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Thickness change and short-term flow variation of Moreno Glacier, Patagonia

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Abstract

Ice-thickness change was studied at the ablation area of Moreno Glacier on the eastern side of the Southern Patagonia Icefield. The thickness remained unchanged between 1990 and 1993. With the data of the frontal fluctuations, it was concluded that the glacier has been in a steady state during the last 50 years. Ice-flow velocities measured at four points were higher in November 1993 than in January-February 1994. Also velocities showed clear daily variations with maxima in the afternoon and minima in the morning. These velocity variations can be attributed to variations in the basal sliding of the glacier. The amount of ablation of 6.3 m in water equivalent was measured during 110 days in summer 1993–94. Using a degree-day method, an annual ablation amount of about 11 m -water was estimated at the mid-reach of the ablation area.

1. Introduction

In Patagonia, the southern part of South America, there exist two vast ice-covered areas which are called the Southern Patagonia Icefield (SPI) and the Northern Patagonia Icefield (NPI). Numerous outlet glaciers discharge radially from the icefields, mostly calving into fjords on the western sides and into lakes on the eastern sides (Fig. 1). The Patagonian glaciers are regarded to be typical temperate glaciers, with large amounts of accumulation and ablation (melting and calving) throughout the year.

Analyses of satellite images and air-photographs taken during the last 50 years revealed that most Patagonian glaciers have been retreating considerably (Aniya, 1988 ; 1992a ; 1992b ; Aniya *et al.*, 1992 ; Aniya and Skvarca, 1992 ; Naruse *et al.*, in press). The maximum retreat was found as 13 km between 1945 and 1986 at O'Higgins Glacier (SPI), whereas Brüggen (Pio XI) Glacier (SPI) has advanced up to 8.5 km during the same 41-year period and Moreno Glacier (SPI) has not fluctuated significantly. When we discuss glacier variations in relation to climatic changes or water cycles, information on changes in ice volumes or thicknesses is greatly called for.

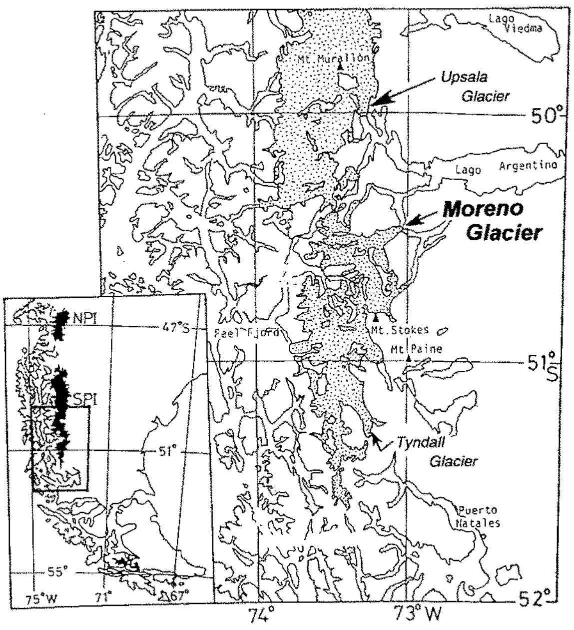

Fig. 1. Map of the southern part of the Southern Patagonia Icefield in South America.

In summers of 1983–84 and 85–86, extensive glaciological, meteorological and geomorphological studies were carried out in the NPI and the SPI (Nakajima, 1987). It was found that Soler Glacier (NPI) was thinning at a rate of 5.2 m/a from 1983 to 1985 (Aniya and Naruse, 1987). This result stimulated us to collect more data on the ice-thickness change at various types of glaciers. Accordingly, field researches were conducted at Moreno, Upsala and Tyndall glaciers (SPI) in summers 1990–91 and 93–94 (Naruse and Aniya, 1992 ; 1995).

