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Energy balance and runoff seasonality of a Bolivian glacier

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Abstract

The runoff of Zongo Glacier (Bolivia, 16°S) shows an appreciable seasonal variability, with low discharges in the dry season (May to August) and high values in the humid season (October to March). Incoming radiation, temperature and precipitation are poorly correlated with discharge and cannot explain the hydrological seasonality and the glacier's response to climate variability in the Tropical Andes. Since 1996, energy balance measurements have been carried out in the vicinity of the mean equilibrium line (5150 m a.s.l.) on Zongo Glacier (2.1 km^2). Comparisons are made with proglacial stream discharges recorded at the main hydrometric station. Each component of the energy balance (net radiation, turbulent heat fluxes, heat transfer into the ice and heat supplied by precipitation) is derived separately from the measurements, and the variability throughout the year is evaluated. Radiation and turbulent fluxes dominate the surface energy balance. Sensible heat flux is small and does not show a significant seasonal change. Latent heat flux is highly variable with low values during the accumulation season and high values during the dry period. This high sublimation loss during the dry season causes well-developed penitents at the glacier surface. In conclusion, incoming energy throughout the year is constant, with no large variations, and humidity controls the balance of this energy between sublimation and melting. During the accumulation season, sublimation is reduced because of a low gradient of vapour pressure and the energy supplied by radiation is directly consumed by melting, explaining why discharge is high. During the dry period, a large part of the energy supplied by radiation is used to sublimate snow or ice and therefore, energy available for melting is low, which leads to low melt rates. Due to the important role of humidity, tropical glaciers are likely to be the climatic indicators the most sensitive to climatic changes like the greenhouse effect.

Keywords: Bolivian glaciers; melting; sublimation

1. Introduction

The aim of this paper is to understand the seasonal variations of the runoff of a tropical glacier, and the crucial forcing terms of the energy budget. The glaciers of the high mountains of the tropics cover a total area estimated at about 2.5×10^3 km^2 which corresponds to 0.16% of the total ice cover of the world (WGMS, 1989). Although negligible in area (if all these glaciers melted tomorrow, the sea level would not rise more than 1 cm!), they are still known to be very sensitive components of the environment and deserve attention in the context of both global change (Kaser et al., 1996) and local and

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regional water supply. Knowledge about the impact of single energy budget components on glacier melt and runoff are poorly known for low latitude glaciers. Some radiation budget studies have been conducted on Lewis glacier, Mount Kenya (Hastenrath and Patnaik, 1980; Hastenrath and Kruss, 1988), and on Quelccaya ice cap, Peruvian Andes (Hastenrath, 1978) but no simultaneous energy balance and runoff measurements have yet been made available for these latitudes. Therefore, a detailed microclimatological–hydrological experiment was carried out on Zongo Glacier, Bolivia, since March 1996, in order to determine single energy fluxes at the glacier surface, and to understand the consequent runoff response. The local surface energy balance is dependent on cloudiness and surface albedo (which influence the radiation balance), on the local wind field, air temperature and humidity (which determine the turbulent fluxes), and on surface and snowpack temperatures (which provide the total upward energy inside the snow/ice). Results of two selected 9-day periods representative of the dry and wet seasons are presented here in order to analyse the differences in glacier energy exchange between these two seasons.

2. Location and instrumentation

Zongo Glacier is located in the Cordillera Real, Bolivia (16°15′S, 68°10′W), approximately 30 km

