Coherence of the glacier signal throughout the tropical Andes over the last decades.

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Abstract

The network of glaciers observed by IRD and South American partners in the Central Andes (Bolivia, 16°S, Perú, 9°S and Ecuador, 0°S) is presented first. Then, we point out the coherence of the glacier signal recorded over the last decades throughout the Tropical Andes. In a discussion, we show that the recession of glaciers is a common response to the atmospheric evolution related to the equatorial Pacific warming since 25 years. Processes involved in the acceleration of the glacier recession are briefly evoked in the light of recent analysis performed in Bolivia and Ecuador from energy balances at the glacier surface.

Key-words: Glaciers – Tropics – Andes – Global Warming – ENSO.

Introduction

Since more than a decade, a network of monitored glaciers has been installed by IRD and South American partners in the Central Andes of Bolivia (16°S), Perú (9-10°S) and Ecuador (0-1°S). These observations on glaciers have provided the scientific community with data concerning glaciers and climate evolution in the tropical mountains (WGMS, 2005; Francou et al., 2005). Nowadays these are the only glaciers being monitored on the long term from ground observations in all the Tropics, that increases their interest for documenting the recent evolution of the tropical troposphere at ~500 hPa. As a response to enhanced greenhouse forcing, GCMs predict a positive temperature trend for the tropical troposphere, which is greater than at the surface and increases with altitude (IPCC, 2001). By surveying glacier evolution and understanding the climatic signal which forces this evolution, a glacier observation network can yield a considerable contribution to the knowledge of the tropical troposphere and its response to the global warming. In 1991, the first instrumental-based system was set on Zongo and Chacaltaya glaciers in Bolivia and since then, permanent mass balance observations have been carried out on

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glaciers of distinct sizes. The monitoring system also includes permanent runoff and meteorological measurements allowing the hydrological balance to be estimated in parallel with the classical glaciological method (Ribstein et.al., 1995; Sicart et al., in press). From automatic weather stations (AWS) on distinct sites of the ablation zone, the energy balance can be estimated year round and ablation processes at the glacier surface are determined with extraordinary time resolution and accuracy (Wagnon et al., 1999ab; Wagnon et al., 2001; Sicart et al., in press). Since 1994, the observation system existing in Bolivia was extended to glaciers located in Ecuador (Antizana 15 glacier; 0°28S) and Perú (Artezonraju glacier; 10ºS). This synthesis focuses on mass balance data obtained from the most contrasting regions, Bolivia (outer tropics) and Ecuador (inner tropics), which also involve the longest series recorded.

Studied glaciers

Figure 1 presents a map of glaciers with permanent observations. These glaciers were selected in function of their representativity. As a consequence, the network involves glaciers extending over a large area and elevation range (> 0,5 Km² and >5.500 m.a.s.l.) and including extensive accumulation areas at Antizana 15 (Ecuador), Artezonraju (Perú) and Zongo (Bolivia) glaciers. On the other hand, small glaciers (< 0,5 Km²) such as Carihuayrazo (Ecuador), Yanamarey (Perú), Chacaltaya and Charquini Sur (Bolivia) are widespread in the Andes, but these glaciers are now situated at too low elevation (<5.400 m.a.s.l) to receive relevant accumulation, because their equilibrium line generally lies close to the highest glacier parts. Zongo, Chacaltaya and Antizana 15 are the best documented glaciers in Bolivia and Ecuador. Zongo (16º 15'S) is a 1,9 Km² glacier extending between 6.000 and 4.900 m.a.s.l. on the Amazonian slope of the Cordillera Real, exposition is to the south in the upper part and to the east for the lower tongue. Outlines and total area of this glacier were recently re-evaluated using a new photogrammetric restitution. This data is used to recalculate mass balance values since the beginning of the observations (Soruco et al., 2005). Chacaltaya (16º 21'S) is a small glacier oriented to the south, towards the Altiplano. It experienced a drastic area reduction between 1992 (0,103 Km²) and 2004 (0,035 Km²). Antizana 15 is part of an ice cap covering the active volcano Antizana (5.756 m.a.s.l.) in Ecuador and is situated, in the same way as Zongo glacier, on the Amazonian slope of the Andes. Facing NW, it is a 0,65 Km² glacier with a snout at 4.900 m.a.s.l. Antizana 15 is divided into two tongues, of which only the left one (south), named 15, has been intensively monitored. All these glaciers present geographical and morphological features, which make it possible to compare their response to climate evolution at a regional scale.