Before the 1970s, only a few preliminary studies had been made on the flow of glaciers in Patagonia (e. g. Raffo *et al.*, 1953 ; Marangunic, 1964 ; Naruse and Endo, 1967). In 1983 detailed surveys of flow-velocity were first carried out at Soler and San Rafael (NPI) glaciers (Naruse, 1985), and in 1985 at Soler and Tyndall glaciers (Naruse, 1987 ; Naruse *et al.*, 1987). Short-term variations in flow velocity were also measured at Soler Glacier in the both periods. It was found out that a maximum flow speed in terms of a few-hour mean was about four times a minimum value (Naruse *et al.*, 1992).

This paper presents the results of a glaciological study at Moreno Glacier undertaken in November 1993, focusing on the ice-thickness change from 1990 to 1993, and on the short-term and seasonal variations in flow velocities. Moreno Glacier flows northeastward along a distance of about 25 km from the ice divide of the SPI (Fig. 1). The current equilibrium line is estimated at 1150 m a.s.l. ; the accumulation and ablation areas are 182 km^2 and 75 km^2, respectively (Aniya and Skvarca, 1992). The ablation area is a valley-type glacier with a length of 15 km and a width of about 4 km. The terminus of the glacier calves into the southwestern arm of Lago (Lake) Argentino and the glacier front reaches currently the opposite bank (Peninsula Magallanes) at 50°30′S and 73°W (Fig. 2).

2. Measurement methods

The same control station (CS) and azimuth point that had been established in the 1990 survey (Naruse *et al.*, 1992) were utilized. The station is located at about 420 m a.s.l. on the southern (right-side) bank about 5 km from the front of Moreno Glacier (Fig. 2). The azimuth point is located about 100 m apart from CS. For the measurements of a short-term velocity, another control station (C2) was established between CS and the base camp. An electronic distance meter (Topcon EDM-Theodolite Guppy with a minimum reading of 1 second) was installed at one of these control stations, and an EDM reflector was placed by a mobile team at survey points on the ablation area of the glacier.

2.1. Surface elevation

Measurements were performed on 10 November 1993 at eight points along a half transverse line (M8-M11) and along a median line (M1-M4) in the mid-reach of the ablation area (Fig. 2). Based on the raw data of the horizontal angles and distances measured in the previous survey, a person at the control station guided a mobile team to locate the same survey points as in 1990. The difference in position between surveys in 1990 and 1993 could be reduced to smaller than 1.3 m, with a mean of the eight being 0.5 m. Of the eleven points surveyed in 1990, three points were not accessible in 1993 due to the existence of heavy crevasses or large supraglacial ponds. From the measurements of slope distance and vertical angle to the eight survey points, surface elevations were measured, then the thickness changes between 1990 and 1993 were obtained.

2.2. Long-term flow velocity and ablation rate

Wooden stakes 1.5 m long and aluminum poles (in 2-m sections) up to 14 m long were placed in holes with a steam drill at four survey points (M1, M2, M8 and M10) on 11 and 12 November 1993. Measurements of positions of the four points and heights of the poles above ice surface were carried out on 12 and 16 (or 27) November, 9 December 1993 and 1 March 1994. Meteorological elements were continuously measured at MS near M11 (Fig. 2) and at the base camp during the period from 12 to 27 November 1993 (Takeuchi *et al.*, 1995a).

2.3. Short-term flow velocity

A tripod with a reflector was set up firmly into the surface ice at R near the right-side margin about 300 m apart from the control station C2 (Fig. 2). Due to the convex ice-surface along the transverse profile near the side margin, the flow direction of the point R coincided exactly (within 1 minute) with the direction toward C2. Furthermore, the measurement line from C2 to R was almost horizontal : the elevation difference between the two points was less than 2 m. Therefore, for the observation of short-term fluctua-

