A potential high-elevation ice-core site at Hielo Patagónico Sur

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ABSTRACT. The Patagonia icefields constitute a unique location in the Southern Hemisphere for obtaining non-polar paleo-records from ice cores south of 45° S. Nevertheless, no ice-core record with meaningful paleoclimate information has yet been obtained from Patagonia. This deficiency is due to extremely harsh field conditions, and to the fact that the main plateaus of both Hielo Patagónico Norte (HPN; northern Patagonia icefield) and Hielo Patagónico Sur (HPS; southern Patagonia icefield) are strongly affected by meltwater percolation. In order to explore the suitability of high-elevation glacier sites at HPS as paleoclimate archives, three shallow firn cores were retrieved covering the altitude range 1543–2300 m a.s.l. The glaciochemical records from the two lower sites confirm the presence of superimposed ice, a clear sign of meltwater formation and percolation. In the core from 2300 m, the glaciochemical signature appears to be preserved, indicating that no significant melting occurred. Although there might be problems associated with wind erosion and extreme melt events, there is good potential for well-preserved paleo-records within glaciers in the Patagonia icefields located higher than 2300 m.

1. INTRODUCTION

Ice cores have provided many of the most detailed high-resolution records of past climatic and environmental conditions. In the Southern Hemisphere, valuable records of past changes in climate and the environment have been obtained through ice-coring in the tropics and subtropics (e.g. Thompson and others, 1995, 1998; Ramirez and others, 2003), as well as in Antarctica (e.g. Petit and others, 1999; EPICA community, 2004). However, there is a lack of ice-core records from southern South America, resulting in a real data gap between Antarctica and South American subtropical latitudes. The Patagonia icefields constitute a unique location in the Southern Hemisphere for obtaining non-polar paleo-records from ice cores south of 45° S. Hielo Patagónico Sur (HPS; southern Patagonia icefield) is the largest body of ice in the Southern Hemisphere outside of Antarctica. It is centered along 73°30′ W between 48° and 51° S with an area of about 13 000 km^2 and an elevation from 800 to 2000 m, with a few peaks exceeding 3000 m (Warren and Sugden, 1993; Aniya and others, 1996; Casassa and others, 2002). The climate in the mid-latitudes of southern South America is dominated by the westerly circulation regime. The southern westerlies are considered as a key component of the global climate system since they may have an impact on the amount of carbon dissolved in the Southern Ocean, on the extent of Antarctic sea ice and on global thermohaline circulation (Imbrie and others, 1992; Toggweiler and Samuels, 1995). Ice-core records from HPS would provide an opportunity to investigate changes in the position and strength of the westerly airflow through time. Despite this fact, no ice-core record with meaningful paleoclimate information has yet been obtained from Patagonia. This deficiency is due to extremely harsh field conditions, and to the fact that the main plateaus of both Hielo Patagónico Norte (HPN; northern Patagonia icefield) and HPS are strongly affected by meltwater percolation.

Only four shallow- to medium-depth firn/ice cores have been retrieved, all of them from temperate sites, in the Patagonia icefields. Analyses of the physical, chemical and isotopic data have shown that the glaciochemical signal in these cores is in general strongly affected by melting. Two of the cores were extracted from HPN. One of these was from 1296 m a.s.l. on Glaciar San Rafael, where a depth of 37.6 m was reached (Yamada, 1987). The firn–ice transition was found at 26.7 m, immediately below an unconfined water aquifer located between 24.9 and 26.9 m, over which a water-soaked layer was observed between 19.6 and 24.9 m. A mean annual accumulation of 3.45 m w.e. was inferred at this site. The second core , 14.5 m long, was drilled in the lower part of the accumulation area of Glaciar Nef (46°56′ S, 73°19′ W; 1500 m a.s.l.) (Matsuoka and Naruse, 1999), where a mean annual accumulation of 2.2 m w.e. was determined. The minimum temperature in the borehole was 0.1°C. In both cores from HPN, the seasonal signal of the stable-isotope ratio $\delta^{18}O$ was disturbed below 6 m depth, indicating that melt processes at these core sites are important and obliterate the climate proxy record at depth.