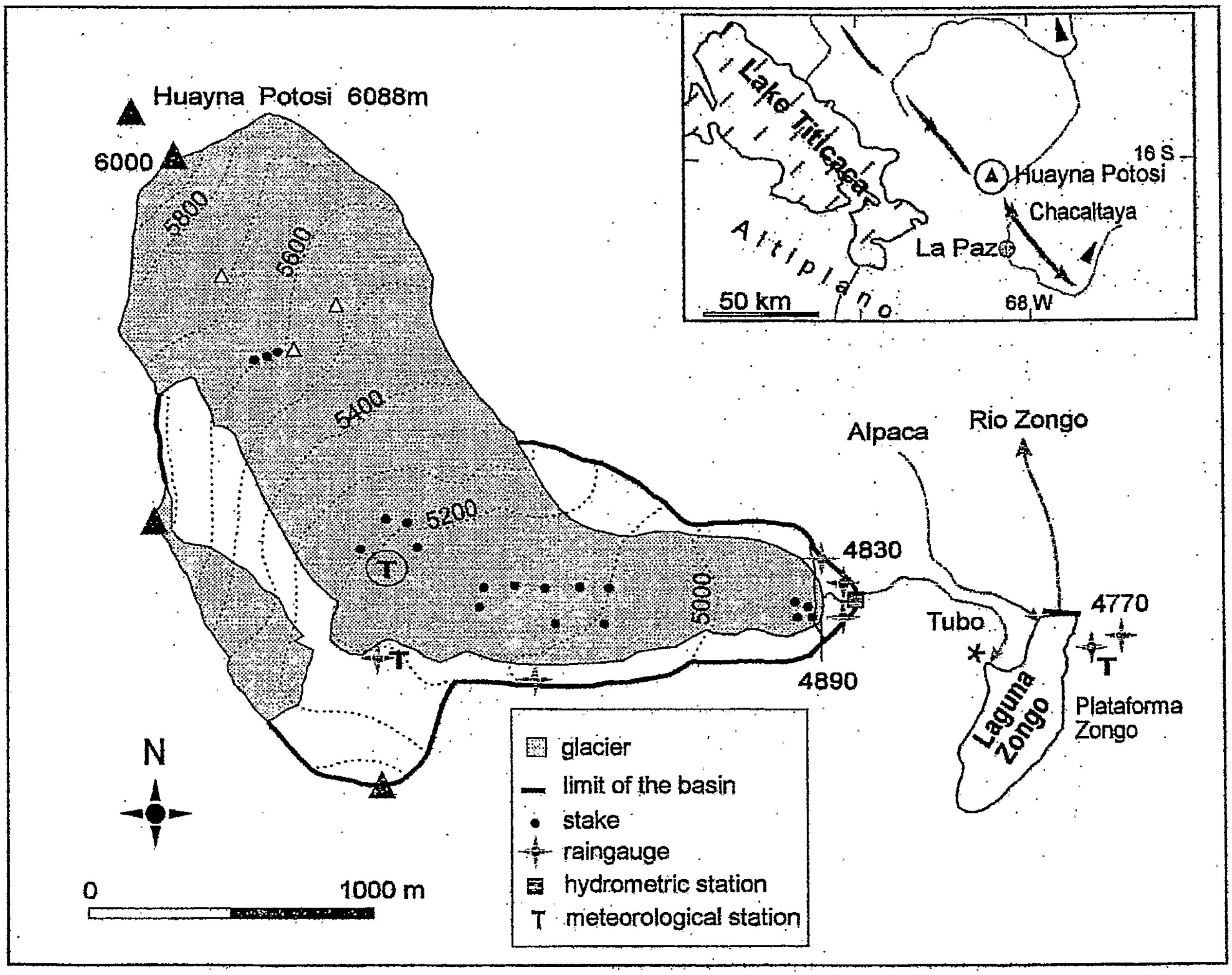

Fig. 1. A simplified map of Zongo Glacier (2.1 km^2) and the hydrological basin (3 km^2) showing location of monitoring equipment.

north of La Paz, and forms part of the Huayna Potosi Massif. This glacier extends from 6000 m a.s.l. to 4900 m a.s.l. and covers 77% of a south-east facing hydrological catchment (3 km^2) (Fig. 1). Since March 1996, a Campbell automatic energy budget station has been located on the glacier close to the mean equilibrium line, at 5150 m a.s.l. Ventilated dry and wet bulb temperatures and wind speed are recorded at two levels above the surface. In addition, wind direction, incident short-wave radiation, reflected short-wave radiation, net all-wave radiation, and temperatures at various depths inside the snow/ice are recorded as half-hourly means over 15-s time steps. Dry and wet bulb temperatures are obtained from psychrometers equipped with Cu–Cst thermocouples and continuously ventilated by a motor whose energy supply comes from a truck battery (12 V/100 A h), recharged by a 43 W solar panel. To prevent measurement errors due to radiation, these psychrometers are shielded with two white interlocked cylinders of 8 and 12 cm diameters, topped by a white 30 cm diameter disk. Campbell Met One and Young anemometers provide wind speed and direction. A Q-6 Campbell net radiometer ($0.25 < \lambda < 60$ μm) measures the net all-wave radiation with an accuracy depending on the horizontality of the sensor (from $\pm 3\%$ while we were on the field site to $\pm 10\%$ the rest of the time). Additionally, incident and reflected short-wave radiation are recorded by SP1100 and Li-Cor pyranometers ($0.35 < \lambda < 1.1$ μm; accuracy $\pm 3\%$). Snow/ice temperatures are measured with Cu–Cst thermocouples. During four selected 9-day periods, additional measurements and observations (for example surface temperature, sublimation with snow-lysimeters, ablation, cloudiness, surface conditions, weather type, wind regime) were made in order to calculate the single heat fluxes as precisely as possible. During these periods, more detailed vertical profiles of ventilated air temperature (Cu–Cst thermocouples) were also available, from a

