FIRST RESULTS OF A PALEOATMOSPHERIC CHEMISTRY AND CLIMATE STUDY OF CERRO TAPADO GLACIER, CHILE

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1. ABSTRACT

In February 1999 a 36 m ice core reaching bedrock of the cerro Tapado summit glacier (5550 m, 30°08' S, 69°55' W) was recovered in order to investigate the suitability of this glacier as paleoenvironmental and climate archive. Site selection was based on the assumption that this area is strongly influenced by the El Niño phenomenon. Glaciochemical data indicate that a record of about 100 years is contained in the ice core and that El Niño periods are characterized by low concentrations of chemical species.

2. INTRODUCTION

The central Andes are a key area for paleoclimate and paleoatmosphere research, since they are located in a transition zone between two precipitation belts, the extratropical westerlies receiving moisture from the Pacific and the tropical circulation with a continental/Atlantic moisture source.

In order to reconstruct past climate variations, especially those related to the El Niño Southern Oscillation (ENSO) phenomenon, a suitable glacier archive was sought. As one

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possible candidate, the ice cap on the cerro Tapado was studied (5536 m, 30°08' S, 69°55' W, Region IV, Chile), which is located in the Norte Chico region of Chile,150 km east of La Serena in the Andean cordillera and on the border with Argentina (Figure 1). Because of its vicinity to the "South American Arid Diagonal" (Joussaume *et al.*, 1986) the glacier is assumed to be affected by a discontinuous winter precipitation regime advected by westerlies. The major precipitation events therefore occur in the short period from May to August (Escobar, 1998) and are annually interrupted by a long dry period. The inter-annual variation in winter snow accumulation is influenced by the ENSO phenomenon, with larger snow accumulation in the Andean sector to the north of 35° S when the magnitude of the positive SST anomaly surpasses +1.0 °C during austral winter (Escobar and Aceituno, 1998).

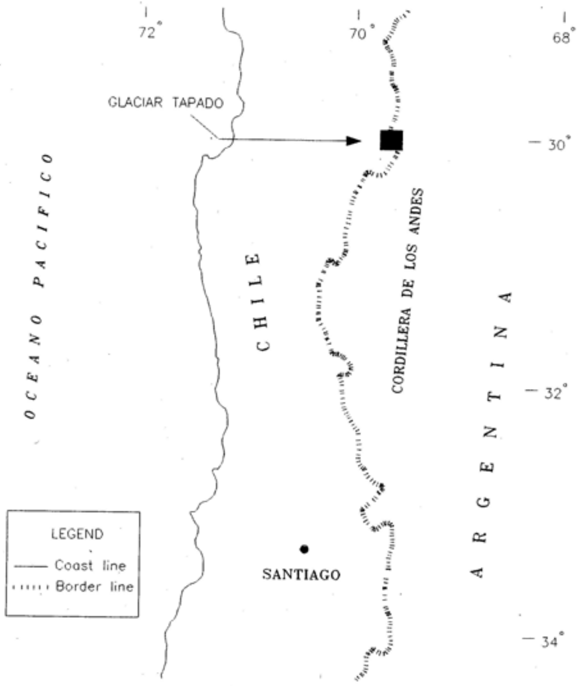

Figure 1. Location in Chile of cerro Tapado Glacier.

3. ICE-CORE RECOVERY AND CHEMICAL ANALYSES, METEOROLOGICAL AND GLACIOLOGICAL INVESTIGATIONS

In February 1999 we recovered a 36 m ice core reaching bedrock of the cerro Tapado ice cap (Figure 2). To do this, we used a new portable 77 mm electromechanical drill which was especially designed for employment on high-altitude glaciers (Ginot *et al.*, in press; FS INVENTOR AG, Switzerland). Its total weight is only about 250 kg including power supply and sheltering tent and can be broken down into handy porter loads. Power is supplied by either flexible solar panels or a light-weight gasoline generator which are connected to an accumulator pack (Figure 3). The drill can be installed in less than one hour and in reasonable conditions it is possible to drill 50 m in 10 working hours. The recommended operation range is a maximum depth of 150 m. All parts in contact with the ice cores are composed of anodized aluminium and polyethylene. The recovered ice cores have a diameter of 77 mm and a maximal length of 900 mm.

