GLACIERS AND CLIMATE IN THE ANDES BETWEEN THE EQUATOR AND 30° S: WHAT IS RECORDED UNDER EXTREME ENVIRONMENTAL CONDITIONS?

U. SCHOTTERER^{1,2}, M. GROSJEAN³, W. STICHLER⁴, P. GINOT⁵, C. KULL³,
H. BONNAVEIRA⁶, B. FRANCOU⁶, H. W. GÄGGELER^{2,8}, R. GALLAIRE⁷,
G. HOFFMANN⁹, B. POUYAUD⁷, E. RAMIREZ⁹, M. SCHWIKOWSKI⁸ and
J. D. TAUPIN⁷

¹*Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstr. 5,
CH-3012 Bern, Switzerland*

E-mail: schotterer@climate.unibe.ch

²*Department of Chemistry and Biochemistry, University of Bern, Switzerland*

³*Institute of Geography, University of Bern, Switzerland*

⁴*GSF – Institute for Hydrology, Neuherberg, Germany*

⁵*Byrd Polar Research Center, Columbus, U.S.A.*

⁶*Institute de Recherche pour le Développement (IRD), Laboratoire de Glaciologie et de
Géophysique de l'Environnement, Saint-Martin d'Hères, France*

⁷*Institute de Recherche pour le Développement (IRD), Quito-Ecuador, Lima, Peru,
and La Paz, Bolivia*

⁸*Paul Scherrer Institute, Villigen, Switzerland*

⁹*Laboratoire des Sciences du Climat et de l'Environnement, Gif sur Yvette, France*

Abstract. Sublimation and melt disturb the environmental information obtained from ice core records in the Andes. In two case studies we demonstrate to what extent these post-depositional processes may remove major parts of the accumulated snow cover. Dark ash layers from the Tungurahua eruption changed the albedo of surface snow on Chimborazo glacier (6268 m, 1°30' S, 78°36' W, Ecuador) between two ice core drilling campaigns and forced substantial melt. Redistribution and washout of the chemical constituents shifted the concentration profiles obtained in December 1999 as compared to an equivalent core drilled in December 2000. The stable isotope records showed that approximately the water equivalent (weq) of an annual layer had melted, and that the percolating melt water penetrated within the firn layer to a depth of at least 16.5 m without refreezing. In the second example, from a site on the dry axis between the tropical and extra-tropical precipitation belts, significant loss of accumulated snow layers occurred by sublimation. A surface experiment at Cerro Tapado glacier (5536 m, 30°08' S, 69°55' W, Chile) revealed that losses of ≈ 2 mm weq (≈ 5 mm snow) per day occurred during the dry period following the 1997/98 El Niño. This loss generally included the entire surface layer enriched in stable isotopes, and thus caused minimal disturbance of the isotopic signature (and hence climatic information) of the net accumulation, yet chemical constituents again experienced considerable changes in concentration. From annual layer counting and direct dating it is obvious that the major part of the accumulated ice on both glaciers is younger than 100 years; however, isotopic and chemical variations at least in the basal ice from Cerro Tapado clearly point to climate conditions different from the recent centuries. This evidence is supported by mass balance considerations derived from a glacier-climate model. The possibility of a third type of disturbance aside from sublimation and melting – in this case a significant hiatus in the environmental chronology – also deserves consideration for other ice core records from this region. Potential disruptions or discontinuities need to be carefully evaluated given the profound changes in climatic and glaciological conditions since the Last Glacial Maximum throughout Holocene times.

1. Introduction

Glaciers in the Andes are particularly important natural archives of present and past climatic and environmental changes, in significant part because of the N-S trend of this topographic barrier and its influence on the atmospheric circulation of the southern hemisphere. Strong gradients in the seasonality and amount of precipitation exist between the equator and 30° S. Large differences in amount east and west of the Andean divide also occur, as well as a change from tropical summer precipitation (additionally modified by the seasonal shift of the circulation belts) to winter precipitation in the west wind belt (e.g., Vuille, 1999; Garraud and Aceituno, 2001). The so-called 'dry axis' lies between the tropical and extra-tropical precipitation regimes (Figure 1). The high mountain desert within this axis responds most sensitively to the smallest changes in effective moisture. An important hydro-meteorological feature on a seasonal to inter-annual time-scale is the occurrence of ENSO events, which strongly control the mass balance of glaciers in this area (e.g., Wagnon et al., 2001; Francou et al., in press). The precipitation pattern is an important factor for the interpretation of climatic and environmental records extracted from ice cores, because much of this information is related to conditions at the actual time of precipitation, and this is especially so for stable isotope records.

