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Glacier Evolution in the Tropical Andes during the Last Decades of the 20th Century: Chacaltaya, Bolivia, and Antizana, Ecuador

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Glacier Evolution in the Tropical Andes during the Last Decades of the 20th Century: Chacaltaya, Bolivia, and Antizana, Ecuador

Mass balance has been continuously monitored on Chacaltaya Glacier (16°S, Cordillera Real, Bolivia) since 1991, and on the Antizana Glacier 15 (0°, Ecuador) since 1995. In ablation areas, mass balance has been surveyed on a monthly scale, providing interesting details about the seasonal pattern in 2 contrasting tropical environments. Intermittent information about ice recession exists in both regions for the last 4 decades. The data point to a clear acceleration in glacier decline during this decade; ablation rates have been 3–5 times higher than during the former decades. Fluctuations measured before on 3 glaciers in northern Peru, allow the assumption that the rate at which the glaciers retreated in the tropical Andes increased in the late 1970s. The present situation is particularly dramatic for the small-sized glaciers (< 1 km²) and many such as Chacaltaya, could disappear in the next 10 years. As evidenced by the data collected, ablation increases significantly during the warm phases of ENSO (El Niño) and decreases during the cold phases (La Niña). Warm events becoming more frequent and intense since the late 1970s, it can be assumed that they have played an important role in the recent glacier decline in the central Andes, together with the global warming.

INTRODUCTION

In the 1970s tropical glaciers represented 5% of the world's mountain glaciers, covering a surface comparable to the glaciers of the Alps (1, 2). Glaciers are scattered over 3 continents, America, Africa, and Indonesia, but 99% are concentrated in the Andes, with 70% in Peru, 20% in Bolivia and the rest in the northern Andes, Ecuador, Colombia, and Venezuela. In spite of their reduced importance in terms of water volume, these glaciers are believed to play an important role as climatic indicators for at least 3 reasons: *i*) they bring a synthetic view of the climatic evolution of the medium troposphere in the tropics; *ii*) they are very sensitive to the climate variation due to the absence of a season without ablation which favors a strong activity at low elevation; *iii*) for this reason and because of their reduced size, these glaciers react rapidly to climate fluctuations. In terms of water resources, glaciers have an important economic value on the regional scale, particularly when the pluviometric regime includes sharp seasonal variability.

BACKGROUND

In contrast to the mid-latitude mountains, glaciers which have supplied continuous and accurate series of mass-balance information in the past, are very seldom found in the tropics (3). This can be explained by the economic restrictions existing in the tropical countries and the relative inaccessibility of these glaciers—generally at more than 4500 m a.s.l. Before the 1990s, only the Lewis glacier in Africa and 4 glaciers of northern Peru had been monitored for more than a decade (Table 1) (4–7). Other information covering a large period of the 20th century but difficult to extrapolate in terms

of glacier mass-balance evolution due to poor resolution have been supplied by photogrammetric restitution methods (8). Since the early 1990s, the IRD (l'Institut de Recherche pour le Développement, France), has together with the South American partners, paid a great deal of attention to these glaciers and has developed a monitoring network which regularly supplies accurate data about mass, hydrology and energy balances from an area between the 16°S and the Equator (Fig. 1). All previous studies had pointed to an accelerated recession of the glaciers in the tropical Andes (5–10). From well-surveyed terminus of 3 small-sized glaciers of the Cordillera Blanca, Peru, it was shown that the recession rates probably increased dramatically from the late 1970s (Fig. 2) (7). Although this important "break date" in glacier evolution has to be confirmed from other places in the Andes, some glaciers monitored for a long period of time in middle latitude areas show the same pattern (11).