At HPS, two firn cores were retrieved. One of these, 13.17 m long, was recovered from the upper accumulation area of Glaciar Perito Moreno (50°38′ S, 73°15′ W; 2680 m a.s.l.) (Aristarain and Delmas, 1993). The elevation of the drilling site was later re-estimated to be only about 2000 m a.s.l. (Godoi and others, 2001). Although the temperature measured at the bottom of the borehole was 0°C, clear seasonal signals were observed in the δD record. However, the concentration profiles of major ions were affected by melting. A mean annual accumulation of 1.2 m w.e. was inferred, contrary to Naruse and others (1995) who estimated that an accumulation of 6–8 m w.e. is needed to maintain Glaciar Perito Moreno at steady state. The second core from HPS was drilled close to the ice divide of Glaciar Tyndall at 1756 m a.s.l. (Godoi and others, 2001, 2002; Kohshima and others, 2002; Shiraiwa and others,

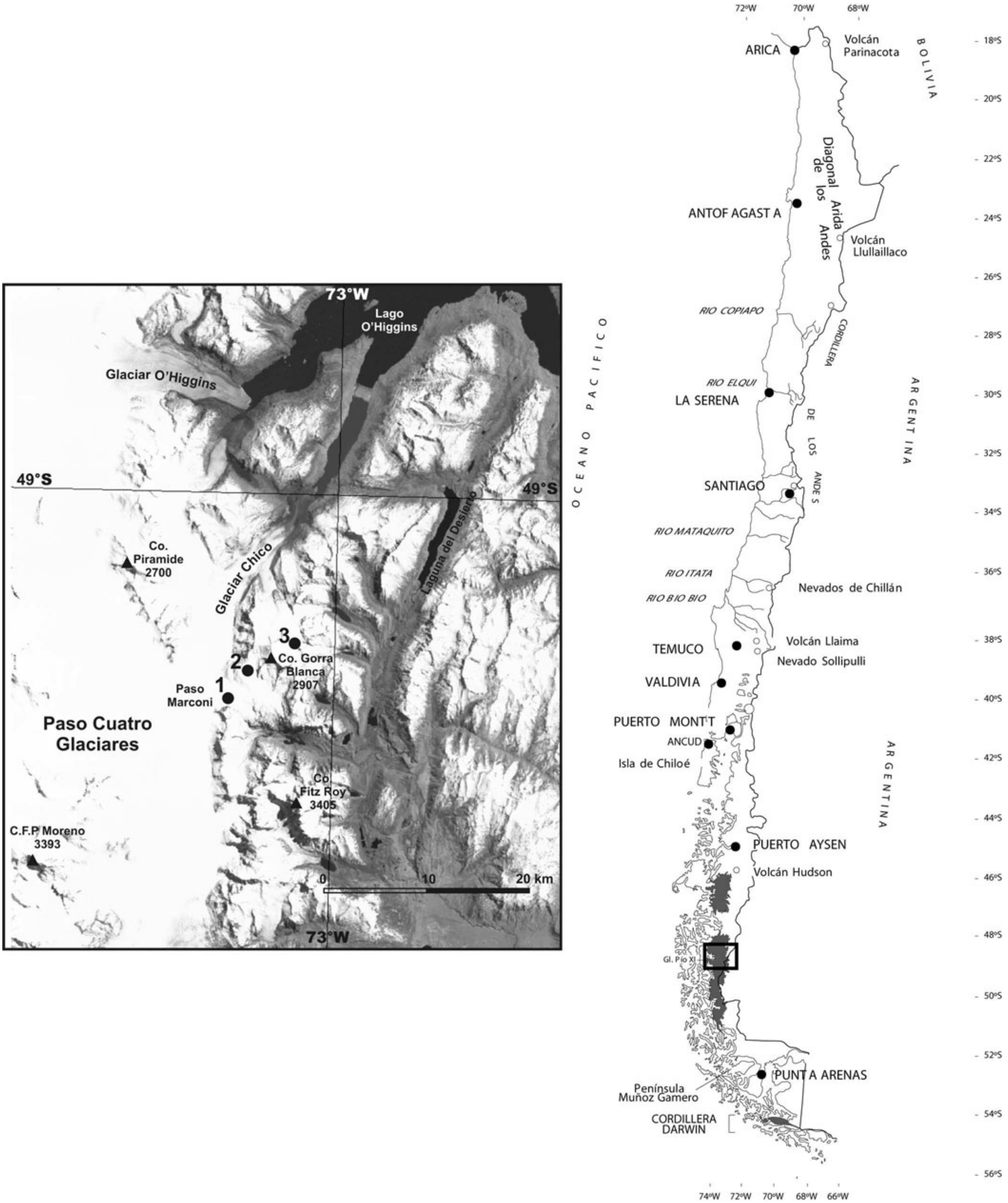

Fig. 1. Satellite image of a selected part of HPS, with location of the drilling sites marked by black dots (1. Paso Marconi (1543 m a.s.l.); 2. Gorra Blanca Sur (1836 m a.s.l.); 3. Gorra Blanca Norte (2300 m a.s.l.)). The location of the HPS sector in Chile is indicated by the rectangle on the large-scale map of the country.