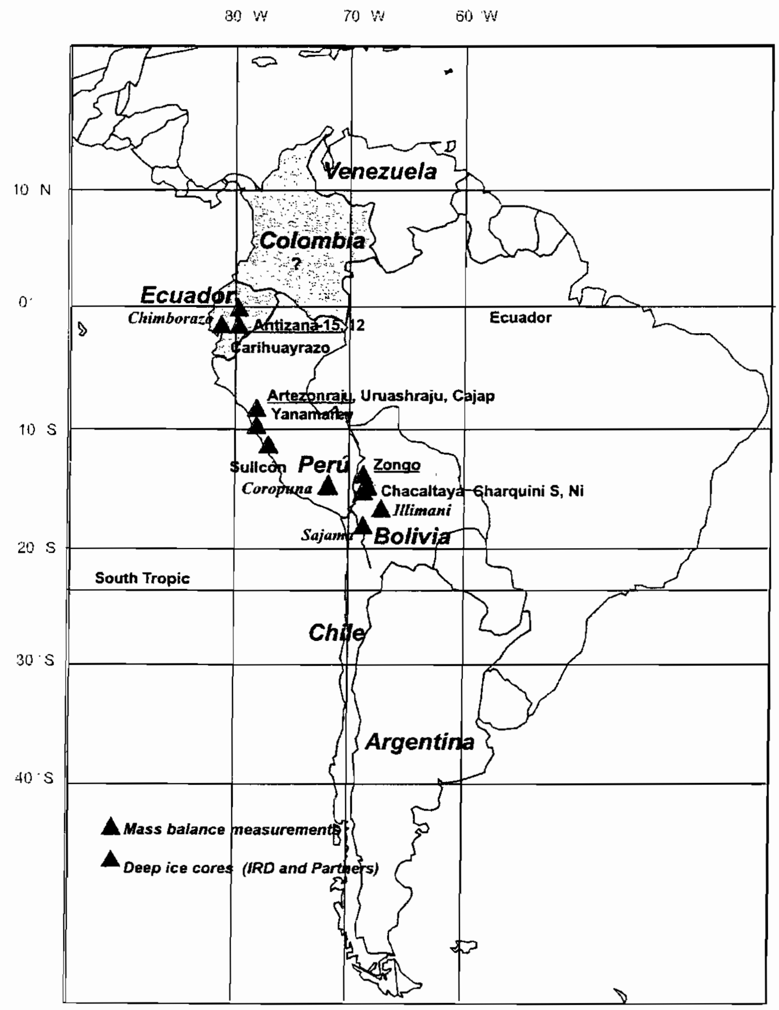


Figure 1. Glaciers permanently monitored for mass balance in the Central Andes (normal fonts). In italic: deep ice cores. Underlined: glacier observations including mass balance, hydrological balance and energy balance.

Methods

The chosen approach for estimating mass balance includes the classical glaciological method of pits and stakes (Francou and Pouyaud, 2004). A limited network of pits is enough to capture the spatial variability of the net accumulation because of its relative homogeneity within each elevation range. This feature is due to several factors: i) snow drift is low, due to the weak winds blowing during the wet season; ii) snow density is high because precipitation falls at a temperature close to the melting point and, hence, snow is never cold and dry when falling during the precipitation period; iii) snow density increases rapidly during the hours and days which follow precipitation events due to the high radiation influx at the glacier surface. Thus, significant changes in the accumulation rates occur only with elevation. The possible errors in estimating net accumulation are mainly due to problems related with the identification of hydrologic cycles from stratigraphy, since melting events are frequent during the summer/accumulation period and not exclusively concentrated during the dry season.

