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TROPICAL GLACIERS: POTENTIAL FOR ICE CORE PALEOCLIMATIC RECONSTRUCTIONS

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Abstract. The objective of this work is to evaluate the potential of tropical glaciers and ice caps for the reconstruction of past climatic conditions by the analysis of firn and ice cores. Samples were collected in pits and from cores retrieved on three snow fields in the South American Andes: Quelccaya Ice Cap and Huascarán in Peru and Chimborazo in Ecuador. These are compared with results from west Africa and Indonesia. Measurements include the microparticle concentration, oxygen isotopic abundance ratios, and total beta radioactivity, which in polar regions often exhibit seasonal depositional cycles. Annual variations in these three parameters are fairly well defined on Quelccaya and Huascarán and are apparently absent on Chimborazo. The Quelccaya Ice Cap contains the best preserved annual signal for all three parameters and, although in some instances the annual cycle is difficult to distinguish, the measurement of more than one stratigraphic parameter aids in the interpretation of the firn core records. The relatively flat bottom topography under Quelccaya suggests a simple ice flow regime, and depth-age calculations indicate that an ice core to bedrock should contain a record of 600 to 1300 years. This inference was confirmed by drilling to bedrock in 1983. This investigation of tropical glaciers indicates that the Quelccaya Ice Cap on the eastern edge of the Peruvian Andes has excellent potential to contain a lengthy and interpretable record of climatic conditions within the tropics of South America.

Introduction

The ice sheets and ice caps of the polar regions have been the central focus of ice core paleoclimatic reconstructions. Tropical ice fields do not contain records as far back in the past; however, they may provide information about past climatic conditions in the tropical regions where such records are virtually nonexistent. Figure 1 illustrates the six tropical ice caps or glaciers where snow samples and ice cores have been collected and preliminary analyses have been conducted. The primary objective of the present review is to assess the potential of various tropical ice fields for ice core paleoclimatic reconstruction.

Microparticle concentrations (p), oxygen isotope ratios (δ), and total beta radioactivity (β) in snow have been measured for three tropical ice bodies in the Andes: Chimborazo, Ecuador (6300 m, 1°28'S, 78°50'W); Huascarán Col, Peru (5990 m, 9°07'S, 77°36'W); and the Quelccaya Ice Cap, Peru (5670 m, 13°56'S, 70°50'W). These three sites provide a cross section of samples ranging south from the equator to the outer tropics of South America. These core data from the Andes are compared with similar measurements from Mt. Kenya and Kilimanjaro in east Africa and Mt. Jaya in Indonesia.

The analyses of the aforementioned constituents (p, δ, β) in shallow pits, in conjunction with visual stratigraphy, provide the fundamental framework for the interpretation of similar records from deeper cores. Such near-surface investigations may be used to eliminate unfavorable sites and to select ice fields where paleoclimatic records are expected to be best preserved and are most amenable to interpretation.

Pit studies reveal a large variation in the seasonal deposition pattern of microparticles, oxygen isotopes, and total beta radioactivity, indicating the necessity to measure more than one variable to aid in clarification of the annual signal when ambiguities occur. These three parameters are associated with different transportation and deposition processes and therefore are only indirectly related. The concentrations of microparticles and total beta radioactivity (^{90}Sr and ^{137}Cs) within the snow stratigraphy reflect (1) the abundance of particulate material in the atmosphere, (2) the efficiency of both wet and dry depositional processes, and (3) the rate of snow accumulation which may additionally dilute or concentrate the material. The influx of microparticles depends upon extent of local source areas, distance from sources, volcanic activity, wind speed, and wind direction.

The seasonal input of beta radioactivity is probably related to the seasonal movement of the southern hemisphere Hadley cell. Vertical transport through the Hadley cell transfers roughly 40% of the stratospheric mass through the tropopause into the troposphere each year [Reiter, 1975]. Additionally, during the dry winter season the descending arm of the Hadley Cell is often positioned over the Quelccaya Ice Cap, bringing this material near the surface. On the other hand, the oxygen isotopic composition reflects (1) the precipitation/evaporation water vapor balance of the air mass along its trajectory from the moisture source over the oceans to its point of deposition and (2) the condensation process and temperature. Because of the dependence of $\delta^{18}O$ upon the precipitation process, large differences in the isotopic composition of the snow can occur between storms or even within a single snow shower. Therefore, no direct physical relationship exists between microparticle, $\delta^{18}O$, and beta radioactivity signals. However, relationships between these parameters may result from their common dependence on the annual regime of large-scale circulation and precipitation in the eastern Andes.

