Modelling melting in low latitude Andean glaciers according to global, regional and local climate variations

CADIER Eric[1], VILLACIS Marcos[1], MAISINCHO Luis[2], MANCIATI Carla[1], AYABACA Edgar[3], LOYO Cristian[2], FRANCOU Bernard[1]

[1] *Institut de Recherche pour le Développement (France), IRD, UR032 Greatice, Casilla 17.12.857 Quito Ecuador*
cadier@ird.fr
[2] *Escuela Politécnica Nacional, EPN, Ladrón de Guevara E11-253. Quito, ECUADOR*
[3] *Instituto Nacional de Meteorología e Hidrología, INAMHI, Proyecto "Glaciares" Iñaquito 700 y Correa Quito Ecuador*
[4]*Empresa Metropolitana de Alcantarillada y Agua Potable de Quito, EMAAP-Q, Quito Ecuador*

Abstract

Introduction:

Tropical glaciers shrinkage is generalised and has been accelerating since the end of the 1970s, especially during warm phases of El Nino events. Several authors have shown the links between Andean climate, glaciers retreat and global climate variations. Locally, ice loss processes (melting and sublimation) are complex and dependent on several variables like temperature, humidity, wind, cloud cover, incident and reflected radiations on the glacier surface (thus of albedo), while its maintenance depends upon precipitation influence. But direct measurements upon glaciers are scarce and we are replacing them by data from meteorological station located in similar climatic situation.

Objectives:

• Set up statistical models that show the links and the respective influence of climatic parameters upon glaciers variations.

• Calibrate, validate and use of these models to reproduce past glacier and climate variations. In order to try to predict future glaciers and water resources evolution, according to IPCC climate scenarios.

Methods

Establish links and models between local (data collected close to the glacier), regional (data collected in Ecuador by the meteorological network or by remote sensing) and global (i.e. ENSO index) climatic information at daily and monthly time scale.

Select the most appropriate models considering data availability to realise the long term calibration and simulation

Results

Using twelve years of mass balance, meteorology, precipitation and runoff data on two glaciers located on the Antizana volcano (Ecuador) very close to the equator, we studied the relations of daily and monthly melting of the glaciers with 50 variables chosen to represent the global, regional and local climate.

Various models were produced. One of them explains 57% of the melt variance. This model takes into account El Niño3+4 index as well as precipitation anomalies at the foot of the Antizana ice cap. Excess (lack) of precipitation during the 9 previous months will incite a decrease (increase) of melting. A warm (cool) anomaly of the ENSO oscillation will incite an increase (decrease) 4 months later.

A second model explains 62% of the melt variance using regional pluvio-meteorological information of several Ecuadorian stations

We simplified this model to get the last model that explains 53% of the melt variance using only temperature data from the oldest Ecuadorian meteorological station ("Quito

Observatorio", observed since 1891)
Conclusions
These models constitute now one of the tools that suggest and facilitate the comprehension of the links between several climatic mechanisms. These models allow generating future glacier and water resources evolutions according to the main IPCC climate scenarios.

Keywords: Andes; Ecuador; El Niño; glacier melting modelling; tropical glacier
Mots clefs: Andes; Equateur; El Niño; modélisation de fusion glaciaire; glaciers tropicaux

INTRODUCTION

Widespread tropical glaciers retreat, which has been accelerating since the end of the 1970s, is probably linked to global warming (*Francou et al.*, 2005). Glacier variations processes are complex and depend on several variables. Ice loss (melting and sublimation) depends on temperature, 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. We try to link glaciers variations to those of the current climate, expecting to contribute to the reconstruction of climatic variations.

Francou et al. (1995a, 1995b) 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). *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, while Sorruco et al (2008, submitted) proposed a modelling of the different aspects of Zongo glacier balance variations. (mass, energy and hydrologic balances)

In Ecuador, Antizana Glacier 15, as labelled and registered by *Hastenrath* (1981), is located at about 30 km south of the equator. The mass, hydrologic and energy 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, 2004 and 2005). *Rossel* (1997), *Villacis* (2001), *Bendix* (2000), *Francou et al.* (2000) and *Vuille et al.* (2000a and b) and studied the links between climate anomalies in the tropical Pacific and Atlantic oceans and those of the Ecuadorian Andes. They showed that an increase (decrease) in air temperatures in the Andes was 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) showed that, in Ecuador, 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 Method

The relationship between glacier variations, and those of the local, regional, and global climate, in order to find the climatic variables which better represent at monthly scale the melting variations of the last ten years were compared. Using and developing the results recently presented by *Francou et al.* (2004), Cadier et al (2007), Manciati et al (2007), Freile and Manciati (2007) and Villacis (2008) who displayed an important relationship between the glacier volume variation and the El Niño4 index temperature anomalies observed 3 months earlier about 11000 Km to the west of Antizana and also wind, local and regional rainfall and temperature anomalies. This relation shows the link between global climate and this glacier.

