Some preliminary results from the Coropuna (Peru) ice core

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Abstract

Ice core studies have been implemented in tropical region over the last 30 years to study the past climatic variability. A 42m-long ice core from the saddle of the Coropuna glacier (Peru) is investigated. The isotopic composition of the water, selected geochemical markers and the pollen concentrations records are presented. As the glacier is temperate at the drilling site both chemical and isotopic signals are disturbed. We discuss several processes as melting, evaporation or sublimation which may perturb the profiles. Some particular events remain identifiable such as soil particle depositions during dry periods or ash layers. The presence of pollen *Nothofagus*, endemic of Patagonia region in southern America, confirms the occurrence of incursions of polar front at high altitudes in the central part of the Andes.

I. Introduction

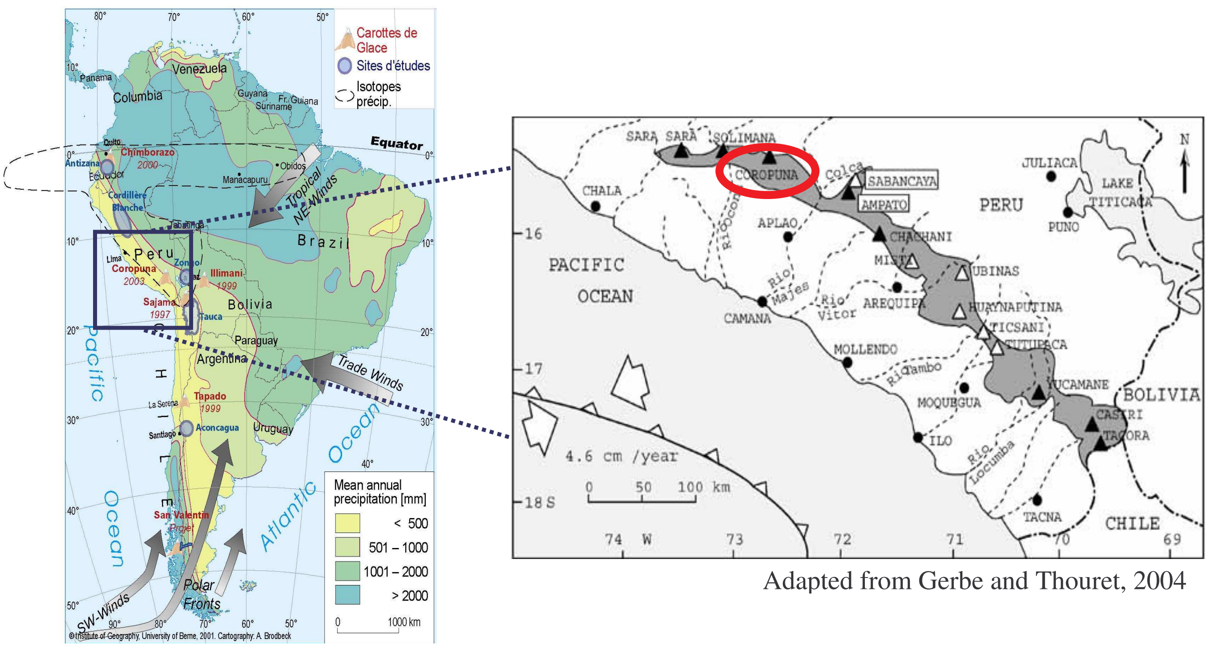
Over the last 30 years an important interest has been developed for drilling high-latitude ice cores in tropical regions. Indeed ice records provide significant information on past climatic and atmospheric conditions (e.g. Ramirez et al., 2003; De Angelis et al., 2003). However possible changes can occur after snow deposition. Even at high altitude tropical glaciers may experience occasional to moderate melt during the summer and sublimation during the winter (Schotterer, 2003). These processes can affect both chemical and isotopic signals and have to be considered while interpreting the records.

Here we investigate the chemical and isotopic signals and pollen concentrations from the ice core drilled at the saddle of Coropuna. In the first part the drilling site is presented. Then the different analyses performed on the core are described. Finally we examine the different processes which may disturb the records at the drilling site and the events which remain recorded.