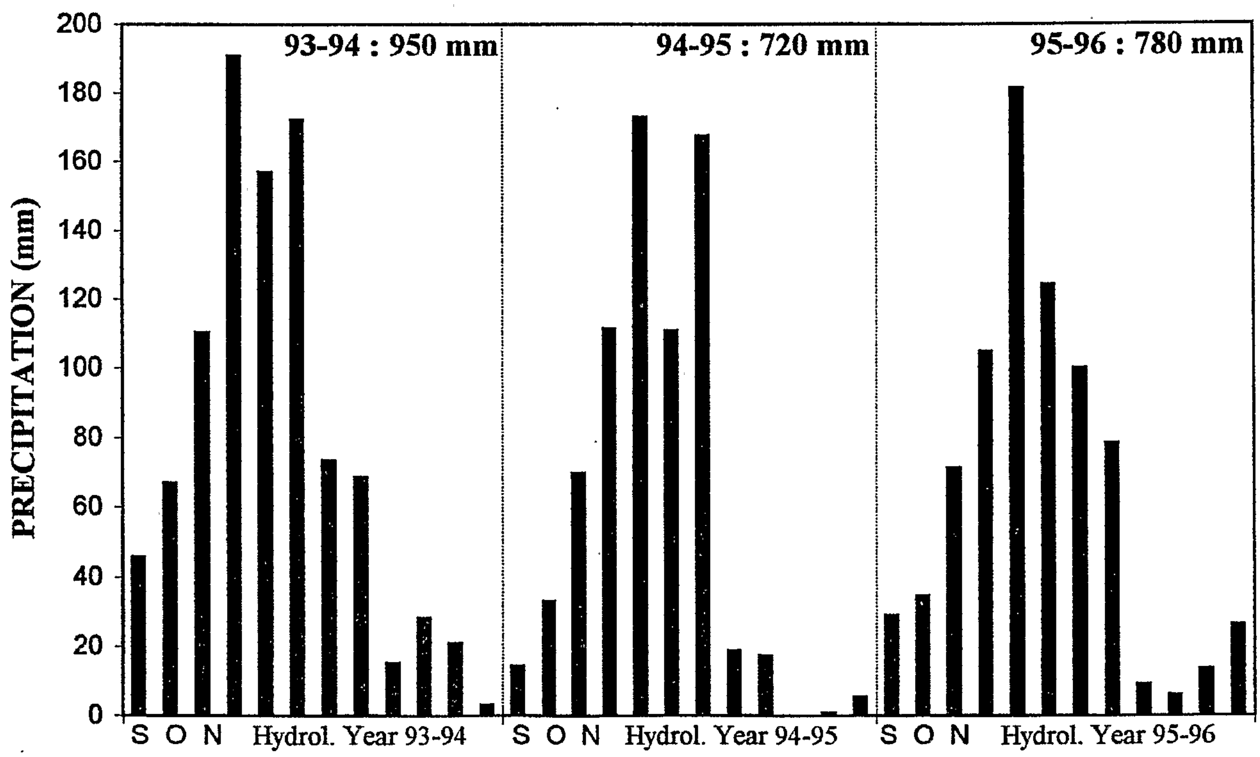

Fig. 2. Monthly precipitation recorded at 4770 m a.s.l., 130 m below the glacier tongue, in the axis of the glacier valley (September 1993–August 1996).

second Campbell datalogger recording mean data every 5 min. These field measurements were made during both the dry and the wet seasons.

3. Climatic conditions

Zongo Glacier belongs to the outer tropics, with a single wet season (October–March) and a pronounced dry season (May–August) (Francou et al., 1995; Ribstein et al., 1995) (Fig. 2). The diurnal and annual ranges of temperature are almost equal, with an annual temperature amplitude not exceeding 8°C (Fig. 3) (Kaser et al., 1996). Ablation occurs throughout the year, with high melt rates concomitant with the accumulation season, and low melt rates during the dry period, as shown by the hydrograph of the proglacial stream (Fig. 3). The annual range of temperature is too low to explain the large seasonality of melting, with discharges about five times higher during the wet than the dry season. The variance of the linear correlation between daily discharge and air temperature, calculated between October 1993 and August 1996 is only 0.26 for 950 days. It is even worse when considering the linear correlation between daily discharge and daily net radiation, measured at the experiment site (Fig. 4): $r^2 = 0.21$, $n = 950$ days. For monthly means, the linear correlation between discharge and air temperature is of course slightly better ($r^2 = 0.45$, $n = 35$ months), although it is worse for net radiation. Neither air temperature nor net radiation is the crucial forcing terms of the runoff seasonality. Moreover, as the 0°C isotherm is located around 5000 m a.s.l. on this glacier and does not vary much in altitude throughout the year, precipitation always falls as snow on the entire glacier. For this reason, precipitation does not directly influence the discharge of the proglacial stream: as this is confirmed by the poor linear correlation between monthly precipitation and discharge ($r^2 = 0.19$ over 60 months).

This observation leads to the conclusion that Bolivian glaciers are subject to conditions drastically different from temperate or polar glaciers, and so