Several ice cores have recently been drilled to bedrock in this area. From Huascarán (Thompson et al., 1995), Sajama (Thompson et al., 1998) and Illimani (Ramirez et al., in press.) climatic information has been reported back as far as 20–25 ky reaching the last glacial maximum (LGM). The detailed information from Quelccaya covers 1500 years (Thompson et al., 1985), and for the last 100 years a coherent isotope history could be established regarding the decadal variability of $\delta^{18}\text{O}$ for Andean ice cores recovered between 9° S and 18° S (Hoffmann et al., 2003). Further work on Tapado and Chimborazo is in progress. Most of the information extracted from these ice cores is based on records of $\delta^{18}\text{O}$, dust, and some major ions; time scales are established by a combination of annual layer counting, discrete time markers (volcanic dust events, radioactive fallout, radiocarbon ages of organic matter), and model considerations. In two cases (Thompson et al., 1998; Ramirez et al., in press), the isotope composition of atmospheric oxygen ($\delta^{18}\text{O}_{\text{atm.}}$) was used to date the basal ice. Regarding the climatic findings from the LGM throughout the Holocene, one has to bear in mind that due to ice flow and layer-thinning this period in general covers only the last 10 to 20% of an ice core with limited time resolution. Below the firn-ice transition crystal diffusion smoothes the seasonality of isotope variations, dating by modeling layer thinning and ice flow assumes age-depth continuity and sufficient material for radiocarbon dating is generally rare. The detailed resolution of the proxy records of the recent one or two centuries relies on seasonal signals of stable isotopes, dust, and chemical species. The Illimani record is seasonally resolved back to the 13th century (Knüsel et al., 2003) by additional continuous high-resolution electrical conductivity measure-

Figure 1. Ice core drilling sites in the Andes between the Equator and 30° S together with the precipitation distribution nearby. Cerro Tapado is situated between two precipitation regimes; today the glacier accumulates precipitation mainly from the south-west.

ments (ECM) on the frozen core (Hammer, 1980) and the 1500 years record from Quelccaya is obviously favored by high accumulation rates and a very regular and distinct sequence of dry season dust markers (Thompson et al., 1985). Errors for a certain year established by annual layer counting methods can be generally reported to be within 2 and 10 years for the last one or two centuries. The uncertainty depends on the number of well-known discrete time markers; errors may increase considerably with depth.

Precise dating is crucial to reconstruct modes of variability of circulation and climate because related changes in precipitation pattern that might change the isotopic composition of precipitation occur on seasonal and inter-annual scales. This implies also that the observed seasonality in an ice core is not changed after

deposition since the amount of precipitation and seasonal distribution of dry and wet periods vary considerably between the equator and 30° S (see also Figure 1).

However, possible changes after deposition have to be taken into consideration for any ice core drilling site. Glaciers are dynamic and open systems for precipitation and as climate changes the ambient conditions to store the climate information also change. For Quelccaya it was already reported that seasonal changes in evaporation could remarkably amplify seasonal changes in $\delta^{18}\text{O}$ (Grootes et al., 1989). On the contrary, smoothing of the original isotope signal due to diffusive mixing of water vapor in firn is also well known and has been described in detail (e.g., Johnsen et al., 1977). In general, post-depositional changes cause a re-distribution and/or a loss of chemical and isotopic tracers (e.g., Davies et al., 1987; Stichler and Schotterer, 2000). Between 1998 and 2000, a French–Swiss team drilled several ice cores on Cerro Tapado, Illimani, and Chimborazo to bedrock. Each site was drilled twice within a one-year interval to examine interannual variability and shallow surface cores covering 10 to 15 years were taken to allow assessment of post-depositional effects over a longer period of time. Additional field experiments during drilling were carried out to study short-term changes in relation to actual meteorological variations. The summit glaciers on Chimborazo at the Equator and on Cerro Tapado at 30° S represent two natural archives existing today under particularly extreme climatic conditions. Although firn temperatures on Chimborazo may be temporarily close to 0°C and melt and sublimation occur frequently, the glacier benefits today from sufficient precipitation and moist conditions throughout the year. On the contrary, dry conditions with sublimation and irregular precipitation events govern the mass balance of the cold glacier on Cerro Tapado. A similar range of conditions might have prevailed for other glaciers in this latitudinal belt under differing climate conditions of the past.