II. Presentation of the site

Nevado Coropuna (15°33´S, 72°36´W, 6425 m) is an inactive volcano (probably since the Last Glacial Maximum) located in the Peruvian part of the Andes (Cordillera Occidental), situated 100 km east from the Pacific Ocean (Fig. 1). In June 2003, a 42 m long core (this study) was drilled at the saddle of the Coropuna glacier at 6080m above sea level by IRD-GreatIce team. Two other ice cores have been drilled in August 2003 by an American team of the Byrd Polar Research Center at the summit (6425m a.s.l., 34 m) and the crater (6350m a.s.l., 140 m). The studies of both ice cores are unpublished as of yet.

Several climatological stations, located in a perimeter of 60 km around the Coropuna glacier (SENAMHI, 15 stations from 645 m to 4270 m asl), provide us with important climatic information from 1964 to 2003. Only one data series covers this time window and is continuous. The data series for 8 stations are continuous and span 22 to 35 years. About 80% of the precipitation in this region falls during the austral summer (December to March). The spatial variability of annual precipitation is strong over the region of Coropuna: from several millimeters near the Pacific coast to 1190 mm in the Cordillera Occidental. Moist air from the subtropical Pacific does not contribute notably to the water budget owing to a persistent temperature inversion at about 800 m a.s.l. (Garreaud, 2003). The dominant water vapor source is the tropical/subtropical Atlantic. The precipitation mostly occurs when the vapor is advected by strong northeasterly trade winds over the Amazon basin.



Adapted from Gerbe and Thouret, 2004

Figure 1: Coropuna drilling site

III. Methodology

At the drilling site the ice core was cut in sections of 65 cm length and sealed in polyethylene bags. The ice samples were transported and kept in a frozen state to the LGGE (Laboratoire de Glaciologie et Géophysique de l'Environnement) in Grenoble, France.

The top of the ice core is assumed to correspond to the first half of the year 2002. Indeed a snow layer of about 70 cm was lost during the installation of the equipment on the drilling site.

Tritium activity (Schotterer, Pers. Com.) was used to date the ice. The maximum Tritium fallout deposit related to tropospheric nuclear weapon tests took place in 1964/1965 in South America. This layer is found at about 22 m. An average net accumulation rate of 0.58 $m.yr^{-1}$ (or 0.39 $mwe.yr^{-1}$) is derived. This accumulation is much lower than that at Quelccaya, Peru (14°S, 71°W; 5670 m), which is situated in the eastern part of the Andes (Cordillera Oriental), with an annual mean accumulation of 1.15 $mwe.yr^{-1}$. The accumulation rates on the other Andean sites are 0,58 $mwe.yr^{-1}$ on Illimani (6350 m; 16.3°S; Cordillera Oriental), 0.44 $mwe.yr^{-1}$ on Sajama (6540m; 18°S; Cordillera Occidental) and 0.7 $mwe.yr^{-1}$ on Chimborazo (6300 m; 1.3°S; Ecuadorian Andes).

The ice was cut in a cold room (-15 °C) into pieces of 4 to 7 cm and prepared for chemical, isotopic and pollen analyses. The $\delta^{18}O$ and δD of the ice were measured at the LAMA (Laboratoire Mutualisé d'Analyse des isotopes stables de l'eau, Montpellier, France) on a GV Instruments Isoprime Mass Spectrometer. $\delta^{18}O$ and δD are expressed in permil units versus V-SMOW, the Vienna Standard Mean Ocean Water. High resolution δD measurements were performed down to 42 m. The continuous $\delta^{18}O$ profile covers the first 11 meters. The experimental precision of the isotopic analysis was 0.5 ‰ for δD and 0.08 ‰ for $\delta^{18}O$.

Chemical analyses required decontamination. The external layers of the ice-core were removed using a plane. Samples were kept in airtight polycarbonate flasks and maintained frozen until analysis. Measurements were performed by conductivity-suppressed Ion Chromatography using a Dionex ICS 3000 at the LGGE's clean room facilities. Profiles of organic and inorganic anions (F^-, Cl^-, NO_3^-, SO_4^{2-}, methanesulphonate, mono and dycarboxylic acids) and cations (Na^+,NH_4^+,K^+,Mg^{2+},Ca^{2+}) were obtained for the first 22 meters of the ice-core with an experimental precision ranging from 10% to 55% depending on the concentration of the sample.