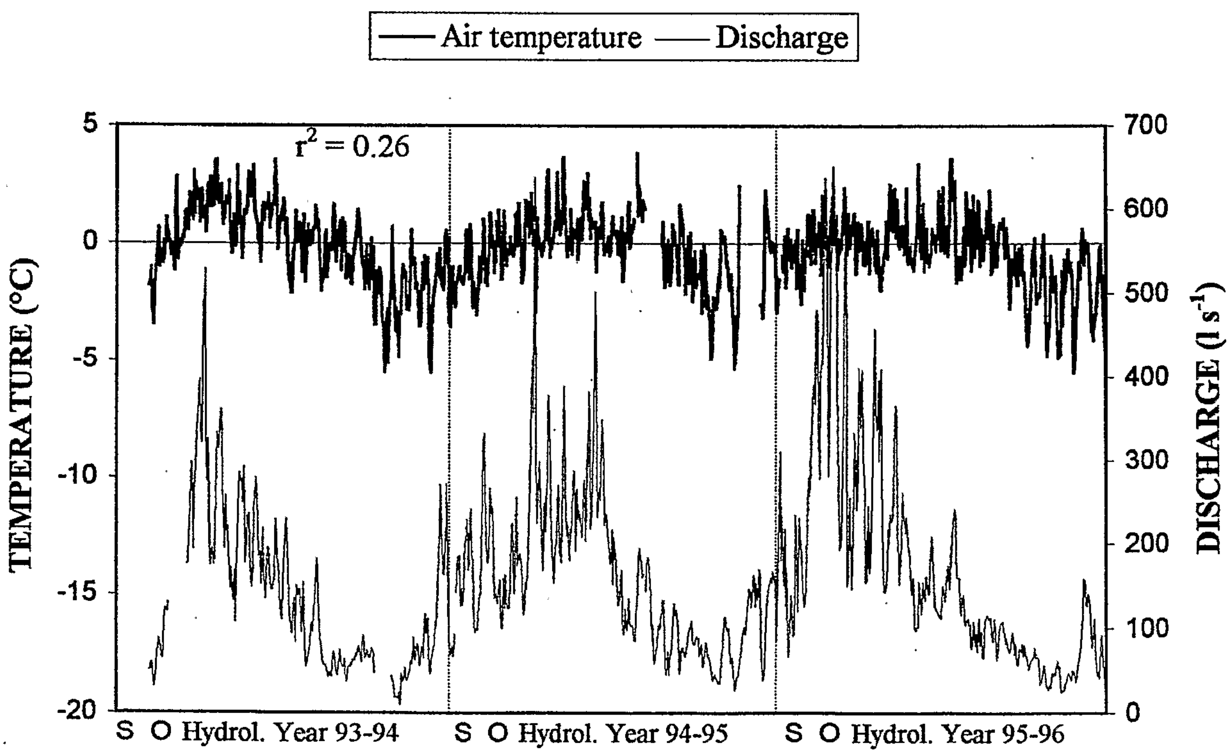

Fig. 3. Daily air temperature recorded by the automatic energy budget station at 5150 m a.s.l. and the daily discharge of the proglacial stream recorded at the gauging station at 4830 m a.s.l. (September 1993–August 1996).

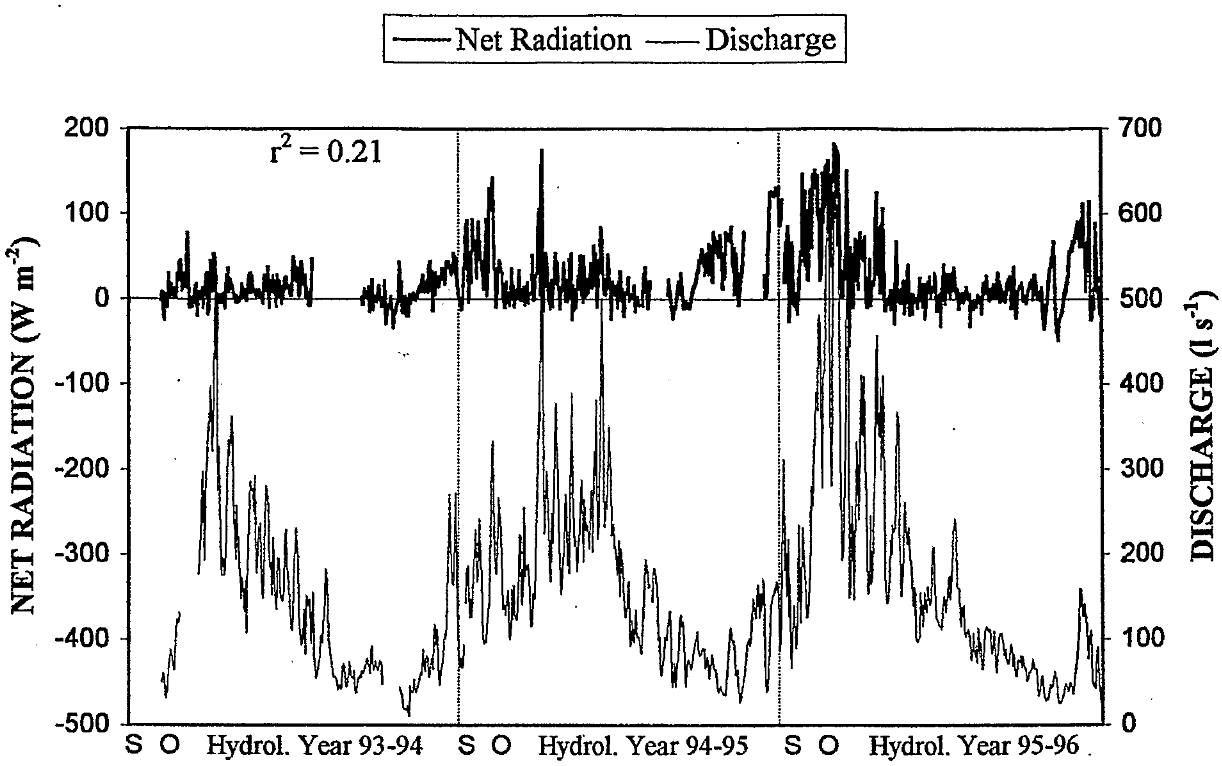

Fig. 4. Net radiation recorded by the automatic energy budget station at 5150 m a.s.l. and the daily discharge of the proglacial stream recorded at the gauging station at 4830 m a.s.l. (September 1993–August 1996).

show a specific energy exchange responsible for this high seasonality of melting, although net radiation or air temperature do not vary a lot. Therefore, a precise energy balance investigation is necessary.