The range of such conditions today is indicated by bore hole temperatures and mean annual net accumulation (accumulated precipitation remaining after wind scour, sublimation, evaporation and melt) in Figure 2. The temperature data from Quelccaya (close to the pressure melting point, not included here) and Huascarán are influenced by a eutectic alcohol–water mixture to keep the borehole open during drilling (Thompson et al., 1985, 1995). The basal ice on Sajama (Thompson et al., 1998), Cerro Tapado, and Illimani (Zweifel, 2000) is frozen to bedrock. This is probably also true for Col Huascarán and Summit Ventimilla on Chimborazo, although on the latter percolating melt to greater depths has been observed (see below). Present mean annual net accumulation is highest on Col Huascarán and Quelccaya (1200–1300 mm) and lowest on Cerro Tapado (300 mm). In the following we will discuss isotopic and chemical results from Chimborazo and Cerro Tapado, noting that following the observed general retreat (Díaz and Graham, 1996; Francou et al., in press) both of these glaciers exist today at the limit of survival. They are limited in ice thickness (54 m and 36 m respectively) as compared to the other ice core drilling sites and thus react very sensitively to the

Figure 2. Borehole temperatures and net accumulation from ice core drilling sites in the Andes between the Equator and 30° S. The basal ice at all sites seems to be frozen to bedrock. Especially on Chimborazo firn temperatures might be influenced temporarily by melt. The lowest temperatures (although the lowest summit glacier in elevation) and lowest net accumulation are measured on Cerro Tapado where the influence of sublimation provides additional cooling but also removes substantial parts of the accumulated snow.

changes in temperature, humidity or global radiation that govern their respective mass balances.

2. Chimborazo

The Ecuadorian Andes have a very complex precipitation pattern. The eastern part of the country is dominated by precipitation originating from the tropical Atlantic and the Amazon basin; the western slopes receive their moisture mainly from the Pacific. As air masses lose much of their moisture on both flanks of the Andes, the precipitation amount in the valleys and basins between the Cordillera Orien-

tal and Cordillera Occidental is rather low, with two rainy seasons influenced by the movement of the circulation belts. On inter-annual time scales variability of circulation and climate is dominant with heavy rains in the coastal area during El Niño and a stable inversion layer during La Niña phases that traps the moisture in the surface layers (Vuille et al., 2000). Glaciers are restricted to the summit regions of both Cordilleras. Glacierization is more pronounced in the Cordillera Oriental because it is better exposed to moisture from the Amazon basin. The variability of glacierization is very high due to the equatorial climatic conditions and is historically very well documented (Hastenrath, 1981).

Chimborazo (6268 m, 1°30' S, 78°36' W), an inactive double-peak volcano is situated on the eastern border of the Cordillera Occidental and therefore exposed to moisture sources from both west and east. A shallow ice-core drilled on Cumbre Ventimilla in December 1999 to a depth of 16.5 m was analyzed for isotopes and chemical constituents in order to verify the preservation of the seasonality of the water isotopes and other trace elements which is key for dating and quantitatively analyzing ice cores. A first tentative annual layer counting resulted in an average yearly net accumulation of about 700 mm water equivalent (Ginot et al., 2002). The bimodal seasonal pattern observed in stable isotopes and chemical species as well was similar to that obtained by a previous study of isotopes in monthly composites of Ecuadorian precipitation (Garcia et al., 1998). The site was therefore re-drilled in December 2000 and the longest core reached bedrock on Cumbre Ventimilla, one of the two main summits, at a depth of 54.4 m. In December 2000 the conditions on the glacier had changed remarkably as compared to the situation in the year before. Frequent and violent eruptions of the neighboring volcano Tungurahua (1°47' S, 78°44' W) starting in October 1999 had continued throughout 2000 and covered the surface snow with thick ash layers. This forced melt and the formation of penitents as can be recognized in the upper part of Figure 3. A first drilling attempt had even to be stopped in the saddle between the two summits because melt water soaked the ice cores at a depth of 28 m. Obviously melt percolating through the firn was collected near the low-permeability firn-ice transition at the deepest point between the two summits.