2002). It was not possible to measure the borehole temperature here, due to the presence of meltwater. A water-soaked layer was observed starting at 42.6 m depth. A combination of micro-algae concentrations and stable-isotope data indicated a mean annual accumulation of 14 m w.e. at the Tyndall site, which corresponds to a record amount of 28 m of firn per year.

The present study was undertaken in order to explore the suitability of a higher-elevation glacier site at HPS (Gorra Blanca Norte (GBN; 2300 m a.s.l.)) as a paleoclimate

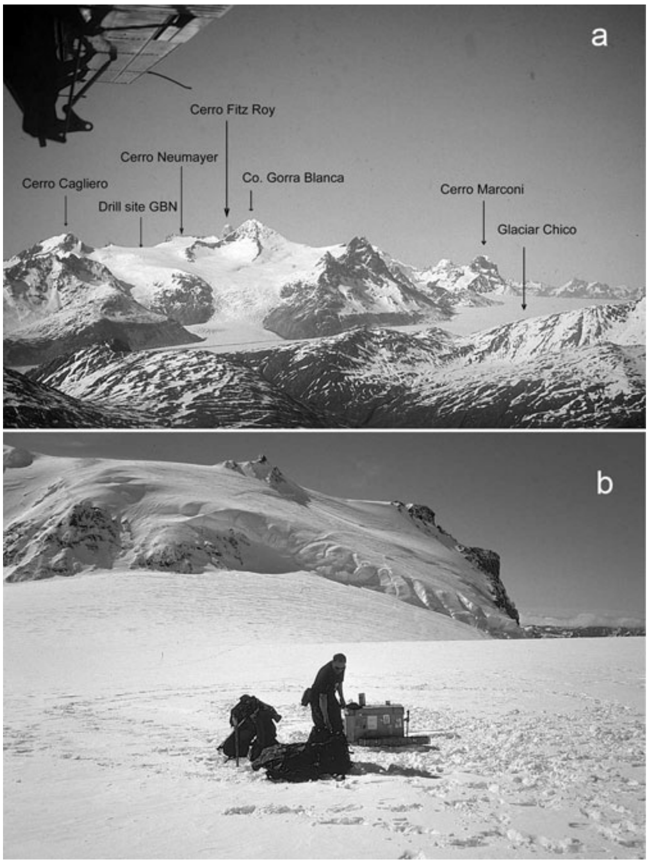

Fig. 2. (a) Picture of GBN taken from the northwest out of the aircraft. (b) Drilling site at GBN with Cerro Cagliero (2584 m a.s.l.) in the background.

archive. For this purpose, three shallow firn cores were drilled at different elevations during the fourth expedition of the Icefields Science Initiative, organized by the Centro de Estudios Científicos (CECS), Valdivia, Chile.

2. FIRN-CORE DRILLING AND CHEMICAL ANALYSES

A 4 m and a 3 m core were retrieved on 25 and 27 September 2001 from Paso Marconi (49°11′2.1″ S, 73°08′40.3″ W; 1543 m a.s.l.) and from Gorra Blanca Sur (GBS; 49°09′22.6″ S, 73°06′51.9″ W; 1836 m a.s.l.) (Fig. 1). The drilling sites were approached from the Marconi base camp by snowmobile. Drilling had to be stopped at 4 and 3 m depth, respectively, because ice was encountered. On 28 September 2001 a 5 m core was collected from the plateau of GBN (49°07′52″ S, 73°03′11″ W; 2300 m a.s.l.; Fig. 2), which was reached by helicopter. On the same day, a reconnaissance flight carried out over Cerro Pirámide and Cordón Gaea showed that both sites are too steep for drilling. The firn cores were packed and sealed in polyethylene bags in the field, shipped frozen to Switzerland and kept frozen in a cold room (–20°C) until analysis. The cores were subsampled with 5 cm resolution. The samples were melted and analyzed for major ions by ion chromatography using standard procedures (Eichler and others, 2000), as well as for stable oxygen and hydrogen isotopes ($\delta^{18}O$, δD). $\delta^{18}O$ and δD analysis were carried out by pyrolysis of the samples at 1450°C in a glassy carbon reactor, and subsequent measurement by standard isotope-ratio mass spectrometry (Delta Plus XL, Finnigan MAT). $\delta^{18}O$ and δD are defined as the per mil difference between the sample composition and the Standard Mean Ocean Water (SMOW). The precision of the measurements was ±0.2‰ and ±1‰, respectively.