Pollens were identified at 1000X magnification. The sample resolution was 70 cm.

IV. DISCUSSION: What information is recorded in the ice of Coropuna?

The isotopic and chemical compositions of the ice depend on the environmental conditions which vary seasonally between rainy and dry seasons. Taking into account the average accumulation rate and the sampling resolution of the analyses, seasonal patterns were expected in the isotopic and chemical data. However such cycles are not identified in the different profiles (Fig. 2 and 3). The borehole temperature profile along the first 3m shows that the ice at the drilling site is temperate (Wagnon, 2003). The average temperature and the temperature at 3.3 m are -5.6 °C and -1.7 °C respectively. In such conditions melting-refreezing with or without evaporation and sublimation are expected to occur. Although the signals seem to be disturbed to some extent, these processes can be studied and some particular events can be identified thanks to isotopic, chemical and pollen analyses.

1) Isotopic analyses

We focus here on the first 11 m of the ice core where the detailed profiles of both δD and $\delta^{18}O$ are available at high resolution. The $\delta^{18}O$ and δD profiles present large variations in the upper part of the ice core above 3 m (Fig. 3). The highest (-83.86‰) and lowest (-166.28‰) values are found at 0.83 m and 1.75 m respectively. Below 3m the isotopic variations are more limited in amplitude and the cycles show a lower frequency. Below 12 m the cyclic variations disappear almost completely. The deuterium excess profile shows two extremely high values at 1.50 m and 4.49 m, and its lowest value at 3.48 m.

a) dExcess

The deuterium excess (d) parameter was defined as d = δD-8δ^{18}O by Dansgaard (1964). It was calculated along the first 10.5 m of our core with the precision of 0,.8‰. The d is mostly sensitive to kinetic processes like evaporation.

Evaporation of meltwater may occur in the firn in a temperate glacier. The water vapour acquires a high d due to the kinetic fractionation during evaporation. Condensation of the enriched water vapour in the firn and refreezing at the surface during night will increase d (Stichler, 2001). This process might be responsible for the positive excursions of d is not observed along this firn core. no specific values are found in the 5 ice layers (Fig. 2).

The lowest d value at 3.48 m indicates that an evaporative process may have occurred in this layer. A sulphate peak at the same depth (Fig. 3) may confirm the evaporation hypothesis. Indeed sulphate may be enriched in the surface layer when evaporation occurs due its low vapour pressure.

