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Monthly balance and water discharge of an inter-tropical glacier: Zongo Glacier, Cordillera Real, Bolivia, 16° S

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ABSTRACT. Measurements of mass balance were performed every month on Zongo Glacier, Bolivia. Simultaneously, water-discharge, temperature and precipitation data were obtained. The first year of the survey, 1991–92, was marked by an ENSO (El Niño–Southern Oscillation) event with high temperature and low precipitation, whilst the following year, 1992–93, was normal. Results point to the early and late wet season (October–December and March–May) as playing a critical role in the determination of the annual mass balance. The wet season is the warmest period of the year and consequently the duration of the wet season is a highly relevant variable in determining mass balance. Both glaciological and hydrological methods for the determination of the mass balance provide similar results. Our study confirms that ENSO events have a major influence on the rapid glacier retreat currently affecting this part of the Andes.

INTRODUCTION

Very few studies have been performed on the mass balance of glaciers situated between the tropics. The only studies so far published are of Lewis Glacier in Kenya (Hastenrath, 1984, 1989) and of two glaciers in the Cordillera Blanca, Peru (Ames, 1985; Kaser and others, 1990). These studies were conducted by collecting data on a yearly basis and were not coupled with systematic runoff measurements.

However, the coincidence at low latitudes between the wet season, favourable to accumulation, and the warm period, when ablation is maximum, makes it difficult to acquire knowledge of glacier mass balance from simple annual data. Furthermore, the precipitation distribution is fairly variable from year to year and the duration of the rainy season is yet more unpredictable. The glacier may be expected to react significantly to this variability.

Thus, if we want to understand the processes that control glacier mass balance in these regions, it is necessary to conduct measurements on a monthly basis and follow up the survey over a period of several years. With such an approach, it is possible to attain a greater understanding of the main factors that control the rapid glacier retreat presently occurring in this part of the Andes (Lliboutry and others, 1977; Ames, 1985; Jordan, 1991), as well as in other low-latitude mountains (Hastenrath and Kruss, 1992). Another question needing to be addressed is the consequence of an ENSO (El Niño–Southern Oscillation) event for the glacier mass balance. According to the study at the Quelccaya Ice Cap, Peru (Thompson and others, 1984), ENSO events could affect mass balance by decreasing snow accumulation at high altitude in the Andes. Nevertheless, the marked reduction in precipitation during these episodes occurs during the warm season, so the effects on the mass balance could also be associated with a strong ablation (Francou, 1992).

Our investigation has concentrated on two glaciers in the Cordillera Real, Bolivia: Zongo Glacier and Chacaltaya Glacier. This paper presents the data collected on Zongo Glacier during the first two hydrological years of the study, from September 1991 to August 1993. It represents a first attempt to present a monthly pattern of glacier mass balance in the tropics and to analyse the effect of an ENSO event.

AREA DESCRIPTION AND DATA-GATHERING METHODS

The glacier is situated in the Huayna Potosí massif (6088 m), at 16° S, in the Amazon basin. This valley-type glacier is 3 km long and has a surface area of 2.1 km^2 (Fig. 1). The upper reaches are exposed to the south whereas the lower section faces east. The maximum and minimum elevations are 6000 and 4890 m a.s.l., respec-