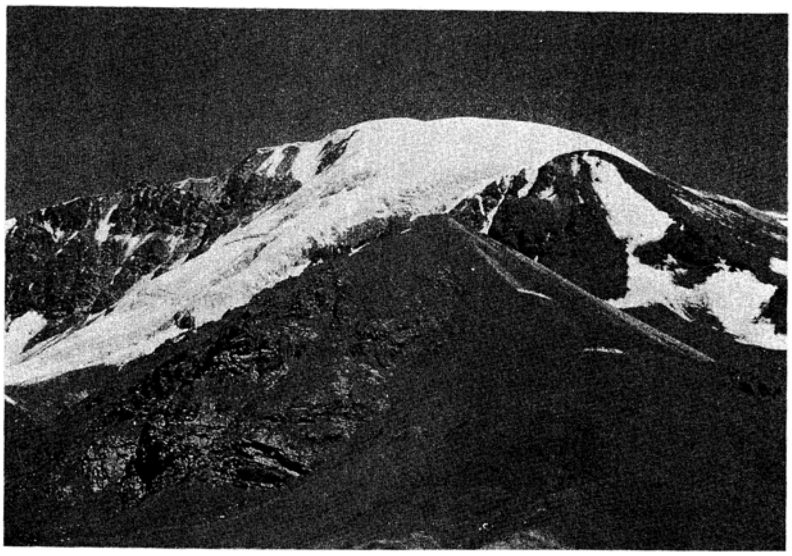

Figure 2. View of the cerro Tapado ice cap.

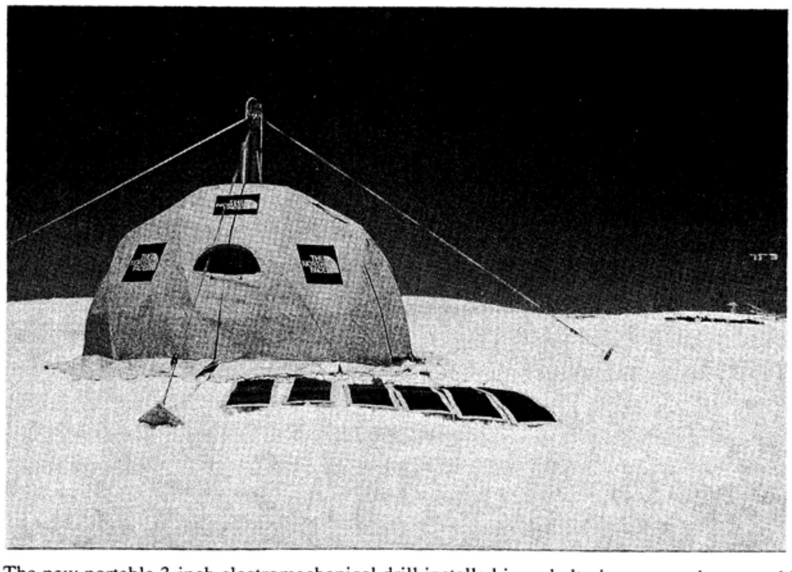

Figure 3. The new portable 3-inch electromechanical drill installed in a sheltering tent and powered by flexible solar panels in operation on the cerro Tapado ice cap.