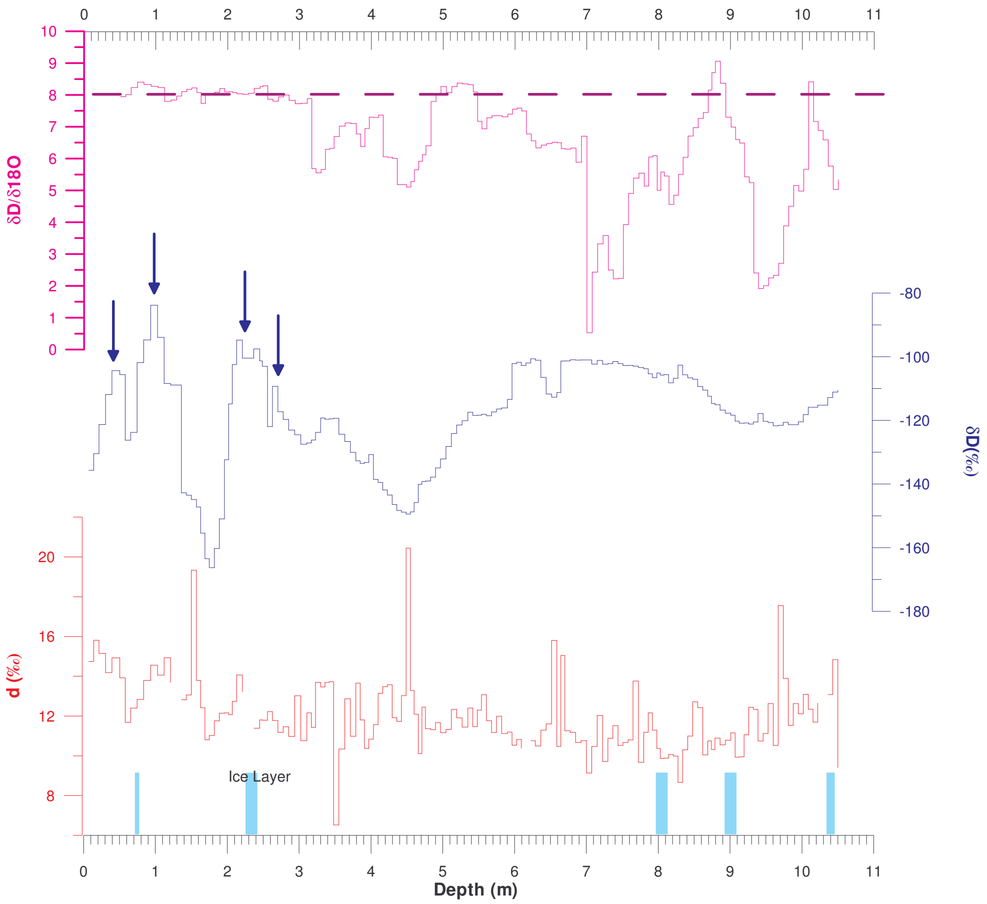


Figure 2: δD/δ^{18}O running slope over 11 points; δD of the ice; Deuterium excess d

b) dD/δ^{18}O slope

To examine the evaporative process a running δD/δ^{18}O slope was calculated over 11 contiguous measurements (80 to 90 cm) (Fig. 2). In the first 3 meters the slopes were close to 8 (the value of the Global Meteoric Water Line) which indicates no surface melting and evaporation. The ice temperature was below -4°C (from -13°C at the surface to -4 °C at 2,5 m). The strong variations in δD and $\delta^{18}O$ indicate a good preservation of the isotopic signal in this part of the core. If we consider that the variations observed are seasonal, we can count up to 4 annual cycles (blue arrows in Figure 2): the 3m-layer might then correspond to the austral summer 1998.

On the other hand between 3.0 and 10.5 m the slopes $\delta D/\delta^{18}O$ vary between 0.5 and 9.1. Most of the values are within or below the typical range of the evaporation line which is close to 5. In this part of the ice core the isotopic signal seems affected by melting and evaporation processes. The ice temperature was close to -2 °C from 3 m down, which is too high a temperature to prevent melting.

2) Chemical analyses

a) Post-depositional processes affecting this site

The chemical analyses are discussed down to 22m where the Tritium maximum, corresponding to 1964/1965, was detected.

It has been observed that when mean air temperature is above -10˚ C, surface melting in tropical temperate glaciers is clearly noticeable (Zagorodnov et al., 2006). Also, it has been shown that in temperate glaciers ions are eluted differentially and in a manner which initially accentuates the loss of sulfuric and nitric acid (Davies, 1982: Davis 1995; Li, 2006). Since the Coropuna saddle drilling site is temperate and it is located upstream of the glacier's melt-water runoff, we do not expect to have a conserved chemical profile. This profile may be affected either by sublimation and/or melting and evaporation, as discussed in the previous section, melting and refreezing in cold points, as borehole temperature measurements and stratigraphy suggest and/or slanted melt-water flow as the topography of the site suggests. None of these mechanisms is exclusive, so they may occur simultaneously.

As the isotopic signal shows, only the first 3 m may provide an unperturbed chemical signal. To identify the limit of a relatively intact chemical signal we use the chloride to sodium ratio (Cl/Na). Marine aerosol number decreases with altitude and the inversion layer observed at this site prevents marine particles to reach high altitude. Hence, we may expect that the principal sources affecting this site are located eastwards from the drilling site and the chemical signature is expected to be mostly continental. Average Cl/Na mass ratio in the upper 2 m of the ice core is 1.5 ± 0.2, which is closer to halite (Cl/Na = 1.4) than to sea-salt ratio (1.8), confirming that NaCl has a continental origin in this site.

In consequence, three periods have been identified: the first 2.1 m, where the halite Cl/Na ratio does not seem to be perturbed; between 2.1 m and 5.0 m, where Cl/Na ratio increases up to 6.1±1.0, and below 5.0 m, where Cl/Na remains around 23.5±2.1, as shown in the figure 3. The increase of the Cl/Na ratio, as an evidence of remobilization of ions, has also been observed in the Chimborazo glacier (Ginot, unpublished results). However, the events triggering this perturbation are different in both cases, since Chimborazo was covered by a volcanic ash layer, which is not the case of Coropuna.