4. Energy balance study

An energy balance study for the period from March 1996 to March 1997 is presented, with focus on selected 9-day periods typical of the dry or wet seasons. The surface energy balance of a melting glacier is given by:

$$R_n + H + \mathrm{LE} + Q_G + Q_P = Q_M \tag{1}$$

where R_n is the net radiation, H is the sensible heat flux, LE is the latent heat flux, Q_G is the heat transfer into the snow/ice, Q_P is the heat supplied by precipitation and Q_M is the energy available for melt. Energy fluxes directed towards the surface are defined as positive and those away from the surface, negative. Since precipitation is always snow in the vicinity of the equilibrium line and since snowfall intensities are usually weak, Q_P remains negligible as compared to the other terms in this Eq. (1).

4.1. Net radiation

The net all-wave radiation was measured directly on the field site by the automatic weather station.

4.2. Turbulent heat fluxes

The turbulent heat fluxes were estimated by the profile method (Monin–Obukhov theory), using vertical gradients of mean wind speed u, mean temperature T and mean specific humidity q (Brutsaert, 1982).

-Sensible heat flux:

$$H = \rho C_P u^* \theta^* \tag{2}$$

-Latent heat flux:

$$LE = \rho L_s u^* q^* \tag{3}$$

with

$$u^* = k(u_2 - u_1)[\ln(z_2/z_1) - \Psi_m(z_2/L) + \Psi_m(z_1/L)]^{-1}$$
$$\theta^* = k(\theta_2 - \theta_1)[\ln(z_2/z_1) - \Psi_h(z_2/L) + \Psi_h(z_1/L)]^{-1}$$
$$q^* = k(q_2 - q_1)[\ln(z_2/z_1) - \Psi_v(z_2/L) + \Psi_v(z_1/L)]^{-1} \quad (4)$$

The stability criterion used is the Obukhov length L:

$$L = \frac{(u^*)^3 \rho}{kg\left[\left(\frac{H}{TC_P}\right) + 0.61E\right]} \quad (5)$$

u, θ and q are the wind speed, the potential temperature and the specific humidity of the air, the subscripts 1 and 2 refer to two different levels z_1 and z_2 (30 and 180 cm, depending on the snow height). k is the Von Karman constant ($k = 0.4$), g is the acceleration due to gravity, C_P specific heat for air and L_s, latent heat of sublimation of ice ($L_s = 2.834 \times 10^6$ J kg^{-1}).

The Ψ functions Ψ_m for mass, Ψ_h for heat and Ψ_v for water vapour depend on the stability of the surface layer:

-Unstable conditions ($z/L < 0$):

$$\Psi_m = 2\ln\left[\frac{1+x}{2}\right] + \ln\left[\frac{1+x^2}{2}\right] - 2\arctan(x) + \frac{\pi}{2} \quad (6)$$

$$\Psi_h = \Psi_v = 2\ln\left[\frac{1+x^2}{2}\right]$$

with $x = (1-16\ z/L)^{1/4}$

-Stable conditions ($0 < z/L < 1$):

$$\Psi_m = \Psi_h = \Psi_v = -5z/L \quad (7)$$

-Very stable conditions ($z/L > 1$):

$$\Psi_m = \Psi_h = \Psi_v = -5[\ln(z/L) + 1] \quad (8)$$

The calculations were performed iteratively between the two measurement levels z_1 and z_2.

In Monin–Obukhov theory, the fluxes of momentum, sensible and latent heats are assumed to be constant with height. Nevertheless, over a melting snow surface, de la Casinière (1974), Halberstam and Schieldge (1981) and Meesters et al. (1997) have observed temperature profile anomalies, probably due to the radiative heating of the air above the snow surface, leading to fluxes variable with height. On Zongo glacier, a similar situation is observed: during the day, a highly stable sublayer formed near the surface, with a persistent warm layer around 20–30 cm, whereas at night, profiles agreed more with classical log–linear forms found in stable air (Fig. 5). Therefore, at night, turbulent fluxes were estimated using the profile method described above, but during the day, as soon as the warm layer appeared, the fluxes were estimated using the profile method between the surface and the first measurement level z_1 ($z_1 = 30$ cm, depending on the snow height), which is equivalent to applying the bulk aerodynamic method with stability correction. During the day, snow was melting at the field site and the surface temperature was assumed to be 0°C, and the vapour pressure was assumed to be the saturation vapour pressure (6.1 hPa). Roughness lengths (z_{0m} for momentum, z_{0T} for temperature and z_{0h} for humidity) were all chosen equal to each other and were estimated iteratively in order to give the best agreement between calculated latent heat flux and sublimation as measured by lysimeters at the field site. During the dry season, when penitents developed at the snow surface, the roughness length was very high and reached 3×10^{-2} m, and it remained high during the wet season (4×10^{-3} m) (Wagnon et al., 1999).