On the other hand, snowfalls during the dry season introduce other uncertainties. These uncertainties are particularly high in Ecuador where snowfalls can occur during all season. To solve this problem, 3-4 m long accumulation stakes have been recently introduced in boreholes on distinct sites of the accumulation zone and are surveyed twice a year – before and after the precipitation season. A denser network of stakes exists in the ablation zone, where the frequency of surveys has been fixed to one month. This monthly survey allows ablation processes to be documented in detail, particularly where an automatic meteorological station exists nearby, which measures the main variables involved with the energy balance. Mass balance could so far not be compared with longer-term volume changes deduced from high-resolution photogrammetric restitutions, since aerial photographs are scarce in these countries and available only at time intervals of 10-15 years. The only possibility is to compare the glaciological balance with the hydrological balance, since discharge of glacier outlets has been measured in runoff stations at a distance less than one kilometre from the glacier snout (Francou and Pouyaud, 2004; Sicart et al. in press). Additional information concerning glacier evolution over the last 50 years derives from photogrammetrical and ground measurements. Systematic ground observations on snout positions and ablation areas were introduced in Perú at the beginning of the 1980s on several glaciers, while in Bolivia and in Ecuador, only the glaciers monitored for mass balance include a ground topographical survey of the lower tongues every year.

Results

Acceleration of glacier retreat over the last 25 years:

Length and area evolution of ten glaciers are presented on figure 2. Even though the series are not continuous before the 1980s, it is possible to point out the following features:

- Between 1948 and 1970 and during the 1970s information is scarce but evidences in Perú (Broggi, Uruashraju, Yanamarey) and in Bolivia (Charquini) indicate a moderate tongue retreat of ~50/150 m per decade;

- After 1980, the retreat was general and fast but proceeded in steps: a first acceleration in the retreat rate occurred in the early 1980s followed by a second one in the middle 1990s, whereas this evolution slowed down in the mid-1980s and in the early 1990s, with small differences between individual glaciers;

- Over the last decade, after a stop in 1999-2001, glaciers again began to retreat rapidly. On the Charquini South glacier (Bolivia), a photogrammetric restitution using aerial pictures from 1940, 1956, 1963, 1974, 1983 and 1997, completed by a ground topography in 2004, features a moderate 300 mm w.e. yr^{-1} mass balance deficit from 1940 to 1974, increasing to 750 mm w.e. yr^{-1} during the last 3 decades (figure 3). This feature confirms the information published by Ramirez et al. (2001) on Chacaltaya glacier, where increasing mass deficits were observed after 1983 and even much more so after 1991. The acceleration of glacier recession from the middle of the 1970s was also verified in Ecuador. The main result obtained from a recent photogrammetric research on the Cotopaxi (5.897 m.a.s.l., 0° 40'S/78° 25'W), one of the most extensive ice capped volcanos of the Andes, is that glaciers stagnated from 1956 to 1976 and that they lost then about 30% of their surface area between 1976 and 1997 (Jordan et.al., 2005).