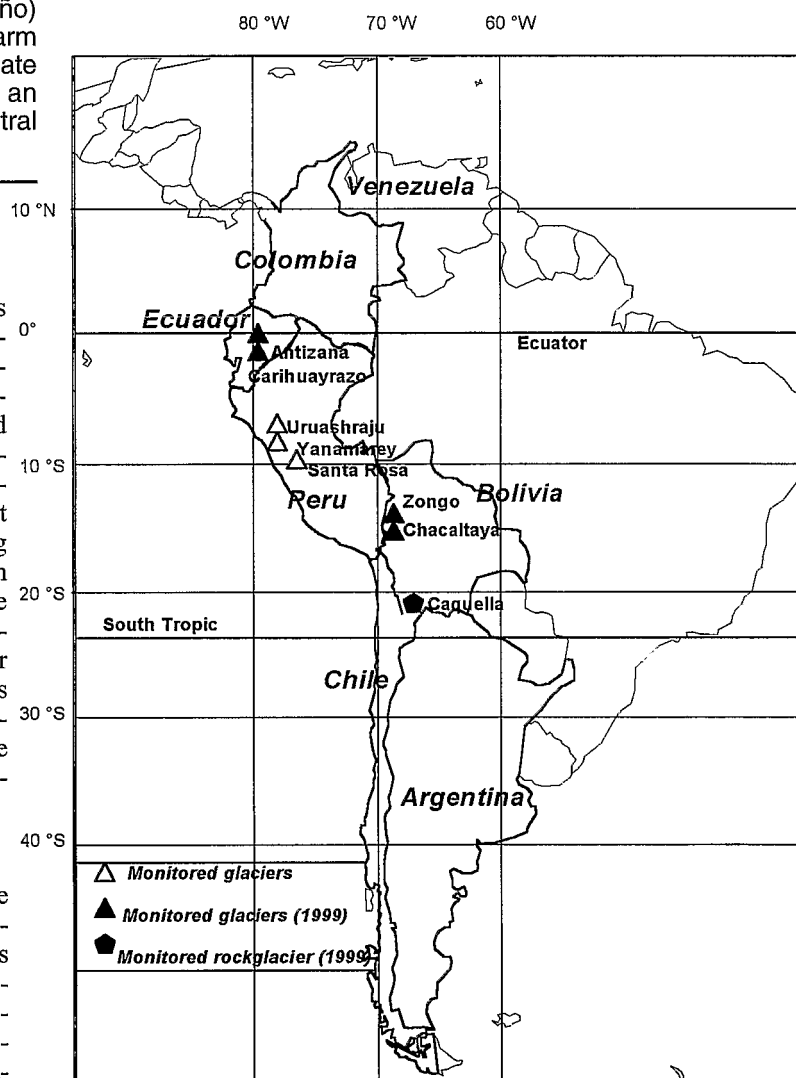
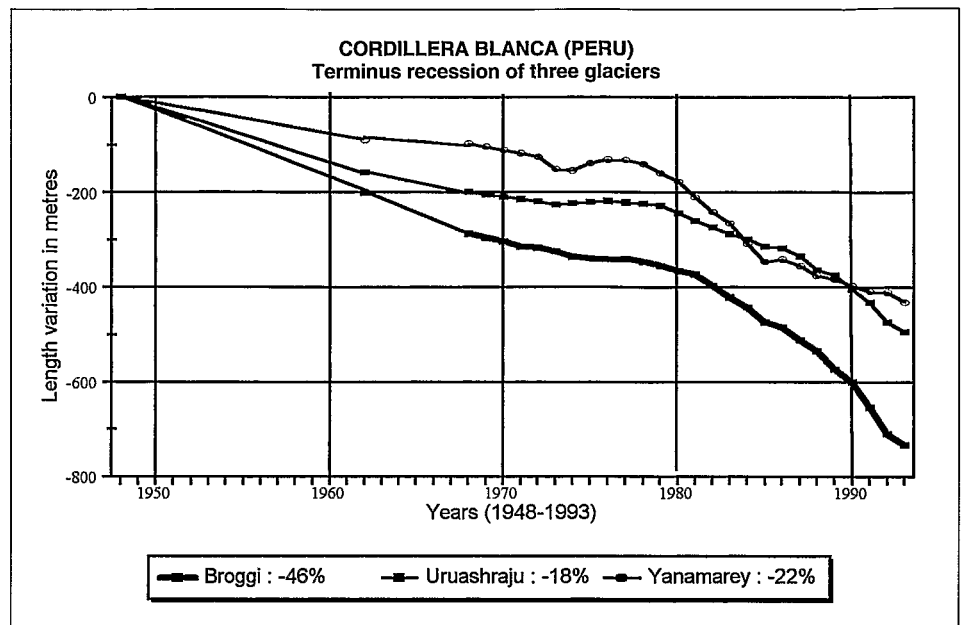


Figure 1. Map of glaciers and rock glaciers monitored in the Central Andes over the last decades. The white triangles refer to sporadic monitorings in ablation areas.

Figure 2. Three glaciers in recession in the Cordillera Blanca, Peru. Retreat of the terminus since 1948. From Ames and Francou (7).



This paper presents information on 2 well-monitored glaciers considered as representative of their respective areas: Chacaltaya glacier, in the outer Tropics (16°S, Bolivia) and Antizana Glacier 15, close to the Equator.

Data on the recent changes that occurred on these glaciers will be presented. The data were obtained by mixing aerial photographic data with mass balances directly obtained by the classical method of stakes and pits. Mass balance observations conducted every month in the ablation areas provide a high resolution view of the response of the glacier to climatic fluctuations over the last decade. This information is connected to ENSO variability, a factor known to be of a great importance in the climate evolution of the tropical Andes, on a decadal scale (12, 13). The question of the physical response of these glaciers to climate, previously developed on the Zongo glacier in Bolivia (14, 15), is not discussed in this paper.

A GLOBAL VIEW OF CHACALTAYA AND ANTIZANA GLACIER RECESSION OVER THE LAST DECADES

Chacaltaya (16°S)

Chacaltaya is a small-sized cirque glacier facing south situated 20 km NE of the city of La Paz in northern Bolivia. In 1998, the altitude range was 250 m, between 5375 m a.s.l. and 5125 m a.s.l. The length and the surface area are 580 m and 0.06 km², respectively. This glacier is representative of the Cordillera Real where 80% of the glaciers are smaller than 0.5 km². Accumulation occurs from January to April, a season with a total of more than 70% of the precipitation, while ablation reaches its maximum in October–December. During the dry season (June–August), radiation fluxes are limited on the glacier surface due to the aspect, and ablation, reduced to sublimation, does not exceed 50 mm month⁻¹ (16). Information about past extensions have been supplied by: *i*) processing an aerial oblique picture taken in 1940; *ii*) analyzing photogrammetrically aerial views dating from 1963 and 1983; *iii*) measuring the contour of the glacier every year since 1992, by a ground topographic survey. A rough estimate of the glacier bulk was carried out in 1996 by seismic-refrac-