The influence of the volcanic eruption on the environmental record is clearly visible in the ice core drilled in 2000 on Cumbre Ventimilla (Figure 4). The top-most ≈ 10 m weq (or 17 m linear depth) are compared to the $\delta^{18}\text{O}$ and sulfate records obtained in the previous year at approximately the same place. Sulfate is of special interest, because it is commonly used to identify volcanic eruptions. The enlargement of the two $\delta^{18}\text{O}$ -profiles on the left indicates what was removed from the accumulated snow by the melting process. The distinct $\delta^{18}\text{O}$ -depletion near the surface in 1999 had disappeared and only a little mixed residual (indicated by the dotted gray and black lines) was left. From the difference of these two profiles it must be concluded that almost the entire 1998/99 accumulation and probably parts of the 2000 accumulation melted and percolated through the layers beneath. The loss, in the order of 700 mm weq, corresponds to the average annual net accumu-

Figure 3. On top the view of Chimborazo (6268 m, 1°30' S, 78°36' W, Ecuador) and beneath the view of Cerro Tapado (5536 m, 30°08' S, 69°55' W Chile). Dark ash layers of volcanic eruptions cause the 50 to 100 cm high penitents, a typical melting and sublimation structure on tropical glaciers. They cover the whole area between the two summits Cumbre Ventimilla (foreground, where the ice core drilling reached bedrock at 54 m depth) and Cumbre Ecuador. The little black spot in the middle indicates the abandoned, water saturated drilling site. The glacier of Cerro Tapado covers an altitude difference of nearly 1000 m, a unique phenomenon in a desert like landscape; however, signs of disintegration today are visible below the equilibrium line altitude (black stars). Bedrock at the summit was reached at 36 m depths.

Figure 4. Distribution of $\delta^{18}\text{O}$ and sulfate in the Chimborazo ice cores before (black) and after (gray) melt was forced by dark ash layers from the eruptions of the Tungurahua volcano. The dotted lines on the enlargement (left) indicate what was left in 2000 from the 1999 depletion in $\delta^{18}\text{O}$. Approximately 0.5 to 0.7 m of water equivalent were removed. The percolating melt changed the sulfate profile in the firm layers below, the $\delta^{18}\text{O}$ -variability remained more or less unchanged (right side). Little vertical shifts in $\delta^{18}\text{O}$ (indicated by the arrows) are due to small differences in the accumulation pattern.

lation derived from seasonal layer counting. From a depth of 1 m weq downwards the $\delta^{18}\text{O}$ -variability in both cores is nearly identical. Small vertical offsets (gray and black arrows) may be attributed to local accumulation differences between the two drilling sites, which are approximately 50 m apart. Notably, the isotope balances for these parts of the cores match exactly, within analytical error, even for the deuterium excess (defined as $d = \delta\text{D} - 8\delta^{18}\text{O}$). From these findings we conclude that the melt water percolated very quickly through the cold firm column (Figure 2) without substantial re-freezing.