The ice cores were sealed in polyethylene tubes at the site and transported to the laboratory in frozen condition. All materials (vials, tubes, cutter) were carefully cleaned with ultra-pure water before coming in direct contact with the samples. Ice-core segments were photographed, measured, weighed, and cut in a cold room maintained at -20 °C. For the different chemical analyses, various cutting resolutions were applied. 1.5 cm sections of the inner part of the core were used to analyze concentrations of ionic species (Na^+, K^+, NH_4^+, Ca^{2+}, Mg^{2+}, F^-, $HCOO^-$, H_3CCOO^-, Cl^-, NO_3^-, SO_4^{2-}, $C_2O_4^{2-}$) by ion chromatography (Döscher *et al.*, 1995; Schwikowski, 1997). In 1.5 cm samples from the outer part of the core, stable isotope ratios ($\delta^{18}O$, δ^2H) were determined by mass spectrometry (see e.g. Schotterer *et al.*, 1997). Samples of 70 cm length were used to measure activities of tritium (see e.g. Schotterer *et al.*, 1998) and ^{210}Pb (Gäggeler *et al.*, 1983).

During the ice-core drilling campaign, surface snow experiments were performed in order to study the effect of sublimation and dry deposition on chemical and isotopical composition of the snow. For this purpose, 1 cm snow samples were collected from the surface twice daily over a 5 day period. In addition, samples were taken from a 38 cm snow pit with a resolution between 1 to 3 cm. In these snow samples, concentrations of major ionic species as well as stable isotope ratios $\delta^{18}O$ and δ^2H were determined. Sublimation was measured with the *lysimeter* technique (Hastenrath, 1997), and meteorological parameters such as temperature, relative humidity, wind direction and speed were recorded at the drilling site. This was accompanied by monitoring the same parameters at 4215 m on a moraine shoulder close to the glacier (Begert, 1999) and temperature at 5250 m on the ice margin since April 1998.

Detailed ice thickness measurements were carried out with a portable radio-echo sounding system. The ground-based digital impulse radar system used a transmitter developed by the University of Bristol, UK, with a maximum output voltage of 670 V_{pp}. The antennas consisted of resistively-loaded dipoles, with a 5 m antenna length, which result in a central frequency of about 10 MHz. The receiver is composed of a digital FLUKE oscilloscope connected to the receiving antennas, transferring the data through a serial port to a portable PC, where they were stored on the hard disk. The antennas were mounted on fiberglass fishing rods, with a separation of 10 m between the receiver and the transmitter. The whole system was carried by two persons, who walked on the surface of the glacier measuring one point every 5 seconds. In order to obtain a geographic position for each thickness measurement, a topographic-quality GPS receiver was used to fix the positions of the stakes. By means of differential correction methods, GPS data was obtained simultaneously at base camp and the horizontal precision attained was 5 m. In addition, firn temperature measurements were performed in the borehole using a thermistor chain.

4. RESULTS AND DISCUSSION

4.1. Glacier characteristics

In this Norte Chico area of Chile, the cerro Tapado appears to be the only summit having a true glacier flowing on its south-western slope. The adjacent mountains, even those of higher altitude such as the cerro de Olivares (6252 m), show only small remains of glaciers or snow fields on the summit or in the crater. The glacier on cerro Tapado extends from 5536 m down to its terminal moraine at 4500 m and is relatively flat at the top. Adjacent to the summit ice cap in the North and East are steep rock faces, free of ice cover. The transition between glacier and rock is characterized by the presence of several small frozen lakes and penitent fields, characteristic of significant ablation affecting the surface of the glacier. This is also observed at other glaciers located close to the "South American Arid Diagonal".

Three radar profiles were measured (Figure 4) indicating a maximum ice thickness of 42 m.