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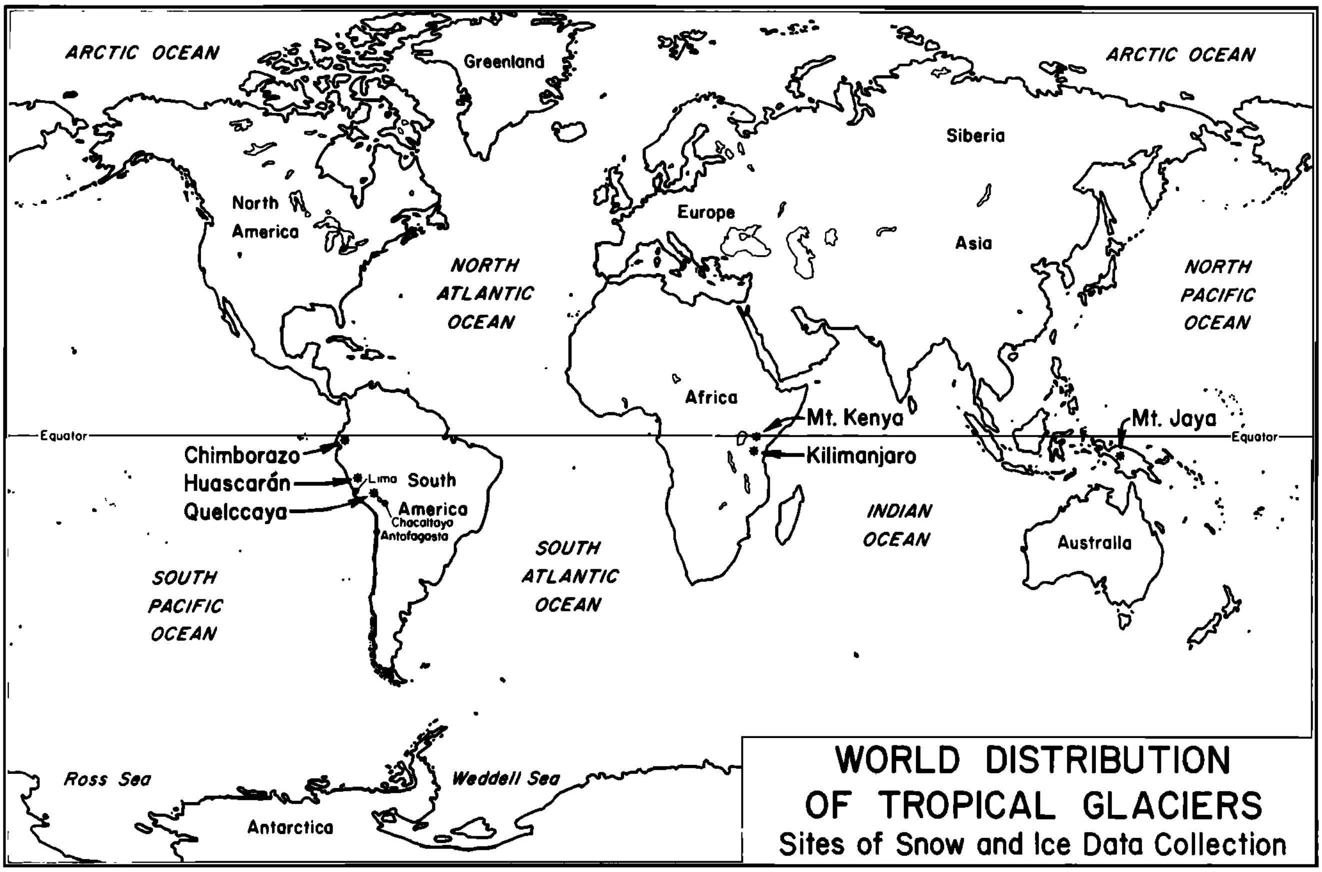

Fig. 1. Distribution of tropical glaciers where snow and ice data have been collected and other locations mentioned in the text.

Quelccaya

The Quelccaya Ice Cap in the easternmost glaciated mountain chain of the Peruvian Andes has been studied most extensively and is the subject of a continuing glaciological program including core drilling to bedrock. The Quelccaya Ice Cap (5,670 m), situated in the outer tropics, is unique among tropical glaciers in various respects. Being the highest object in the immediate vicinity, local disturbances of both the depositional stratigraphy and radiation balance are minimized. From depth-age calculations based upon the net accumulation and monopulse ice radar ice thickness determinations (180 $\pm$ 10 m) and assumed ice deformation properties, it was inferred that a core to bedrock would probably contain between 600 and 1300 years of accumulation [Thompson et al., 1982]. This estimate was confirmed by drilling to bedrock in 1983. Bore-hole (15-37 m) temperatures on the summit of Quelccaya are 0°C indicating that the ice cap is temperate in the upper portion [Thompson, 1980]. During 1983 drilling to bedrock, freezing was observed each night at the bottom of the drill hole. This observation indicates that temperatures below 43 m in the ice cap are below freezing. Therefore the stratigraphic record contained within this ice cap, situated in a cold environment with a mean annual temperature of -3°C, should be minimally disturbed by percolation of meltwater.

In order to place the paleoclimatic interpretation of ice cores on solid footing, the glaciological work was complemented by studies of modern climate, heat, and mass budget [Hastenrath, 1978; Mosley-Thompson, 1982]. Automatic weather stations first installed in 1976 on the summit of the Quelccaya Ice Cap have recorded wind direction and speed, temperature, sunshine duration, and, since 1979, total shortwave radiation. These records extend from July (installation) over about 8 months, but the length of each record varies depending upon equipment failure or burial by snow. These observations at the Quelccaya summit (5,670 m) are meaningfully compared to the 500 mbar (50 kPa) standard isobaric surface, which in this area (as in much of the tropics) stands around 5,850 m [Chu and Hastenrath, 1982]. The nearest radiosonde stations are Lima and Antofagasta along the Pacific coast (Figure 1). Taking the 500 mbar (50 kPa) level as primary reference, the autographic records at the Quelccaya summit show a good spatial and temporal (annual cycle and interannual variability) consistency with the general circulation and climate in the greater Andean region.