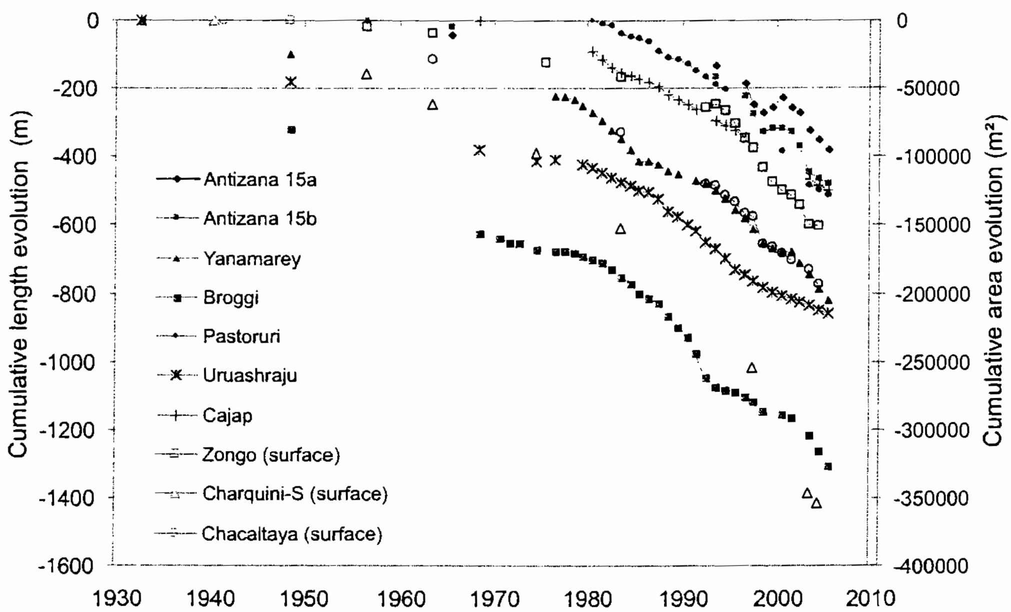


Figure 2. Evolution of glacier length and area for 10 glaciers of the Central Andes. Information is from ground measurements and aerophotogrammetric restitutions. Broggi, Pastoruri, Uruashraju, Cajap are glaciers of the Cordillera Blanca, Perú. Geometric changes are either expressed in length or area (see legend inset).

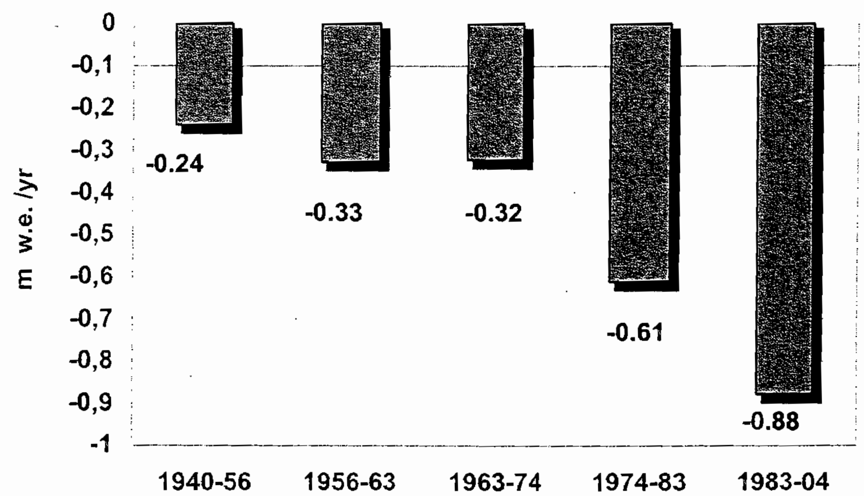
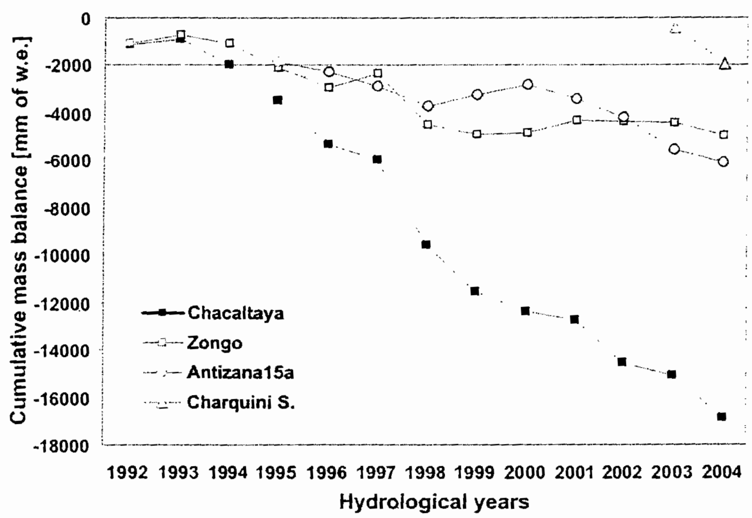


Figure 3. Mean annual mass balance estimation over several periods of time on Charquini Sur glacier (Cordillera Real, Bolivia). The periods before 1997 were analyzed from aerophotogrammetry.

