High net accumulation rates at Campo de Hielo Patagónico Sur, South America, revealed by analysis of a 45.97 m long ice core

TAKAYUKI SHIRAIWA,1 SHIRO KOHSHIMA,2 RYU UEMURA,3 NAOHIRO YOSHIDA,3
SUMITO MATOBA,1 JUN UETAKE,2 MARIA ANGELICA GODOI4
1Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819, Japan
E-mail: shiraiwa@pop.letem.hokudai.ac.jp
2Faculty of Bioscience and Biotechnology, Tokyo Institute of Technology, Ookayama 2-12-1, Meguro-ku, Tokyo 152-8551, Japan
3Department of Environmental Science and Technology, Tokyo Institute of Technology, Yokohama 222-8902, Japan
4Instituto de la Patagonia, Universidad de Magallanes, Casilla 113-D, Punta Arenas, Chile

ABSTRACT. A 45.97 m long ice core was recovered in the accumulation area of Glaciar Tyndall (50°59'05" S, 73°31'12" W; 1756 m a.s.l.), Campo de Hielo Patagónico Sur (southern Patagonia icefield), during December 1999. The firm core was subjected to visual stratigraphic observation and bulk density measurements in the field, and later to analyses of water isotopes (δ18O, δD), major dissolved ions and snow algal biomass. The drillhole remained dry down to about 43 m depth, where a water-soaked layer appeared. Seasonal cycles were found for δ18O, δD, although the amplitudes of the cycles decreased with depth. Major dissolved ions (Na+, K+, Mg2+, Ca2+, Cl−, SO42−) and algal biomass exhibit rapid decreases in the upper 3 m, probably due to meltwater elution. Annual increments defined by the δ18O and D-excess peaks suggest that the minimum net accumulation rates at this location were 17.8 m a−1 in 1997/98–1998/99 and >11.0 m a−1 in 1998/99–1999/2000. These are much higher values than those previously obtained from past ice-core studies in Patagonia, but are of the same order of magnitude as those predicted from various observations in ablation areas of Patagonian glaciers.

INTRODUCTION

Since the pioneering work of Meiér (1984), the contribution of mountain glaciers to sea-level rise has been a key issue for understanding the effects of global warming. Of particular importance is the mass balance of the huge temperate glaciers in Alaska and Patagonia (Houghton and others, 1996) because the sensitivity of equilibrium-line altitude to temperature change is more pronounced at high precipitation rates (Oerlemans and Fortuin, 1992). The glaciers in Patagonia are maritime; furthermore, Campo de Hielo Patagónico Norte (HPN; northern Patagonia icefield) at 4200 km² and Campo de Hielo Patagónico Sur (HPS; southern Patagonia icefield) at 13000 km² together constitute the world's largest ice mass outside the polar regions (Warren and Sugden, 1993; Aniya and others, 1996). Accordingly, changes in their mass balances are closely related to world sea level.

Mass-balance estimates have been made using ice cores recovered from the icefields. Three ice-core drillings have been performed so far; these yielded estimated net accumulation rates of 3.45 m a−1 at the Glaciario San Rafael drilling site (HPN, 46°44' S, 73°32' W; 1296 m a.s.l.) (Yamada, 1987), 1.2 m a−1 at Glaciar Perito Moreno (HPS, 50°38' S, 73°15' W; 2680 m a.s.l.) (Arístarain and Delmas, 1993) and 2.2 m a−1 at Glaciar Nef (HPN, 45°56' S, 73°19' W; 1500 m a.s.l.) (Matsuoka and Naruse, 1999). Arístarain and Delmas (1993) suggested that the 1.2 m a−1 value might have been influenced by wind scouring and surface melting. Surface melting could be more critical for ice cores at lower altitudes. It is therefore necessary to obtain ice cores from a site where there is minimal influence on mass balance from meltwater discharge and wind scouring.

This paper presents a new estimate of net accumulation rates at HPS, based on analyses of δ18O and δD as well as major ions and algal biomass along a 45.97 m long ice core. The high values calculated are considered to be typical of this glacier in the light of synoptic-scale climate analyses of the region. Glaciar Tyndall can therefore be classed as one of the most extreme maritime glaciers in the world.

GEOGRAPHICAL SETTING

The drilling site is located at 500 m east of a divide between Glaciar Tyndall to the east and Glaciar Amarga to the west in the southernmost part of HPS (50°59'05" S, 73°31'12" W; 1756 m a.s.l.). A map of the region is shown in Figure 1. Glaciar Tyndall flows southwards for 32 km, covering a total area of about 331 km², and eventually calves into a proglacial lake (Aniya and others, 1996).