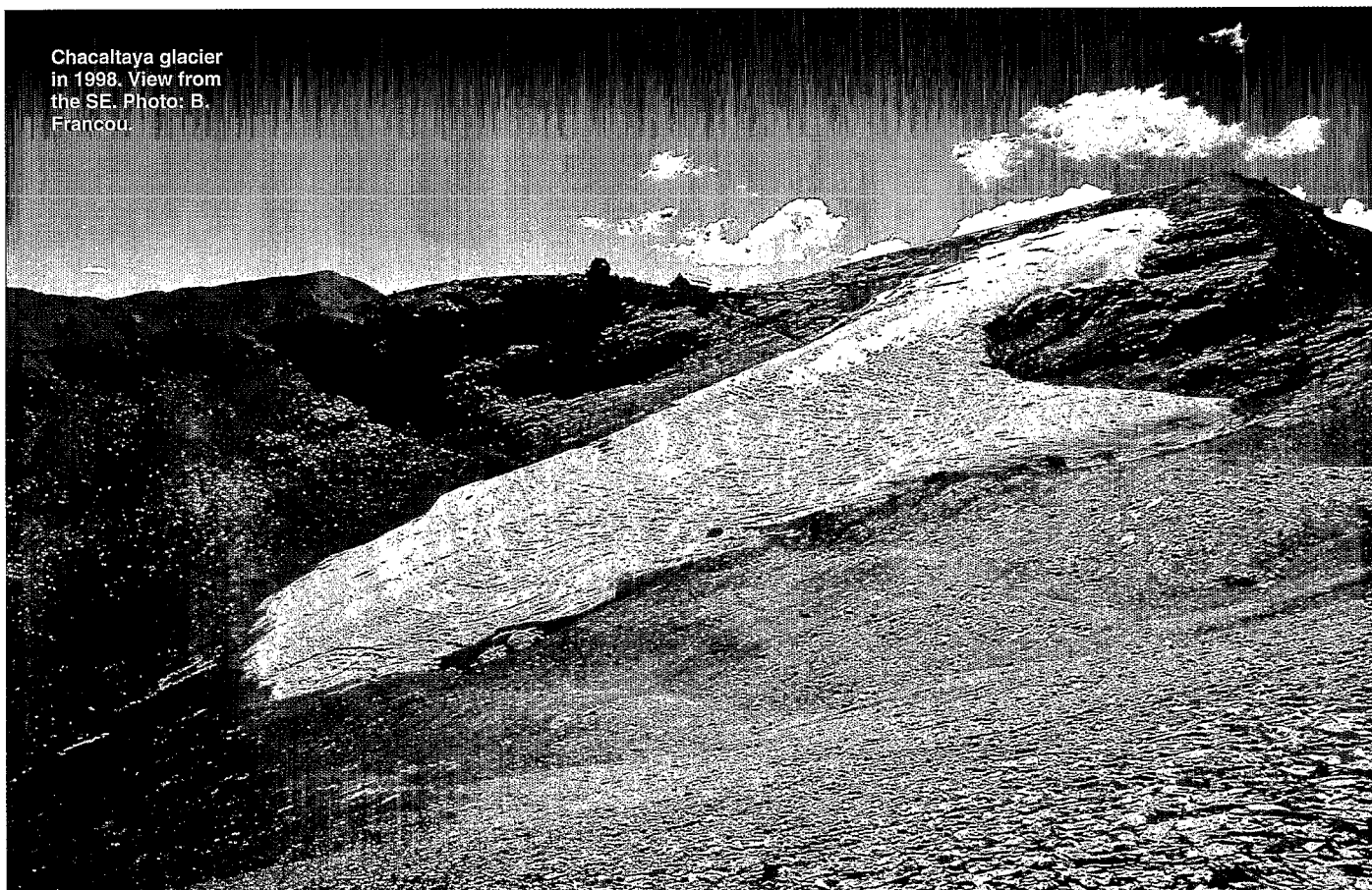
tion soundings (16) and completed with better accuracy in 1998 by a radar prospection. From these measurements, it was possible to draw a 3-dimensional representation of the glacier (17).

Since 1991, a network of 6 stakes, extended to the whole glacier surface in 1996 with 15 stakes, has been surveyed every month in order to estimate mass balance. From 1940 to 1983, the glacier has lost 62% of its mass, with the recession increasing dramatically during the past 2 decades (Fig. 3). In 1998, Chacaltaya was reduced to 7% of the 1940s ice volume (Table

Table 1. The principal glaciers monitored in the Tropics.

Glaciers and Location	Monitoring system	Authors
Lewis Kenya – 00°09'S	<ul style="list-style-type: none"> • Geometric evolution (1899–1997) • Mass balance (1978–1997) • Surficial velocity, geophysical soundings 	Hastenrath, Kruss (4)
Yanamarey Cordillera Blanca Peru – 9°30'S	<ul style="list-style-type: none"> • Terminus fluctuations (1939–1995) • Mass balance in the ablation area (1977–1995) • Surficial velocity in the ablation area 	Ames, Hastenrath (5)
Uruashraju Cordillera Blanca Peru – 9°30'S	<ul style="list-style-type: none"> • Terminus fluctuations (1939–1995) • Mass balance in the ablation area (1977–1995) • Surficial velocity in the ablation area 	Ames, Hastenrath
Broggi Cordillera Blanca Peru – 9°30'S	<ul style="list-style-type: none"> • Terminus fluctuations (1932–1993) 	Kinzi, Ames, Portocarrero
Santa Rosa Cordillera Raura Peru – 9°S	<ul style="list-style-type: none"> • Terminus fluctuations (1961–1980) • Mass balance in the ablation area (1977–1983) • Surficial velocity in the ablation area 	Ames, Hastenrath (6)
Zongo Cordillera Real Bolivia – 16°S	<ul style="list-style-type: none"> • Geometric evolution (1956–1999) • Mass balance (1991–1999) • Surficial velocity • Energy balance • Hydrology (1973–1999) 	IRD (14, 15, 21, 22, 23) and Partners
Chacaltaya Cordillera Real Bolivia – 16°S	<ul style="list-style-type: none"> • Geometric evolution (1940–1999) • Mass balance (1991–1999) • Surficial velocity • Geophysical soundings • Hydrology (since 1998) 	IRD (16, 17) and Partners
Antizana 15 Cordillera Oriental Ecuador – 0°28'S	<ul style="list-style-type: none"> • Geometric evolution (1956–1999) • Mass balance (1991–1999) • Surficial velocity • Geophysical soundings • Energy balance • Hydrology (since 1997) 	IRD (18, 19) and Partners
Carhuayrazo Cordillera Occidental Ecuador – 1°S	<ul style="list-style-type: none"> • Mass balance (1998–1999) • Surficial velocity 	IRD and Partners

Chacaltaya glacier in 1998. View from the SE. Photo: B. Franco.