Regional homogeneity of mass balance evolution over the last 15 years:

The trend in the mass balance evolutions over the last 15 years presented on figure 4a features a strong dependence on glacier size. While Zongo and Antizana 15 lost 400 - 600 mm w.e. yr^{-1} on average, the Chacaltaya's deficit was as high as 1.300 mm mm w.e. yr^{-1}, which is coherent with the mass lost by Charquini Sur glacier (figure 3).

Moreover, this trend masks a strong inter-annual variability. On figure 4b, it can be observed that Zongo and Antizana 15 glaciers experienced strong fluctuations between balanced situations and deficits of 1.000/2.000 mm yr^{-1} (means for the measured periods were -380 mm yr^{-1} and -611 mm yr^{-1} w.e. respectively). In view of the current climate variability, only such glaciers as Zongo and Antizana, which have conserved a large accumulation zone at high elevation (>5.500 m. a.s.l.), can now and again recover mass but these transitory gains do not compensate the cumulative deficits. On the other hand, mass balances of small glaciers such Chacaltaya and Charquini Sur have been permanently negative under recent climatic conditions. Thus, it can be stressed that the small-sized glaciers lacking permanent accumulation zones are strongly unbalanced and that, with a deficit of around 1.000 mm w.e. y^{-1}, they are in risk of complete extinction within one or two decades. Finally, it is interesting to note that glaciers such as Zongo and Antizana 15 distant from 16 degrees latitude, display, despite marked differences in the timing of the annual hydrological cycle, a similar and synchronic overall evolution. This fact points to a common climatic forcing at the regional scale.



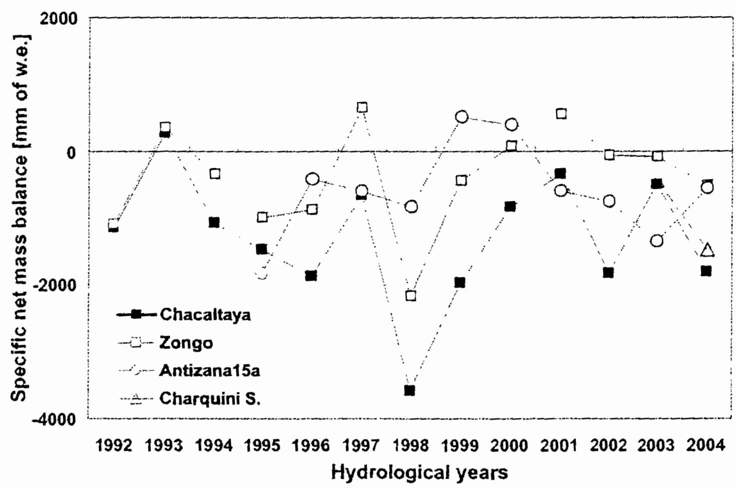
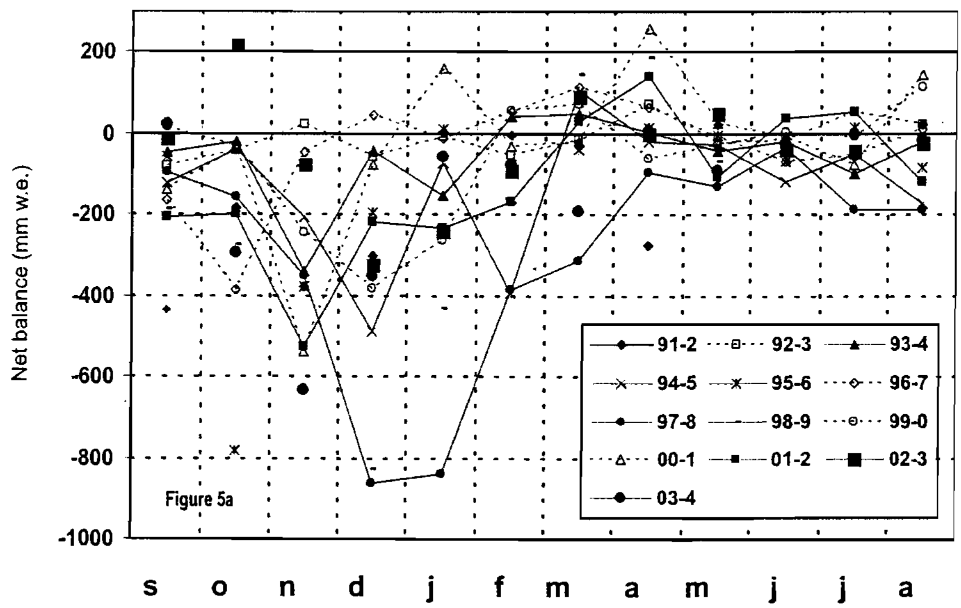