During most of the year, an anticyclonic axis in the 500 mbar (50 kPa) flow pattern sits over the general area of the South American Altiplano. Accordingly, winds at Quelccaya are quite variable, with a directional steadiness of 10-30 %. From June to September, winds on Quelccaya are predominantly from the west and northwest [Mosley-Thompson, 1982] which is consistent with the large-scale 500 mbar (50 kPa) flow pattern [Chu and Hastenrath, 1982]. During the southern winter, wind speeds are higher (average = 4.4 m s^{-1}) as the Quelccaya region comes under the influence of southern hemisphere mid-latitude westerly wind regime. Progressing toward southern summer, wind speeds decrease (average = 3.3 m s^{-1}), and the tropical easterlies become more prevalent. The flow pattern is complicated by the evolution of a summertime anticyclone over the Altiplano and adjacent southern Amazonia, albeit most prominent in the upper rather than the middle troposphere [Sadler, 1975; Hastenrath, 1977; Virji, 1981; Chu and Hastenrath, 1982]. This upper-tropospheric anticyclone is related to the summertime latent heat release over the Altiplano and adjacent southern Amazonia. Throughout the year, the wind at the Quelccaya summit tends to be strongest during daytime, seemingly as a result of enhanced convection and downward momentum transfer.

The annual mean temperature at the Quelccaya summit is around -3°C, and the annual range is of the order of 2°C, which is common in the tropics. Temperatures recorded at the Quelccaya summit are somewhat higher than values interpolated from the nearest radiosonde stations (Lima and Antofagasta), but the Quelccaya autographic records share with these upper-air stations the major characteristics of both annual cycle and interannual variability.

On Quelccaya, as over most of the Altiplano, the southern winter is the dry season and the summer is the precipitation season. The latitudinal shift of the anticyclonic axis in the lower to middle troposphere is plausibly associated with changeovers in the divergence and vertical motion pattern, with a tendency toward enhanced subsidence in winter. Moreover, as described above, the westerly wind regime prevails during the dry winter, while easterlies are a feature of the wet summer. The Atlantic or Amazon side of South America must be regarded as the major moisture source region for precipitation over the eastern Andes and the Altiplano [Johnson, 1976; Ratisbona, 1976]. Field observations indicate that precipitation-bearing weather disturbances originate over the Amazon Basin to the east.

The Quelccaya Ice Cap summit receives roughly 3 m of new snow each year, or an annual net accumulation of 1 m of water equivalent. In June or July of each year since 1976, snow pits were excavated on Quelccaya, and samples were collected for the analysis of microparticle concentrations (p), oxygen isotopic ratios (δ), and total beta radioactivity (β) in the previous years' accumulation. On this basis, annual signals in the aforementioned parameters (p, δ, β) can be identified. Figures 2 and 3 summarize these data for each year since 1976.

The microparticle concentrations on Quelccaya exhibit a distinct seasonal variation with high concentrations associated with the dry season [Thompson et al. 1979; Thompson, 1980]. Often, these concentration variations can be traced from one pit to another in a given year (Figures 2 and 3). The association of high particulate concentrations with the dry season is a function of the following: (1) high radiation receipt with little accumulation (with minor sublimation or near surface melting insoluble particles will remain on surface), (2) dominant wind direction from the west and northwest transporting material from the high, dry Altiplano, and (3) higher wind speed during that season. It is noteworthy that on the Lewis Glacier on Mt. Kenya (Figure 1) two microparticle concentration maxima are found each year, coincident with the two seasons of reduced