Its quick variations show its reactivity and the importance of this type of glacier in the investigation of climatic oscillations (*Kaser and 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) Regional climate variations: climatic variables provided by NCEP-NCAR reanalysis of climatic variables close to Antizana (*Kalnay et al.*, 1996) and data from ground Ecuadorian hidrometeorological network stations. iii) Local precipitation and meteorological anomalies measured close or at the surface of the glacier 15.
We shall then choose the most pertinent variables and propose melting models.

ANTIZANA VOLCANO, ITS GLACIERS AND ITS MONITORING NETWORK.

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

Antizana’s climate description

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

Principal climatic variations from 1996 to 2006

Throughout the last ten years, several climatic episodes are observed (Figure 1)**:**

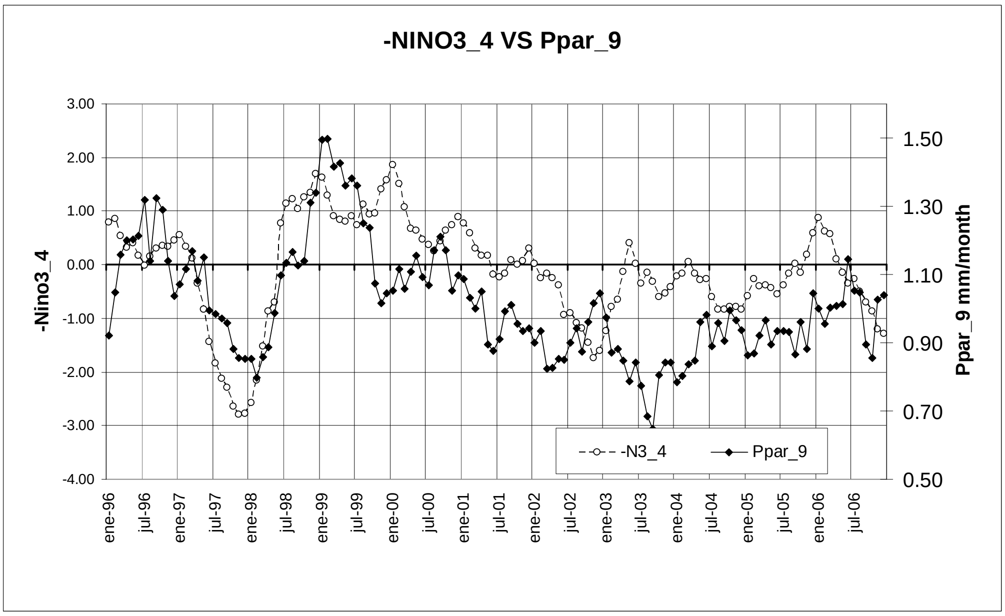

Figure 1. Indices (El Niño3+4) and rainfall anomalies for 9 months. Note: The ENSO index is inversed

(a) Several “El Niño” periods inducing temperature increases and a glacier retreat acceleration (Weak and long El Niño in 1994-95, very strong in 1997-98, latent El Niño with prolonged deficit of precipitation in 2002-04).

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

(c) But also distinct variations of precipitation with long periods of excess (1996-97, 1999-2001) or deficit (1995; 2002-04) (*Lhuissier*, 2005).

Monitoring network

Figure 2 displays the position of glacier 15 and the meteorological and rain gauges stations. A snow stake network allows measurement of the melting between 4850m.a.s.l. and the glacier equilibrium line (ELA) placed on average at 5100m.a.s.l. The automatic meteorological station, close to the rain gauge P0, is located on glacier 15 at an altitude close to 4900m.a.s.l.