Figure 4. Cumulative (top) and annual (bottom) mass balances on four glaciers of the Central Andes. Hydrological years from Bolivia and Ecuador are different: 1995 = September 1994 - August 1995 for Zongo and Chacaltaya, and January - December 1995 for Antizana 15 glaciers.

Contrasting seasonal patterns in Bolivia and Ecuador:

Seasonality of ablation in Bolivia is well depicted on figure 5a, where monthly mass balance of Chacaltaya has been plotted for the 13 years from 1991 to 2004. The October-April (summer) period reflects the main part of the annual ablation but also the maximum variability, while the May-August (winter) period is more balanced and more constant. The summer months therefore explain 98% of the inter-annual mass balance variability, the largest fraction (78%) being concentrated in December-January-February (Francou et al., 2003).

In Ecuador, on Antizana 15α glacier, the seasonal mass balance pattern is less pronounced and significant inter-annual variability is observed during all parts of the year (figure 5b). Seasonality of accumulation at high elevation is not well known, because only one measurement exists above 5.200 m.a.s.l. at the beginning of the accumulation cycle. In rain gauges situated close to the ablation zone, we observed decreasing precipitation amounts from November to January, the time period which allows a high-density and sometimes dusty surface layer to be formed. However, such trends in seasonal accumulation are more or less clear, depending on individual years. The main accumulation months are typically April-May-June and September-October. At lower glacier elevations, the inter-annual variability of mass balance features a more confuse pattern than in Bolivia. Two short periods are more constant in time with moderate ablation rates: June-July and November-January. The most variable months are February-March-April-May and August-September and these months explain more than 98% of the total variance of the annual mass balance.