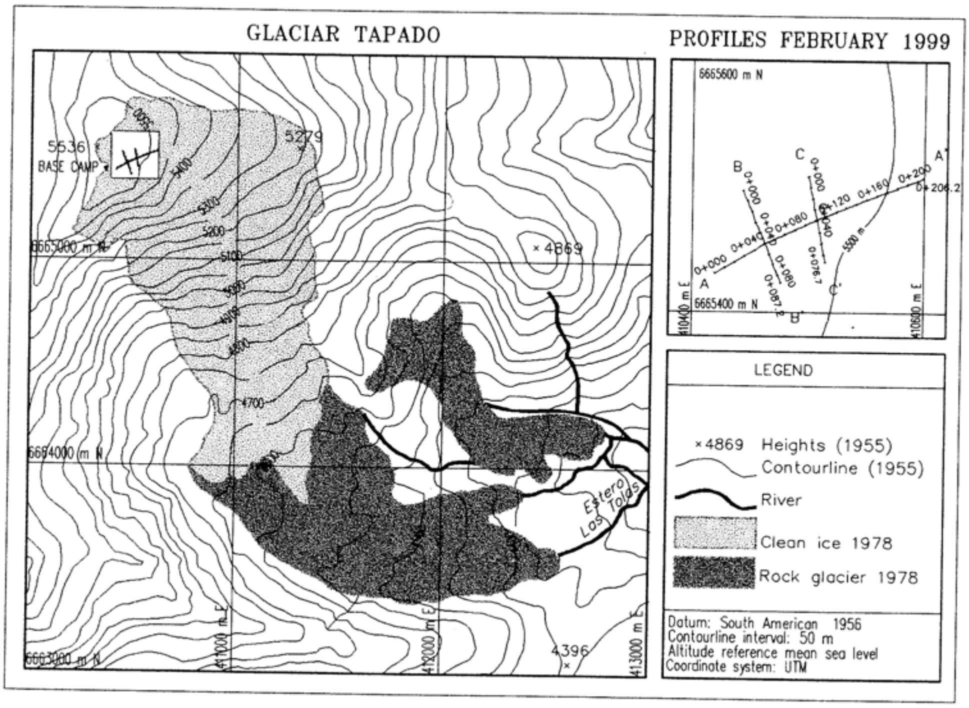

Figure 4. Topographic map of the glacier on the cerro Tapado along with the location of the radar profiles.

Near the ice-core drilling site the ice thickness reaches 33 m (Figure 5). This corroborates earlier results from the first radar survey conducted during the exploratory drilling of shallow firn cores in 1998. The ice thickness data was georeferenced to the regular cartography of the IGM (Instituto Geográfico Militar of Chile), which was compiled and digitized in order to produce the final chart of the study area (Figure 4).

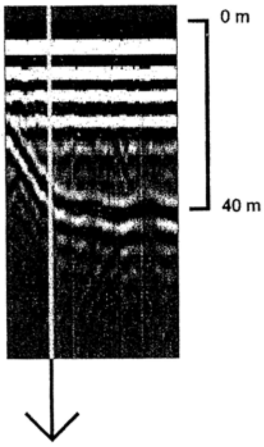

Figure 5. Radar reflectivities indicating ice thickness along profile A-A'

The firn temperatures decrease from -8.5 °C at the surface to -12.5 °C near bedrock (Figure 6), indicating that the glacier consists of cold firn and ice which is frozen to the ground. This presence of cold firn and ice is a prerequisite for the conservation of glaciochemical records of water-soluble species.

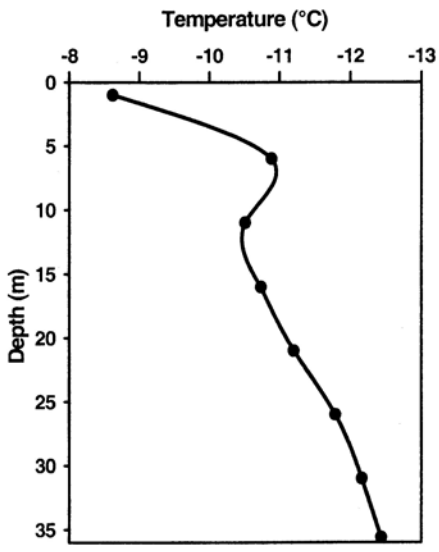

Figure 6. Firn temperatures measured in the 36 m borehole.