The glacier surface at the drilling site is inclined by 1° to the east. There are nunataks approximately 2 km south of the drilling site (Fig. 2), but the underlying surface is otherwise flat for at least 2 km in the other directions. Preliminary radio-echo soundings suggest that the glacier might be >600 m thick (personal communication from A. Rivera and G. Casassa, 1999), although its exact thickness at the drilling site is unknown.

According to our meteorological observations during the 24 day drilling campaign, weather conditions in this region are extreme: we recorded an average hourly wind
from a snow cave located below the glacier surface. The tents
ice cores had to be processed immediatel
ICE-CORE DRILLING AND ANALYSIS
Because of the harsh environment
speed of 13.6 m s\(^{-1}\) and a snow accumulation of approximately 3.5 m (about 175 m w.e.) from 30 November to 23 December 1999. Visibility exceeded 50 m on only 4 days out of 24. Air temperature varied from 3.3\(^\circ\)C to -8.2\(^\circ\)C, with an average of -3.5\(^\circ\)C during the campaign.

Fig. 1. Location of the drilling site. Previous drilling sites and the location of Punta Arenas are also shown.

The borehole was dry down to 42.55 m depth. The core consisted of layers of firn and melt features that varied in thickness between 1 and 50 mm down to 42.55 m depth. Neither dirt layers nor ash layers were encountered, but was prevented by meltwater inflow into the core strata. The depth of pore close-off (Fig. 3). The best fit by a quadratic equation is \(\rho_d = -0.147d^2 + 14.66d + 45991\) (\(r^2 = 0.94\)). The depth of pore close-off, 42.5 m, is greater than the depths of 20–30 m recorded in other temperate glaciers (Kawashima and Yamada, 1997). This may be due to the abnormally high accumulation rate mentioned below.

Figure 3 also compares the depth–density curve of Glaciar

PHYSICAL PROPERTIES OF THE ICE CORE
The core consisted of layers of firn and melt features that varied in thickness between 1 and 50 mm down to 42.55 m depth, below which water-soaked firn–ice layers continued to 45.97 m depth. Neither dirt layers nor ash layers were found throughout the profile. Snow grains were mostly coarse granules.

The bulk density \(\rho\) gradually increases with depth \(d\) and attains the firn/ice transition (\(\sim 830 \text{ kg m}^{-3}\)) at 42.5 m depth (Fig. 3). The best fit by a quadratic equation is \(\rho_d = -0.147d^2 + 14.66d + 45991\) (\(r^2 = 0.94\)). The depth of pore close-off, 42.5 m, is greater than the depths of 20–30 m recorded in other temperate glaciers (Kawashima and Yamada, 1997). This may be due to the abnormally high accumulation rate mentioned below.
Tyndall with those from previous measurements on other Patagonian glaciers. The curve of Glaciar Tyndall (1756 m) is similar to that from Glaciar Perito Moreno (2680 m at HPS; Astarain and Delmas, 1993), despite the 924 m difference in elevation. Altitudes of the drilling sites at Glaciares San Rafael (1296 m at HPN; Yamada et al., 1987) and Nef (500 m at HPN; Matsuoka and Naruse, 1999) are much closer to that of Glaciar Tyndall (1756 m). At a given depth, however, the firm densities of Glaciars San Rafael and Nef are much higher than those of Glaciares Tyndall and Perito Moreno.

Another important point is the occurrence of water-saturated firm–ice layers at 42.5 m on Glaciar Tyndall, 19.7 m on Glaciar San Rafael and 13.3 m on Glaciar Nef. This suggests that below these depths any chemical and isotopic signals in the ice cores may have been eluted by the meltwater, as already found at the two glaciers in HPN.

WATER-ISOTOPE, ION-CHEMISTRY AND BIOMASS ANALYSES

\[ \delta^{18}O, \delta D \text{ and D-excess} \]

Average values and the standard deviations of all 183 samples of \( \delta^{18}O, \delta D \) and D-excess \( (d = \delta D + 8 \delta^{18}O; \text{Dansgaard, 1964}) \) measured from the surface to the bottom of the ice core are \(-11.9 \pm 1.5\%o, \ -84 \pm 12\%o \text{ and } 10 \pm 2\%o \), respectively. In order to check the dependence of water isotopes on altitude, the averaged value of the \( \delta^{18}O \) is compared with those obtained for Glaciares San Rafael (Yamada, 1987), Perito Moreno (Astarain and Delmas, 1993) and Nef (Matsuoka and Naruse, 1999) and for Punta Arenas (53.00°S, 70.51°W; 37 m a.s.l.) (Fig. 4). Average values were obtained for Glaciares San Rafael and Nef by averaging all of the \( \delta^{18}O \) values appearing in each report. The averaged \( \delta^{18}O \) of Glaciar Perito Moreno was calculated and converted from the reported \( \delta D \) values by assuming a meteoric water relationship. The averaged \( \delta^{18}O \) for Punta Arenas was obtained from the International Atomic Energy Agency/World Meteorological Organization global network of isotopes in precipitation (GNIP) database, Release 3 October 1999 (http://www.iaea.org/programs/ri/gnip/gnipmain.htm) for the period 1996–97. The four average values of \( \delta^{18}O \) are linearly related to altitude \( z \) (m a.s.l.); the best-fit equation is \( \delta^{18}O = -0.002z - 8.49 \). The \( \delta^{18}O \)/altitude effect is \(-0.2\% \) for each 100 m, which is the same as for the Swiss Alps (Schotterer and others, 1997). Although the data used are variable in both quality and quantity and may lack statistical significance, it seems that the water isotopes over the Patagonian icefields are controlled mainly by altitude.