For the chemical constituents however, melting had distinct ion-specific consequences. The 1999 concentration variability attributed to the seasonal ion-specific wash out during pertinent precipitation (Ginot et al., 2002) was changed and/or partly removed. Only for ammonium and with some restrictions for nitrate are the records comparable. The two sulfate profiles in Figure 4 illustrate such changes. The high surface concentration observed in 1999 originates from the first violent eruptions of Tungurahua that were accompanied by SO_2 emissions up to 10 tons per day (Hall et al., 1999; see also reports of the volcanic activity from the Instituto Geofísico, in Quito, Ecuador, <http://www.igepn.edu.ec/>). Surprisingly, no ash layer could be observed. In the 2000 record the surface peak is washed out by the melt similar to the stable isotope record but contrary to the latter, sulfate double peaks not observed in 1999 occur further down in the 2000 record. If one attributes the

new sulfate input to the continuing volcanic eruptions, the signal is shifted by the melt to a depth of 4 m and 9 m weq or back in time by 6 and 12 years respectively. Similar ion-specific wash out effects were observed also in ice core studies from the Alps. The elution sequence was explained by ion re-arrangement during snow metamorphism; however, no distinct enrichment for sulfate, for example, could be found further down in this record (Eichler et al., 2001). The reason for the different behavior of sulfate wash-out will be further investigated. A careful examination of the Cumbre Ventimilla ice core reaching bedrock is necessary because it contains numerous volcanic ash layers in the lower part. A shift of sulfate (and calcium) peaks has to be taken into account for calibration of annual layer counting and absolute dating by identifying historical volcanic eruptions.

3. Cerro Tapado

The glacier of Cerro Tapado (5536 m, 30°08' S, 69°55' W), situated at the southern rim of the dry axis, is a unique feature of the otherwise dry environment at the border between Chile and Argentina (lower part in Figure 3). The cold glacier (see also Figure 2) spreads over an altitude difference of nearly 1000 m from the top to the tongue. The equilibrium line altitude (ELA) today is at 5300 m. Since only patchy ice fields exist on neighboring Cerro Olivares, in spite of its greater elevation (ca. 6000 m), local conditions evidently favor the existence of the Cerro Tapado glacier. The region to the southwest is characterized by a winter precipitation regime. Between May and September the blocking anticyclone moves southwards, moist air masses from the southwest penetrate the Andes as far north as 28° S and lead to snowfall. This situation is enforced during the occurrence of El Niño (Escobar and Aceituno, 1998). However, convective summer storms from the summer precipitation regime in the east (see also Figure 1) may also produce snowfall as experienced during the drilling seasons 1998 and 1999.

Surface experiments were carried out during the ice core drilling in February 1999, when bedrock on the summit was reached at 36 m depth. They were designed to estimate more quantitatively the influence of sublimation on environmental tracers stored in the accumulated surface firn layers and to collect data supporting mass balance considerations (Ginot et al., 2001; Stichler et al., 2001). The timing of the experiment was ideal because the 1997/98 El Niño was followed by an extremely dry period of six months according to our automatic weather station at 4200 m. The amount of sublimation was measured and modeled independently by lysimeters and the relevant meteorological data set recorded during the time of drilling. These studies resulted in a loss of ≈ 2 mm weq (ca. 5 mm snow) per day. The snow pit-sublimation experiment itself included 14 chemical species, deuterium and oxygen-18. From a $\delta D/\delta^{18}O$ plot of the high-resolution pit samples it could be observed that isotopic enrichment took place down to a depth of 7 cm, below which values matched the global meteoric water line ($\delta D = 8\delta^{18}O + 10$). For the

Figure 5. Results of the sublimation experiments on Cerro Tapado. According to the increasing influence of sublimation with time the snow surface is continuously enriched in stable isotopes. Due to the more pronounced enrichment in $\delta^{18}\text{O}$ as compared to δD the deuterium excess ($d = \delta\text{D} - 8 * \delta^{18}\text{O}$) decreases. According to their properties the sublimation effect separated three different groups of chemical species (soluble (b), insoluble (c), volatile (d)). The concentration-sublimation factor stands for the changing ionic concentrations normalized to the increasing water loss due to sublimation (indicated by the thick gray line in (b), (c), and (d)).