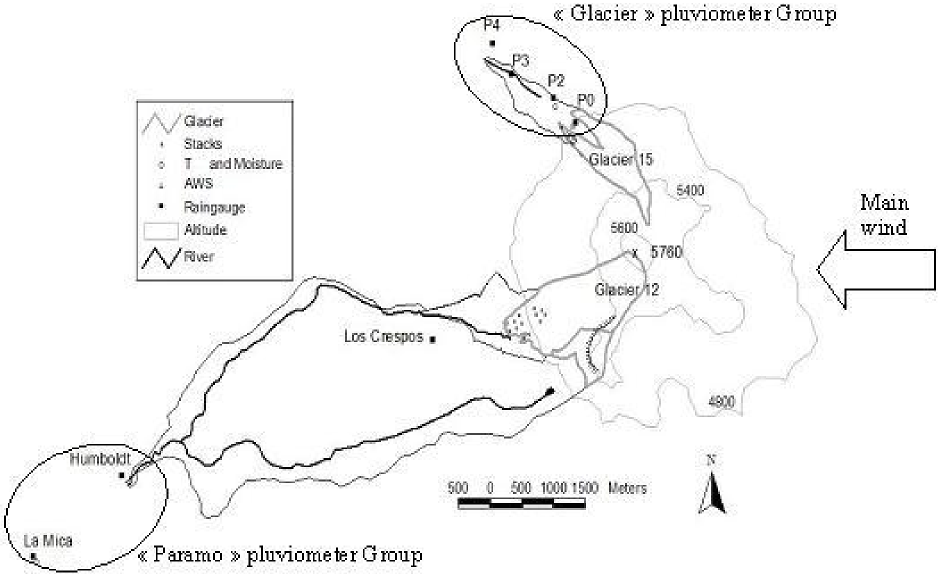

Figure 2. Map of glacier position, monitoring network and pluviometric groups

DATA

In this study, we analyse the monthly values of the climatic and glaciological variables with complete series during the period 1996-2006.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 in the 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 characteristics of global climate. We have selected the classic global indices linked to ENSO oscillations on the Pacific Ocean: SOI, indices El Niño1+2, El Niño3, El Niño4, OLR, etc. The El Niño 4 zone is located west of the Pacific between 5°N and 5°S and 160°E and 150°W, being close to 11000km further west.

(b) Variables linked to 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) Regional data selected from 50 stations from the Ecuadorian hydrometeorological network .

(c) Local precipitation and meteorological anomalies in the zones close to the glacier (Pglacier between 4500 and 4900m a.m.s.l.) and in lower zones (Pparamo around 4000m a.m.s.l).

RELATIONSHIP BETWEEN GLACIER VARIATION AND CLIMATE VARIABLES

Relationship between precipitation and glacier volume variations

The means anomalous precipitation over “n” preceding months in the two climatic zones of the Glacier and the Páramo were calculated. Thus Pglacier2 is the mean anomalies of precipitation in the “glacier” zone for the two preceding months, Pparamo9 in the "Páramo" zone for the nine preceding months, and so on.

The best correlations are obtained for rainfall anomalies of the 9 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 *Wagnon et al.* (2001), *Sicart* (2002) and *Favier et al.* (2004) results.

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	0.36	0.53	0.57	0.58	0.53	0.54
Pparamo	0.37	0.56	0.61	0.64	0.63	0.63

Relationship between melting and global climate variables

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

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 600hPa (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”.

Relationship between melting and regional data selected among 50 stations from ground Ecuadorian hydrometeorological network

We tested the relations between 50 network stations. The chosen stations of the Ecuadorian meteorological network for this study were: TM003, temperature of Izobamba, a mountain range station, located in “Provincia de Pichincha”, M376 pluviometry of Pilahuin, a mountain range station, located in “Provincia de Tungurahua”. We included a global parameter temperature reanalysis at 700 hPa.

The best relation is 70% with temperature of the Izobamba station (Table 3).

Table 3. Correlation between "Bal" and regional meteorological variables

Meteorogical variables used	TM003	M376	T700
Correlation	0.70	0.38	0.52

STATISTICAL MODELLING OF GLACIER VOLUME VARIATIONS.

We 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.

