Glaciers of the outer and inner tropics: A different behaviour but a common response to climatic forcing

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[1] We have compared the annual surface energy balance (SEB) of Zongo Glacier (16°S, Bolivia, outer tropics) and Antizana Glacier 15 (0°S, Ecuador, inner tropics). On annual time scale energy fluxes are very similar in the ablation zone: turbulent heat fluxes compensate each other and net short-wave radiation dominates the SEB. Albedo is central in controlling the melting. Consequently solid precipitation occurrence manages the annual mass balance variability. In the outer tropics, the annual melting is directly related to the annual distribution of precipitation, the period December–February being crucial. However, in the inner tropics, liquid precipitation can occur on the ablation zone, and snowline altitude remains very sensitive to air temperature. Tropical glaciers react rapidly to El Niño events, mainly because of an induced precipitation deficit in the outer tropics and to a temperature increase in the inner tropics, both leading to a rise in snowline altitude. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Favier, V., P. Wagnon, and P. Ribstein (2004), Glaciers of the outer and inner tropics: A different behaviour but a common response to climatic forcing, *Geophys. Res. Lett.*, *31*, L16403, doi:10.1029/2004GL020654.

1. Introduction

[2] The relationship between glacier behaviour and climate has long been a central issue in glaciology [e.g., *Kuhn*, 1981; *Oerlemans*, 1994; *Hock*, 2004]. However, glacier-atmosphere interactions are complex especially in the tropics where accumulation and ablation are synchronous and ablation is permanent throughout the year [e.g., *Hastenrath and Ames*, 1995; *Kaser*, 2001]. Combined glacier mass and energy balance studies on low-latitude glaciers provide valuable knowledge on the tropical and global climate [*Wagnon et al.*, 2001; *Francou et al.*, 2003, 2004]. We compare herein the annual cycle of the surface energy balance (SEB) of two glaciers: Zongo Glacier, located in Bolivia (16°15′S, outer tropics) [*Wagnon et al.*, 1999; *Sicart*, 2002] and Antizana Glacier 15, located in Ecuador (0°28′S, inner tropics) [*Favier et al.*, 2004]. We also present some short-term SEB measurements performed over a non-permanent snow field, Caquella in southern Bolivia (21°30′S, subtropical climate), in order to briefly compare with ablation processes under dry subtropical conditions. In the tropical climate characterized by a lack of thermal seasonality, glaciers are particularly sensitive (i) to albedo itself controlled by the occurrence and the amount of solid precipitation throughout the year, (ii) to incoming long-wave radiation mainly related to cloudiness and (iii) to air humidity that conditions the sharing of energy between melting and sublimation. Although their mass balance is directly related to the moisture content of the atmosphere (precipitation, cloudiness, specific humidity), glaciers of both the outer and the inner tropics react differently to climatic forcing. In this paper, after a short description of these glaciers, their climatic setting, the data and the methodology, the differences in their respective SEB will be outlined in order to better understand the climatic response of outer and inner tropics' glaciers.

2. Glaciers, Climatic Setting, Data and Methodology

[3] Table 1 describes the major morphological, geographical and glaciological features of Zongo Glacier, Antizana Glacier 15 and Caquella snow field. Within the tropical climate, *Kaser* [2001] distinguishes the inner tropical climate with more or less continuous precipitation throughout the year to the outer tropical climate characterized by one dry season (where subtropical conditions prevail, April–September) and one wet season (where tropical conditions are dominant, October–March). The subtropical climate of southern Bolivia is characterized by an extreme dryness of the air and precipitation is not high enough to maintain glaciers. Half-hourly records of an Automatic Weather Station (AWS) installed at the glacier surface allow us to study local climatic setting and local surface energy balance. Figure 1 displays the dimensionless values of several meteorological variables measured at 5050 m a.s.l. and 4890 m a.s.l. on Zongo Glacier and Antizana Glacier 15 respectively and Table 2 gives the annual means and the standard deviations of these variables. The tropical climate is characterized by homogeneous temperature conditions throughout the year with a slight seasonality of air temperature in the outer tropics (higher temperatures during the austral wet summer, October–March). At low latitudes, incident solar radiation is also more or less constant throughout the year, the seasonality of the extra-terrestrial irradiance in the outer tropics being attenuated by the pronounced cloudiness seasonality. In the humid inner tropics, stable humidity conditions cause accumulation and ablation to occur simultaneously throughout the year, whereas the outer tropics are characterized by a pronounced