2). On average, ice wasting has increased in the ratio of 1:3 between the 2 periods 1940–1983 and 1983–1998; a trend which has tended to accelerate since 1992 (Table 3). As indicated by the Figure 4, the balance has been generally negative between 1991 and 1998, with an average loss of water as high as 1400 mm yr⁻¹. This information is consistent with the 1359 mm yr⁻¹ directly estimated by the topographic surveys for the same period. For 7 years the regressed Equilibrium Line Altitude (ELA) was located at the top of the glacier or above. Thus, lacking ac-

cumulation area, the glacier could disappear in the near future. Given a maximum thickness of 15 m, by simple extrapolation of the recent average mass balance (i.e. 1400 mm yr⁻¹), Chacaltaya may not survive more than 10 years. Assuming melting to be the principal cause of the increasing ablation, and given the latent heat of melting, $L_m = 33 \times 10^4 \text{ J kg}^{-1}$, the supplement of energy required to dispose of 1400 mm of ice is estimated to be about 14 W m⁻². By comparison with the 2.1 km² Zongo Glacier 40 km away and situated in a same environment, it can be

Figure 3. Chacaltaya Glacier. Area and volume depletion estimations for the last six decades.

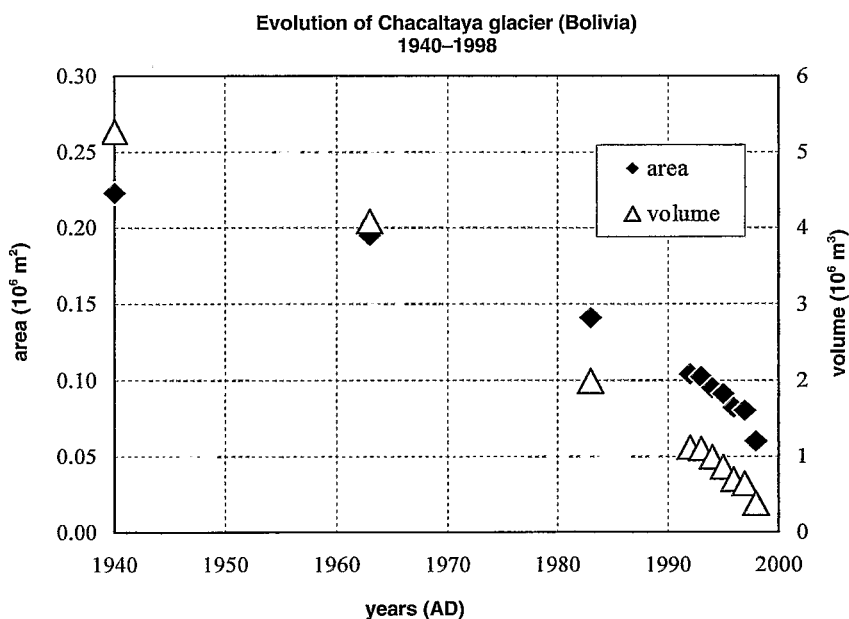


Table 2. Area and volume evolution of Chacaltaya Glacier for the last 6 decades.

Years	Area ¹	Volume ⁵ (and % lost ⁶)
1940 ¹	223 110	5 264 000
1963 ²	194 734	4 086 065 (22)
1983 ²	140 659	1 987 387 (62)
1992 ³	103 621	1 113 587 (79)
1993 ³	102 079	1 095 109
1994 ³	94 806	984 612
1995 ³	90 715	854 375
1996 ³	82 133	688 584
1997 ³	79 821	633 987 (88)
1998 ³	59 729	373 514 (93)

¹ oblique view

² photogrammetry from aerial view

³ ground topographic survey

⁴ in m²

⁵ in m³ of ice

⁶ % of ice lost since 1940

assumed that the deficit radically affects the small-sized glaciers, which cannot recover mass during more favorable climatic conditions (Fig. 5).

Antizana Glacier 15 (0°28'S)

Antizana 15 is an ice cap and a slope glacier located 40 km east of Quito, Ecuador, at the head of an important hydraulic system which supplies water to the city. Facing NW, between 4800 m and 5760 m a.s.l. this 2-km long glacier covered, in 1998, an area of about 0.74 km². The summit forms an extensive ice cap located on a volcano, considered to be active. Since 1956, the low part (< 5000 m a.s.l.) has been separated into two tongues, named 15 α and 15 β , respectively. Antizana area is representative of the eastern Cordillera directly exposed to the moist winds coming from the Amazon Basin. Precipitation falls all year round, generally, with a slight decrease in November–January during the “veranillo” (“little summer”), but the temperature has no seasonal trend. Information concerning the past extensions of glaciers is rare in Ecuador, in spite of important archival material covering the last 2 centuries (18). On Antizana Glacier 15, 3 methods have been used to analyze the recent evolution: *i*) photogrammetric restitution of aerial views dating from 1956, 1965, 1993 and 1997, which provide information on glacier fluctuations over the last 4 decades; *ii*) a survey once a year since 1996 of the terminus contour and the ablation stakes; and *iii*) a network of 15 ablation stakes (surveyed once a month) in the ablation area and 5 pits dug twice a year (19).

The evolution of the glacier is mapped in the Figure 6. The agreement between

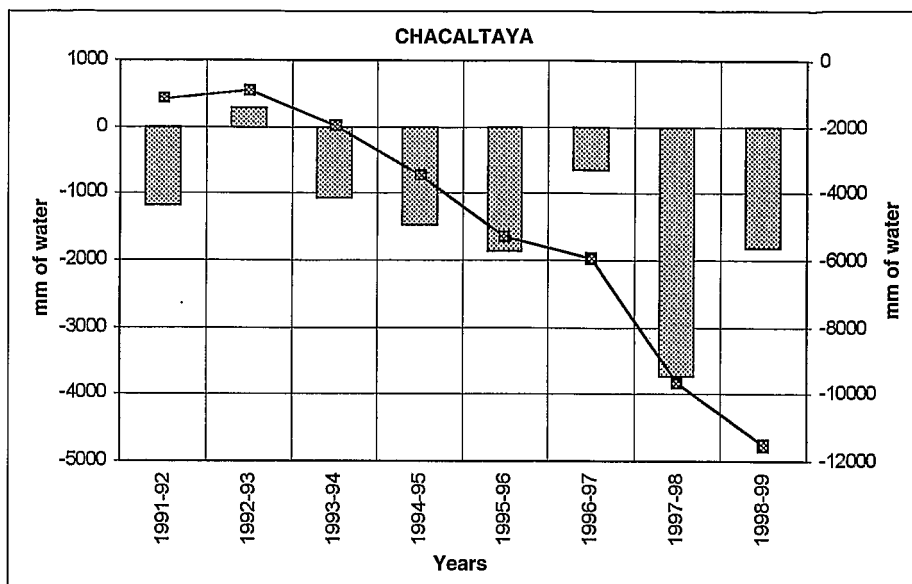


Figure 4. Chacaltaya Glacier. Specific net balance (hydrological year September–August). Cumulative water loss for the eight years: 11 515 mm.