Profiles of \( \delta^{18}O \) and D-excess in the ice core are given in Figure 5. Hereafter, all depths are given by their water equivalent. The amplitudes of the two signals are relatively large in the upper 10 m, ranging from \(-8\%o \) to \(-17\%o \) in the case of \( \delta^{18}O \), but smaller at greater depths, ranging from \(-9\%o \) to \(-14\%o \). It is, however, possible to find oscillations whose strongest \( \delta^{18}O \) peaks are at 11.0 and 28.8 m depths if the upper 10 m is smoothed by an 11-data running mean (thick line in Fig 5). D-excess has peaks at 8.6 and 23.3 m and shows fluctuations similar to those of \( \delta^{18}O \). The difference between the two profiles is that they are slightly shifted in their peaks: D-excess peaks postdate those of \( \delta^{18}O \).

To explain why the \( \delta^{18}O \) peaks predate D-excess peaks in the ice core, we examined seasonal fluctuations in the two signals observed at the nearest meteorological station, Punta Arenas (Fig. 1), where water-isotope data are currently available at the GNIP database mentioned previously. These are plotted in Figure 6 by calculating monthly averages from the dataset during 1990–97. Although the measurement

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**Fig. 3.** Profile of the ice-core bulk density (solid dots). Ordinate is the measured core depth \( d \) (m). For comparison, profiles of bulk densities from other glaciers on the Patagonia icefields are given: Glaciar San Rafael (Yamada, 1987), Perito Moreno (Astarain and Delmas, 1993) and Nef (Matsuoka and Naruse, 1999). Arrows indicate depths at which water-saturated firm first appeared.

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**Fig. 4.** Relationship between averaged values of \( \delta^{18}O \) and altitudes in the two Patagonia icefields and the nearest meteorological station. Original data for Glaciar San Rafael are from Yamada (1987); for Glaciar Perito Moreno from Astarain and Delmas (1993) and for Glaciar Nef from Matsuoka and Naruse (1999). Data for Punta Arenas were obtained from the GNIP database (http://www.iaea.org/programs/ri/gnip/gnipmain.htm). Solid dots and bars are the average value and the standard deviation of each dataset used for analyses. See text for further explanation.
Fig. 5. Profiles of $\delta^{18}O$ (%o), D-excess (%o), major ions (ppb or $\mu$L$^{-1}$) and algal biomass ($\mu$m$^3$ mL$^{-1}$). Depth is given by the water equivalent value. Thick lines in $\delta^{18}O$ and D-excess are 11-data running mean.

Fig. 6. Seasonal changes in $\delta^{18}O$ (%o) and D-excess parameter at Punta Arenas (53.00° S, 70.51° W; 37 m a.s.l). The original data were obtained from the GNIP database, and the monthly average data from 1990 to 1997 were used for this analysis.

The period is not long enough to determine definite statistical relationships, the monthly averages of $\delta^{18}O$ and D-excess show slightly shifted seasonal patterns too: the strongest $\delta^{18}O$ and D-excess peaks appear in February and April, respectively. This pattern is very similar to what we found in the ice core, where $\delta^{18}O$ peaks appeared approximately several meters lower, i.e., earlier than D-excess peaks. D-excess's time lag behind $\delta^{18}O$ remains unexplained, but it suggests that the fluctuations of both signals found in the ice core would correspond to the annual cycles in water isotopes.

Major ions and biomass

Major dissolved ions (Na$^+$, K$^+$, Mg$^{2+}$, Ca$^{2+}$, Cl$^-$, SO$_4^{2-}$) exhibit rapid decreases in the upper 4 m (Fig. 5). NO$_3^-$ was below the detection limit throughout the profile. Several additional peaks are, however, detectable above the upper level of the water-soaked layer at 28.94 m w.e. These peaks are located at 5–7, 20–21 and 24–25 m. The peaks for the dissolved ions correspond to the peaks for the snow algal biomass.