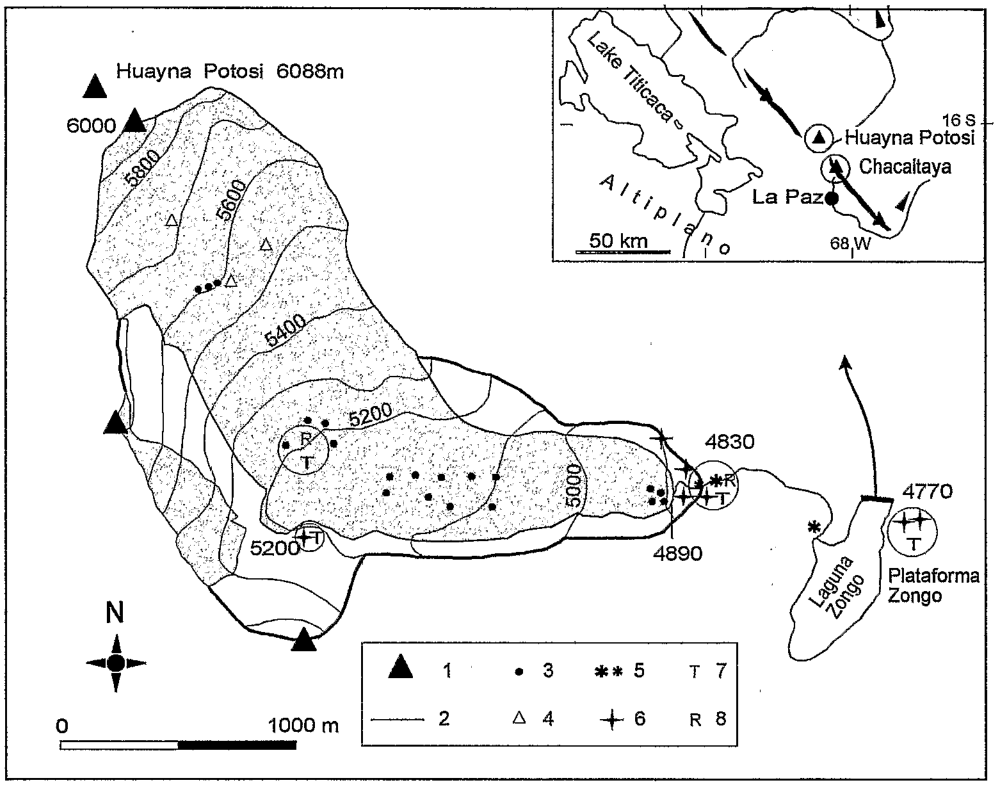

Fig. 1. Huayna Potosí and Zongo Glacier with the survey system in 1993. 1, Principal peaks; 2, Limits of basin; 3, Stakes; 4, Pits and crevasses; 5, Water-level recorder; 6, Rain-gauges; 7, Thermograph; 8, Pyranometer.

tively. The accumulation zone amounts to 60% of the total area under steady-state conditions (annual mass balance approaching zero), at an equilibrium-line altitude (ELA) of 5100 m. Under similar conditions, average precipitation at the ELA totals 1.0 m a^{-1} and the average temperature is −2°C. Thus, it can be deduced that this glacier is mainly temperate with a limited cold surface near the summit.

A 15 stake network was placed in the ablation zone in order to determine the mass balance and the surface velocity, augmented by a further three stakes and several pits in the accumulation zone from 5500 to 5800 m (Fig. 1). The 15 stakes in the ablation zone were surveyed every month and the surface density of the snow and ice was measured in order to obtain the amount of accumulation and ablation in water equivalent. The accumulation in the upper reaches of the glacier was recorded immediately before and after the wet season, in September and April. Annual net balance was evaluated between the beginning and end of the hydrological year, September–August. For the ice falls not surveyed by the stake network (the 5050–4950 and 5500–5300 m altitude ranges), net balance was estimated by linear interpolation. Mass balance was also computed independently by means of a hydrological method (Ribstein and others, in press), whereby we have the possibility of verifying the mass-balance values obtained by the glaciological method. In order for this to be done, a water-level recorder was set at 4830 m (150 m below the glacier terminus), providing continuous runoff measurements. Five storage rain-gauges, surveyed monthly, were placed near the glacier at 5200 and 4900–4850 m. These rain-gauges, with a cross-section of 2000 cm^2, have proved to be suitable for measuring snow precipitation and have shown an increase of 20% over the precipitation levels indicated by the lone classical 314 cm^2 rain-gauge in place since 1970 on Plataforma Zongo (4770 m).

In order to obtain estimates of the parameters controlling glacier ablation, thermographs with radiation shields were placed at 5200, 4830 and 4770 m. More recently, in 1993, pyranometers capable of measuring global radiation were sited at 5200 and 4830 m, with a radiometer placed at 5200 m so as to record the net all-wave radiation.

Every year since 1991, a topographic survey has been conducted in August on the 15 ablation stakes and on the terminus contour to give estimates of the surface velocity and of the terminus fluctuation. During the first year of the study, the measured glacier retreat was 10–20 m, whereas during the second year the glacier terminus was stationary.

The easy accessibility of the glacier all the year round makes it possible to claim high levels of accuracy for data collected during the 2 years. But the progressive adjustment of the survey network during this time does not allow us to use all the collected data in this paper.

