, this may lead to reasonable results, although the flux divergence method provides only a rough knowledge of accumulation.

### Acknowledgement

We greatly appreciate the helpful comments by Keith A. Brugger which improved the final version of the paper considerably.

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*Manuscript received August 1998, revised and accepted December 1998.*