Curiously, the Br/Na ratio (not shown) strongly correlates along the whole profile with Cl/Na (r=0.92), suggesting that halogens are affected in the same manner by this remobilisation processes. This indicates that Na^+ may not be affected by remobilisation whereas halogens are.

The precipitation data from the stations around the Coropuna indicate low precipitation during the period 1982-1983. Dust layers between 12 and 12.5 m may correspond to this dry period. The theoretical net accumulation of snow, calculated by subtracting measured daily sublimation (measured on the field) from daily precipitation (measured at the stations), predicts a reduced accumulation for this period. We expected high sublimation with concentration of non volatile species in the upper layers (Ginot , 2001; Stichler, 2001) but it is not observed between 12 and 13 m (red dotted line III in Fig. 3). Sublimation effects may have been diminished or erased by melt-water flow.

b) An absolute dating?

Even if Ca^{2+} may be affected by elution, the profiles that we have obtained show a well conserved signal for the cations. Therefore, we assess annual layers using Ca^{2+} peaks associated with seasonal dust inputs, considering that maximum dust and dry deposition takes place during the austral winter. Due to the very low marine salt contribution, we consider that the marine fraction of $Ca^{2+}$is negligible (2,5% of the total), therefore Ca^{2+} may be considered as entirely originated from eroded soils. Thus we can clearly identify seasonal dust layers in the first 10 m. Below this level, an increase of the peak number complicates the counting, suggesting either an accumulation rate change or the arrival of more than one seasonal input of eroded soils.

Accumulation rate was calculated by these means to be 0.5 $m.yr^{-1}$ above 10m and 1.4$m.yr^{-1}$ below this level, which is consistent with the estimate of 0.58 $m.yr^{-1}$ derived from Tritium data.