MONTHLY NET BALANCE IN THE ABLATION ZONE, 1991–93

The climates of 1991–92 and 1992–93 present very different patterns. The first year was marked by mature-phase ENSO conditions (Kousky, 1993). Values of the south-oscillation index (the difference between the standardised sea-level pressure anomalies at Tahiti and

Darwin) were strongly negative, with a minimum −2.2 standardised value for the 5 month running mean. This is the lowest monthly value since the 1982–83 episode, which has been described as a very strong event. Such a situation in the Pacific is associated with low precipitation levels in the central Andes. This observation was first pointed out in the Quelccaya Ice Cap by Thompson and others (1984), and analysed further by Francou and Pizarro (1985) and Tapley and Waylen (1990), using data collected from meteorological stations.

The second year was quite normal. Temperatures recorded over a period of 30 a at the Chacaltaya station (5230 m), 10 km south of Zongo Glacier, and precipitation collected over a 20 a period at Plataforma Zongo (4770 m) enable us to calibrate each month during both observed years (Fig. 2). Thus, a clear positive deviation of the maximum temperature could be observed from January to May during the first year, linked with a higher radiation input and a deficit of rainfall. During a normal hydrological year, 7 months have more than 50 mm of precipitation, whereas in 1991–92 only 4 exceeded this total.

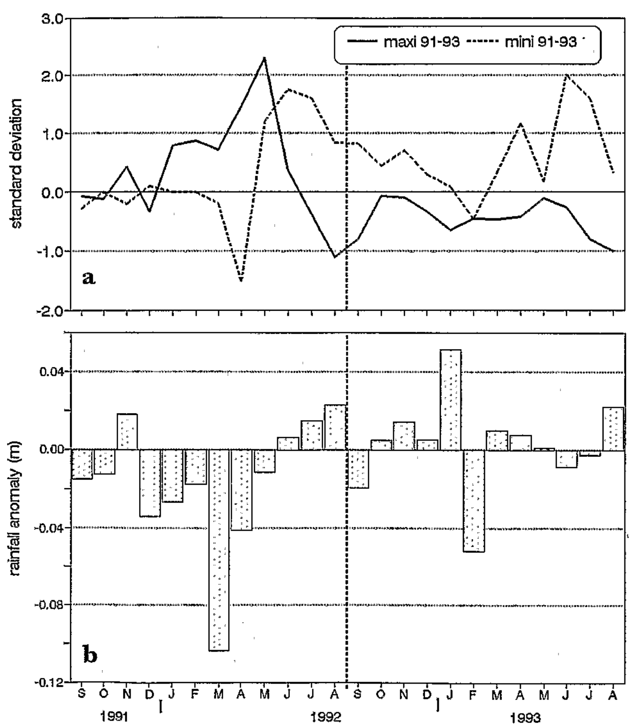

Fig. 2. Standard deviation of (a) maximum and minimum 1991–93 monthly temperatures from the 1953–93 mean at Chacaltaya (5230 m); (b) monthly 1991–93 precipitation from the 1972–93 mean at Plataforma Zongo (4770 m).

As presented in Figure 3, the monthly evolution of glacier balance in the ablation zone is more complex than may be inferred from the simple wet season/dry season alternation typical of the tropics. During the ENSO event of 1991–92 a markedly negative net balance occurred in October–December and March–May, just before and after a short period of accumulation (January–February). During the average year 1992–93, negative mass balance was limited to the beginning of the hydrological year, with April and May showing limited ablation. The variation in the balance from 5200 m to the terminus for every month of the first year of the study is presented in Figure 4a. Immediately before and after the January–March period the major part of the glacier experienced a strong ablation regime, even right up to high elevations. On the other hand, during a normal year such as 1992–93 (Fig. 4b), the monthly balance switched rapidly to a positive value. Whilst awaiting data over a longer period of time, we can already stress that October–December and March–May are decisive in the determination of the annual mass balance. In the central Andes, these are the months when variability of climate is at a maximum. However, it is obvious that the cold, dry months of June–August do have a limited influence at year scale, since the mass balance during these months approaches zero.