4.3. Heat transfer into the snow/ice

The heat flux into the snow/ice was estimated from temperature–depth profiles of seven Cu–Cst thermocouples down to a depth of 2.7 m, depending on the snow height. This heat flux is given by:

$$Q_G = -K\frac{\partial T}{\partial z} \quad (9)$$

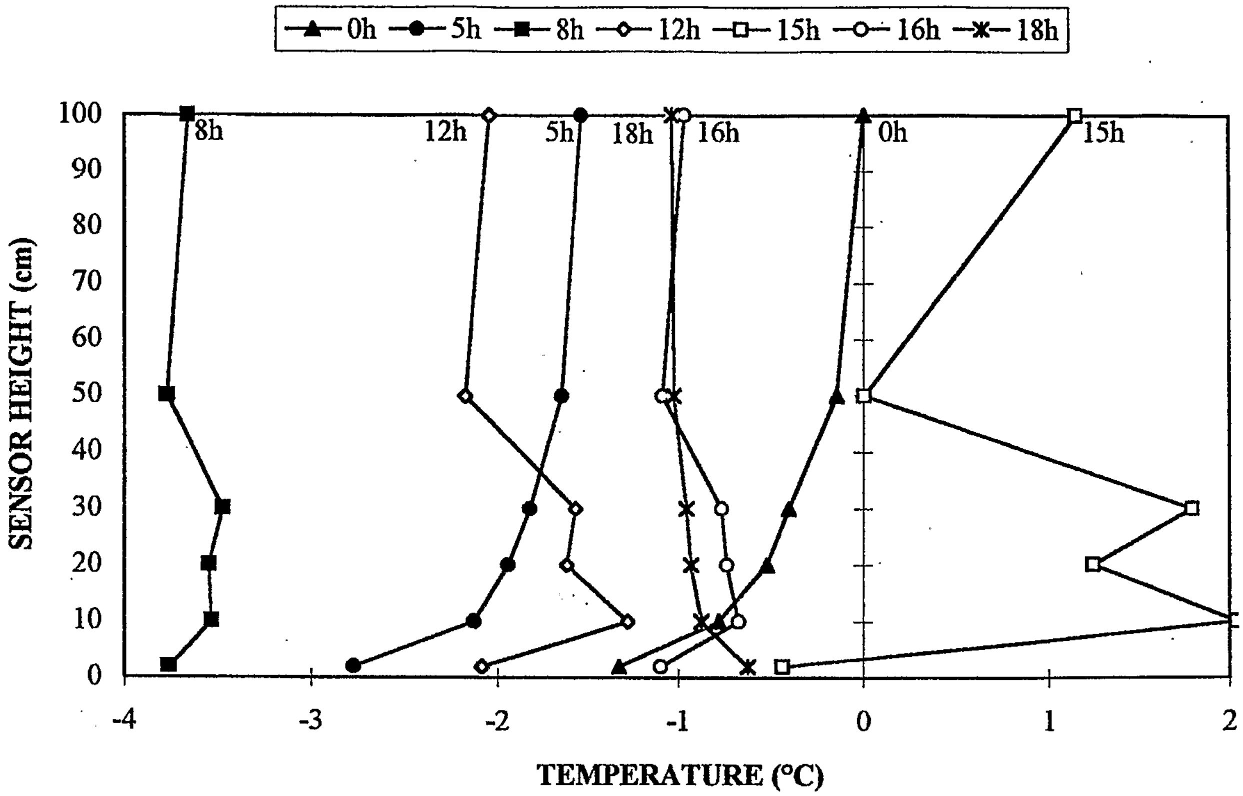

Fig. 5. Evolution of the vertical profiles of ventilated air temperature above the snow surface between 0 a.m. and 6 p.m. on March 3, 1997. At night, the profiles show a classical log–linear form, but during the day, a warm layer develops around 20–30 cm above the surface.

where K is the thermal conductivity of snow/ice: $K = 2.2$ W m^{-1} K^{-1} for pure ice and 0.4 W m^{-1} K^{-1} for old snow (Oke, 1987).

5. Results and discussion

Half-hourly values of the first four terms of Eq. (1) are presented in Figs. 6 and 7, for two 9-day periods: July 23–31 and October 14–22, 1996, respectively. The two selected periods are representative of the dry and wet seasons as shown by Table 1. The algebraic sum of these four terms corresponds to the total heat flux passing the surface. If this sum is positive, the total heat flux is used first to increase the snowpack temperature up to the melting point, and then to melt snow/ice. If it is negative as at night, the water at the surface starts to re-freeze and as soon as the snowpack is dry, its temperature drops. Mean values over the two 9-day periods of these four components of the energy balance are presented in Table 2.