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Table 1. Morphological, Geographical and Glaciological Features of Zongo Glacier, Antizana Glacier 15 and Caquella Snow Field

	Zongo Glacier	Antizana Glacier 15	Caquella Snow Field
Country	Bolivia	Ecuador	Bolivia
Climatic zone	Outer tropics	Inner tropics	Subtropics
Latitude	16°15′S	0°28′S	21°30′S
Longitude	68°10′W	78°09′W	67°55′W
Elevation max	6000 m a.s.l.	5760 m a.s.l.	5960 m a.s.l.
Elevation min	4900 m a.s.l.	4840 m a.s.l.	5400 m a.s.l.
Surface	2.4 km^2	0.71 km^2	Several km^2
Exposition	South	North-West	South-East
Mean ELA	5240 m a.s.l.	5050 m a.s.l.	-
Altitude of the AWS	5050 m a.s.l.	4890 m a.s.l.	5450 m a.s.l.
Sky view factor[a]	0.94	0.95	≈0.98
Measurement period	Aug. 99–Aug. 00	Mar. 02–Mar. 03	04/25–04/28/01

[a]At AWS.

seasonality of specific humidity, precipitation and cloudiness. Thus, notable accumulation occurs only during the humid season and ablation, strong during the wet months, is reduced the rest of the year [*Kaser*, 2001].

[4] The energy stored into the top layers of the glacier ΔQ is calculated as (fluxes toward the surface positive) [e.g., *Oke*, 1987]:

$$\Delta Q = S\downarrow (1 - \alpha) + L\downarrow - L\uparrow + H + LE(\text{in W m}^{-2}) \quad (1)$$

where $S\downarrow$ is the incident short-wave radiation, α is the albedo ($S = S\downarrow(1 - \alpha)$ is the net short-wave radiation), $L\downarrow$ and $L\uparrow$ are incoming and outgoing long-wave radiation respectively ($L = L\downarrow - L\uparrow$ is the net long-wave radiation), and H and LE are turbulent sensible and latent heat fluxes respectively. Conduction into the ice/snow or heat supplied by precipitation are neglected. Although conduction is not negligible on Caquella, this hypothesis does not affect the results presented here. When the surface temperature is at the melting point, ΔQ represents the melting calculated in equation (1). The four radiative fluxes are measured locally at 5050 m a.s.l., at 4890 m a.s.l. and at 5450 m a.s.l. on Zongo Glacier, Antizana Glacier 15 and Caquella respectively with a CNR1 Kipp&Zonen net radiometer. The turbulent fluxes are calculated using the bulk aerodynamic approach calibrating the roughness lengths on direct sublimation field measurements. Temperature and humidity are measured using an artificially ventilated HMP 45 Vaisala sensor and wind speed is measured using a Young 05103 anemometer. See *Wagnon et al.* [1999] and *Favier et al.* [2004] for details.

3. Results

[5] Table 2 and Figure 2 give a full comparison of all the terms of the SEB of both glaciers for two annual cycles, the hydrological year 1999–2000 (September 1–August 31) for Zongo Glacier [*Sicart*, 2002] and March 14, 2002–March 14, 2003 for Antizana Glacier 15 [*Favier et al.*, 2004]. Although both cycles are not synchronous and slightly differ regarding ENSO conditions, they allow the main features of each SEB to be pointed out and to be compared to each other, which is the aim of this paper. Moreover, this comparison makes sense, since annual mass balance of both cycles reflected quite well the average of mass balance recorded over 10 years and 8 years on Zongo Glacier and on Antizana Glacier 15 respectively.

[6] Considering the meteorological variables, both sites are very similar. However, the moisture conditions on Antizana Glacier 15 are slightly affected by a fohen effect [*Favier et al.*, 2004] and the moisture values are site-specific to some extent. Taking into account the altitude difference, the annual mean temperatures are identical and the mean specific humidity is a little lower on Zongo Glacier than on Antizana Glacier 15. Very small standard deviations in Ecuador underline the absence of thermal seasonality in the inner tropics. Only wind speed, higher on Antizana Glacier 15, is strongly variable throughout the year with a marked windy season from June to October, coinciding with a slight minimum in moisture. Although we might have expected a much higher cloudiness and heavier precipitation in Ecuador in relation with the humid climate of the inner tropics, the difference in the annual cloudiness and in the annual precipitation between these two glaciers is not significant, only the seasonal distribution of the cloud cover and the precipitation being completely different. Finally, precipitation always falls as snow on Zongo Glacier, whereas more than one quarter of the total precipitation is rain at the altitude of the AWS on Antizana Glacier 15 [*Favier et al.*, 2004].