sublimation experiment surface samples of 1 cm thickness were taken twice a day. The first sample is 'fresh' snow (the old surface had been removed to establish a surface not influenced by previous sublimation) and the consecutive ones had increasing exposure length with four days in total for the last sample. As shown in Figure 5a the stable isotopes (represented by $\delta^{18}\text{O}$) are continuously enriched as exposure time increases, while simultaneously decreasing deuterium excess d reveals progressive deviation from the global meteoric water line. Modeling of this isotopic enrichment yielded a mean sublimation loss of 4 mm weq per day, as compared to an upper limit of ≈ 2 mm weq/day as derived from the direct sublimation studies (noting, however, that mass loss derived from lysimeters does not include the loss by moisture transport from deeper firn layers to the surface). Therefore, 2 mm might be a conservative lower limit for the dry conditions during the experiment. Moreover, the range of 2 to 4 mm is comparable to sublimation studies over a longer period of time on the Altiplano at 23°S (Vuille, 1996).

Most major ions varied significantly. Chloride concentration for instance more than doubled, calcium increased by a factor of 5, and ammonium and formate remained stable (though actually decreased when accounting for loss of water

by sublimation). Three groups could be distinguished according to the chemical properties (soluble, insoluble, or volatile), the deposition characteristics, and the resulting concentration factors of the individual ions. The evolution of the concentration factors within these groups is plotted in Figures 5b–d; the gray line illustrates the increasing water loss by sublimation. From the group of soluble ions in Figure 5b chloride was chosen as a chemical index for the degree of sublimation. The sodium/chloride ratio indicated that the influence of sources other than sea salt is minor and hence that dry deposition from salars does not contribute appreciably (at least under present day climatic conditions) to the chloride input on Cerro Tapado. If the high-resolution chemical data from the snow pit are used to estimate independently exposure time and amount of sublimation of the dry period following the 1997/98 El Niño, the results (206 days and 412 mm sublimation loss as an upper limit) agree well with the findings derived from the long-term meteorological data sets (Ginot et al., 2001).

4. Mass Balance Considerations

Mass loss from melt and/or sublimation and the modification of chemical constituents has to be considered not only for the interpretation of proxy data but also for the age-depth continuity of the records. The summit glaciers of Chimborazo and Cerro Tapado show some similarities since (1) more than 80% of the firn and ice cover has accumulated in the 20th century and therefore much of the stored proxy information may be related to recorded meteorological or other environmental data and (2) there is evidence – at least for Cerro Tapado – that the basal ice originates from a climatic period distinct different from the last centuries. Nevertheless, most of the accumulated firn and ice is comparably young on both glaciers, indicating a high turn-over rate and pronounced glacier dynamics. In view of the dramatic retreat of Andean glaciers observed during the last decades (Diaz and Graham, 1996; Francou et al., in press), mass balance considerations become increasingly relevant not only for climate reconstruction but also for conservation of water resources.

Dating of the Cerro Tapado ice core was performed by a combination of annual layer counting (assuming that regular wet and dry periods lead, respectively, to low and high concentration of chemical constituents), ^{210}Pb , tritium fallout from nuclear weapons tests, and firn densification and flow model considerations. Similar methods (supported by ECM) were applied for the Chimborazo ice cores. Although still preliminary because of the observed melting processes involved, annual net accumulation rates (Figure 2) and layer thinning are comparable to what was observed on Illimani (Knüsel et al., 2002). The series of volcanic ash layers around 50 m depth might therefore correspond to the heavy Tungurahua eruptions of 1916–1918. However, whether the basal ice contains also the historical Tungurahua record of the last 3000 years (and thus was formed under different climate conditions) is not yet clear.

There is more evidence for different climate conditions in the basal ice of the Cerro Tapado summit glacier, where a distinct change is recognized in the lower part of the ice core records. The change is observed in the stratigraphy and in the concentration profiles of stable isotopes and chemical species. In Figure 6a the stratigraphy is plotted from 14 m weq down to bedrock together with records of deuterium excess, chloride and calcium. At 14 m weq the absence of measurable tritium from nuclear weapon tests indicates the pre-bomb level prior to 1952. Dating further down is less certain; however, with ^{210}Pb measurements suggesting that the beginning of the 20th century corresponds to ≈ 24 m weq. Below that depth chloride and calcium concentrations are highly variable with rapid swings between low and high values and the deuterium excess starts to decrease. Moreover, a distinct change is observed in the shape of the occluded air bubbles. The shift from round to elliptical indicates a shear stress between the active glacier moving downward and an inactive ice body frozen to bedrock, as suggested schematically in Figure 6b.

