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Variations of a low latitude Andean glacier according to global and local climate variations: first results

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Abstract We have 10 years of mass balance, meteorology and precipitation data on glacier 15 of Antizana, located in Ecuador, very close to the equator. Starting with the results of Francou *et al.* (2004), we studied the relation of monthly ablation zone volume variations of the glacier with 20 variables chosen to represent the global and local climate. The statistical model provided explains 58% of the melt variance. This model implicates the Niño3+4 index, as well as precipitation anomalies at the foot of Antizana. Excess (lack) of precipitation during the nine previous months corresponds to a decrease (increase) of melting. A warm (cool) anomaly of the ENSO oscillation corresponds to an increase (decrease) of melting 4 months later.

Key words Andes; Ecuador; El Niño; glacier melting modelling; tropical glacier

INTRODUCTION

Tropical glaciers are valuable indicators of low latitude climate variations. Their generalised retreat, which has been accelerating since the end of the 1970s, is probably linked to global warming (Francou *et al.,* 2005). We shall try to link glaciers variations to those of the current climate, expecting to contribute to the reconstruction of climatic variations. The processes of glacier variations are complex and dependent on several variables. Ice loss (melting and sublimation) is dependent on temperature, air humidity, wind, cloud cover, incident and reflected solar radiation on the glacier surface (thus of albedo), while its maintenance depends upon precipitation. Furthermore, the entire glacier moves downwards.

Francou *et al.* (1995a,b) and Ribstein *et al.* (1995) highlighted the links between variations of the global climate (ENSO) and that of the Zongo glacier in Bolivia (16°S). In Bolivia, Wagnon *et al.* (1999, 2001) and Sicart (2002) studied the mechanisms of Bolivian glaciers, showing that their melting depended both on the ENSO and temperatures, and also on the importance of the snow cover, which directly influences albedo.

In Ecuador, Antizana Glacier 15, as labelled and registered by Hastenrath (1981), is located about 30 km to the south of the equator. The mass, hydrological and elements of energetic balances monitoring began in 1994 and have been published in eight reports by Sémiond *et al.* (1998), Bontron *et al.* (1999), Favier *et al.* (2000) and Cáceres *et al.* (2001, 2002, 2003, 2005). Rossel (1997), Villacis (2001), Bendix (2000), Francou *et al.* (2000) and Vuille *et al.* (2000a,b) studied the links between climate anomalies in the tropical Pacific and Atlantic oceans and those of the Ecuadorian Andes. They highlighted an increase (decrease) in air temperatures in the Andes linked to warm (cold) phases of the ENSO, and an increase in wind during cold phases. However, the influence of these anomalies on precipitation is less evident. Later, Favier *et al.* (2004), Menegoz (2004) and Favier (2004) studied the mechanics of melting and sublimation in relation to findings from Bolivia. They showed that, despite a weak seasonality in terms of temperatures and incident radiation, the increase in winds between June and September produced an increase in sublimation, to the detriment of melting. These authors confirmed the fundamental role of the albedo of the glacier surface in the radiative balance and melting control.

Objectives and methods

We now have 10 years of mass balance data concerning a glacier of the Antizana. We shall compare on a monthly scale the relations between glacier variations, and those of the local, regional, and global climate, in order to find the climatic variables which better explain the melting variations of the last 10 years. We shall try to develop the results recently presented by Francou *et al.* (2004), which display an important relationship between the glacier volume variation and the Niño4 index temperature anomalies observed 3 months earlier about 11 000 km to the west of Antizana. This relation shows that there is a link between global climate and this glacier. Its quick variations show its sensitivity and the importance of this type of glacier in the investigation of climatic oscillations (Kaser & Osmaston, 2002).

We shall begin by analysing the relationship of the glacier ablation zone volume variations, represented by the variable “Bal” and: (i) Global climate variations (SOI, ENSO indices, etc.), starting from the results of Francou *et al.* (2004). (ii) Local and regional climate variations: climatic variables provided by NCEP-NCAR reanalysis of climatic variables close to Antizana (Kalnay *et al.*, 1996). (iii) Precipitation anomalies measured close to glacier 15. (iv) Meteorological measurements taken on the surface of the glacier. We shall then choose the most pertinent variables and propose a melting model.