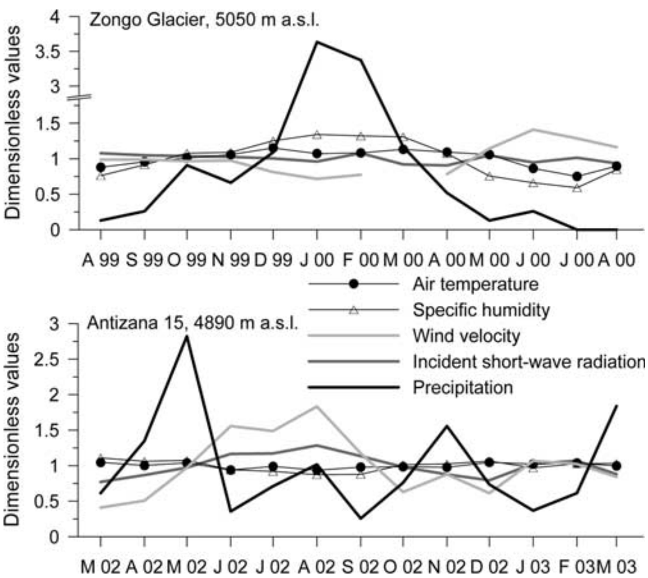

Figure 1. Dimensionless values of incident short-wave radiation, air temperature, specific humidity and wind speed at 5050 m a.s.l. on Zongo Glacier (Aug. 1999–Aug. 2000; upper panel) and at 4890 m a.s.l. on Antizana Glacier 15 (Mar. 2002–Mar. 2003; lower panel). Also shown are the dimensionless values of precipitation at 4750 m a.s.l. and 4650 m a.s.l. on Zongo Glacier and Antizana Glacier 15 respectively. Variables were made non dimensional by dividing the monthly mean by the annual mean. Air temperatures for both glaciers have been artificially shifted by +10°C in order not to mix negative and positive values. Note that the y-axis for Zongo glacier is broken. In the lower panel, dimensionless values of March 2002 are for 15 days only (except for precipitation amount).

Table 2. Annual Mean Values and Standard Deviations (Calculated From Daily Values) of Each Meteorological and SEB Variable of Zongo Glacier at 5050 m a.s.l. (From [*Sicart*, 2002]) and of Antizana Glacier 15 at 4890 m a.s.l.; Also Presented Are the Mean Values Over 3.5 Days (April 25–28, 2001) of Each Meteorological and SEB Variable of Caquella Snow Field

	Zongo Glacier (5050 m a.s.l.) 09/01/99–08/31/2000 [*Sicart*, 2002]		Antizana Glacier 15 (4890 m a.s.l.) 03/14/02–03/14/2003		Caquella (5450 m a.s.l.) 04/25–28/2001
Variable[a]	**Annual Mean**	Standard Deviation	**Annual Mean**	Standard Deviation	**Mean**
T (°C)	**−0.8**	1.4	**0.3**	0.7	**−4.2**
RH (%)	**71**	21	**81**	11	**12**
q ($g\ kg^{-1}$)	**4.7**	1.5	**5.5**	0.7	**0.61**
u ($m\ s^{-1}$)	**2.7**	1.2	**4.8**	3.5	**5.6**
cloudiness	**0.53**		**0.50**	0.23	**0.27**
$S\downarrow$ ($W\ m^{-2}$)	**209**	61	**239**	68	**247**
$S\uparrow$ ($W\ m^{-2}$)	**137**	48	**116**	51	**162**
α	**0.66**	0.18	**0.49**	0.18	**0.70**
$L\downarrow$ ($W\ m^{-2}$)	**258**	45	**272**	29	**195**
$L\uparrow$ ($W\ m^{-2}$)	**303**	13	**311**	3	**297**
T_{surf} (°C)	**−3.1**	2.1	**−1.4**	0.7	**−5.2**
S ($W\ m^{-2}$)	**72**	49	**123**	57	**85**
L ($W\ m^{-2}$)	**−45**	35	**−39**	27	**−102**
R ($W\ m^{-2}$)	**27**	36	**84**	46	**−16**
H ($W\ m^{-2}$)	**21**	27	**21**	19	**7**
LE ($W\ m^{-2}$)	**−31**	41	**−27**	31	**−71**
z_0 (mm)	**3.2**	-	**2.9**	-	**0.07**
H+LE ($W\ m^{-2}$)	**−10**	20	**−6**	17	**−64**
R+H+LE ($W\ m^{-2}$)	**19**	40	**78**	49	**−80**
total precip. (*mm*)	**925**	-	**970**	-	**<300**
solid precip. (*mm*)	**925**	-	**715**	-	**?**
liquid precip. (*mm*)	**0**	-	**255**	-	**0**
melting (*mm w.e.*)	**1800**	-	**7400**	-	**0**
sublimation (*mm w.e.*)	**346**	-	**300**	-	**790**[b]