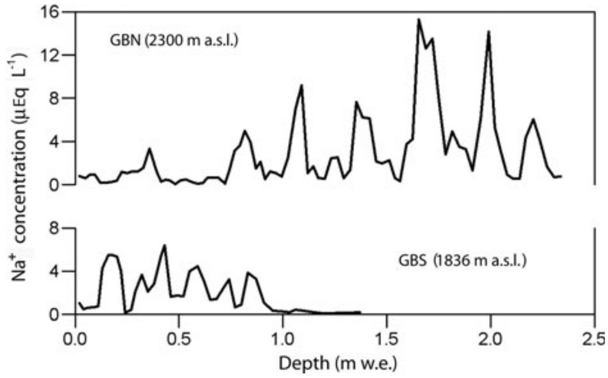

Fig. 3. Na^+ concentrations in the cores from GBS and from the plateau of GBN.

3. RESULTS AND DISCUSSION

Records of the Na^+ concentrations and of $\delta^{18}O$ for the cores from GBS and from the plateau of GBN are compared in Figures 3 and 4. At GBS, both parameters are observed to fluctuate down to about 1 m w.e. depth. Below that depth, a constant level is reached, indicating that the 2001 austral winter precipitation signal is still preserved in the record, whereas the signal deeper in the core, corresponding to summer 2000/01, was destroyed by meltwater percolation. This is consistent with a sudden increase of density from 0.55 to 0.73 g cm^{-3} at 0.87 m w.e. depth and also with the huge ice layers already encountered at 3 m below the surface (corresponding to 1.4 m w.e.). At the lower site, Paso Marconi (1543 m a.s.l.), ice was encountered 4 m below the surface. We assume that this site is likewise affected by melt, so the core is not analyzed further. At GBN, on the other

Table 1. Average values (μEq L^{-1}) of major-ion concentrations from GPN compared to data from Glaciar Perito Moreno (from the six shallowest samples representing about 1 year of precipitation) and to pre-industrial median values from the Colle Gnifetti (European Alps) core

Site	Source	Na^+	Cl^-	Mg^{2+}	Ca^{2+}	NH_4^+	NO_3^-	$nssSO_4^{2-}$
GPN	This study	2.72	2.65	0.50	0.84	0.57	0.44	0.56
Glaciar Perito Moreno	Aristarain and Delmas (1993)	4.30	4.85	–		0.77	0.32	0.65
Colle Gnifetti	Schwikowski and others (1999)	0.96	1.18	0.90	3.89	1.61	1.17	1.48

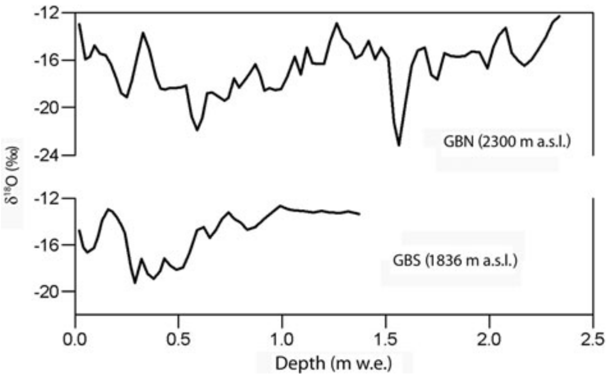

Fig. 4. $\delta^{18}O$ records from GBS and from the plateau of GBN.

hand, variations of the Na^+ concentrations and $\delta^{18}O$ occur in the 5 m core (2.5 m w.e.; Figs 3 and 4), suggesting that no significant melting took place. Pronounced concentration variations over the entire core are also found for all the other major ions (Fig. 5). There was no obvious decreasing trend with depth, such as was the case for NO_3^- and SO_4^{2-} in the core from Glaciar Perito Moreno, where both species showed a rapid decrease by >50% in the first 3 m, corresponding to about 2 years (Aristarain and Delmas, 1993). Our interpretation that melting is of minor importance at the GBN glacier is supported by the visual stratigraphy of the core, where only thin ice layers of <1 cm were seen. We propose that the GBP site is located high enough and is not significantly influenced by melting.