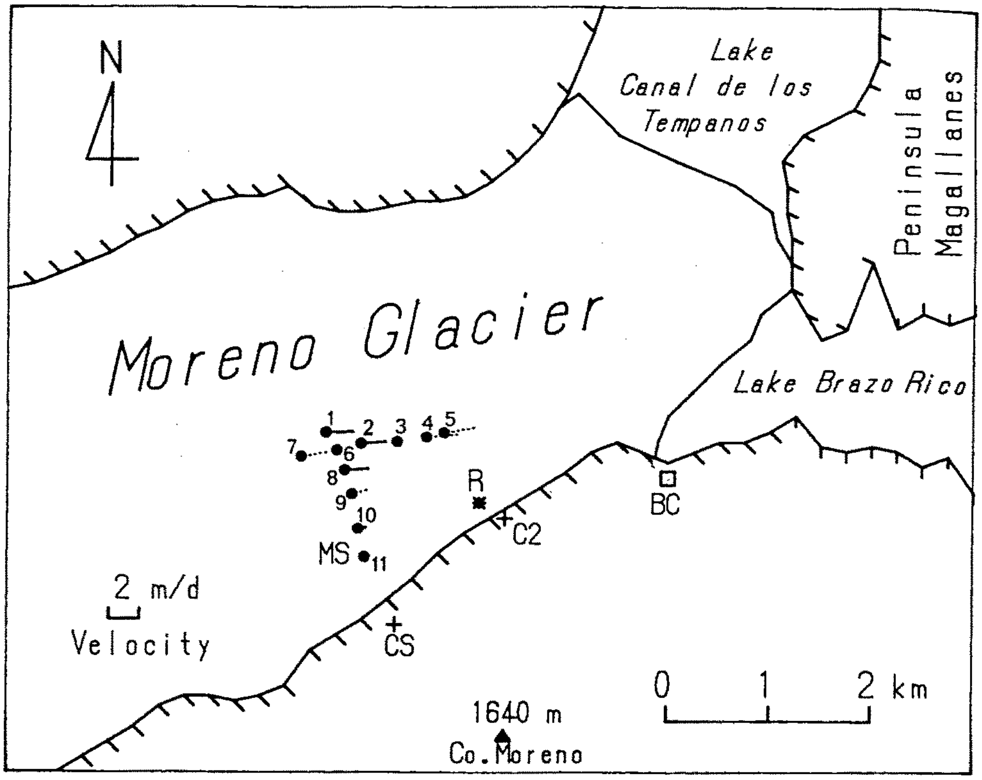

Fig. 2. Location map of the ablation area of Moreno Glacier. Solid circles with numbers (1, 2, 3 ...) indicate survey points M1, M2, M3 ... in 1990 and 1993. Solid lines starting from circles show surface flow velocities measured with an interval of four days in November 1993 ; dotted lines those with a one-day interval in November 1990. Marks + indicate control stations (CS and C2), MS the meteorological station and R a survey point of short-term velocity variation.

tions in flow velocity, only slope distance was measured from C2 at intervals of about two hours in daytime and about eight hours in nighttime during a period from 22 to 27 November 1993.

3. Measurement results

3.1. Ice-thickness change

Changes in the ice-thickness during the three years ranged from +2.66 m to −2.92 m. Annual thickening rates are plotted against the distance in Fig. 3. A mean thickening rate of the eight points was obtained as +0.17 m/a. A tendency may be noticed that an area near the margin (M9 and M10) was thinning while an area along the median line (from M8 to M4) was thickening. However, since there are numerous crevasses, and ice mounds and depressions with a relief of up to (3 or) 5 m over the glacier surface, the thickness change smaller than ca.

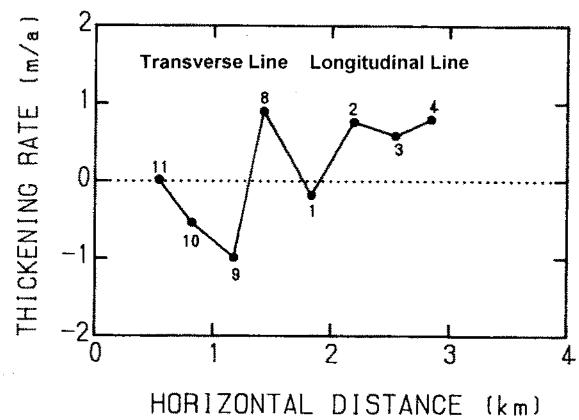

Fig. 3. Distribution of annual thickening rate of ice. The negative sign indicates thinning. Numbers (1, 2, ... and 11) attached to solid circles indicate survey points M1, M2, ... and M11. Points from M11 to M1 are along a transverse line and points from M1 to M4 are along a longitudinal line (see Fig. 2).