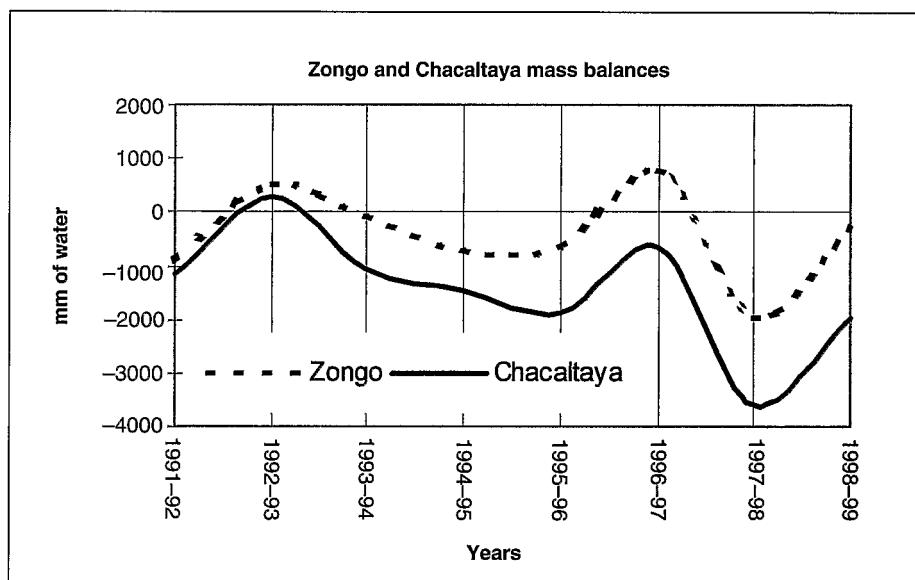


Figure 5. Mass balance evolution of Zongo and Chacaltaya glaciers. In August 1999, the cumulated loss amounted 11 500 mm on Chacaltaya and 3350 mm on Zongo.

Table 3. Area/volume evolution of Chacaltaya Glacier and mass balance reconstruction over the past 58 years.

Years	Mean area ¹	ΔV^2	ΔH^3	Bn ⁴	Bn ⁵ _{we}
1940–63	208 922	1 178 000	5.63	-245	-220
1963–83	167 696	2 098 678	12.51	-626	-563
1983–92	122 140	873 800	7.15	-795	-715
1992–98	81 675	740 073	9.06	-1510	-1359

¹ in m²
² difference in ice volume (in m³)
³ difference in height (in m)
⁴ net balance (in mm ice per year)
⁵ net balance (in mm water equivalent per year, with $d_{ice} = 0.9 \text{ g cm}^{-3}$)

Table 4. Length (L) and surface (S) evolution of Antizana Glacier 15 (1956–1998).

Time	L (α)	L (β)	S ($\alpha + \beta$)
1956	2235	2380	967638
1965	2193	2359	924595
1993	2103	2216	804673
1996	2049	2158	771636
1997	1989	2104	747180
1998	1963	2065	737305

L: length in m
S: area total (alpha + beta) in m²

Table 5. Area/volume evolution of Antizana Glacier 15 α and mass balance reconstruction over the past 41 years.

Years	Mean area ¹	ΔV^2	ΔH^3	Bn ⁴	Bn ⁵ _{we}
1956–1965	452 660	-1136590	2.51	-279	-251
1965–1993	407465	-1855895	4.55	-163	-146
1993–1997	358 080	-957487	2.67	-668	-602

¹ in m²
² difference in ice volume (in m³)
³ difference in height (in m)
⁴ net balance (in mm ice per year)
⁵ net balance (in mm water equivalent per year, with $d_{ice} = 0.9 \text{ g cm}^{-3}$)

the results obtained from topography and from photogrammetry makes it possible to obtain the trend of the glacier recession since 1956 (Fig. 7; Table 4). Volume depletion is given in Table 5. The presence of a gap in the 1980s limits the comparison with Chacaltaya, but the glacier decline clearly appears to have accelerated during the present decade. During the last 5 years, the 2 tongues have retreated 7 or 8 times faster than during the period 1956–1993, whereas the whole area has decreased 3 times faster. During the most recent 5-year period, the length and the area were reduced by 7% and 9%, respectively. This evolution is related to a series of strong negative net balances, as it can be observed in Figure 8.

The mass deficit on Glacier 15 α has averaged 950 mm yr⁻¹ of water during the last 4 cycles. However, taking into account the photogrammetry, a negative balance of about 600–700 mm yr⁻¹ could be the most representative for the entire decade (Table 5). Assuming melting to be the principal cause of the increasing ablation, a supplement of energy required to melt 600–700 mm ice is estimated to be 6–7 W m⁻².