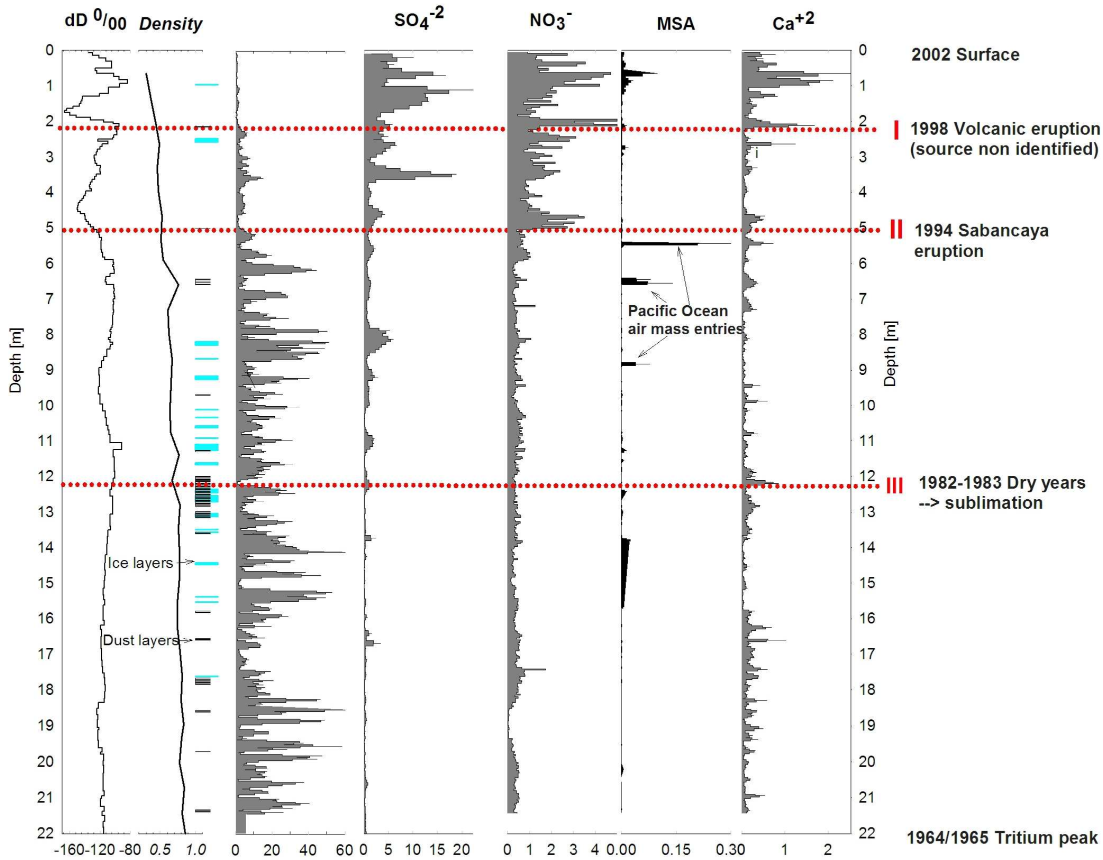


Figure 3: Coropuna saddle chemical profile. Only the first 22 m of the total length 40 m are shown. Densitiy is given in $g.cm^{-3}$, Cl/Na is given in $eq.eq^{-1}$ and ions concentration is given in $meq.l^{-1}$.

c) Volcanic activity triggering post-depositional processes?

A small tropospheric volcanic signal is observed at 2.1m (high concentrations of $SO_4^{2-}$and Cl^-, and peaks of F^- and H^+, not shown) accompanied with a dust layer (red dotted line I in the figure 3). This level should correspond to 1998, according to Ca^{2+} counting, year in which the Sabancaya volcano had a strong degassing activity. However, we did not find evidence of volcanic plumes passing over the drilling site. But this dating is differs slightly from the isotopic dating in which points to the dry season of 1999.

A larger volcanic event is observed at 5.0m (dotted line II), with the same characteristics mentioned above. Ca^{2+} layers point to 1994, a year when Sabancaya volcano had one of its most important eruptions. Forward trajectories for Sabancaya's eruptions confirm that the plume passed over the drilling site during May of this year (HYSPLIT - HYbrid Single-Particle Lagrangian Integrated Trajectory - model via NOAA ARL READY, http://www.arl.noaa.gov/ready/hysplit4.html).

Interestingly, we observe that in both cases, below the eruption level, Cl/Na perturbations seem to occur and differential elution of sulphuric and nitric acid is clearly observed. We hypothesize that enhanced heating of the surface induced by dust particles may have increased the surface melting. Volcanic HCl may have been neutralized by ammonia and, under these circumstances H+ produced the elution of SO_4^{2-} and NO_3^-. F^- remobilization is also observed below 5 m. Although this is usually driven by diffusion (De Angelis, 2003), this process may have been enhanced by slanted melt-water flow.

d) Marine inputs

In spite of remobilization of species, important peaks of methanesulfonic acid (MSA) - an indicator of marine biogenic activity - persist, showing evidence of secondary marine inputs from the Pacific Ocean.

3) Pollen concentrations: regional scale recorders?

The mountainous steppe characterized the vegetation on the Coropuna. In the ice core the most represented pollen is the *Asteraceae* representative of the vegetation around the Coropuna (not shown). *Podocarpus* is characteristic of the rain forests distributed on the oriental slope of the Andes and is brought by the air masses coming from the Amazon Basin (concentrations not shown).

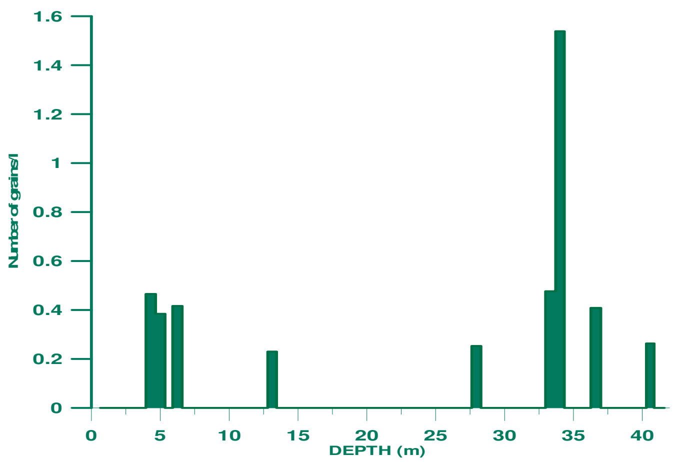


Figure 4: *Nothofagus* concentrations over the entire ice core

Nothofagus is distributed in Patagonia. With a size of 20µm it is easily airborne and transported by the winds. The presence of these specific pollen grains on the Coropuna glacier (Fig. 4) is a feature of a polar front incursion coming from southern America. This discovery confirms a large scale circulation and the presence of incursions of polar fronts at high altitude in the western part of the Andes.