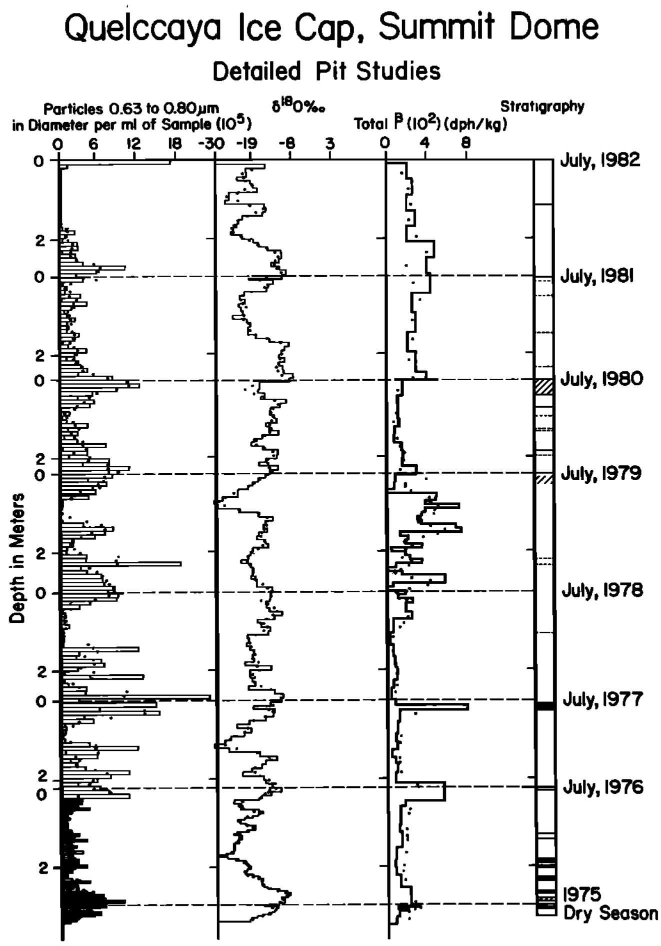

Fig. 2. Annual variations in microparticle concentration, $\delta^{18}O$, total beta radioactivity, and stratigraphy determined from snow pits sampled on the summit of Quelccaya. Those pits for which all three parameters were available have been arranged in a time series. The dashed lines transecting all three profiles represent the July surface when the pits were excavated. Each pit represents one annual layer at the surface and thus all densities are similar. Microparticle data are given as the number of particles between 0.63 and 0.80 μm in diameter per millimeter of sample, oxygen isotope abundance ratios are presented in parts per mil (°/oo), and total beta radioactivity is reported in disintegrations hr^{-1} kg^{-1} of water (dph/kg). The dots represent the three-sample running mean which slightly smooths the high frequency or intersample variations. The visual stratigraphy is illustrated on the right. The dashed line represents minor (≈0.005 m thick) ice layers while solid lines represent thicker ice layers (0.01 - 0.02 m). The diagonal lines illustrate visually dirtier layers.

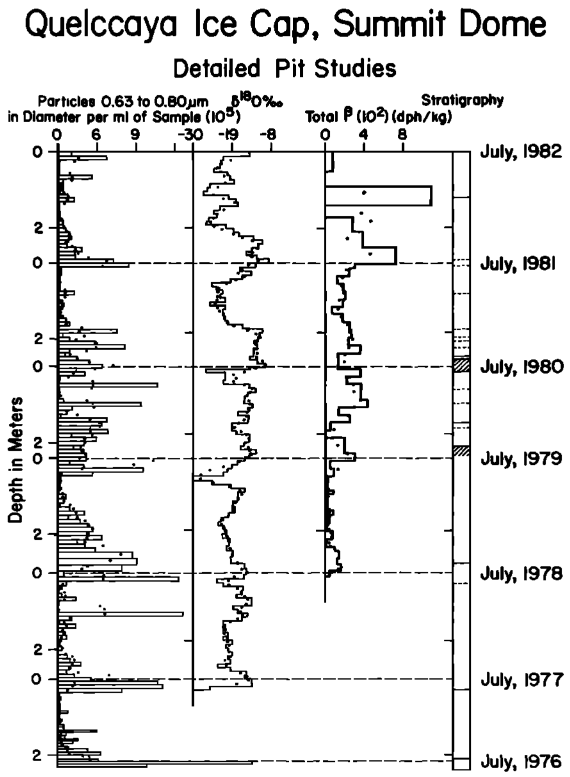

Fig. 3. Same as Figure 2 except that the profiles represent data from a second set of pits excavated near the summit of Quelccaya. Oxygen isotope and total beta radioactivity data are not available for all of the second suite of pits. These second pits were excavated 20 m from the pits illustrated in Figure 2 except the 1979-1978 pit which was excavated 800 m to the east of the summit pit illustrated in Figure 2.

precipitation [Thompson and Hastenrath, 1981]. On Quelccaya, ice layers vary considerably in number from one year to another (e.g., compare 1976 to 1977). As ice layers are associated with intense radiation receipt, their numbers and thickness within a given year reflect the annual variability of cloud cover which controls the receipt of radiation. In addition, microparticle analyses of shallow cores (10 to 15 m) confirm that the seasonal signal is preserved within the ice [Thompson, 1980].

The oxygen isotopic composition of snow, $\delta^{18}O$, also exhibits an annual cycle with least negative $\delta^{18}O$ values associated with winter snowfall [Thompson and Dansgaard, 1975]. Summer snow is isotopically very light. In several cases, however, the record shows significant short-term variations in $\delta^{18}O$ within a single year which makes it sometimes difficult to identify annual cycles. Examples are the isotope records for 1979 and 1980 which exhibit a semiannual peak (Figure 2). The metamorphic processes by which the firn is transformed slowly into ice will smooth the minute details (now visible in pits) within the annual unit. The primary signals which will survive the firnification process and be preserved within an ice core are the distinct differences between the characteristics of summer (wet) and winter (dry) snowfall.

Total β radioactivity, illustrated in Figures 2 and 3, often exhibits a seasonal cycle with high beta generally associated with high particle concentrations and less negative oxygen isotope values. As Figures 2 and 3 illustrate, β concentrations do not always show this distinct seasonal variation. The ^{90}Sr concentrations in surface air measured at Chacaltaya Observatory, Bolivia (5222 m, 16°21'S, 68°08'W, Figure 1) show a very distinct annual variation in activity with a peak value measured in the dry season [Environmental Measurement Laboratory, Environmental Quarterly, U.S. Department of Energy, 1977].