ANNUAL NET BALANCE AND WATER DISCHARGE

For each year, the net balance β_n has been calculated by integrating the mass balance over the total surface area S, according to Equation (1).

$$\beta_n = \int_{S_c} b_n \mathrm{d}S + \int_{S_a} b_n \mathrm{d}S \qquad (1)$$

where S_c and S_a are the areas computed for the accumulation and ablation zones, respectively.

Over the two years, the specific net balance (β_n) per year was:

in 1991–92: −1.38 m of water

in 1992–93: +0.02 m of water.

The ELA was situated in 1991–92 at 5300 m and in 1992–93 at 5100–5150 m (Fig. 5). In the same figure, we note that: (1) the curves are more-or-less parallel from one year to the other, as already observed on many middle-latitude glaciers, first by Meier and Tangborn (1965) and Lliboutry (1974); (2) during the ENSO event of 1991–92 the amount of accumulation at high elevation is very low and this confirms the observations of Thompson and others (1984) in Quelccaya. In such a case, even a glacier which like Zongo Glacier extends over a great altitude range may be almost completely submitted to an ablation regime.

As indicated in Figure 6, the ENSO event 1991–92 was characterised by high runoff depths from October to December, with the December maximum 100 mm (33%) higher than during the following year. Furthermore, a second runoff peak occurred in March 1992, with runoff then remaining high in April and May. This confirms that a marked deficit in the precipitation late in the warm season, March–April 1992, allows a rapid melting of the snow cover accumulated in January–February. The water discharge at the outlet of the 3 km^2 basin was 5.38×10^6 m^3 in the first year and 3.24×10^6 m^3 in the second. Considering the average precipitation (P) collected in the rain-gauges, the total precipitation received by the glacier was 0.916 m in 1991–92 and 1.060 m in 1992–93. We may assume that the area outside the glacier, 0.9 km^2, has a runoff coefficient of 0.8. This coefficient is quite important for a free glacier catchment

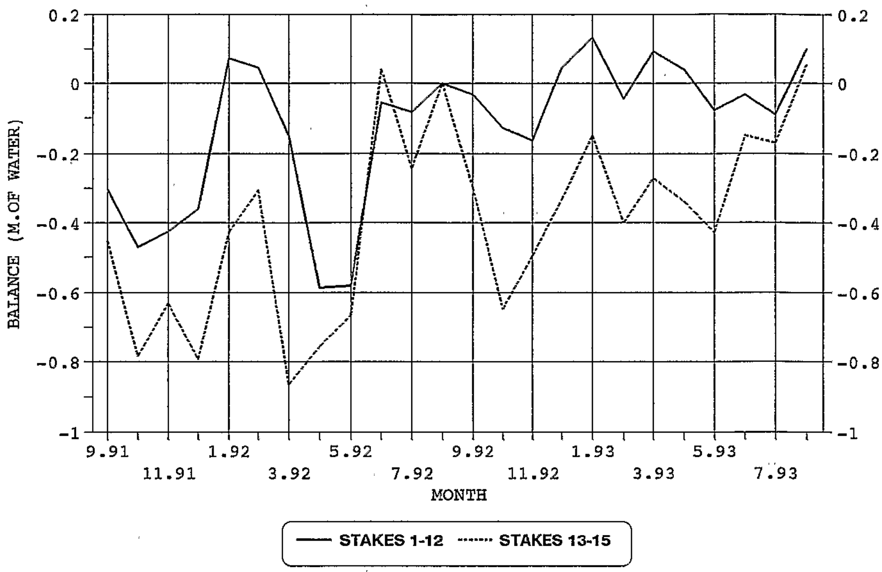

Fig. 3. Monthly balance from September 1991 to August 1993 in the ablation zone, calculated using two groups of stakes. Stakes 1–12 are situated near the ELA (5200–5100 m) and stakes 13–15 are near the glacier terminus (4900 m). The balance was estimated from a monthly stake reading and a density measurement of the snow/ice surface.