[a] *T* is air temperature, *RH* and *q* are relative and specific humidity respectively, *u* is wind speed, $S\downarrow$, $S\uparrow$ and *S* are incident, reflected and net short-wave radiation respectively, α is albedo, $L\downarrow$, $L\uparrow$ and *L* are incoming, outgoing and net long-wave radiation respectively, *R* is net all-wave radiation, T_{surf} is surface temperature, *H* and *LE* are turbulent sensible and latent heat fluxes respectively and z_0 is the calibrated roughness length.
[b] For 1 year.

[7] Considering the radiative fluxes, due to similar values for cloudiness, specific humidity and air temperature, incoming long-wave radiation is only slightly lower on Zongo Glacier but with a higher standard deviation stemming from its pronounced seasonality (Table 2). Outgoing long-wave radiation shows that on both glaciers, melting conditions are encountered almost every day, at least during a few hours, but refreezing processes are more efficient on Zongo Glacier than on Antizana Glacier 15, as shown by the lower surface temperature. Due to the latitude and the thick cloud cover over Bolivia during the summer months of maximum potential irradiance (October–March), incident short-wave radiation is smaller on Zongo Glacier than on Antizana Glacier 15. Reflected solar radiation depends on albedo which is difficult to compare because albedo is very variable from year to year [*Wagnon et al.*, 2001] and strongly site-dependent. Besides, albedo is lower on Antizana Glacier 15 mainly because the AWS is located closer to the glacier terminus than on Zongo Glacier, and because part of the precipitation is rain.

[8] Considering the turbulent heat fluxes, noting that AWS' locations with respect to the equilibrium line altitude are similar, a similar situation is observed with a strongly negative latent heat flux (corresponding to a mass loss through sublimation) partly counter-balanced by a positive sensible heat flux. This is surprising because in the humid inner tropics, sublimation was expected to be weak [*Kaser*, 2001]. In fact, the latent heat flux is almost as important as in the outer tropics because of stronger winds that favour turbulence in the surface boundary layer between June and October.

[9] Figure 2 displays the monthly ablation (melting + sublimation) together with the monthly albedo on both sites. During the wet season in the outer tropics like during the entire year in the inner tropics, an anticorrelation is visible between melting and albedo, suggesting that inner tropics conditions prevail during the wet season in Bolivia. During the dry season in the outer tropics, sublimation is high,

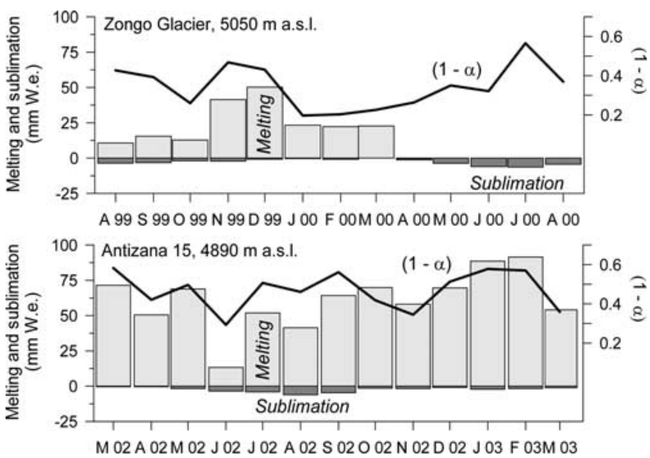

Figure 2. Monthly mean values of melting, sublimation and 1-albedo ($1-\alpha$) at 5050 m a.s.l. on Zongo Glacier (Aug. 1999–Aug. 2000; upper panel) and at 4890 m a.s.l. on Antizana Glacier 15 (Mar. 2002–Mar. 2003; lower panel). In the lower panel, mean values of March 2002 are for 15 days only.

leaving almost no energy for melting that occurs only a few hours a day. This situation is more typical of the subtropics.