ANTIZANA VOLCANO, ITS GLACIERS AND ITS MONITORING NETWORK

Antizana (0°28′S; 78°09′W) is located in Ecuador, about 30 km south of the equator. Despite being close to the Pacific Ocean, located 200 km to the west, it is mainly subject to easterly air flow, principally responsible for precipitation.

Antizana's climate description

In these regions, close to the equator, temperature, radiation and extraterrestrial radiation vary little throughout the year. The wind, cloud cover and precipitation vary much more. Favier *et al.* (2004) observed two major weather types throughout 2003: (i) Type P1 occurring generally between June and September–October characterized by strong winds (6.6 ms^{-1}), low cloud cover (0.37) and reduced precipitation levels. (ii) Type P2, from October to May, presents weaker winds (3.6 ms^{-1}), but higher cloud cover (0.59), precipitation, temperature and humidity.

Principal climatic variations from 1995 to 2004

Throughout the last 10 years, we observed several climatic episodes (Fig. 1):

(a) Several "El Niño" periods inducing temperature increases and a glacier retreat acceleration (weak and long Niño in 1994–1995, very strong in 1997–1998, latent Niño with prolonged deficit of precipitation in 2002–2004).

(b) A strong "La Niña" period between September 1998 and October 2000, which was cool, windy and wet, throughout which was observed a stabilization or slight glacier advance.

(c) But also distinct variations of precipitation with long periods of excess (1996–1997; 1999–2001) or deficit (1995; 2002–2004) (Lhuissier, 2005).

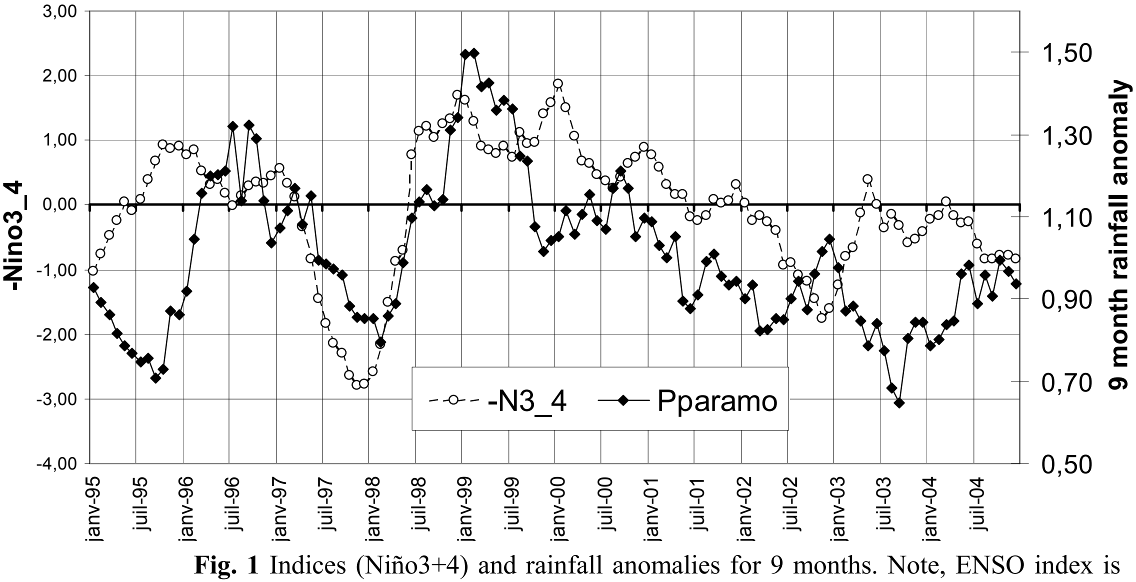

Fig. 1 Indices (Niño3+4) and rainfall anomalies for 9 months. Note, ENSO index is inversed.

Monitoring network

Figure 2 displays the position of glacier 15, of the meteorological and rain gauges stations. A stake network allows measurement of the melting between 4850 m a.m.s.l.