During the 8 days of direct measurements, a daily rate of sublimation of 1.89 mm water equivalent (weq) was observed, representing nearly 5 mm of snow. Sublimation showed a diurnal cycle with maximum values during the day in accordance with the diurnal variation of the meteorological parameters causing sublimation: atmospheric temperature and moisture, radiation and wind speed (Hastenrath, 1997; Cline, 1997). The obtained sublimation rate is significantly higher than the 0.1 mm reported for the period from morning to evening on Quelccaya ice cap (Hastenrath, 1978), but comparable to the 1.1 mm/day observed at Zongo Glacier during the dry season (Wagnon *et al.*, 1999). At El Laco in northern Chile (23.85° S, 67.49° W, 4400 m), located on the northern margin of the "South American Arid Diagonal", a maximum sublimation rate of 3 mm/day was estimated (Vuille, 1996).

The observed sublimation rate is corroborated by mass balance modeling (Kull, 1999), predicting an average sublimation of about 2 mm/day for the period between the last significant snowfall event in September 1998 and the beginning of the drilling campaign in February 1999. However, modeling results using the mean meteorological conditions in this region suggest that glaciation cannot exist due to the lack of moisture. An equilibrium line altitude (ELA) is not existent up to 6000 m and this is obviously the reason for the missing glaciation on adjacent mountains.

In order to obtain an ELA at 5300 m on cerro Tapado (similar to field observations), an annual accumulation of 750 mm at 5500 m must be assumed. Annual sublimation removes 490 mm, resulting in a net accumulation of 260 mm which is in good agreement with the value estimated from ice-core analyses (see below). Thus, it is obvious that at the cerro Tapado, local climatic and topographic effects such as blowing snow and moisture capturing on the west facing wall in combination with the high albedo of the snow surface lead locally to higher accumulation rates and preserve a perhaps relict glaciation.

4.2. Effects of post-depositional processes on snow composition

Results from the 5-day surface snow experiment demonstrate the strong influence of post-depositional processes such as sublimation of water and dry deposition on the chemical composition of the exposed snow surface. Three classes of ionic species could be identified by their different concentration development. Group 1 consisting of NH_4^+, $HCOO^-$, H_3CCOO^-, and H^+ showed a weak increase or decrease in concentration. This indicates that these species were reversibly deposited by snow and were subsequently released from the snow surface. Group 2 is formed by Cl^-, K^+, SO_4^{2-}, NO_3^-, MSA, and $C_2O_4^{2-}$. These ions showed a medium increase in concentration, which can be directly related to the enrichment resulting from the removal of water by sublimation. Thus, group 2 ions were irreversibly deposited and were not significantly released from the snow surface. Group 3 consists of Ca^{2+}, Mg^{2+}, Na^+, and F^- which showed a strong increase in concentration over the 5-day period, suggesting that besides sublimation, dry deposition of soil particles also affected the concentration.

These results agree in principle with the concentration profile observed in a 38 cm deep snow pit. The topmost 3.5 cm of the snow pit showed enhanced concentrations of group 2 and 3 ions compared to the lower part. From the enrichment, an exposure time of 120 to 160 days was estimated, during which sublimation and dry deposition affected the surface snow layer. This is consistent with meteorological measurements recording the last significant snowfall from 11 to 15 September 1998, i.e. about 150 days before the snow pit was sampled.

4.3 Glaciochemical record

Annual layer-counting using seasonal parameters cannot be applied throughout the core because of the absence of seasonal distribution of precipitation at the cerro Tapado (see above), which causes the lack of an annually-varying signal. Therefore, dating of the ice core was performed using the measured activity of the naturally produced radioactive isotope ^{210}Pb that decays with a half-life of 22.3 years. This method has been successfully used to establish the chronology of ice cores from Alpine Glaciers for time-scales of about 100 years (Gäggeler *et al.*, 1983; Eichler *et al.*, 2000). A linear regression fit of the ^{210}Pb activities reveals an age of about 100 years for the principal part of the core (Figure 7).