[10] Table 2 also displays the records of a short duration measurement campaign conducted on Caquella snow field, under the dry and stable conditions of the subtropical climate, mainly under the influence of subsiding dry air masses [*Vuille*, 1999]. Despite the short duration of the measurement period (3.5 days), these measurements can be briefly and qualitatively compared to those performed on the previous tropical glaciers (Table 2). The main difference comes from the extremely low specific humidity that implies a record latent heat flux (sublimation rates higher than 2 mm water equivalent per day) and an exceptionally low incoming long-wave radiation (in relation with the very low cloudiness and the very high altitude), that is not compensated by the increase in incident solar radiation (also related to low cloudiness). Therefore, melting conditions are not encountered on this snow field any more and ablation occurs almost only through sublimation. Anyway, glaciers do not exist in this region because precipitation is too weak to compensate sublimation.

4. Discussion and Conclusion

[11] The SEB in the ablation areas of Zongo Glacier and Antizana Glacier 15 is dominated by the net short-wave radiation S which is partly compensated by the negative net long-wave radiation L (Table 2). Since S is closely related to albedo, albedo appears as a central variable controlling the amount of energy available at the surface of the ablation area of inner and outer tropics' glaciers. With its positive feedback on albedo, solid precipitation is therefore a key meteorological variable to the variability of the melting of all tropical glaciers. In the outer tropics where liquid precipitations almost never occur on glaciers, the mass balance is closely related to the total amount and the annual precipitation distribution. However, in the inner tropics, air temperature is still a very important meteorological variable managing the mass balance of the glaciers in that it controls the phase of the precipitation. Subtropical dryness illustrates an extreme situation where the precipitation deficit prevents glacier from developing.

[12] The seasonality of the precipitation hence that of the melting is also very different between both climatic zones, which induces a different functioning of the respective glaciers. In Bolivia, precipitation is weak and sporadical between October and December, low albedo bare ice is usually exposed at the surface of the ablation area, and absorption of short-wave radiation is thus maximum, leading to an intense melting. This situation ends between December and February as soon as precipitation becomes high and frequent enough to maintain a permanent snow cover of high albedo on most of the glacier surface [*Sicart et al.*, 2003]. Thus, the inter-annual variability of the mass balance of the glacier mostly depends on the inter-annual variability of the precipitation especially during the crucial period December–February [*Francou et al.*, 2003], reflecting weakened (enhanced) easterly wind conditions and reduced (increased) moisture influx from continental lowlands [e.g., *Vuille*, 1999]. However in Ecuador, on seasonal time scales mean ablation rates remain at a quite constant level throughout the year, and the inter-annual variability of the mass balance of the glacier is mainly controlled by year-to-year variations in air temperature that govern the snow-line altitude [*Francou et al.*, 2004]. Glaciers of the inner tropics are therefore more sensitive to temperature changes and especially to global warming than glaciers of the outer tropics which have a 4- to 6-month dry season of very reduced melting (Figure 2). Indeed, the elevation of the equilibrium line with respect to the 0°C-level, a suitable criterion to describe the glacier sensitivity to temperature change, increases with latitude [*Kuhn*, 1981]. In the subtropics, this altitude difference reaches several hundred meters, making glaciers, if there were any, very little sensitive to air temperature and restricting ablation to only sublimation as seen for Caquella snow field.

[13] The climatic change affecting the tropical part of South America is nowadays dominated by El Niño periods. The last decade was marked by long [*Trenberth and Hoar*, 1996] and vigorous El Niño events [*Fedorov and Philander*, 2000]. During these periods, tropical glaciers usually experience strongly negative mass balances [*Wagnon et al.*, 2001; *Francou et al.*, 2004]. Although precipitation decreases and temperature increases are observed on both sites during El Niño periods, the relationship implying a negative mass balance is different when considering glaciers of the outer or the inner tropics. In Bolivia, ablation is strongly enhanced because of the deficit of precipitation (particularly between December and February) and the subsequent albedo decrease prevailing during El Niño conditions [*Wagnon et al.*, 2001], whereas in Ecuador El Niño episodes warm conditions induce a rise in the snowline altitude, and therefore a decrease in albedo under this altitude. The result is identical: melting is enhanced and the mass balance is negative [*Francou et al.*, 2004]. Consequently, most tropical glaciers are not in equilibrium under the present climate and should the present trend of intense El Niño periods extend in the future, tropical glaciers would retreat at a fast rate.

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