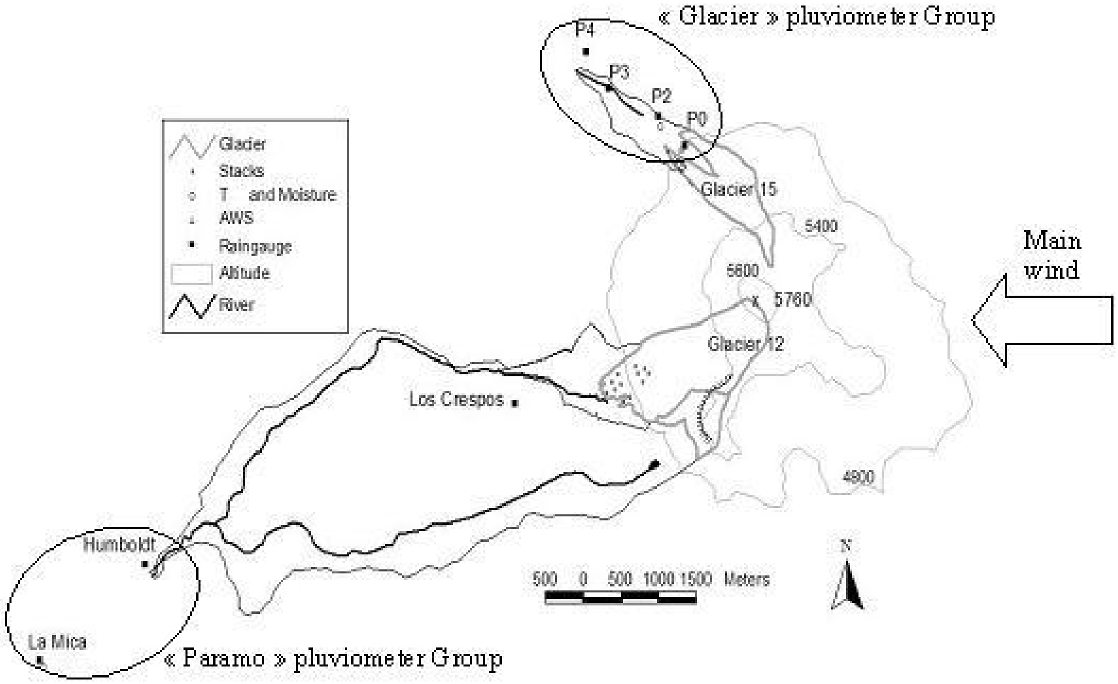

Fig. 2 Map of glacier position, monitoring network and pluviometric groups.

and the glacier equilibrium line (ELA) placed on average at 5100 m a.m.s.l. The automatic meteorological station, close to the rain gauge P0, is located on glacier 15 at an altitude close to 4900 m a.m.s.l.

DATA

In this first study, we analyse the monthly values of the climatic and glaciological variables with complete series during the period 1995–2004. We seek to explain and model the glacier's volume variation using the variable "Bal" defined by Francou *et al.* (2004) as: the volume variation of glacier ablation zone, divided by the ablation surface, expressed in mm of water per month. Negative (positive) values correspond to a glacier retreat (accumulation in ablation zone).

For this modelling, we used:

(a) Variables characteristic of global climate. We have selected the classic global indices linked to ENSO oscillations on the Pacific Ocean: SOI, indices Niño1+2, Niño3, Niño4, OLR, etc. The Niño 4 zone is located west of the Pacific between 5°N and 5°S and 160°E and 150°W, being close to 11 000 km further west.

(b) Variables linked to local and regional climate: (i) variables (temperature, wind, humidity, radiation, OLR) resulting from NCEP/NOAA reanalysis in the east sector of Antizana at levels 500, 600, and 700 hPa. (ii) Precipitation in the zones close to the glacier base (Pglacier between 4500 and 4900 m a.m.s.l.) and in lower zones (Pparamo around 4000 m a.m.s.l).