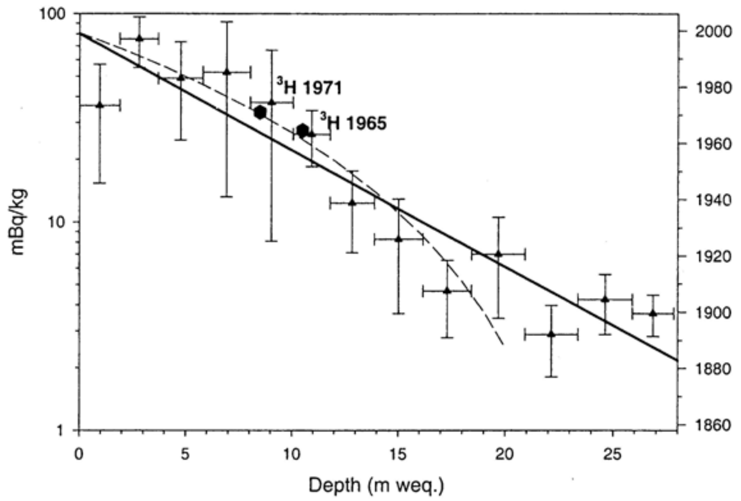

Figure 7. ^{210}Pb activities versus depth of the ice core together with a linear regression fit. In addition, the age-depth relationship obtained by a simple ice-flow model considering ice thinning is shown (dashed line). Two stratigraphic horizons are indicated. The right axis gives the resulting time scale. 1 Bq corresponds to 1 disintegration per second.

With this fit the thinning of the ice is not taken into account. The effect of thinning is illustrated by the depth-age relationship obtained with a simple 1D ice flow model. This agrees well with stratigraphic horizons such as the tritium maxima due to thermonuclear weapon tests, which occurred in 1965 and 1971 in the Southern Hemisphere. Applying this dating, gives a mean annual net accumulation of about 300 mm. Preliminary results using dust horizons as indicator to identify individual years in the record reveal a variation in annual accumulation which is in agreement with precipitation recorded at a nearby weather station (La Laguna). Higher annual accumulation and precipitation rates were observed during El Niño periods. The effect of the El Niño phenomenon on the accumulation at the cerro Tapado Glacier is additionally illustrated by good correlation with the Sea Surface Temperature Anomalies (SST) associated with El Niño for the period 1985-1999, for which annual layers could be identified in the core using dust horizons. In agreement with results from the surface snow experiments, distinct effects of sublimation and dry deposition were observed in the chemical records (Figure 8).