A high degree of correlation from sample to sample among p, $\delta^{18}O$, and β profiles within a single pit is not generally found, nor should it be expected as each is controlled by different mechanisms. Additionally, the correspondence among these profiles will depend partially upon the detail with which the pit was sampled and the nature of individual snowfall events. Three measures of correlation (the Pearson product moment correlation coefficient, the Spearman rank correlation coefficient, and the Kendall tau; the latter two tests are nonparametric [Daniel, 1975] and do not require that the sample population be bivariate normal) were calculated for each set of pit profiles. The correlations range from excellent to zero. Correlation coefficients for particle concentrations and $\delta^{18}O$ were significant at the 95% level or better for 1976, 1979 (pits 1,2), 1981 (pits 1,2), 1982 (pits 1,2). In the 1977, 1978, and 1980 pits, correlations were very near zero. The correlation among these three parameters is much stronger in the core records where smoothing of high frequency events has occurred and only the seasonal differences remain [see Thompson et al., 1979, Figures 3 and 4].

Each year since 1976 net annual accumulation has been measured on Quelccaya by using both stakes and pit stratigraphy. In addition, net accumulation estimates from cores dating back to 1960 reveal that annual net accumulation was less than normal in 1965, 1972, and 1976, all years of major El Niño events [Ramage and Hori, 1981]. The net annual accumulation in the 1977 pit (represents July 1976 to July 1977) is 2.2 m (Figures 2 and 3) and contrasts sharply with snow accumulations of 3 m or more in the other pits. During the 1983 Quelccaya field season, accumulation from July 1982 to July 1983 was found to be 2 m, a substantial reduction from the usual 3 m. The 1982-1983 period has been recorded as one of the strongest El Niño events this century. These data are inconclusive, but suggest the potential for an El Niño signal in the net balance record of the Quelccaya Ice Cap. Longer net accumulation records obtained from the deeper cores will allow comparison between net accumulation on Quelccaya and major El Niño events back to 1790.

Huascarán

In July 1980, an ice radar sounding [Jezek and Thompson, 1982] and a drilling program was conducted on the La Garganta glacier (5,990 m) (the col) of the highest tropical mountain, Huascarán. The core, drilled from the surface to a depth of

10 m, was cut and sampled for microparticle, oxygen isotope, and total β radioactivity measurements. Mean values of microparticle concentrations and oxygen isotopes are similar to those measured on the Quelccaya Ice Cap as illustrated in Table 1.

For surface values (Figure 4) representing snow deposited during the dry season (June, July, and August) high particle concentrations are associated with high total beta radioactivity and with less negative $\delta^{18}O$ values. While the microparticle and oxygen isotope records are ambiguous, the total radioactivity record shows very distinct peaks. This may reflect, in part, the larger sample sizes used in the collection of the radioactivity samples which tend to smooth the high frequency signals. Some of the ambiguity in these records may reflect the difficulties in drilling the upper unconsolidated firn and may account for why the microparticle, oxygen isotope, and β radioactivity records are more comparable below 6 m depth where the firn becomes more dense and is easier to recover. Assuming that the total beta radioactivity peaks are annual, as they are on Quelccaya and in the Chacaltaya, Bolivia, record, this record provides the first estimate of annual net accumulation (A_n) on Huascarán. Over the presumed four year period, A_n equals 0.97 m of water. Note that the $\delta^{18}O$ variations exhibit ranges similar to those measured on the Quelccaya Ice Cap, (i.e., a range of about 22‰ (Table 1) between the most negative and least negative values in surface snow). Similarly, the least negative $\delta^{18}O$ values apparently represent the dry season precipitation.

Microparticle concentrations are of the same magnitude as those measured on Quelccaya, 5° latitude further south. Mean surface $\delta^{18}O$ values, mean $\delta^{18}O$ values for all samples, and average particle concentrations for Huascarán and Quelccaya are similar. This similarity may be attributed, at least in part, to the fact that both sites share a common annual cycle of large-scale circulation and common moisture source, the vast Amazon Basin to the east of the Andes. Thus these data suggest for the first time that paleoclimatic records established from ice cores in the Quelccaya Ice Cap may reflect conditions prevalent over a large area of the tropical Andes.

Chimborazo

In 1981 a lightweight hand operated drill was employed to extract a 6-m core from the relatively flat summit of the north peak of Chimborazo, Ecuador (6300 m, 1°28'S, 78°50'W). Figure 5 illustrates that the $\delta^{18}O$ record shows no clear seasonal signal, although the range between maximum and minimum $\delta^{18}O$ is about 10.3‰ Similarly, the particle profile is difficult to interpret. Perhaps the high particle concentrations at the surface and again at a depth of 3 m represent an annual cycle. On the other hand, the beta profile suggests possibly one cycle in the 6 m, although the very large sample size precludes elucidation of higher frequency variations. Conceivably, the reduced seasonality and double-peaked precipitation regime characteristic of the Ecuadorian Andes [Johnson, 1976; Hastenrath, 1981] may result in a weak annual signal in the ice core records.

Ambiguities in the data profiles may also result from incomplete core recovery which was due to the large grained, unconsolidated character of the firn. In addition, very high easterly winds dominate on this mountain and have been reported in the literature [Hastenrath, 1981; Whymper, 1892]. These strong winds may disturb the surface to such an extent that any seasonal depositional cycle is obscured.

Discussion

Table 1 summarizes the results from glaciological investigations of six tropical glaciers. Sources of information for the Lewis Glacier, Africa, include Thompson [1981], Thompson and Hastenrath [1981]; for the Meren and Carstensz Glacier of Mt. Jaya, New Guinea, Allison [1976]; and Kilimanjaro, Tanzania, Gonfiantini [1970].