Averages of major-ion concentrations show the dominance of sea-spray constituents Na^+ and Cl^- in the ion budget (Table 1). The total ion content is rather low, typical for a remote site located near the ocean. The low ionic concentrations in the GBN core are not caused by percolation, because the ion profiles fluctuate, in contrast to to the GBS core where the concentrations approach zero in the section of superimposed ice (as shown for Na^+ in Fig. 3). Concentrations of ions of anthropogenic origin, such as NO_3^-, NH_4^+ and $nssSO_4^{2-}$, are even lower than pre-industrial medians from a core from the European Alps (Schwikowski and others, 1999) (Table 1). This is also the case for the concentration levels of the main mineral dust tracers Ca^{2+} and Mg^{2+}. Generally, average concentrations in the GBN core and of the six shallowest samples in the Perito Moreno core, which are assumed to be unaffected by melting (representing about 1 year of precipitation), are comparable (Table 1). The mean Cl^-/Na^+ ratio of 1.08 at GBN is close to the sea-spray ratio of 1.16, indicating that preferential elution of Cl^- due to meltwater percolation is insignificant. A preferential elution of Cl^- was observed in the Perito Moreno core, altering the Cl^-/Na^+ ratio from 1.13 for the first year of accumulation to about 0.75 at 7 m w.e. depth (Aristarain and Delmas, 1993).

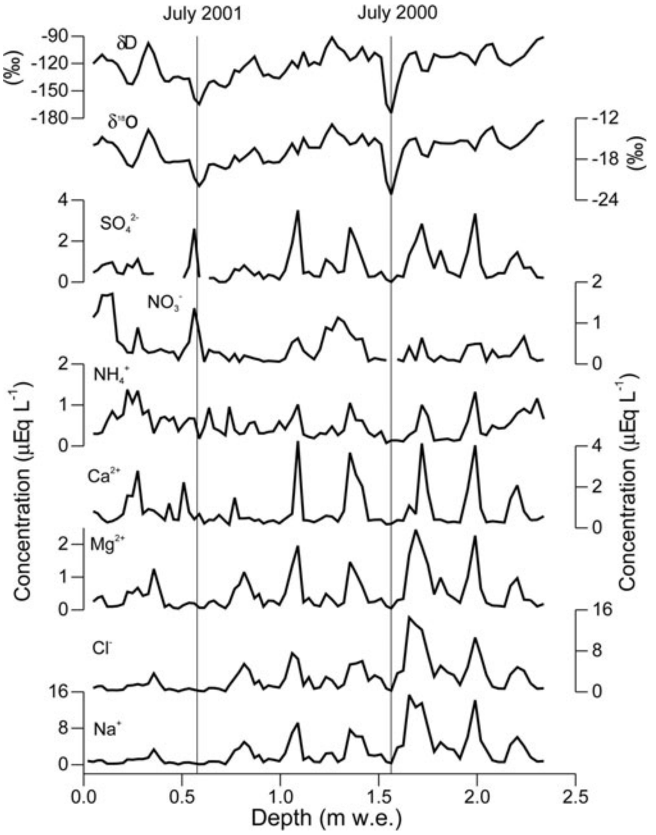

Fig. 5. $\delta^{18}O$, δD and major-ion concentration records from the plateau of GBN. A preliminary attribution of two minima in $\delta^{18}O$ to July 2001 and July 2000 is indicated.

Compared to the different shallow cores from HPN and HPS, average stable-isotope ratios $\delta^{18}O$ and δD at GBN and GPS are significantly lower (Table 2). This cannot be explained by the altitude effect alone. Assuming a $\delta^{18}O$/altitude gradient of –0.2‰ $(100\,m)^{-1}$, as was established for the Swiss Alps (Schotterer and others, 1997), would result in

Table 2. Average $\delta^{18}O$ and δD values of the different shallow cores from HPN and HPS, along with elevation of each site and estimated net accumulation

Site	Source	Elevation m a.s.l.	$\delta^{18}O$ ‰	δD ‰	Net accumulation m w.e. a^{-1}
GPN	This study	2300	–16.7	–122.3	0.97
GPS	This study	1836	–15.0	–113	–
Glaciar Perito Moreno	Aristarain and Delmas (1993)	~2000[1]	–14[2]	102	1.2
Glaciar Tyndall	Shiraiwa and others (2002)	1756	–11.9	–84	14.4
Glaciar Nef	Matsuoka and Naruse (1999)	1500	–11.4	–	2.2
Glaciar San Rafael	Yamada (1987)	1296	–11.3	–	3.45

[1] Re-estimated by Godoi and others (2001).