Net radiation is the main source of energy at the glacier surface, and as already shown in Fig. 4, does not vary significantly throughout the year. Heat transfer into the snow/ice remains quite small throughout the year but slightly higher during the dry season when surface temperature may drop to -10°C at night. Sensible heat flux remains small and positive during the year. On the other hand, the contribution of latent heat flux to the energy balance is very variable. During the dry season (Fig. 6), sublimation rates are high with mean monthly values of 1.1 mm day^{-1}, but during the wet season (Fig. 7), sublimation drops to rates of 0.3 mm day^{-1} or even less. Due to high sublimation at the glacier surface and the absence of precipitation, penitents can grow at the glacier surface and may reach a few tens of centimetres at the end of the dry season. This high

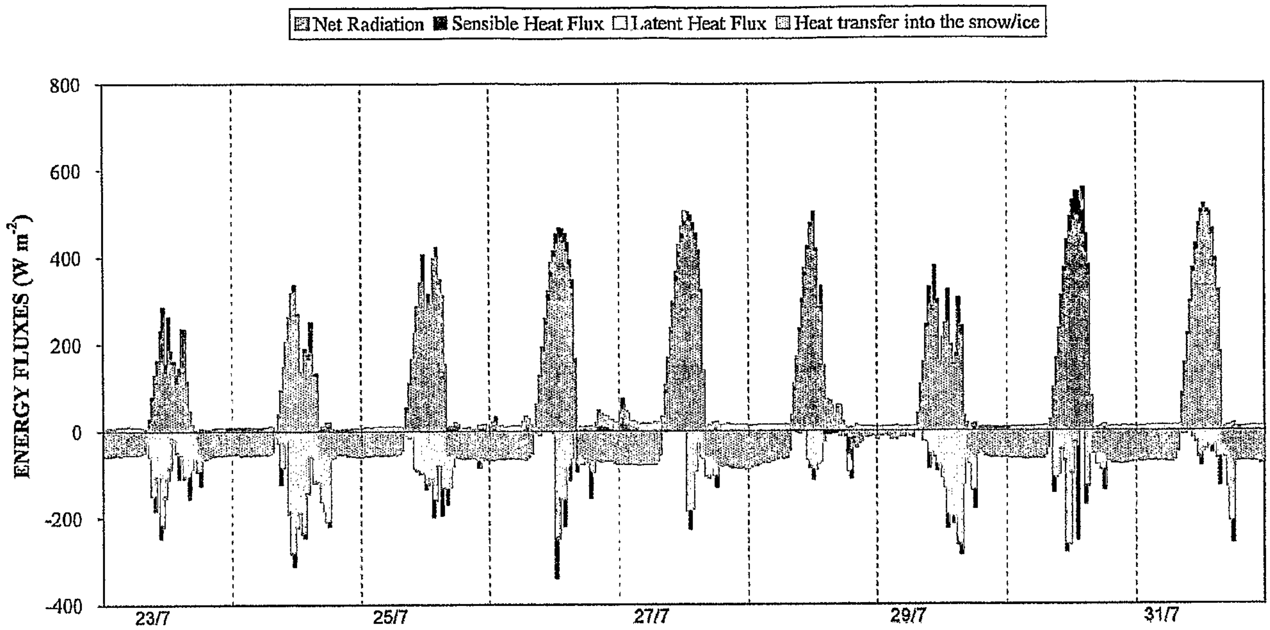

Fig.6

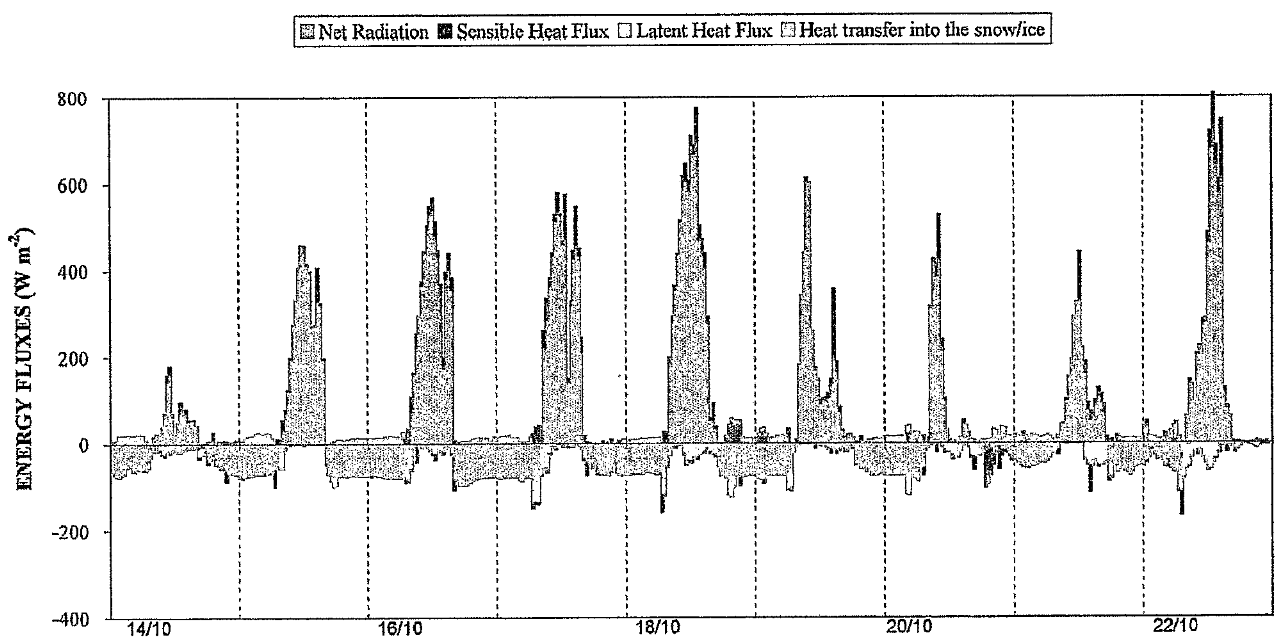

Fig.7

Fig. 6. Half-hourly values of the different terms of the energy balance (R_n, H, LE, Q_G) during a selected 9-day period of the dry season (July 23–31, 1996). During the dry season, net radiation is the main energy source at the glacier surface but is almost totally consumed by the strong sublimation.