Concentrations of each ion in this ice core are one order of magnitude higher than those reported from Glaciar Perito Moreno (Aristarain and Delmas, 1993) as far as the samples from the surface 4 m are concerned. This is not due to contamination during processing of the samples and the analy-
Fig. 7. Profiles of $\delta^{18}$O (%o), D-excess (%o), Cl⁻/Na⁺ (µeq L⁻¹) and melt-layer percentage. Thick lines in each profile are 11-data running mean. The two horizontal bands are possible summer (February) horizons; the two arrows in the D-excess profile are possible April horizons.

**ESTIMATE OF ANNUAL ACCUMULATION RATES**

Our multi-signal analyses on the ice core suggest that fluctuations of $\delta^{18}$O and D-excess along the ice core are similar to those obtained at the nearest meteorological station, Punta Arenas; thus we may use these signals in the ice core as seasonal markers. However, the fluctuations of the signals for the major ions and algal biomass are difficult to interpret since they are considered to have been substantially disturbed by meltwater after deposition. Meltwater can also destroy the isotopic signals as occurred on Glaciares San Rafael and Nef in HPN; nevertheless, the original isotopic profiles can be maintained for at least a few years when the amount of meltwater is not significant (e.g. Krouse and others, 1977). Therefore, it may be possible to determine net accumulation rates at the drilling site from the $\delta^{18}$O and D-excess in the depth profiles.

The highest peaks in the $\delta^{18}$O profile are located at depths of 11.0 and 23.8 m (the two horizontal bands in Fig. 7). The profile suggests that another peak is forming at the surface. Because the $\delta^{18}$O peak appears in February at Punta Arenas, we tentatively assume that $\delta^{18}$O in the ice core also peaks in February. D-excess peaks are located at depths of 8.6 and 23.3 m, which could represent April snowfall (arrows in Fig. 7). This seems reasonable since the topmost level of D-excess is still relatively low; thus another peak probably appears much later than our drilling period in December.
Occurrences of melt layers in the ice core support the above-mentioned speculations (Fig. 7). The melt layers are usually formed in summer, when meltwater at the surface percolates to a certain depth of the glacier. In this ice core, however, one can recognize two horizons where melt layers are almost absent: at 4–7 and 20–25 m. These two depths are also characterized by lower $\delta^{18}O$ values, so they would correspond to winter horizons.

As a result, we calculate that the net accumulation rate from the austral summer (February) of 1997/98–1998/99 was 17.8 m a$^{-1}$ w.e., whereas that of 1998/99–1999/2000 is expected to be 11.0 m a$^{-1}$ plus the amount that was supplied until February 2000, as indicated by the two horizontal bands in Figure 7. These values do not include the meltwater discharged from the site, so the calculated values are lower bounds of the actual net balances. However, the amount of meltwater from firm layers is likely insignificant at this altitude since the isotopic profiles would have washed out if the amount were high.

Mass balances of the Patagonian icefields are poorly understood to date. Besides the ice-core data mentioned above, specific mass balances were estimated for a part of HPS only, by glacial dynamical methods (Skvarca and Naruse, 1997; Rott and others, 1998). Annual precipitation over both the HPS and HPN accumulation areas has been estimated either by the hydrological method (Escobar and others, 1992) or by meteorological observations (Fujiyoshi and others, 1997). All of the studies estimated a high annual mass input of 5–10 m w.e. on average in the accumulation area. Although our estimates are almost double the above-mentioned values, we believe that they are not far from the realistic value if we remember the actual accumulation rate we observed during our drilling operation (3.5 m in snow height per 24 days in December 1999).

Finally, we ask whether the calculated high net accumulation rates are normal or abnormal at this location. K. Kubota (unpublished information) analyzed the synoptic-scale weather conditions over Patagonia by using data on geopotential height, wind speed and moisture flux at 850 hPa from 1985 to 1993. He compared the December monthly averages of these parameters from 1999 with those from other years. December 1999 was found to be nearly the average of the 15 year period, so this was not an unusual year. Hence, the extremely high snow accumulation observed for December 1999 is likely typical for this glacier. This means that Glaciar Tyndall must rank as one of the most maritime glaciers in the world.

CONCLUSIONS

From our ice coring at Glaciar Tyndall on HPS we found that

1. field campaigns here are very strenuous due to high winds and heavy snowfall;
2. the glacier is temperate even at its highest saddle at 1750 m a.s.l.;
3. the seasonal cycles in $\delta^{18}O$, $\delta^D$ and D-excess were more or less preserved for at least 2 years;
4. major ions and algal biomass were substantially eluted by meltwater;
5. the seasonal cycles of $\delta^{18}O$ and D-excess together with the melt-layer distribution helped to reconstruct the lower bounds of net accumulation rates for 1997/98–1998/99 (17.8 m a$^{-1}$) and 1998/99–1999/2000 (>11.0 m a$^{-1}$).

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