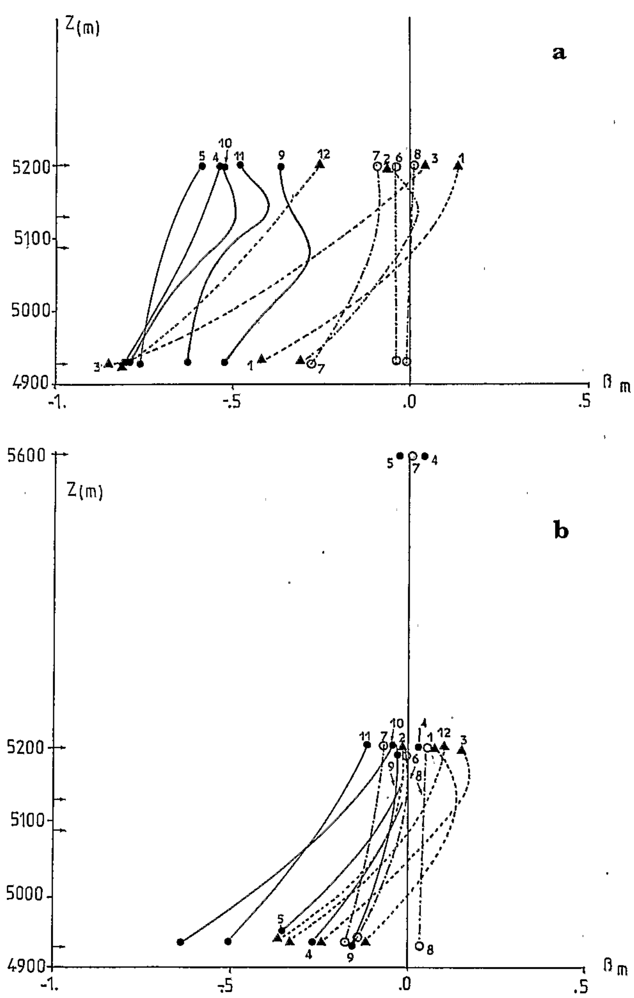

Fig. 4. Monthly net balance (β_m in m of water) as a function of altitude (Z) during (a) 1991–92, and (b) 1992–93. Numbers 1–12 refer to the months. Solid line: September, October, November, April, May. Dashed line: June, July, August. Dotted line: December, January, February, March.

in this Andean region (Bourges and others, 1992). Hence, the water discharge corresponding to this area was $0.66 \times 10^6\,m^3$ in 1991–92 and $0.76 \times 10^6\,m^3$ in 1992–93. Thus, the amount of melted snow and ice corresponding to a 2.1 km^2 surface area is:

in 1991–92: 2.25 m

in 1992–93: 1.18 m.

The specific net balance (β_n) and the precipitation (P) being known, the total ablation (A) is deduced from Equation (2):

$$A = P - \beta_n. \qquad (2)$$

In 1991–92: 2.30 m

in 1992–93: 1.04 m.

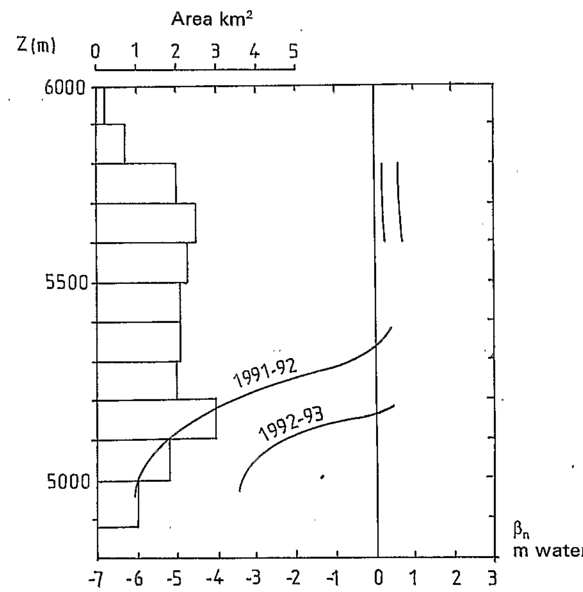

Fig. 5. Annual net balance (β_n in m of water) as a function of the altitude Z during 1991–92 and 1992–93. It should be noted that the ELA was at 5300 m in 1991–92 and at 5100 m in 1992–93.