The lowest particle concentrations are found on the Quelccaya Ice Cap. Here the average concentration of particles with diameters $\geq$0.63 μm is 2 x 10^3 ml^{-1}. Chimborazo exhibits the highest particle concentrations which are attributed directly to the very high winds and desert source area for particulates immediately to the west of the mountain. Similarly, the high particle concentrations on the Lewis Glacier result from the exposed rock surfaces near the core sites. These tropical values are an order of magnitude higher than the average Holocene particle concentrations of 5 x 10^4 particles $\geq$0.63 μm ml^{-1} found in the Camp Century core, Greenland, and 1.3 x 10^4 particles $\geq$0.63 μm ml^{-1} found in the Dome C core, east Antarctica.

These tropical regions exhibit small annual temperature variations, and there is no clear relationship between $\delta^{18}O$ and mean surface temperature. This is unlike the situation in the polar regions where air temperature seems to be well correlated with the oxygen isotopic distribution. The $\delta^{18}O$ ratios from Mt. Kenya and Kilimanjaro are similar, reflecting a similar climatic environment and geographical proximity. Likewise, there is a correspondence between Quelccaya, Huascarán, and Chimborazo. Of the six ice bodies investigated, the average $\delta^{18}O$ values are lowest for the Quelccaya Ice Cap, and $\delta^{18}O$ values become less negative toward the equator for sites of similar elevation. The seasonal range of $\delta^{18}O$ values is largest for Quelccaya and Huascarán. The large seasonal range (about 22‰) combined with high annual precipitation makes it more likely that the annual $\delta^{18}O$ record is preserved with time and depth on Huascarán and Quelccaya.

Huascarán is less favorable than Quelccaya for obtaining a tropical ice core record for several reasons. First, as the drill site is located in a col, the complex ice dynamics may substantially distort any preserved record. Second, the approach to the col is difficult due to severe crevassing in some years.

The most striking features of the three Andean oxygen isotope records are (1) the light (very negative $\delta^{18}O$) average precipitation and (2) the large annual variation. Both may be explained by

TABLE 1. Summary of the Oxygen Isotope and Microparticle Data Available From Six Tropical Glaciers.

Tropical Glacier (location)	Elevation m	Mean Air Temperature °C	Mean $\delta^{18}O$ ‰[a]	Mean for Near-Surface Samples $\delta^{18}O$ ‰	Mean for All Samples $\delta^{18}O$ ‰	Range $\delta^{18}O$ ‰	Particle Concentration, Diameter ≥ 0.63 µm ml^{-1}	Primary Reference for This Work
Quelccaya Ice Cap, Peru (13°56'S, 70°50'W)	5670	-3		-21.0	-19.4	22[b,c]	2×10^5/ml	Thompson and Dansgaard [1975]; Thompson et al. [1979]
Huascarán Col, Peru (9°07'S, 77°36'W)	5990			-17.4	-17.5	22.3[b,d]	2.8×10^5/ml	this paper
Chimborazo, Ecuador (1°28'S, 78°50'W)	6300			-14.7	-15.4	10.3[e]	11.6×10^5/ml	this paper
Lewis Glacier, Kenya, Africa (0°9'S, 37°19'E)	4870	-0.5		-7.8	-6.0	5.4[f]	8×10^5/ml	Thompson [1981]
Mt. Jaya, New Guinea (4°05'S, 137°10'E)	4800	0		-15.3	-15.7	4.3[g]		Allison and Peterson [1976]
Kilimanjaro, Tanzania (3°S, 37°20'E)	4600		-3.7					Gonfiantini [1970]
	4700		-4.1					
	4850		-4.2					
	5100		-4.6					
	5200		-4.7					
	5300		-5.4					
	5400		-5.9					
	5700		-6.8					

[a] For surface snow samples collected at these elevations.
[b] Most negative $\delta^{18}O$ values occur during warm season (opposite to polar regions).
[c] Maximum, -11; minimum, -33.
[d] Maximum, -6.6; minimum, -28.9.
[e] Maximum, -13.0; minimum, -23.3.
[f] Maximum, -4.8; minimum, -10.2.
[g] Maximum, -12.7; minimum, -17.0.