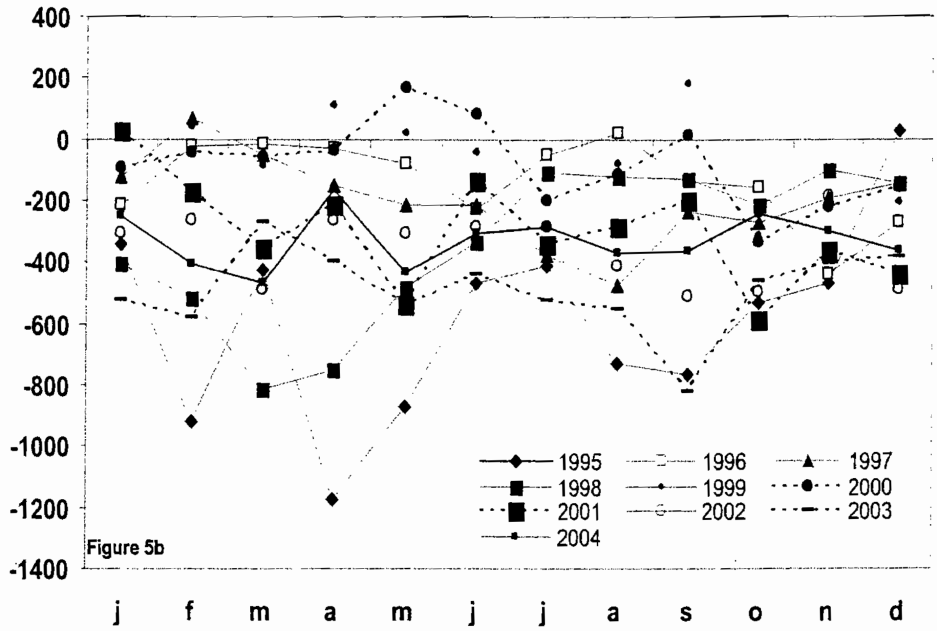


Figure 5. Mass balance evolution (in mm w.e.) from September to August on Chacaltaya glacier (Bolivia; top) and from January to December on the ablation zone of Antizana 15 glacier (bottom). Monthly mass balance refers to the whole glacier on Chacaltaya and to the ablation zone on Antizana 15 glacier.

Synchronous evolution of ablation throughout the Central Andes:

Mass balance in the ablation zone reflects, at monthly scale, the evolution of the energy balance at the glacier surface. We present mass balance evolution during a minimum of one decade for two glaciers, Zongo and Antizana 15 (figure 6). The two curves represent the cumulative mass balances in distinct ablation zones. These ablation zones concern the main part of the lower zone of Antizana 15 and a significant part of the upper ablation zone of Zongo glacier. With the elevation ranges of these zones being different, it is not relevant to compare the mass balance trend but it is interesting to observe the coincidence in time of ablation rates. Ablation peaked in 1995 and 1997-1998 on two glaciers, whereas 1993, 1996 and 1999-2000 were more balanced years. The continuously high ablation rates in the Antizana 15 glacier after 2001 have not been observed in Bolivia before 2004. Antizana's mass balance leads up Zongo's one by around 6 months and this rapid response of Antizana glacier to the regional climate reflects in part the weak seasonality of climate close to equator: climate variability is transmitted to glacier whatever the period of the year, whereas in Bolivia, glacier response is limited to the summer period.