We try to adjust three different models according to the following concepts:

Firstly we try to explain the glacier variations using all the variables available (including the local variables) during the 1996-2006 period, generating a model called "Model-1-Complete model"

Secondly we replace the local variables that do not exist before 1996 by regional or global variables (that present long time series), generating a second model called "Model-2-Regional model". This model is used to generate melting simulations in periods previous to 1996-2006)

And thirdly we propose a "Model-3-Simplified model" using as input data only ground temperature in the oldest Ecuadorian meteorological station the "Quito Observatorio" that allows to generate a 104-year output series.

“Model-1-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 (El Niño3+4 index) were selected for the best model construction. This complete model (figura 3) explains 57% of the “Bal” variance by the following equation.

Bal = 478*Pparamo9 + 180*Pparamo2 – 73*N3+4(lag of 4 months) -943 ($r2=0.57$; $r=0.75$)

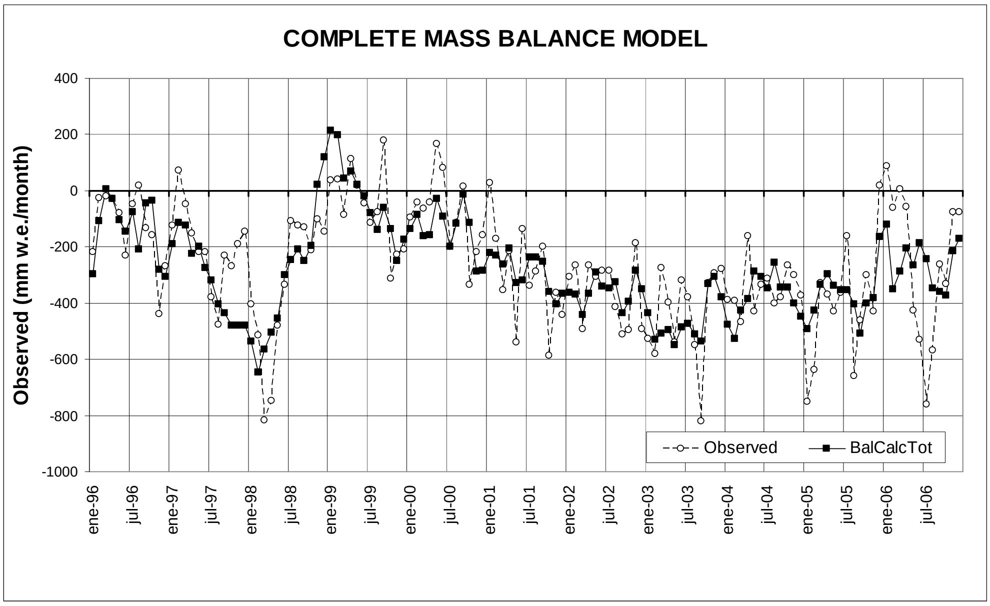

Figura 3. Complete ablation zone mass variation model on Antizana glacier15. Time series comparison: Observed values = open circles; Calculated values = solid squares (model 1)

According to the proposed equation an ablation increase is linked to an increase in the El 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 temperature, rain-snow limit, snow line elevation, and an albedo diminution, thus accelerating ablation. The opposite occurs with excessive rainfall.

The model correctly reproduces the melting variations throughout the concerned period.

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

N3+4 component effect

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

Pparam9 component effect

This model (Bal = 716*Pparamo9+ 170*Pparamo2 -1175; r=0.67) explains 45% of the variance. It seems that it better reproduces quick ablation variations, but it does not reproduce accurately the acceleration observed during the strong Niño of 1997-98.

We do not present in this paper the component effects of variables not selected by the model.

“Model-2-Regional model”

This model (Bal = 30580.-150.4*TM003+ 1.7*M376 -103.4*T700) explains 62% of the variance. This model uses variables such as temperature and pluviometry of mountain range stations (TM003 Izobamba, Pichincha and M376 Pilahuin, Tungurahua), and a reanalysis temperature at 700 hPa. It does not allow generating the information of the balance of ablation zone before 1964 because the previous input data are lacking.