RELATIONSHIP BETWEEN GLACIER VARIATION AND CLIMATE VARIABLES

Relationship between precipitation and glacier volume variations

We have calculated the means of anomalous precipitation over *n* preceding months in the two climatic zones of the glacier and the Páramo. Thus Pglacier2 is the mean of the anomalies of precipitation in the "glacier" zone for the two preceding months, Pparamo9 in the "Páramo" zone for the nine preceding months, etc.

The best correlations are obtained for rainfall anomalies of the nine preceding months for the zone "Páramo" (r = 0.69, r2 = 0.47). (Table 1). This table shows that an excessive (insufficient) precipitation corresponds to a decrease (increase) of glacier melting, corroborating the results of Wagnon *et al.* (2001), Sicart (2002) and Favier *et al.* (2004).

Relationship between melting and global climate variables

Global climate variables directly linked to ENSO oscillation like SOI, ocean temperature anomalies of Niño3+4 block, etc. are correlated to glacier balances. The best correlation (r = –0.59, r2 = 0.35) is obtained between "Bal" and "N3+4" observed 4 months before, suggesting that a positive anomaly of western Pacific ocean temperatures is followed 4 months later by an acceleration of glacier ablation during the 120 months studied period (Table 2).

Table 1 Correlations between the glacier volume variations (Bal) and the averaged rainfall anomalies over the last n month of the two pluviometric groups.

Month number	1	2	4	6	9	12
Pglacier	0.34	0.51	0.54	0.59	0.61	0.56
Pparamo	0.36	0.55	0.58	0.65	0.69	0.64

Table 2 Correlations between the glacier volume variations (Bal) and the main global climatic variables for different time lag.

Variable	N3+4	N3+4	N3+4	N3+4	N3+4	N3+4	SOIMb	OLR	T600	Humed
Lag (month)	0	3	4	5	6	7	0	0	0	0
Correlation	–0.38	–0.58	–0.59	–0.58	–0.56	–0.52	0.51	–0.44	–0.57	0.53

The variables coming from NCEP-NCAR reanalysis close to Antizana present slightly lesser correlations. The most significant is the temperature at 600 hPa (r = –0.57). Time lag attempts for these temperatures have worsened this relationship. The relationship between "Bal" and the other NCEP-NCAR reanalysis variables are not as good. Note the correlation of –0.44 with "OLR" and 0.53 with "Humed".

STATISTICAL MODELLING OF GLACIER VOLUME VARIATIONS

We shall try to model the glacier volume variations using all these variables. The multiple linear regressions model calculated by the Stagraphics ® software selects and proposes a minimum amount of variables, which better explain the variance.

Complete model

The rainfall anomalies concerning the 9 and 2 previous months in the Páramo zone some 10 km west of the glaciers (variables Pparamo9 and Pparamo2) and the anomalous values of Pacific ocean temperatures 4 months earlier (Niño3+4 index) were selected for the best model construction. This complete model (Fig. 3) explains 58% of the "Bal" variance by the following equation:

Bal = 478*Pparamo9 + 180*Pparamo2 – 73*N3+4(lag of 4 months) –943 (r2 = 0.58; r = 0.76)