Fig. 7. Half-hourly values of the different terms of the energy balance (R_n, H, LE, Q_G) during a selected 9-day period of the wet season (October 14–22, 1996). During the wet season, net radiation has not changed much in average and remains the main contribution to the energy balance at the glacier surface. Nevertheless, the latent heat flux is very low, leaving a large amount of energy available for melting.

Table 1
Comparison of various climatological and hydrological data for the two selected 9-day periods, and the respective data for the dry and wet seasons. The two selected periods are well representative of each season

Mean values	July 23–31, 1996	Dry season (May–August)	October 14–22, 1996	Wet season (October–March)
Temperature (°C)	−4.3	−3.1*	−0.1	−0.3*
Net rad. (W m^{-2})	49	20**	54	24**
Prec. (mm day^{-1})	0	0.5***	1	3.7***
Discharge (mm day^{-1})	1.3	2.0***	6.7	6.1***

*Mean values calculated from records of the last hydrological year, 1996–1997.
**Mean values calculated from records of three hydrological years, 1993–1994, 1994–1995 and 1995–1996.
***Mean values calculated from records of five hydrological years, 1991–1992, 1992–1993, 1993–1994, 1994–1995, and 1995–1996.

seasonality of latent heat flux is responsible for the high seasonality of melting reflected by the hydrological regimes of the proglacial stream. During the dry season, almost all the energy available from net radiation and sensible heat flux is consumed by sublimation. The rest of the energy available is used to change the snowpack temperature from time to time during the day, and the snow surface remains dry. Therefore, melting conditions are not encountered in the vicinity of the equilibrium line; they might occur lower in altitude but in any event, melting is limited and the discharge of the proglacial stream remains very low. During the wet season, the same amount of energy from net radiation is still available at the glacier surface but at this time, is only partly consumed by sublimation. Most is available to create melting conditions at the beginning of the wet season, and then to melt snow/ice. Hence, during this period, due to high air humidity of the surface layer, a larger area of the glacier remains in melting condition for several months, providing a significant supply in water for the proglacial stream, and high discharges.

Table 2
Mean values of each component of the energy balance over the two selected 9-day periods, July 23–31, 1996 and October 14–22, 1996

Mean values	July 23–31, 1996	October 14–22, 1996
R_n (W m^{-2})	49.0	53.8
H (W m^{-2})	3.6	5.6
LE (W m^{-2})	−34.6	−10.9
Q_G (W m^{-2})	4.6	3.8
Specific discharge (mm day^{-1})	1.3	6.7
Sublimation (mm day^{-1})	1.1	0.3

6. Conclusion

Energy balance investigations are necessary to understand the glacier–climate interaction. They may help to understand glacier behaviour under different climatic regimes. The outer tropics provide a glacier regime which is clearly different from the mid and high latitudes, but also from the inner tropics (Kaser et al., 1996). Indeed, Bolivian glaciers are subject to totally different climatic conditions from those of temperate or polar glaciers, with the lack of thermal seasonality and an hydrological year showing alternatively one dry and one wet season. In consequence, their response to these climatic peculiarities is special compared to other climatic regimes: net radiation as the main source of energy does not show any seasonal variability; in addition to small seasonal variations of net radiation and temperature, the negative latent heat flux becomes crucial for the seasonality of the melt rates. Whereas this energy flux is mostly of minor importance in mid-latitude or polar conditions (Male and Granger, 1981; Plüss and Mazzoni, 1994; Hock and Holmgren, 1996; ...), it becomes the key value to explain the high seasonality of melting under tropical conditions. The high dryness of the lower atmosphere during the dry season is favourable for strong sublimation from the glacier surface, consuming almost totally the energy available at the surface. Therefore, melt rates are low during this period. On the other hand, high air humidity during the wet season causes low sublimation rates and consequently, most of the available energy can be used to melt snow/ice. Melting is high during this season.

In conclusion, in the outer tropics, humidity is the main meteorological input controlling the runoff seasonality of the proglacial stream, because it is responsible for the partitioning of the energy available at the surface between sublimation and melting. The strongly negative latent heat flux characteristic of tropical glaciers, makes these glaciers extremely sensitive to climatic changes like the greenhouse effect. They are not only affected by any greenhouse warming which increases the sensible heat flux but also, and to a large extent, by the specific humidity increase which reduces the latent heat flux and makes energy available for melting. This is the main reason why tropical glaciers show a dramatic retreat since the beginning of the eighties.

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