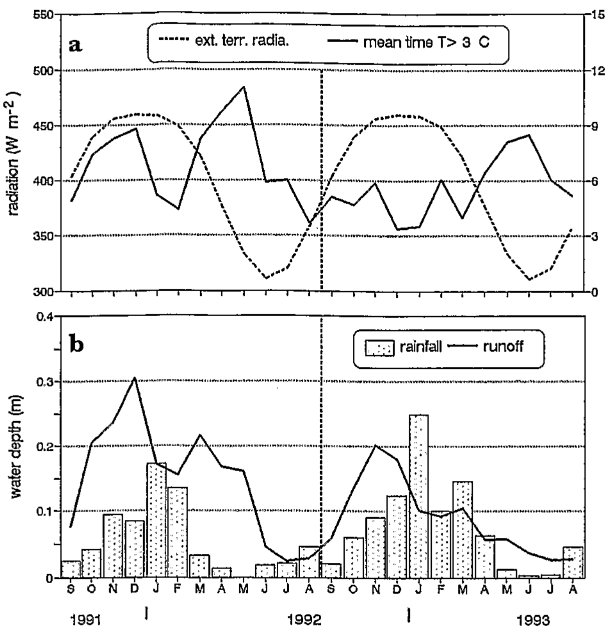

Fig. 6. (a) Extraterrestrial radiation and mean of hours per day with temperature above 3°C, and (b) rainfall and monthly runoff depth, on Zongo Glacier during the 2 years of the study.

Consequently, it should be noted that the glaciological and hydrological balances give similar results. The loss by sublimation seems to be very small, lower than 10% of the total ablation. Considering the data accuracy, the sublimation cannot be determined by means of the hydrological balance. This is consistent with the low values of sublimation obtained by Hastenrath (1978) at the summit of the Quelccaya Ice Cap.

FACTORS CONTROLLING THE GLACIER BALANCE

Whilst awaiting the opportunity to model the glacier ablation from recently installed temperature and radiation records, we can make a preliminary attempt to ascertain which variables are important in estimating the specific net-balance evolution in the ablation area of the glacier (i.e. between 5200 and 4890 m).

A stepwise multiple linear regression was applied to a large number of possible independent variables. From amongst all of the independent variables, the best result obtained pinpointed the following three as being the most critical:

(1) the amount of radiation from the Sun arriving at the outer edge of the atmosphere, also called extra-terrestrial radiation: H_o in W m^{-2}. This is constant at year scale, and obviously has a great influence at high altitudes at this low latitude. The monthly radiation values (Table 1; Fig. 6a) were calculated using the equations of Paltridge and Plate (1976);

(2) the average daily duration of air temperature greater than 3°C at Plataforma Zongo (4770 m): $_dT_3$ in h d^{-1} (Table 1; Fig. 6a). Given the lapse rate of 0.74°C 100 m^{-1} calculated between the two thermographs at 4770 and 5200 m, this 3°C temperature is equivalent to a positive temperature over practically all of the ablation zone;

(3) the precipitation collected at 4770 m: P in m (Table 1; Fig. 6b).

With the specific net balance estimated in the ablation zone of the glacier (β_{na} in m of water (Table 1; Fig. 6b)), the linear regression using the monthly data is:

$$\beta_{na} = -0.07565(_dT_3 - 0.00329(H_o) + 1.74P + 1.413 \quad \text{with } r^2 = 0.84,\ n = 24, \qquad (3)$$

where r^2 is the correlation coefficient and n is the number of data.

It may be noted that $_dT_3$ is the best correlated variable ($r = -0.72$).

With the runoff depth Q (in m) as the dependent variable (Table 1; Fig. 6b), the best regression was obtained using the H_o and $_dT_3$ variables:

$$Q = 0.00128(H_o) + 0.02358(_dT_3) - 0.538 \quad \text{with } r^2 = 0.86,\ n = 24. \qquad (4)$$

This time, the variable with the best correlation coefficient is H_o: $r = 0.80$.

These results suggest the following three comments:

(1) Temperature and radiation closely control the ablation in the lower part of the glacier.

(2) The greatest amount of solar radiation, leading to the melting of the greatest quantity of snow and ice, occurs near the time of the summer solstice. Therefore, we can begin to understand why a deficit in precipitation, and hence less frequent cloud-cover during this period, leads to the most significant melt. According to the observations of Ribstein and others (in press), the highest discharge recorded at the limnimetric station occurred after a 10 d dry period during the warm season (October–March). It is clear that dry periods during the warm season are more frequent during ENSO events. It should be noted that the ablation produced during the dry season (April–September) with low radiation is not very significant at year scale.