According to the findings of the sublimation experiment (Ginot et al., 2001) the swings between high and low chloride concentrations likely reflect fluctuations between dry and humid conditions. The high variability could therefore be related to a shift in climate, as also suggested by the changing deuterium excess in this part of the ice core. The latter parameter was chosen as a climate indicator, because it varies in phase with dry and wet conditions in the upper tritium-dated part of the ice core. Humid El Niño conditions produce more depleted stable isotope values (indicating increased rainout of atmospheric moisture) and lower deuterium excess values. During dry phases the condensation level is elevated, allowing only limited rainout between the source of moisture and the summit regions; therefore stable isotopes are more enriched and the deuterium excess is generally higher.

Unfortunately, the age of the lowermost part of the Tapado ice core remains uncertain. However, modeling of modern and late Pleistocene glacio-climatological conditions can be used to develop mass balance scenarios under which this ice might have been formed in the past. Global radiation, wind speed, humidity, and temperature were measured by an automated weather station between the two drilling campaigns from 1998 to 1999 near the Cerro Tapado base camp at 4215 m. A second weather station was installed on the summit during the ice core drilling in 1999. Data from the overlapping period were used to calculate annual cycles for the summit region. Applying these data to a glacier-climate model (Kull and Grosjean, 2000) the mass balance remains negative up to 6000 m. This explains the absence of glaciers even in the permafrost belt of this region, though not the existence of the Cerro Tapado glacier itself under current climate conditions. Indeed, mean annual accumulation of 750 mm is needed to reproduce the observed net accumulation of about 300 mm (Kull et al., 2002; Figure 7). Higher accumulation may be attributable to wind-drifted snow, as indicated by huge snow-cornices at the crests of the summit region, and/or to enhanced cloud cover and precipitation from higher moisture transport locally.

Figure 6. Stratigraphy (firn in white, ice in gray, occluded air in round and elliptic circles, dust layer in hatched dark gray) and proxy records of the Tapado ice core below 14 m weq (a). The ice and firn layers above have been accumulated since 1952. Distinct changes in deuterium excess, chloride and calcium variability suggest that the lower parts of the glacier have been accumulated during climatic conditions different from the recent centuries. The bubbles of occluded air become elliptic below 24 m weq. This indicates a shear zone between the basal ice (frozen to bedrock at -12°C) and an overlying active layer moving downward. The old inactive ice body thus might represent a hiatus and a discontinuity in the age–depth distribution (b).

Figure 7. Mass balance of the Cerro Tapado glacier today. Modeled with current climatic data, the mass balance remains negative also on the summit (a). Only when the accumulation is increased to 750 mm at 5500 m the observed net accumulation of ca. 300 mm can be reproduced.

Assuming that present day processes were also active in the past and using the chloride concentrations as a proxy for the amount of sublimation similar mass balance scenarios can be developed for the climate conditions that might have caused the observed high variability in the records. The paleoclimate conditions would then differ from today mainly in a more extreme winter-summer contrast and higher precipitation amounts. Sublimation during summer could have been more than two times higher than the modern average. Of course, these model results are sensitive to the glacier mass balance inferred from chemical ice core data that are a function of (unknown) past environmental conditions. But in the light of the recent dynamics of glaciers at the edge of survival, the question arises about the implications and long-term changes since the last glacial maximum that could match for instance the Cerro Tapado scenario.

5. Glacier Variability: The Long-Term Perspective

A variety of paleoclimatic archives evidence multiple high-amplitude and rapid changes of moisture and temperature in the central Andes and emphasize the long-

term variability of the climate system and the respective biogeophysical responses, including the behavior of glaciers. Striated bedrock and glacial deposits provide information of multiple substantial glacial advances along the Andes in the tropical (north of ca. 25° S) and the extra-tropical (south of ca. 27° S) rainfall regimes. Nevertheless, one has to be aware that such geomorphological indicators may report glacial advances but not retreats, and the chronology of the advances remains tentative.