V. Conclusion

The isotopic analysis underlines the postdepositional processes like melting and evaporation. Some particular events are recorded in the ice core, such as volcanic eruptions and dry periods. Both isotopic and chemical signals remain undisturbed in the upper 3 meters. However neither the isotopic nor the chemical signals provide us climatic information at the annual scale below 2-3 m. The ice core has been affected by melting/evaporation/refreezing processes, as expected for a tropical temperate glacier. Pollen data suggest sporadic inputs from high altitude polar fronts in the study region.

This study underlines the melting of high altitude temperate tropical glaciers. The consequences on glaciers as perennial water resources and as environmental archives are drastic. This would happen with a certain lag that depends on glacier meteorological conditions.

In spite of post depositional processes observed, we can conclude that the Coropuna glacier is under strong continental influence, even though it is rather close to the Pacific Ocean.

Comparison with two other ice cores (summit and crater) extracted from the Nevado Coropuna in August 2003 and other Andean sites will complete this study.

References

Dansgaard, W., *Stable isotopes in precipitation*, 1964. Tellus, *16*(4), p. 436-468.

Davies, T.D., C.E. Vincent, and P. Brimblecombe, *Preferential elution of strong acids from a Norwegian ice cap.* Nature, 1982. 300 (5888): p. 161-163.

Davis, R.E., C.E. Petersen, and R.C. Bales, *Ion flux through a shallow snowpack: effects of initial conditions and melt sequences*, in *Biogeochemistry of Seasonally Snow-Covered Catchments*, IAHS, Editor. 1995: Boulder. p. 115-126.

De Angelis, M., et al., *Volcanic eruptions recorded in the Illimani ice core (Bolivia): 1918-1998 and Tambora periods.* Atmospheric Chemistry and Physics, 2003. **3**: p. 1725-1741.

Delachaux, F., *Etudes des phénomènes de dépôt auxiliaire et de post-dépôt sur le glacier du Coropuna au Pérou (15°S, 6350m), en vue d'interpréter une carotte de glace*. 2004.

Garreaud, R., et al., *The climate of the Altiplano: observed current conditions and mechanisms of past changes*, Palaeogeography Palaeoclimatology Palaeoecology, 2003. *194*(1-3), p. 5-22.

Gerbe, M.-C. and J.-C. Thouret, *Role of magma mixing in the petrogenesis of tephra erupted during the 1990–98 explosive activity of Nevado Sabancaya, southern Peru.* Bulletin of

Volcanology, 2004. **66**(6): p. 541-561

Ginot, P., et al., *Effects of postdepositional processes on snow composition of a subtropical glacier (Cerro Tapado, Chilean Andes).* Journal of Geophysical Research, 2001. **106**(D23): p. 32,375-32,386.

Li, Z., et al., *Seasonal variability of ionic concentrations in surface snow and elution processes in snowfirn packs at the PGPI site on Urumqi glacier No. 1, eastern Tien Shan, China.* Annals of Glaciology, 2006. **43**: p. 250-256.

Ramirez, E., et al., *A new Andean deep ice core from Nevado Illimani (6350 m), Bolivia*, Earth and Planetary Science Letters, 2003. *212*(3-4), p. 337-350.

Schotterer, U., et al., *Glaciers and climate in the Andes between the Equator and 30 degrees S: What is recorded under extreme environmental conditions?*, Climatic Change, 2003. *59*(1-2), p. 157-175.

Stichler, W., et al., *Influence of sublimation on stable isotope records recovered from high-altitude glaciers in the tropical Andes.* Journal of Geophysical Research, 2001. **106**(D19): p. 22613-22620.

Wagnon, P., *Compte rendu de mission - Mesures météorologiques et de chimie de surface, Coropuna, 17 juin au 1er juillet 2003*. 2003, IRD.

Zagorodnov, V., O. Nagornov and L. G. Thompson, *Influence of air temperature on a glacier's active-layer temperature*. Annals of Glaciology , 2006. **43**: 285-291.