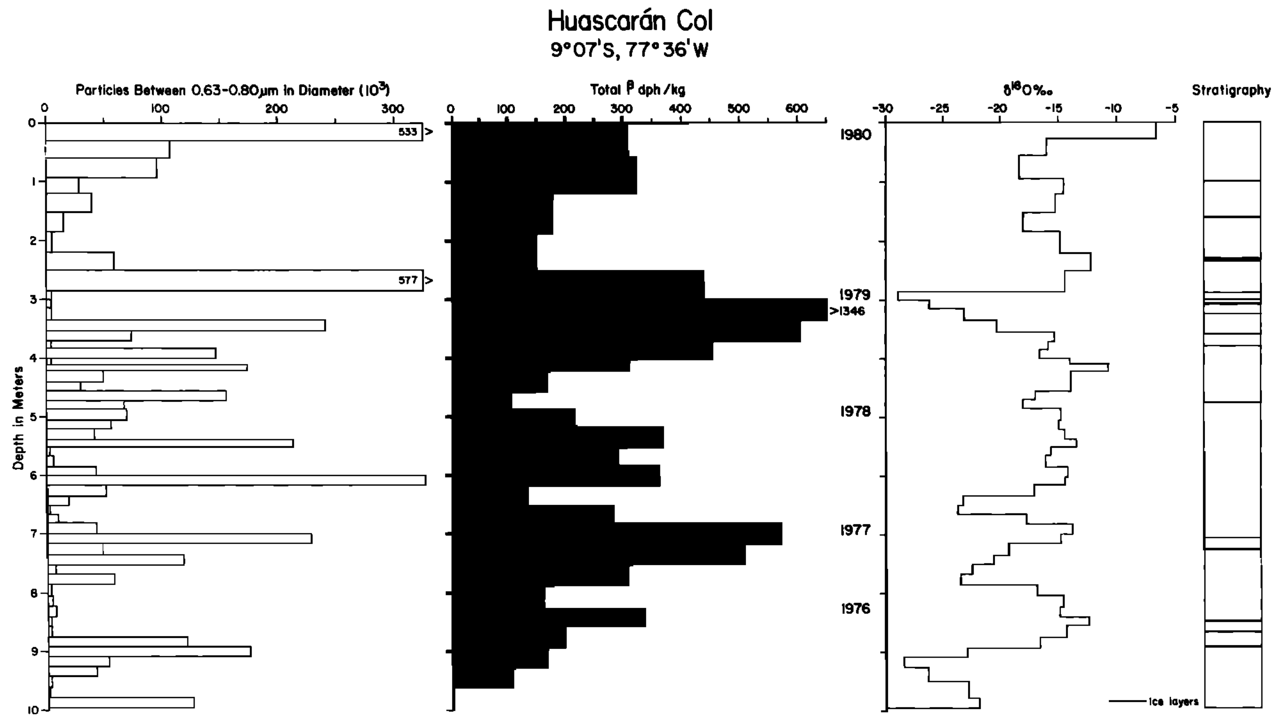

Fig. 4. Microparticle, total beta radioctivity, and $\delta^{18}O$ measurements from a 10-m firn core collected July 1980 from the col of Huascarán. (a) Vertical distribution of microparticle concentrations (particles 0.63 to 0.80 μm in diameter per ml of sample), (b) total beta radioactivity (dph/kg), (c) $\delta^{18}O$ (‰), and (d) visible stratigraphy (solid lines indicate ice layers).

considering (1) the high altitude, (2) the characteristics of the air masses from which the precipitation is derived, (3) the seasonal differences in the hydrological cycle of the Amazon Basin, and (4) the primary process of precipitation (convective showers).

The Quelccaya Ice Cap is located on the first rise of the Andes, and the abrupt change in elevation from the Amazon Basin (500 m) to the Quelccaya Ice Cap (5650 m) over a distance of 150 km contributes to the negative average $\delta^{18}O$ values of Quelccaya precipitation. In temperate regions the altitude effect is estimated to be approximately -0.2‰ per 100 m [Dansgaard, 1964; Ambach et al., 1968; Burk and Stuiver, 1981]. Thus a similar elevation effect alone can account for a depletion of about 10‰ and contribute to the very low $\delta^{18}O$ values (average $\delta^{18}O$ about -20‰) measured on Quelccaya. However, the exact nature of the altitude effect must be more firmly established for tropical latitudes.

As discussed above, the Amazon Basin is the major source of moisture for the eastern Andes throughout the year. Accordingly, the seasonal $\delta^{18}O$ record on Quelccaya may reflect seasonal differences in the isotopic composition of the moisture from the Amazon Basin. This is determined by (1) the nature of the air masses advected into the Amazon Basin and by (2) the seasonal relationship between precipitation and evapotranspiration processes.

The hydrological cycle of the Amazon Basin is difficult to quantify for lack of surface hydrological data and radiosonde observations. However, four investigations [Molión, 1975; Lettau et al., 1979; Salati et al., 1979; Longinelli and Edmond, 1983] provide enough information to suggest that seasonal differences in the recycling of water vapor lead to large seasonal variation in $\delta^{18}O$ in both the precipitation in the basin and in water vapor ascending the Andes. During the wet season, precipitation associated with intense convection far exceeds that replaced by evapotranspiration. The removal of water vapor from the air mass as it moves west results in depletion of heavier isotopes, leading to more negative $\delta^{18}O$ ratios recorded within precipitation on Quelccaya. Additionally, during the summer the heavy convective showers due to intense local heating over the altiplano lead to isotopically light precipitation [Dansgaard, 1964]. The lower average $\delta^{18}O$ values on Quelccaya reflect a combination of (1) the elevation effect, (2) water vapor depletion over the Amazon Basin, and (3) the convective shower effect discussed above. These processes are described more quantitatively in another paper [P. M. Grootes et al., manuscript submitted, 1984].