There is evidence for a dynamic glacier history during the thermally relatively stable Holocene. It is of interest in this context that paleolimnological data from the Altiplano (ca. 16–27° S) show significantly more arid conditions during the mid-Holocene (ca. 9–4 cal kyr B.P., Baker et al. 2001; Grosjean et al., 2001), with the level of Lake Titicaca as much as 85 m below the modern level, and precipitation decreased by more than 20% compared with today (Talbi et al., 1999). Such extremely dry conditions are expected to have moved the borderline of survival for glaciers further north than 18° S to the inner tropics. We hypothesize that glaciers like Sajama suddenly found themselves during the mid-Holocene in a situation comparable with modern Cerro Tapado, where the net mass balance at the summit for individual years or even for irregular periods of unknown duration might have been negative. This could have resulted in a hiatus of ice accumulation similar to our findings from Cerro Tapado. Gaps in ice accumulations or ‘missing years’ beyond the possibility of annual layer counting (the recent 200 to 300 years may be extended only in exceptional cases) are difficult to detect; a few available data points with absolute ages, even when supported by model considerations, do not necessarily allow detection of such features.

Yet, evidence for massive glacial advances has also been reported. In the Encierro Valley (29° S, in the vicinity of Cerro Tapado) ELAs were as low as 4500 m between 3000 and 1800 yr B.P. (Grosjean et al., 1998). During that time, regional lake levels were somewhat higher than today. This suggests that even a slight increase in humidity in this area – if the threshold of positive mass balance is surpassed – results immediately in the extension of glaciers. However, this late Holocene glacier most probably disappeared as quickly as it grew. In the light of (a) the moisture sensitivity of glaciers in this area and (b) the widespread early and mid-Holocene aridity in Mediterranean-subtropical Chile, we suspect that the area between 27 and ca. 32° S was largely ice-free during the mid-Holocene. Subsequently, glaciers formed and advanced between 3000 and 1800 yr B.P., and later disappeared again. Whether the ice body on the summit of Cerro Tapado survived (Figure 8) has to be proved ultimately by absolute dating methods. Dendrochronological and paleolimnological studies from central Chile 32° S suggest that the years 1820–1910 (interrupted by arid periods around 1860 and 1890 as indicated in the early precipitation data from La Serena) was the longest wet period during the past 800 years and thus the most favorable period for glacier growth. Observations from 32° S suggest glaciers at maximal stages at the beginning of the 20th century

Figure 8. Sketch of the glacier distribution and equilibrium line altitude (ELA) between 18° S and 30° S from Pleistocene to modern times. The basal ice on top of Cerro Tapado might have been accumulated during the late Holocene.

(Luckman and Villalba, 2001). This might be another potential period of time for the build-up of Tapado glacier.

6. Conclusion

Mass loss from melt and/or sublimation changes the environmental information in ice cores recovered from the tropical and subtropical Andes. Whilst the stable isotope signal is removed without major changes of the record left the modification of chemical constituents have significant consequences. Concentration or loss due to sublimation and the elution sequence due to melt are ion-specific and difficult to quantify. Depending on the climate and environmental conditions, some ions (such as chloride on Cerro Tapado glacier) can be used to better quantify the amount of sublimation and the effect on other chemical species. Melt has to be considered especially with respect to the identification and the timing of historical volcanic eruptions. Moreover, mass loss has an influence on the age-depth continuity of the ice core records. On shorter time scales missing years or missing parts of annual precipitation may disturb the seasonal variability, though this probably has little influence on the decadal-scale variability of stable isotopes. On centennial time

scales discontinuities have to be considered in the ice build-up of glaciers between the Equator and 30° S. The dynamic history of glacial advances and retreats reflects the variability of austral summer rains and the extra-tropical frontal winter rains. Both regimes show that the humidity-driven threshold for the existence of glaciers fluctuated back and forth at different time-scales over more than 5–8° latitude. This fluctuating borderline may be responsible for highly variable waxing and waning of glaciers. The high mass turnover and the related glacier dynamics on Chimborazo and on Cerro Tapado reflect the high sensitivity to slight changes in mass balance terms.

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