MASS BALANCE ON A MONTHLY SCALE: EVIDENCE OF A CONNECTION BETWEEN GLACIER EVOLUTION AND ENSO EVENTS

ENSO impacts have been recognized to be important for tropical glaciers ever since the ice core drilled on the summit of Quelccaya ice cap (Southern Peru) indicated a mass deficit during the recent warming events (20). Not too long ago, several authors (13, 21–23) pointed to a significant increase in ablation rates of Peruvian and Bolivian glaciers during these events. The physical mechanisms involved are now being precisely documented from the energy balance measurements conducted on the Zongo Glacier (15). A similar approach is in progress in Ecuador on the Antizana Glacier 15. The Multivariate ENSO Index (MEI) is an indicator commonly used to describe the ENSO variability in the Pacific (24). Although more relevant for analyzing the glacier evolution would be to characterize the mid-troposphere above the central Andes during these events (analysis in progress), the MEI is presented here as a first approach to put in parallel the mass balance observed in the ablation areas of the 2 glaciers and the Equatorial Pacific variability.

The Month Evolution at Chacaltaya:

Over the 96 months measured, 3 large ablation peaks were observed (Fig. 9); one very strong in 1997–1998, followed by two others in 1994–1995 and 1991–1992, all of these fitting into ENSO warm events or being delayed by several months. The very strong 1997–1998 event and the 1994–1995 peak were followed by strong negative mass balances over 2 consecutive years. On the other hand, the moderate 1995–1997 La Niña event coincided with the second weak ablation period of the series. However, a slight positive mass balance (also recorded on the nearby Zongo glacier) occurred during the the 1992–1993 ENSO warming event. This confirms the close link that exists between the ENSO-related climate variability and the glacier evolution in Bolivia, as stressed before by authors

from a 25-year reconstruction of monthly ablation rates on the Zongo glacier (21, 23). However, in some cases, the relation seems to be inconsistent, as in 1992–1993. The origin of this discrepancy may be found in the ENSO-related atmospheric mechanisms. Two features are noteworthy: *i*) during the austral summer 1992–1993 the tropical troposphere at 500 hPa was unusually cold; *ii*) the ENSO in 1993 was short and peaked during the dry and cold season (austral winter), a coincidence which tends to limit its impact on the glacier.

The Monthly Evolution on the Antizana Glacier 15

On the 48-month series of the Antizana Glacier 15 α , 2 periods of strong ablation rates were observed, the first in 1995, and the second between April 1997 and May 1998 (Fig. 10). By contrast, 2 minima are clearly identified, one centered in 1996, another one beginning in May–June 1998. The 2 ablation peaks

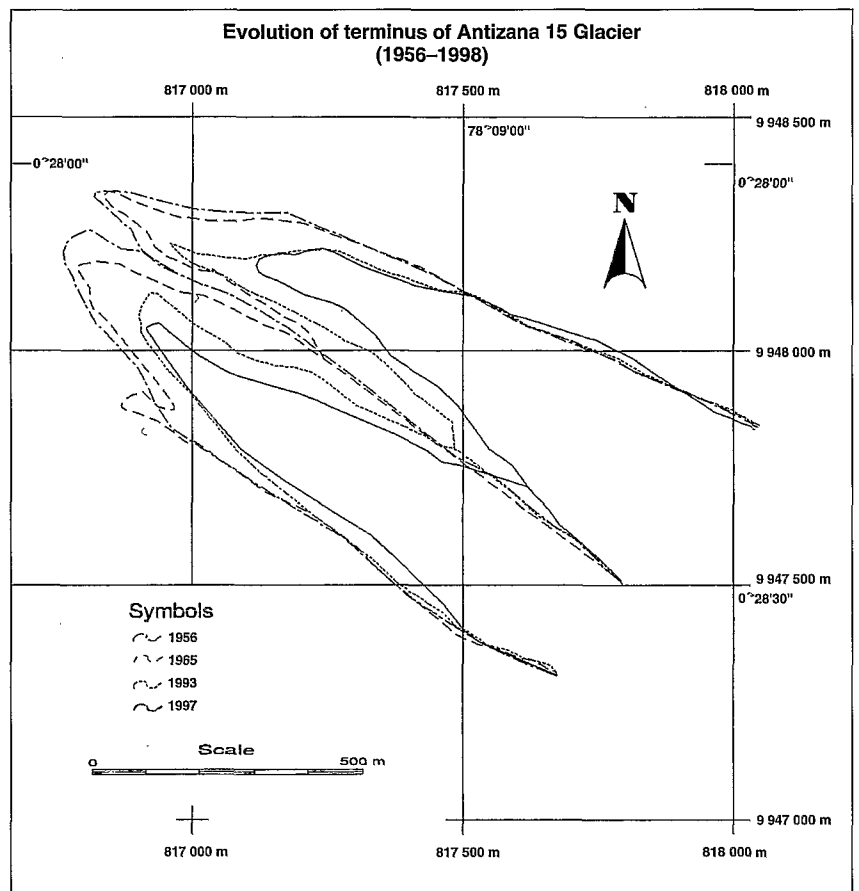


Figure 6. Antizana Glacier 15: terminus fluctuations over the last four decades.