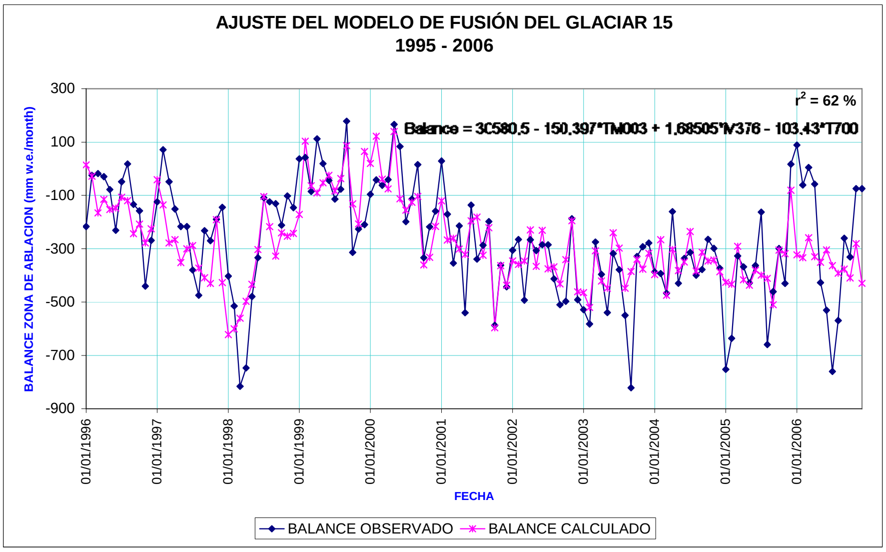

Figure 4. Model 2 - Regional Model adjustment.

“Model-3-Simplified model”

This model (Bal = 2671-244.6*TM003) explains 53% of variance.

This model uses only one variable, temperature at Izobamba, which is close to "Quito Observatorio" that is the oldest station of the meteorological network in Ecuador. The two stations have a relation of 64%, and then we could generate a composite series issued from Izobamba and "Quito Observatorio" temperature data to generate a fictitious long time series of mass-balance (1891-2006).

Finally, we compared (Figure 6) these 104 years mass balance series with the temperature variation of the Earth’s surface. It can be seen that the inverse glacier balance trend is similar to temperature variation trend, which means, that as the temperature is going up, the situation with the glacier is probably getting worst.