3 m may be resulted from the local surface undulation. Hence, we conclude from the result in Fig. 3 that Moreno Glacier has been in an equilibrium condition between 1990 and 1993.

3.2. Distribution of flow velocity and its seasonal variation

Distribution of vectors of flow velocities measured with an interval of four days in November 1993 is shown by straight lines in Fig. 2. Also shown by dotted lines are velocity vectors measured at some points in November 1990 (Naruse *et al.*, 1992). The flow direction at each point in 1993 is identical with that in 1990. However, the magnitude of velocity was slightly lower in 1993 than in 1990.

Variations in flow velocities from the middle of November 1993 to the beginning of March 1994 are shown in Fig. 4. It is clearly recognized at all the four points that the velocity is larger in late spring or early summer than in mid-summer. This trend indicates the seasonal variation in glacier flow, that can be attributed to variations in the basal sliding speed.

Surface strain of the glacier was measured at around MS with a rectangle strain grid with the sides ranging from 170 m to 320 m long. A mean strain rate obtained from 14 to 16 November was -3.3×10^{-4} 1/day with an error of 30 %. However, since the ice surface at the grid undulates with crevasses and supraglacial ponds, we may not be able to regard this strain rate as a representative value over the whole ablation area of the glacier.

3.3. Short-term variation in flow velocity

Figure 5 shows flow velocity measured at R with intervals from two to eight hours during five days starting from 22 November 1993. It also exhibits the hourly air temperature observed at MS and the daily ablation rate averaged over the eight stakes set up between MS and R (Takeuchi *et al.*, 1995a ; 1995b).

Since tilting of tripods of the EDM at C2 and of the reflector at R was too small to be detected during the five-day period, an observation error due to tilting may be neglected. As the data of horizontal and vertical angles were not used for obtaining velocities, errors due to the refraction of light (Andreasen, 1985a) are not contained in the present results. Hence, the total error involved in a velocity (mm/hour) can be estimated as less than ±2 mm/hour.

It was found in Fig. 5 that the velocity fluctuated significantly from 4 mm/hour to 11 m/hour within

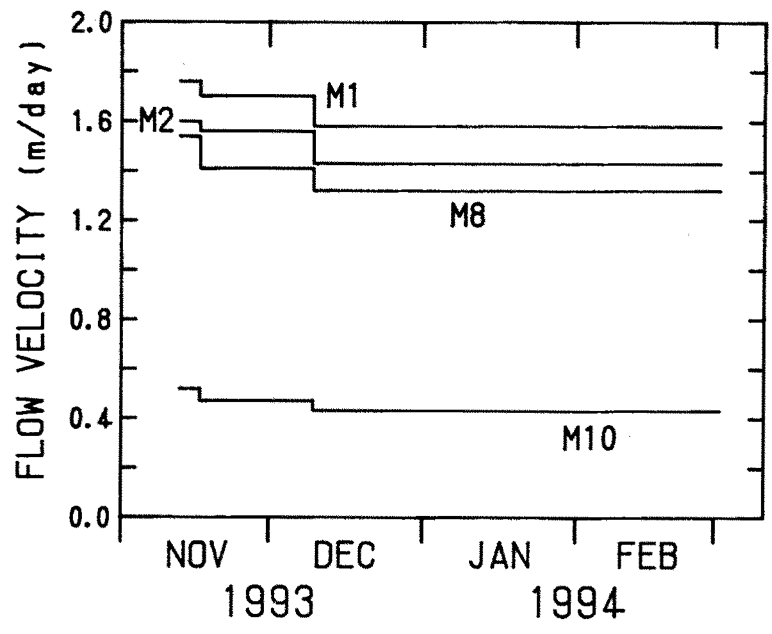

Fig. 4. Variations in surface flow velocities at four points from 12 November 1993 to 1 March 1994.