[2] Calculated from δD assuming meteoric water relationship.

much smaller difference in the average δ^{18}O. The relatively high δ^{18}O values at Tyndall, Nef and San Rafael glaciers suggest that meltwater drainage results in a δ^{18}O bias towards less negative values. For example, in the case of a 50% melt loss by drainage, solid/liquid isotope fractionation would yield a 2‰ less negative (less depleted) δ^{18}O of the remaining ice. This was estimated assuming Rayleigh isotope distillation and an ice/water equilibrium isotope fractionation factor α (^{18}O/^{16}O) = 1.00291 (Lehmann and Siegenthaler, 1991).

A preliminary determination of the net accumulation rate at GBN was attempted by attributing the two minima in the δ^{18}O record at 0.59 and 1.56 m w.e. to July 2001 and July 2000, respectively (Fig. 5). July is the month with the coldest air temperatures at stations located on the western and eastern sides of HPS (Carrasco and others, 2002). This attribution would place summer 2000/01 at about 1 m w.e. depth, which coincides with the depth where melt influence was observed at GBS (Figs 3 and 4). Another argument for this dating is that major peaks of sea-spray tracers seem to occur in summer (at 1.1, 1.4, 1.7 and 2.0 m w.e.), the season with the highest wind speeds (Carrasco and others, 2002), favoring sea-spray formation. In addition, distinct peaks of snow algae, which grow near the glacier surface only during the melt season, and of pollen, which disperses during summer, were observed at about 1 m w.e. depth in both the GBN and GBS cores (personal communication from S. Kohshima and others, 2005). These peaks also support the summer 2000/01 attribution. This dating indicates an annual net accumulation of 0.97 m w.e.

The GBN net accumulation is in reasonable agreement with the mean annual accumulation of 1.2 m w.e. deduced from the Perito Moreno core (Aristarain and Delmas, 1993), but much lower than at Tyndall, Nef and San Rafael glaciers (Table 2). In January 1996, a metal pole was installed in the upper reaches of Glaciar Chico (49°11′ S, 73°11′ W; 1445 m a.s.l.), approximately 10.5 km southwest of GBN, and its height has been measured almost every year. Pole heights in combination with snow-pit data yielded a mean net accumulation of 0.57 ± 0.21 m w.e. a^{-1} for the period 1994–2002 (Rivera, 2004). Data of ablation from stakes measured for periods shorter than 1 month, together with a degree-day factor model, indicate a mean ablation of 3.5 m w.e., presumably due mainly to melting, but also to sublimation and wind erosion. This results in a mean annual precipitation of 4.07 ± 0.54 m w.e. for the site. Data from meteorological stations show annual precipitation with a maximum of 7000 mm on the western and <700 mm on the eastern side of HPS (Carrasco and others, 2002). Thus, this is a region with an extreme west–east precipitation gradient. The location of the GBN site at the eastern margin of the HPS, together with potential erosion of snow by strong winds at this higher-elevation glacier, can explain the relatively low accumulation rate at GBN.

CONCLUSIONS

The dating of the shallow core from GBN and the subsequent determination of annual net accumulation is preliminary only, since no independent time markers (e.g. volcanic layers) were detected. Nevertheless, the glaciochemical records resulting from this study indicate considerable influence of meltwater percolation up to at least 1800 m a.s.l. at HPS. In contrast, at the higher-elevation glacier, GBN (2300 m a.s.l.), no signs of melting were detected in the 5 m core, which is interpreted to correspond to a period of 2 years. Since extreme melt events can occur, an ice core containing meaningful paleoclimate information from that region would ideally be recovered from a higher-elevation glacier exposed to lower temperatures. Besides GBN, such glaciers exist on a number of mountains at HPS (e.g. Volcán Lautaro (3380 m a.s.l.), Cerro F.P. Moreno (3393 m a.s.l.)), HPN (San Valentin (3910 m a.s.l.)) and in between (San Lorenzo (3706 m a.s.l.)). Because of the strong west–east precipitation gradient in this region, a glacier on the eastern margin of the Icefields with lower accumulation rates would be preferable for obtaining a long-term record. Due to the high wind speeds induced by the westerlies in these latitudes, some snow erosion might occur, especially at high-elevation sites. Several cores and a comprehensive glaciological survey will be required to assess the extent of this problem.

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