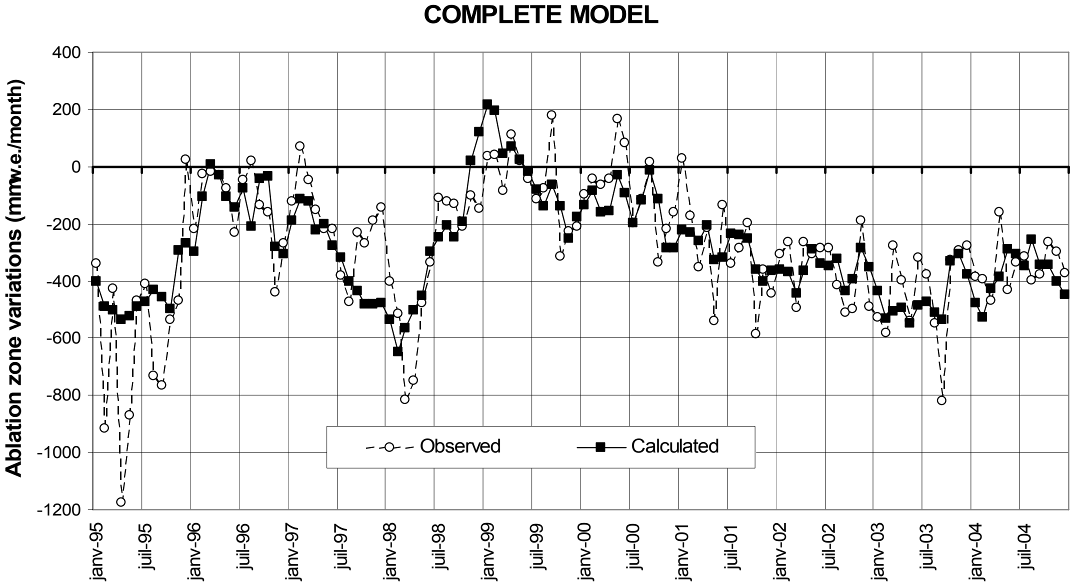

Fig. 3 Complete ablation zone mass variation model on Antizana glacier15. Time series comparison: Observed values = open circles; Calculated values = solid squares.

According to the proposed equation an ablation increase is linked to an increase in the Niño3+4 index (thus a warm ocean temperature anomaly) and/or a period of prolonged lack of precipitation over the 9 and 2 previous months. This lack of precipitation is generally accompanied by an elevation of the temperature, of the rain–snow limit, of the snow line altitude, and an albedo diminution, thus acceleration in the ablation. The opposite occurs with excessive rainfall.

The model correctly reproduces the melting variations throughout the concerned period. Note the systematic under estimation of the ablation in year 1995, and of some of the high-melting months.

Component effect: partial melting models

To better appreciate the variables role, we adjusted one model using only the global variable N3+4(lag of 4 months), and another using only the local variables Pparamo9 and Pparamo2

First model This model (Bal = –138*N3+4 (lag of 4 months) –279; r = 0.59) now explains only 35% of the variance. The Niño index, which varies slowly, correctly reproduces the ablation tendencies over several months, but cannot reproduce quick variations.

Second model This model (Bal = 716*Pparamo9+ 170*Pparamo2 –1175; r = 0.67) explains 45% of variance. It seems that it better reproduces quick ablation variations, but does not reproduce accurately the acceleration observed during the strong Niño of 1997–1998.

We have not presented here the component effects of variables not selected by the model.

DISCUSSION AND CONCLUSION

The complete model allowed us to explain close to 60% of the variance of Glacier 15's ablation using only two variables:

The first is the anomaly, 4 months prior, of sea surface temperature in block Niño3+4 at over 11 000 km further west, which represents the climate's oscillations for several months' amplitude. A warm (cool) anomaly of ENSO oscillation will result in an increase (decrease) in melting or glacier ablation 4 months later.

The second is a precipitation anomaly index throughout the nine previous months, representing the local climate's influence on the glacier, which influences the snow cover protecting the glacier and controls its global albedo. Excessive precipitation during the nine previous months in the Antizana region will result in a reduction in ablation.

Limitations

Note the linear statistical modelling technique used is fast and effective, but has its weaknesses: (i) It cannot correctly represent phenomenon that are probably non-linear. (ii) The model's variable selection is based upon the variance reduction that each variable adds to the model. However, we must check (in the present work and in its future developments) that the model stays compatible with the melt's physical mechanics. (iii) These models have been adjusted with monthly values. Yet, one same month could contain periods where meteorological conditions and melt mechanisms have been very different.

The data may contain errors. Moreover, it may be that exceptional conditions may occur (such as a volcanic eruption), which would require other models and equations.

Prospects

These first results are promising, and they confirm and complement the conclusions of Francou *et al.* (2004). We show, as a new complementation, a local precipitation influence on ablation reduction in addition to the Niño4 index effect already demonstrated. We now continue the work: (i) By the same method, we shall analyse the modelling of other glaciers and melting floods. (ii) We shall soon validate these models by observations of the glacier melt for 2005. (iii) We are analysing the mechanisms and modelling of the glacier melt using more precise time steps (hourly or daily) (Favier, 2004; Villacis, in press). (iv) Continuing the research for the melt's explicative variables under tropical conditions.