(3) Precipitation appears to be poorly correlated with glacier ablation and runoff, since in general the precipitation is of a solid form. Accumulated snow and hail have a melt time varying according to the climatic conditions. It might be possible at a later stage to determine these conditions.

CONCLUSIONS

For the first time, the collection of monthly data on an inter-tropical glacier allows us to highlight the most important factors that control mass balance at low latitudes. These factors are the duration of the wet season within the warm period, and the temperature

Table 1

Month	*Balance*[1] m	*Runoff*[2] m	*Precipitation*[3] m	$_dT_3$[4] h	H_o[5] $W\,m^{-2}$
September 1991	−0.378	0.076	0.025	4.9	403.8
October 1991	−0.627	0.205	0.042	7.4	439.2
November 1991	−0.528	0.237	0.090	8.3	455.9
December 1991	−0.576	0.305	0.081	8.8	459.8
January 1992	−0.178	0.171	0.164	5.2	458.3
February 1992	−0.131	0.154	0.129	4.4	448.5
March 1992	−0.507	0.217	0.032	8.3	421.5
April 1992	−0.671	0.168	0.015	9.7	377.5
May 1992	−0.624	0.160	0.001	11.0	334.0
June 1992	−0.008	0.045	0.018	5.9	311.6
July 1992	−0.162	0.025	0.021	6.0	320.9
August 1992	0.000	0.029	0.045	3.7	357.9
September 1992	−0.165	0.059	0.021	5.1	403.8
October 1992	−0.388	0.136	0.060	4.7	439.2
November 1992	−0.329	0.202	0.090	5.9	455.9
December 1992	−0.144	0.179	0.123	3.4	459.8
January 1993	−0.009	0.102	0.249	3.5	458.3
February 1993	−0.222	0.092	0.100	6.1	448.5
March 1993	−0.089	0.104	0.146	4.0	421.5
April 1993	−0.149	0.058	0.063	6.4	377.5
May 1993	−0.252	0.058	0.013	8.1	334.0
June 1993	−0.090	0.036	0.003	8.5	311.6
July 1993	−0.130	0.026	0.004	6.1	320.9
August 1993	+0.077	0.028	0.046	5.2	357.9

[1] Mean net specific glacier balance in the ablation zone 5200–4900 m.
[2] Runoff depth related to the basin area of 3.0 km^2 recorded at the limnimetric station.
[3] Precipitation at Plataforma Zongo, 4770 m.
[4] Daily mean of hours with temperature > 3°C at Plataforma Zongo, 4770 m.
[5] Extraterrestrial radiation.

level during the sensitive period which precedes and follows January–February, the height of the rainy season.

Hence, it can be noted that mass-balance determination is more complex for tropical glaciers than for their cousins at middle latitudes, for which only the three summer months appear to be critical. Since the climate in this part of the Andes is so variable, a longer-term study will be necessary to better understand this subject.

The second conclusion reached concerns the effect of the ENSO events. In comparison with the "normal" 1992–93 hydrological year, 1991–92 (an ENSO event) was characterised by: (1) a markedly negative net balance, with a water depletion equivalent to twice the amount of the precipitation accumulated; (2) an increase in the elevation of the ELA by 200 m; (3) a reduction of the AAR (accumulation-area ratio) from 86% to 58%; (4) a very low accumulation rate at high altitude.

The above effects are a consequence of a marked increase of ablation due to a rise in the maximum temperature during the summer period, associated with increased radiation input, and also linked to the deficit in accumulation arising from a foreshortened season of 2 instead of the normal 4 months.

Thus the conclusions reached by Thompson and others (1984) from the study of the Quelccaya Ice Cap concerning a decrease in the accumulation during ENSO events are confirmed. Furthermore, we can add that the ENSO effect modifies not only the accumulation term in the mass-balance equation, but also the ablation term, particularly in the present case study. The observations made during the 1991–92 ENSO event are confirmed by our analysis of water-level records from the Zongo Glacier outlet over a 20 a period (Ribstein and others, in press). The records reveal that the highest levels of runoff over this period were obtained during the three previous ENSO events (1976–77, 1982–83 and 1986–87), with a particularly high peak during the strong 1982–83 event.