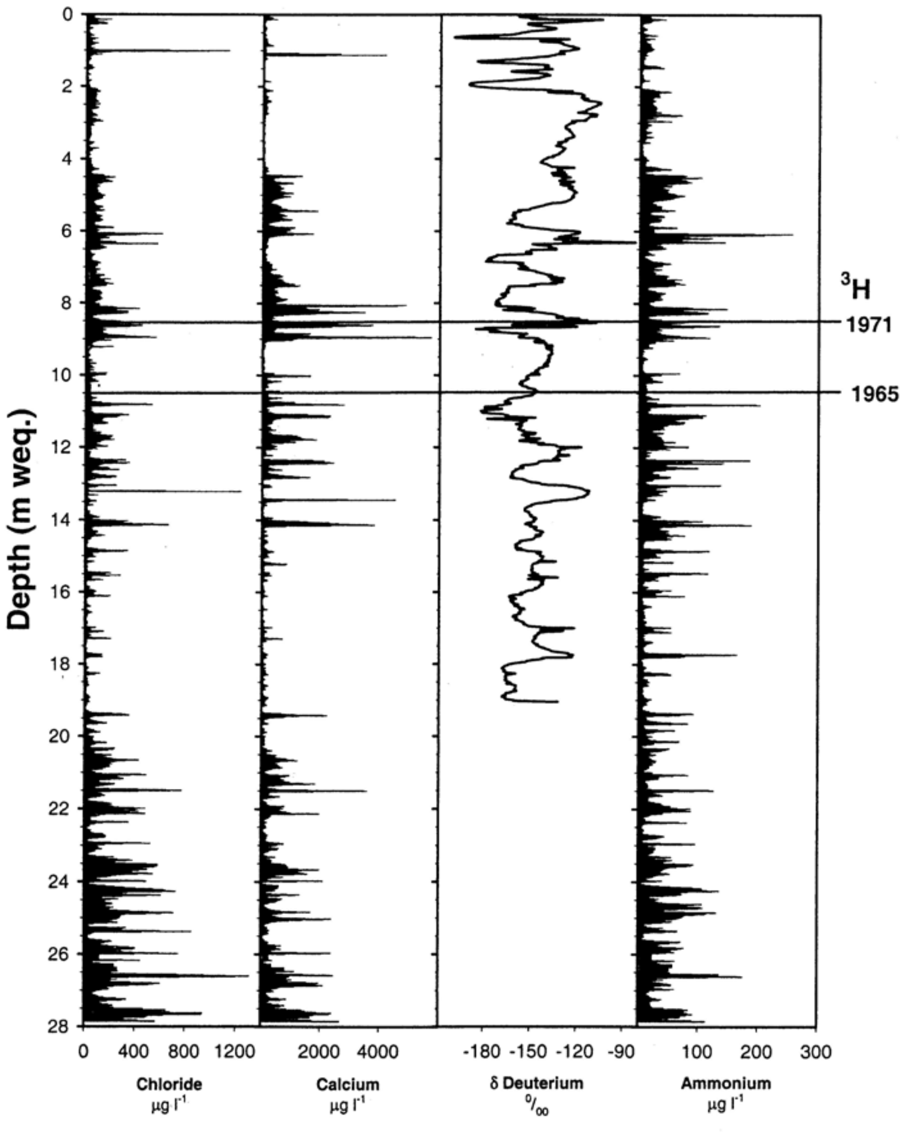

Figure 8. Concentrations of Cl^-, Ca^{2+}, and NH_4^+ as well as the isotopic ratio δ^2H versus depth of the ice core (28 m weq represent 36 m absolute depth).

Strong sublimation is marked by concentration peaks of chemical species (e.g. Cl^-, Ca^{2+}, NH_4^+, at 6 and 8 m weq. in Figure 8). Dry deposition resulted in horizons located just above the levels marked by sublimation, characterized by high concentrations of ionic species contained in the surrounding volcanic rocks (Ca^{2+}, Mg^{2+}, SO_4^{2-}, K^+). However, wet periods were characterized by low concentrations of chemical species (for example between 0 and 2 m weq. in Figure 8). Thus the variation in the concentration of chemical species in the core allows identification of dry and wet periods in this area that could be related to the La Niña/El Niño phenomenon.

5. CONCLUSIONS

Initial glaciochemical data retrieved from the 36 m cerro Tapado ice core indicate that a time period of about 100 years is accessible by this archive. The year-to-year variability of annual accumulation at this glacier site can strongly be influenced by the La Niña/El Niño phenomenon, with higher accumulation during El Niño periods. This is consistent with precipitation data recorded at a nearby meteorological station in the Elqui Valley.

Due to the fact that precipitation occurs mainly in the short period from May to August, post-depositional processes such as sublimation and dry deposition become important during the long dry period. As demonstrated by short-term snow-surface experiments, the effects of these processes on the chemical composition of the surface snow contribute significantly to the variability in the glaciochemical record. Dry and wet periods in this area related to the La Niña/El Niño phenomenon might be identified by enhanced and low concentrations of chemical species, respectively.

6. ACKNOWLEDGMENTS

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