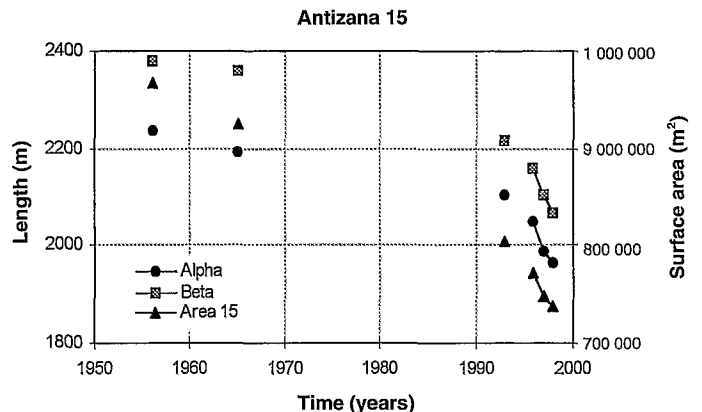
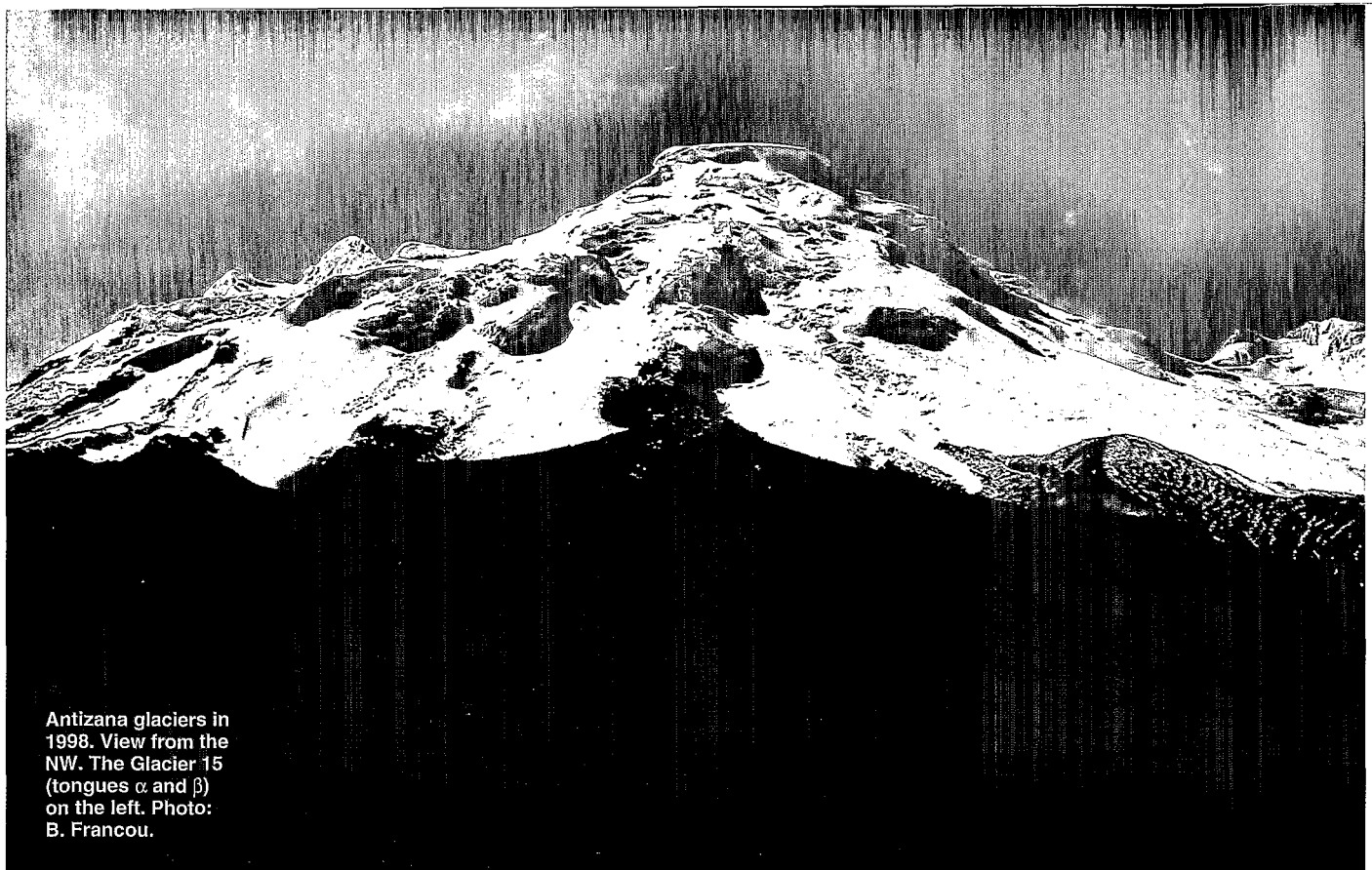


Figure 7. Antizana Glacier 15: length and area evolution 1956–1998.



Antizana glaciers in 1998. View from the NW. The Glacier 15 (tongues α and β) on the left. Photo: B. Francou.

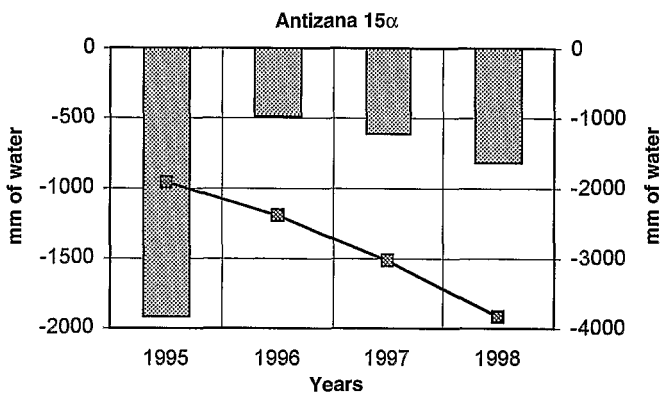


Figure 8. Antizana 15 α Glacier: net balance evolution during the last four years. Cumulative loss: 3830 mm we. Hydrological year: January–December.

and the 2 minima fit well into the warm ENSO phase (El Niño) and the cold ENSO phase (La Niña), respectively. The response of the glacier to the Pacific forcing does not seem to suffer a significant lag time, which suggests a more strong and direct influence of the ENSO in the Ecuadorian cordilleras. It can be assumed that the proximity of the Pacific and the absence of seasonality can explain the good relation between the ENSO and the glacier mass balance in Ecuador.