The continuation of the present study over a period of several years would clearly be beneficial in furthering our understanding as to why tropical glaciers are currently experiencing such rapid retreat. Of further use would be a long-term study of mass-balance data from various other Andean glaciers.

It is already widely acknowledged that global atmospheric warming is a cause of glacier retreat. However, our study suggests that another important factor is the occurrence of short periods of warm, dry weather during the rainy season, a combination that is frequently linked to ENSO events.

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Short-pulse radar wavelet recovery and resolution of dielectric contrasts within englacial and basal ice of Matanuska Glacier, Alaska, U.S.A.

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ABSTRACT. Wavelets transmitted by short-pulse radar are recovered from continuous profiles and used to determine interfacial dielectric contrasts within the englacial and basal ice at the terminus area of Matanuska Glacier, Alaska, U.S.A. The field studies were in the ablation region, where radar horizons could, at some point, be identified with interfaces between clear ice and air, water or basal ice, and were performed in early spring before drainage fully developed. The profiles used closely spaced antennas with bandwidths centered near 50 and 400 MHz. Transmitted wavelets reflected from interfaces of known dielectric contrasts are used to establish a phase reference for other events from interfaces between unknown contrasts. Migration and Fourier-transform filtering are then applied to the profiles and shown to recover these wavelets from diffractions and reflections. Interfacial dielectric contrasts are determined from the relative phase of the wavelets. Near the terminus lake, some basal ice events above 8 m depth are interpreted as voids. Further up-glacier, most englacial events are interpreted as voids, but deeper localized reflectors and horizons to 90 m depth and within the basal zone are interpreted as voids, water or debris. Phase cannot be determined for the basal-substrate transition reflections. Recommendations are made for improving the wavelet recovery process and the quality of GPR migration.

INTRODUCTION

As part of ongoing research at Matanuska Glacier, Alaska, U.S.A., on subglacial hydrologic and sedimentation processes, we initiated studies of the use of short-pulse, ground-penetrating radar (GPR) to identify and map ice facies, debris distribution, conduits and cavities within and below the glacier, and to determine the nature of the englacial–basal and ice–substrate interfaces. The terminus region of Matanuska Glacier is easily accessible and we chose the early spring for surface-based GPR surveying in hope of exploiting the general absence of surface meltwater and the probable presence of unfilled drainage conduits. In addition, ice thicknesses in the terminus region were within the anticipated depth capabilities of the radar system, and crevasse danger and survey interference were minimal. Data existed on the basal-ice zone characteristics and distribution, and the occurrence and revelation by late summer of numerous englacial and subglacial conduits due to ablation (Lawson and Kulla, 1978; Lawson, 1979a, b, 1986, 1987) were critical to interpreting the radar records.

The objective of these studies is to determine whether transmitted wavelets (i.e. pulses) can be recovered from high-resolution GPR profiles of englacial and basal ice so that interfacial dielectric contrasts can be interpreted from the wavelet phase. At the outset, it was not clear that wavelet recovery would be possible for a complex structure such as basal ice in the terminus zone of a sub-polar glacier. Diffractions, which dominate radar soundings of glaciers, and secondary reflections from embedded anomalies and layers could interfere with primary wavelet resolution. Surface-based antennas operating at 50 and 400 MHz center frequencies were towed along multiple transects, a few of which are discussed here. After establishing the form and phase of the transmitted wavelet, the data were migrated to reduce diffractions and, in one case, filtered using a two-dimensional Fourier transform. Although it is the purpose of migration to perform spatial imaging by "collapsing" diffractions through summation, the main intent of this superposition process was to recover the temporal form of the transmitted wavelet to derive its phase. In a subsequent paper, we will describe the nature of the glacier's internal features from a detailed interpretation of the radar records using various ground-truth data.

Radio echo-sounding (RES) rather than GPR had been the common method of sub-surface glacier exploration since the late 1950s. RES uses the envelope of a wavelet consisting of six–fifteen cycles of a 35–65 MHz carrier (e.g. Gudmandsen, 1975; Hodge and others, 1990). The resulting bandwidth permits a radar-performance figure (i.e. working range of signal/noise ratio) in excess of 200 dB, and penetration to the depths of continental ice sheets. RES has been used primarily to obtain information on ice thickness, bottom topography