The high proportion of explained variance by this first model opens up perspectives to work on the glaciers and water resources evolution, in association with other more sophisticated and physically based models. For instance, IPCC scenarios could be considered, using the recent past LIA glacier regression (Little Ice Age), which is well documented in the Antizana region, to try to adjust and validate this simple kind of linear model to different global climate conditions.

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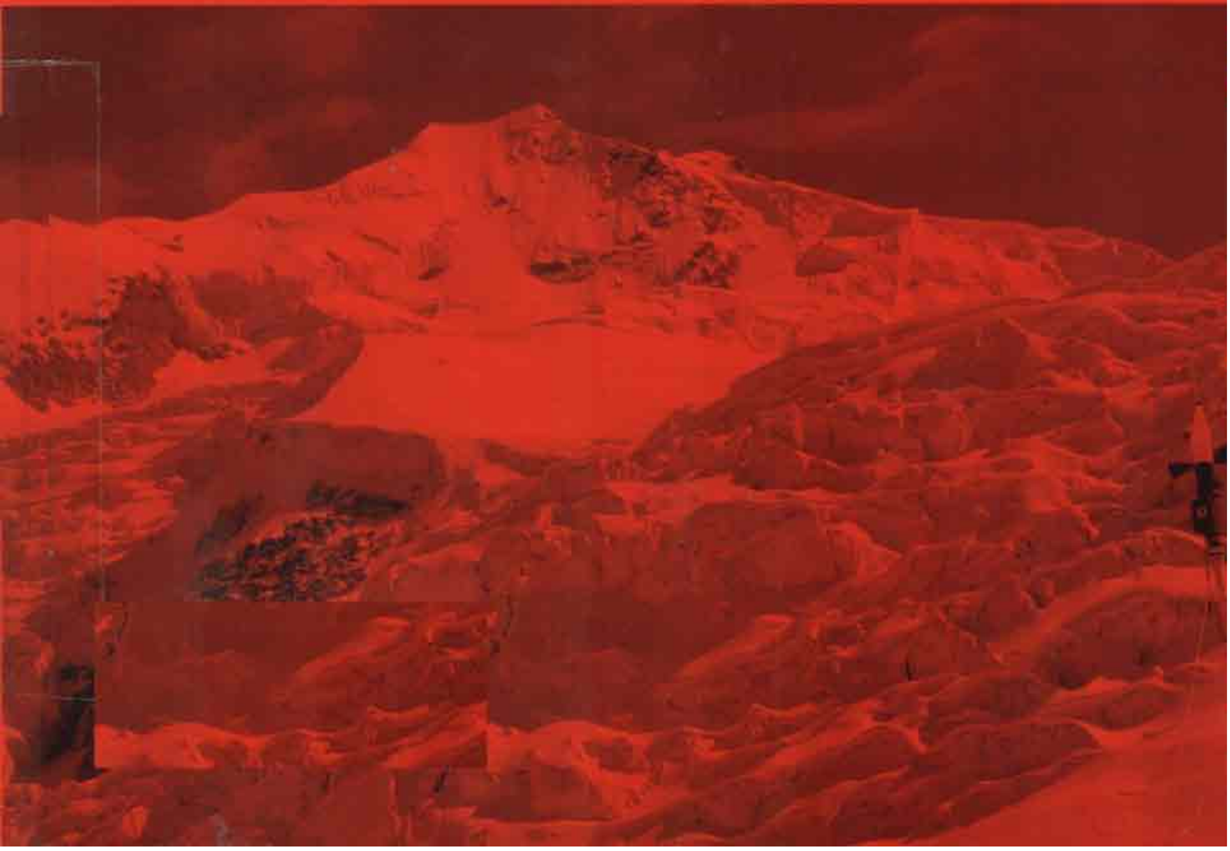

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