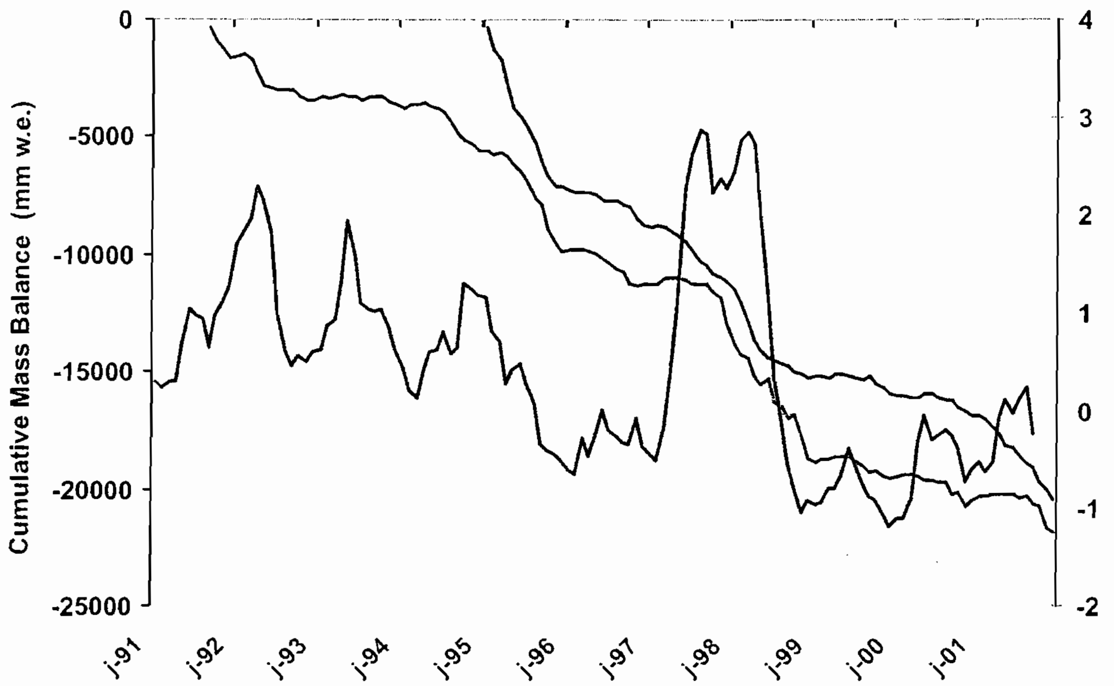


Figure 6. Cumulative mass balance in distinct sectors of the ablation zones of two glaciers in the Central Andes, Zongo (from 1991) and Antizana 15α from 1995 (left scale). Multivariate ENSO Index (light black line; right scale). MEI data are normalized and processed by bimonth periods (Source: NOAA-CIRES, Climate Diagnostic Center (CDC), University of Colorado at Boulder). Positive/negative MEI values indicate warm/ cold phases in the Pacific. Note than the two longest periods of moderate ablation on Zongo glacier have corresponded to contrasting situations in the Pacific, the first one being synchronous with a long warm event and the stratospheric veil from the Pinatubo explosive eruption.

Discussion and conclusion: what drives glacier mass balance variability of the Central Andes?

Figure 6 suggests that strong/weak ablation periods generally coincide with warm/cold anomalies of the Equatorial Pacific. These anomalies have been captured by the Multivariate ENSO Index (MEI). Warm events occurred in 1997-1998, 1994-1995 and 1991-1992 (measured only in Bolivia) and cold ones in 1996-1997 and 1998-2000. In Ecuador, as shown by Francou et al. (2004), the two opposite phases of ENSO explain most of the contrasting situations on the Antizana glacier. Since the SST anomaly (SSTa) occurs in the central Pacific around the boreal winter (November-February) and the atmospheric response of ENSO is delayed by 3 months over the Ecuadorian Andes, year-to-year variations in mass balance are at maximum from February to May. During the warm ENSO phases, the increasing temperature favours rainfall up to an altitude of 5.100-5.200 m.a.s.l., which –together with the slight deficit in precipitation and in cloudiness– explains the constantly low values of the albedo and the high melting rates (Favier et al., 2004ab). In contrast to this, the cold ENSO phase brings a colder temperature, higher snowfall amounts and cloudiness, which all prevent the albedo to decrease below the typical values of fresh snow (0,8) for a long time and, hence, reduces the amount of energy available for melt. At a lesser degree, winds are stronger during the austral winter and save energy for melting. Mass balance in the lower part of glaciers and the SST anomaly (SSTa) show the highest correlations in the Niño-4 domain (5N to 5S, 160E to 150W) of the central equatorial

Pacific (Francou et al., 2004). In Bolivia, glacier evolution is also to a large extent controlled by the tropical Pacific SSTa (Francou et al., 2003). During the ENSO warm phases (El Niño), precipitation decreases by 10-30% and dry periods occur more frequently during the summer (Vuille et al., 2000). This situation enhances incoming solar radiation, reduces snow accumulation and decreases albedo on the glacier surface (Wagnon et al., 2001). On average, near-surface summer temperature is 0,7-1,3 °C higher during El Niño as compared to La Niña, enhancing sensible heat flux to the glacier surface. During the relatively wet and cold La Niña periods, opposite conditions prevail, which can lead to near-equilibrium mass balances. The best correlations between mass balance in the ablation zone and the equatorial Pacific SSTa is in the Niño 1+2 region during spring and early summer, August to February (2-month lead; Francou et al., 2003). The higher SST off the coast of South America observed since the Pacific climate shift in 1976/77, most likely contributed to the accelerated glacier retreat on the Ecuadorian and Bolivian glaciers. This strong signal coming from the Pacific may interfere with discrete large-scale atmospheric events. Such a discrete large-scale atmospheric event occurred in June 1991 with the Pinatubo explosive eruption, which affected glacier mass balance through the cooling effect of volcanic sulphate aerosols. This event interrupted the long 1990-1995 El Niño period during several months, causing the decreasing ablation observed on Figure 6 for the Zongo glacier.

As a consequence, we can assume that the higher frequency of El Niño since the mid 1970s in combination with a warming troposphere over the tropical Andes most likely explains the recent dramatic shrinkage of glaciers in this part of the world.

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