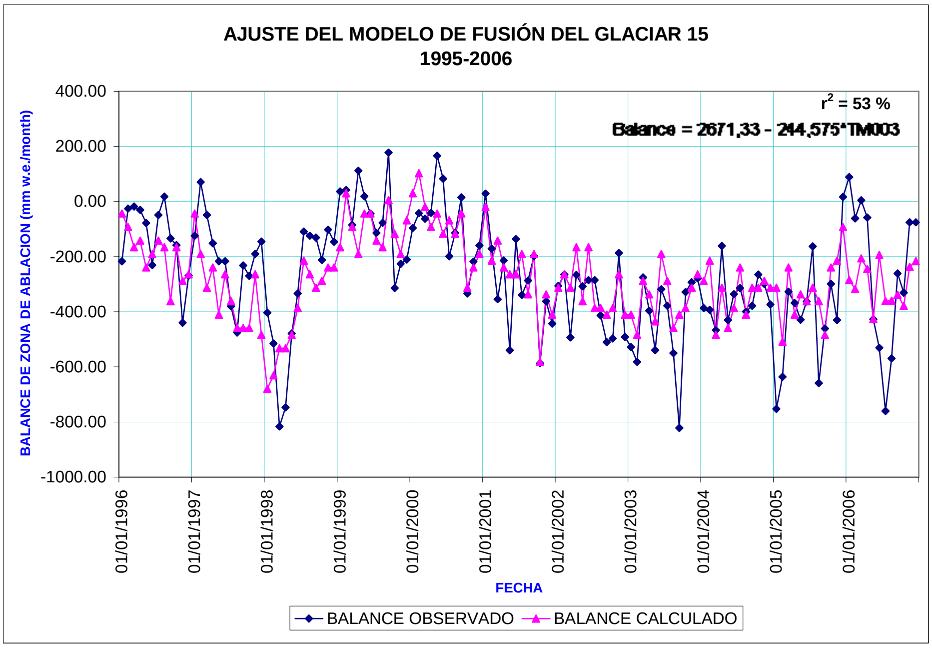

Figure 5. Model 3 - Simplified Model adjustment

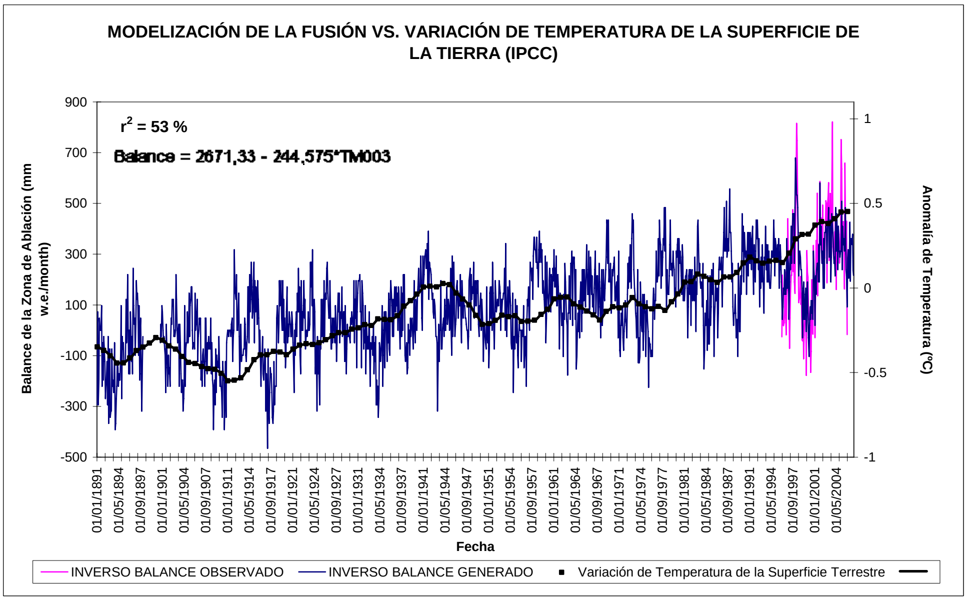

Figure 6. Comparison between balance of ablation zone generation and temperature variation of Earth's surface for the period 1891-2006 (Phil Jones and Mike Salmon)

DISCUSSION AND CONCLUSION

The first model allowed us to explain around the 60% of the variance of the Glacier 15's ablation using only two variables: one local and one regional. The first variable is the anomaly, 4 months prior, of sea surface temperature in block El Niño3+4 at over 11000km 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 four months later. The second variable is a precipitation anomaly index throughout the 9 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 9 previous months in the Antizana region will result in a reduction in ablation.

The second model "Model-2-Regional model" does not use any local variable. It explains 62% of variance but using a relatively complex linear regression that will be difficult to extend for a large period.

The third model "Model-3-Simplified model" explains 53% of balance variability with only one regional parameter. This parameter is the temperature in an Ecuadorian principal meteorological station, located close to Quito. Using this relation we could generate a fictitious balance series of 104 years duration that we compared with temperature variation of the Earth's surface.

Limitations

It should be noted that the linear statistical modelling technique used is fast and effective, but has its weaknesses: i) It cannot represent correctly the phenomenon that are probably non-linear. ii) The model's variable selection is based upon the variance reduction that each variable add 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. However, it is possible that one 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 confirm and complement *Francou et al.* (2004), Cadier et al (2007), Manciati et al (2007), Freile and Manciati (2007) and Villacis (2008) conclusions. We show, as a new complementation, a local precipitation influence on ablation reduction in addition to the El Niño4 index effect already demonstrated. The work can continue 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 year 2005. iii) We are analysing the mechanisms and modelling of the glacier melt using more precise time steps (hourly or daily) (*Favier*, 2004). iv) Continue 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.

REFERENCES

Bendix, J. (2000) Precipitation dynamics in Ecuador and northern Peru during the 1991/92 El Niño: A remote sensing perspective. Int. J. RemoteSens. 21(3), 533– 548.

Bontron G., Francou B., Ayabaca E., Cáceres B., Maisincho L., Chango R., de la Cruz A., Garzón, L. A., & Neubert D., (1999) El Glaciar 15 del Antizana – Mediciones glaciológicas, hidrométricas y topográficas (años 1997-1998), Informe n^{0} 2 IRD-INAMHI-EMAAP-Q.

Cáceres, B., Maisincho, L., Favier, V., Francou, B., Ramírez, J., Vargas, A., Chango, R., Cruz, F. & Neubert, D. (2001) Glaciar 15 del Antizana (Ecuador). Balance de masa, topografía, prospección geofísica, meteorología, hidrología y balance de energía. Año 2000. Informe 3, IRD, INAMHI, EMAAP-Quito, INGEOMINAS-COLOMBIA: 110 p.