DISCUSSION AND CONCLUSION

This analysis confirms the recent dramatic recession of glaciers in the tropical Andes. During this decade, the average mass deficits of these glaciers, including the Zongo (15), have been in the 600 mm yr^{-1} – 1400 mm yr^{-1} range. The small-sized glaciers have been most affected, and many might disappear in the next decade if the trend does persist. Such an imbalance implies a rise in the ELA of 100–200 m above the equilibrium elevation (ELA_0). In spite of incomplete information for Bolivia and Ecuador before 1990, it seems that glacier recession has accelerated in the tropical Andes since the late 1970s. On a monthly scale, the data confirm that the mass-balance variability is closely controlled by the ENSO-related climate forcing. During the ENSO warm phases, mass balance is generally negative, a feature principally caused by an increasing ablation. This leads to the conclusion that the sharp succession of ENSO warm events since the late 1970s could have played an important role in the process of ice wasting in the central Andes, together with global warming. In the future, 2 types of analyses will need to be conducted to identify the climatic background of this recent evolution. *i*) The physical response of glaciers to the contrasted situations will have to be precisely analyzed

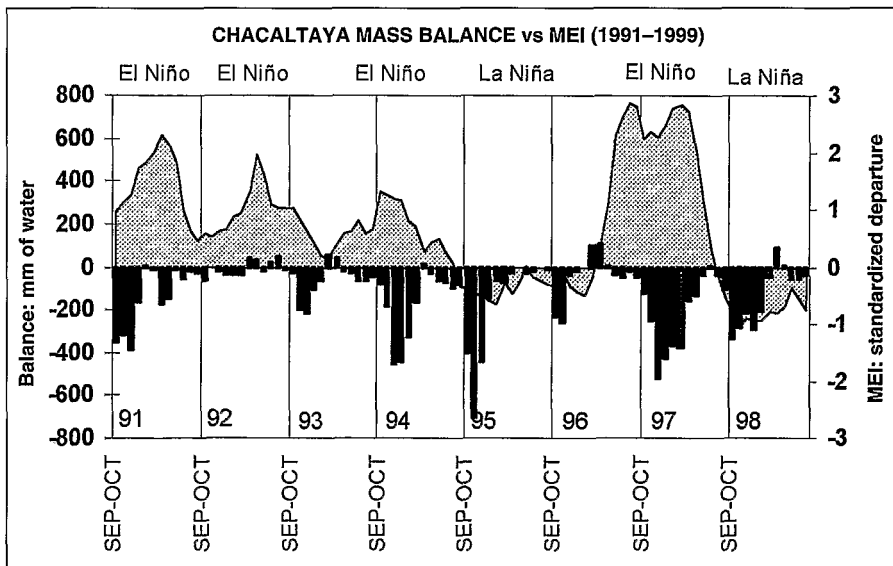


Figure 9. Chacaltaya Glacier: monthly evolution of the net balance at 5170 m a.s.l. (bars) and Multivariate ENSO Index (line) from September–October 1991 to July–August 1999. The two variables have been processed as bimonthly periods (Sept–Oct, Oct–Nov, etc.).

in terms of heat budget at the glacier's surface. A first attempt to characterize the warm/cold ENSO phases was made at 5150 m a.s.l. on the Zongo Glacier (15). The results during the warm events point to albedo as the key-factor, magnifying the response of the glacier to an anomalous situation involving a decrease in precipitation and an increase in air temperature. *ii*) The evolution of the medium troposphere during the ENSO events needs to be precisely characterized. A significant increase in temperature has been noted at 4000 m a.s.l. in Peru and Bolivia during the warm ENSO phases (13), a departure also well observed in the Andes of Ecuador and in the free atmosphere at 500 hPa. At more global scale, a recent analysis of the evolution of the

freezing heights close to Equator by Diaz and Graham (25), confirmed that important changes have occurred in the mid-tropical troposphere of the Andes in the deep tropics (ca 15°N – 15°S). The positive height anomaly for the 1970–1988 is about 100 m, a trend which is related to a long-term (over decades) increase in sea-surface temperature in the tropics, and the consequent enhancement of the hydrological cycle. In addition to temperature, analysis will have to focus on other variables which could have changed in the recent times, such as humidity, which is known to affect strongly the energy balance in tropical glaciers (4, 14).

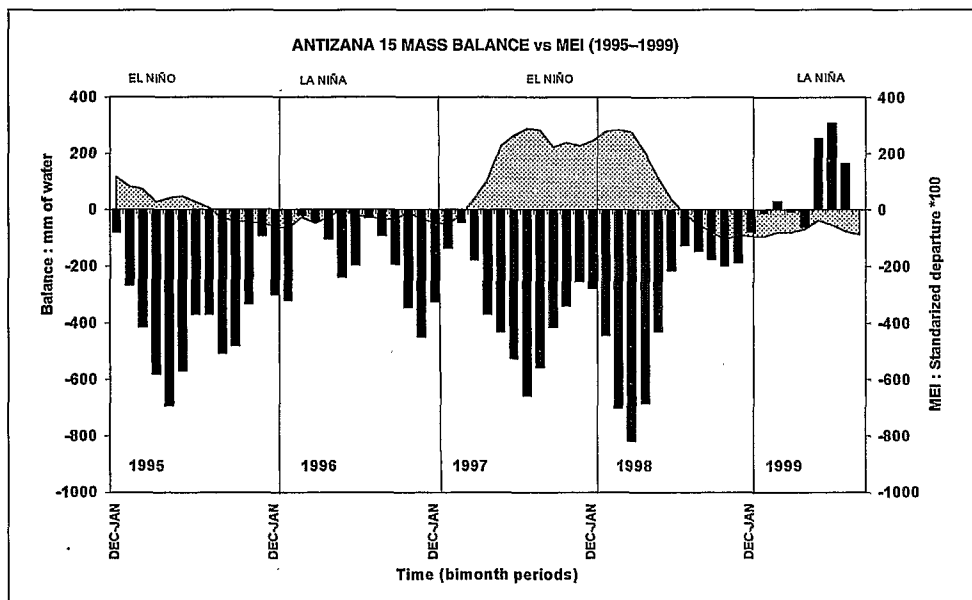


Figure 10. Antizana Glacier 15: monthly evolution of the net balance in the ablation zone (bars) and Multivariate ENSO Index (line) from December–January 1994–1995 to July–August 1999. The two variables are processed as bimonth periods.

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