Conclusions

Measurements of microparticle concentrations, oxygen isotopic ratios, and total beta radioactivity in snow pit and ice core samples from tropical glaciers around the world yield quite varied results (Table 1). To a large extent the annual variations in the magnitude of these snow parameters and their stratigraphic preservation are a function of the local climatic conditions

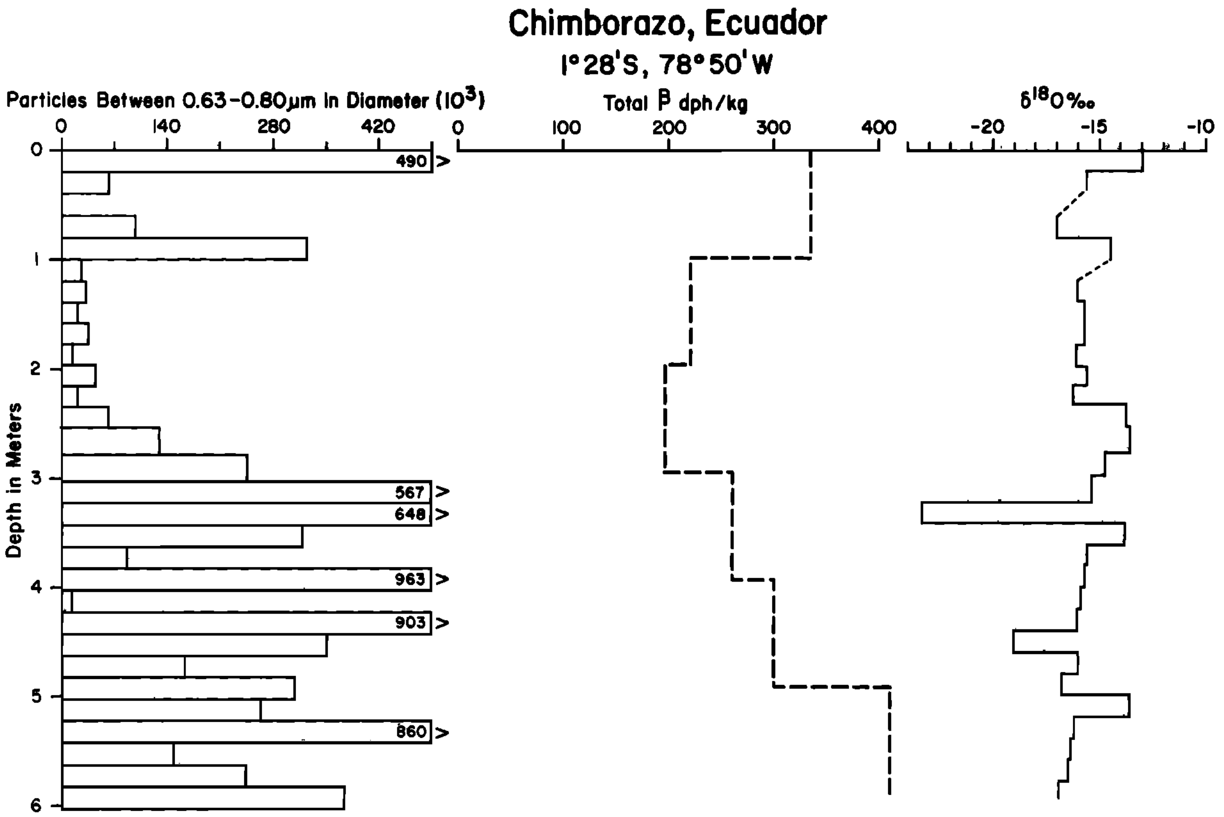

Fig. 5. Microparticle, total beta radioactivity, and $\delta^{18}O$ measurements in a 6-m firn core collected July 1981 from Chimborazo, Ecuador. (a) vertical distribution of microparticle concentrations (particles between 0.63 to 0.80 μm in diameter per ml of sample), (b) total beta radioactivity (dph/kg), and (c) $\delta^{18}O$ (‰).

and physical environment. However, similarities in these snow properties do exist within smaller regions such as the tropical portion of the Andes Mountains or the glaciers of east Africa. This is illustrated by comparing the p, $\delta^{18}O$, and β measurements for Quelccaya, Huascarán, and Chimborazo in South America.

These investigations have provided the first estimate of net annual accumulation on Huascarán (0.97 m of water). These analyses also reveal the limited potential of the snowfield on Chimborazo as a drill site since no easily interpretable record is preserved.

Of the tropical glaciers investigated, the Quelccaya Ice Cap in Peru has the greatest potential to contain a lengthy and interpretable ice core record. The extensive analysis of the particles, $\delta^{18}O$ and β, in surface accumulation illustrates that a seasonal cycle is deposited and is preserved within the ice stratigraphy. The microparticle record allows identification of annual layers from which a net balance and precipitation chronology may be constructed. The oxygen isotope ratios are eventually to be interpreted in relation to the water vapor history along the upstream trajectory and thus more remotely in terms of the large-scale vertical motion pattern. Beyond these immediate objectives, recent investigations of tropical climate anomalies (see bibliography in Hastenrath and Wu [1982]) suggest that the long ice core records, such as those anticipated for Quelccaya, may be related to the general circulation and climate dynamics of the global tropics.

This preliminary appraisal of tropical ice core records indicates a relationship between glaciological evidence and both the local and, in some cases, regional climate. The Quelccaya ice core reflects the seasonal precipitation regime in the outer tropics of southern Peru. Drilling to bedrock in 1983 revealed that the paleoclimatic information contained in the Quelccaya ice cores will cover one and a half millennia.

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