Cáceres, B., Maisincho L., Taupin JD, Tachker P., Chazarin J.P., Francou B., Favier V. (2002) Glaciar 15 del Antizana (Ecuador). Balance de masa, topografía, meteorología, hidrología y balance de energía. Año 2001. Informe 4, IRD, INAMHI, EMAAP-Quito 91p.

Cáceres, B., Maisincho, L., Taupin J.D.; Favier, V., Tachker, P., Chazarin, J.P., Francou, B., Cadier, E., & Cruz, F. (2003) Glaciar 15 del Antizana (Ecuador). Balance de masa, topografía, meteorología, hidrología y balance de energía. Año 2002. Informe 5, IRD, INAMHI, EMAAP-Quito,: 111 p.

Cáceres, B., Maisincho, L., Taupin, J.D., Bucher, R., Paredes, D., Villacís, M., Chazarin, J.P., Francou, B., Cadier E... (2004) Glaciar 15 del Antizana (Ecuador). Balance de masa, topografía, meteorología e hidrología. Año 2003. Informe 6, IRD, INAMHI, EMAAP-Quito,: 77 p.

Cáceres, B., Maisincho, L., Taupin, J. D., Francou, B., Cadier, E., Delachaux, F., Bucher, R., Villacis, M., Paredes, D., Chazarin, J. P., Garces, A. & Laval, R. (2005) Glaciares del Ecuador: Antizana y Carihuyarzo, balance de masa, topografía, meteorología & hidrología. Informe del Año 2004. IRD, EMAAP-Q, INAMHI Quito 176p.

Cadier, E., Villacis, M., Garcés, A., Lhuissier, Maisincho, Laval, R., Parédes, D., Cáceres, B., & Francou, B., 2007. Variations of a low latitude Andean glacier according to global and local climate variations: first results. Glacier Mass Balance Changes and Meltwater Discharge (selected papers from sessions at the IAHS Assembly in Foz do Iguaçu, Brazil, 2005). IAHS Publ. 318 : 66-74.

Favier, V., Cáceres, B., Maisincho, L., Francou, B., de la Cruz, A., Chango, R., & Neubert, D., 2000 : El Glaciar 15 del Antizana (Ecuador). Mediciones glaciológicas, hidrométricas, meteorológicas y topográficas (año 1999). Informe NGT-Ecuador, 3, IRD, EMAAP-Quito, INAMHI 97 p.

Favier, V., Wagnon, P., Chazarin, J.P., Maisincho, L. & Coudrain, A. (2004) One-year measurements of surface heat budget on the ablation zone of Antizana Glacier 15, Ecuadorian Andes, J. Geophys. Res., 109, D18105, doi:10.1029/2003JD004359.

Favier V. (2004) Etude du bilan d'énergie de surface et de la production des écoulements de fonte d'un glacier des Andes d'Equateur, relation glacier - climat en zone tropicale, Ph.D. thesis, Univ. de Montpellier II France

Freile, D. y Manciati, C. Febrero 2007. Relación a escala mensual y estacional entre la información hidrometeorológica local y regional y la fusión de los glaciares tropicales del Ecuador. Casos de estudio Glaciar 15 y Glaciar "Crespos" del nevado Antisana. Proyecto previo a la obtención del título de Ingeniero Civil. Escuela Politécnica Nacional.

Francou, B., Ribstein, P. Sémiond, H., Portocarrero, C. & Rodríguez, A. (1995a) Balance de glaciares y clima en Bolivia y Perú. Impactos de los eventos ENSO. Bull. Inst. Fr. études andines, 24(3), 643– 654.

Francou, B., Ribstein, P. Tiriau, E., & Saravia, R. (1995b) Monthly balance and water discharge on an inter tropical glacier. The Zongo glacier, Cordillera Real, Bolivia, 16_S. J. Glaciol., 42(137), 61– 67.

Francou, B., Ramirez, E., Cáceres, B. & Mendoza, J. (2000) Glacier evolution in the tropical Andes during the last decades of the 20th century. Chacaltaya, Bolivia, and Antizana, Ecuador. Ambio, 29(7), 416–422.

Francou, B., Vuille, M., Favier, V. & Cáceres, B. (2004) New evidence for an ENSO impact on low latitude glacier: Antizana 15, Andes of Ecuador, 0°28'S. J. Geophys Res. 109, D18106

Francou, B., Ribstein, P., Wagnon, P., Ramirez, E. & Pouyaud, B., (2005): Glaciers of the Tropical Andes, indicators of the global climate variability. In Global Change and Mountain Regions: A State of Knowledge Overview, U. Huber, K.M. Harald & M. A. Reasoner (eds), Springer.

Jones P. and Salmon M. September 2007. CLIMATIC RESEARCH UNIT. University of East Anglia, Norwich, UK. http://www.cru.uea.ac.uk/cru/data/temperature/#datdow

Hastenrath, S. (1981) The Glaciation of the Ecuadorian Andes. Balkema, Rotterdam, Netherlands.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R. & Joseph, D. (1996) The NCEP/NCAR 40–year reanalysis project. Bull. Am. Meteorol. Soc., 77(3), 437–471.

Kaser, G., & Osmaston, H. A. (2002) Tropical Glaciers. Cambridge Univ. Press, New York.

Lhuissier, P. (2005) Mise en évidence de modèles de comportement pluviométrique sur le volcan Antizana. IRD, Quito, Ecuador

Loyo C., Villacís, M.; Manciati C.; and Cadier E., 2007 Estimaciones del comportamiento hidrológico de los recursos hídricos de alta montaña. Caso de estudio: cuenca del río Antisana y glaciar "los Crespos" del volcán Antisana 9p. Memorias IX Congreso Nacional de Hidráulica y I de Manejo Integral de Recursos Hídricos, Quito 2007

Manciati, C., Freile, D., Galárraga, R., Cadier, E. and Francou, B., 2007. Modelación delbalance de masa de glaciares tropicales de América del Sur. Caso de estudio en elnevado Antisana, Ecuador, IX Congreso Nacional de Hidráulica y 1ero de ManejoIntegral de Recursos Hídricos. EPN, CD ROM, Quito, Ecuador.

Menegoz M. (2004) Etude de la couche limite atmosphérique sur le glacier de l'Antizana (Equateur) et estimation des flux turbulents. MSc. Thesis Univ. Grenoble France

Ribstein, P., Francou, B,. Tiriau, E. & Saravia, R. (1995) Tropical climate and glacier hydrology. A case study in Bolivia. J. Hydrol., 165,221–234.

Rossel, F. (1997) Influence du Niño sur les régimes pluviométriques de l'Equateur. PhD. thesis 289 pp, Univ. de Montpellier II France

Sémiond H., Francou B., Ayabaca E., de la Cruz A., & Chango R. (1998). El Glaciar 15 del Antizana (Ecuador): investigaciones glaciológicas 1994-1997. ORSTOM-IFEA-EMAAP-Q-INAMHI, Quito.

Sicart, J. E. (2002) Contribution à l'étude des flux d'énergie, du bilan de masse et du débit de fonte d'un glacier tropical: Le Zongo, Bolivie. Ph.D. thesis, 330 pp., Univ. de ParisVI, Paris.

Villacis, M. (2001) Influencia de El Niño-Oscilación del Sur sobre la precipitación en los Andes centrales del Ecuador. Tesis de grado, 199pp., Esc. Pol. Nac., Quito, Ecuador.

Villacis, M. (2008) Ressources en eau glaciaire dans les Andes d'Equateur en relation avec les variations du climat : Cas du volcan Antisana. Phd Tesis 220p Université de MontpellierII

Vuille, M., Bradley, R. S. & Keimig F. (2000a) Interannual climate variability in the central Andes and its relation to tropical Pacific and Atlantic forcing. J. Geophys. Res., 105, 12,447

Vuille, M., Bradley, R. S. & Keimig F. (2000b) Climatic variability in the Andes of Ecuador and its relation to tropical Pacific and Atlantic sea surface temperature anomalies. J. Clim., 13, 2520– 2535.
Wagnon, P., Ribstein, P., Francou, B. & Pouyaud B. (1999) Annual cycle of energy balance of Zongo glacier, Cordillera Real, Bolivia. J. Geophys. Res., 104, 3907– 3923.
Wagnon, P., Ribstein, P., Francou, B.& Sicart, J.E., (2001) Anomalous heat and mass budget of Zongo glacier Bolivia, during the 1997–98 El Niño year. J. Glaciol., 47(156), 21–28.