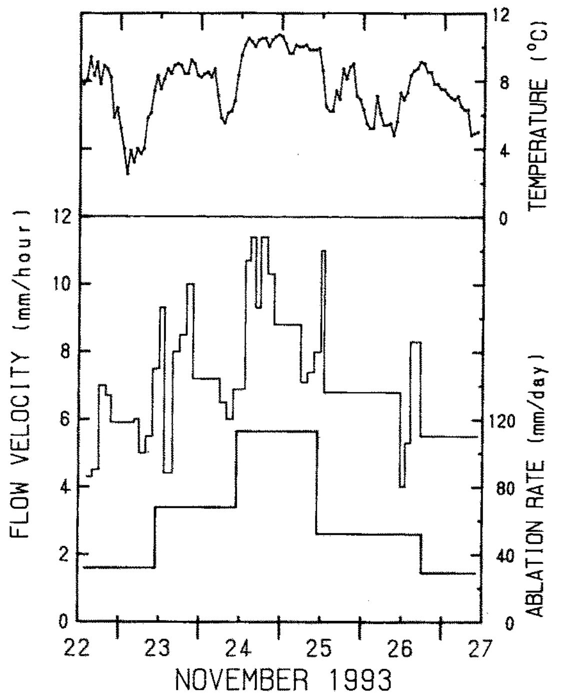

Fig. 5. Short-term variations in surface flow velocity (middle), air temperature (top) and daily ablation rate (bottom) in November 1993.

several hours. We can further recognize that, in general, velocities were larger in afternoons and smaller in mornings. A relatively high correlation can be noticed between velocities and air temperatures. No remarkable correlation was observed between air temperature and global radiation (Takeuchi *et al.*, 1995a). As to a general trend seen in Fig. 5, the flow velocity was largest in the afternoon of the 24th when the ablation rate was largest, while velocities were smaller in the 22nd–23rd and the 26th–27th when the ablation rates were smaller. Hence, we may consider that the velocity correlated best with the ablation rate.

3.4. Long-term ablation

In Fig. 6, the cumulative ablation amounts (in water equivalent) are shown by solid circles, that were obtained from measurements at M1, M2, M8 and M10 around 350 m a.s.l. on 12 and 27 November, 9 December 1993 and 1 March 1994. During 110 days in summer, a mean ablation at the four sites was 7.0 m in ice thickness, that is 6.3 m in water equivalent by assuming the ice density as 900 kg/m^3. As to solid and broken lines in Fig. 6, see sub-section 4.3.

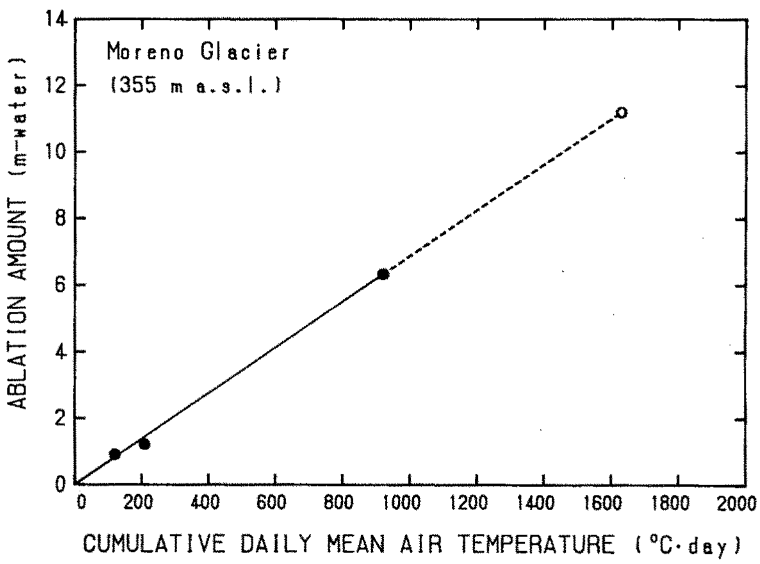

Fig. 6. The cumulative amount of ablation plotted against the cumulative daily mean air temperature (degree-day). The solid line indicates a relationship obtained during a period from 12 November 1993 to 1 March 1994; the broken line is an extrapolated relationship throughout the year (see text).

4. Discussion

4.1. Steady-state Moreno Glacier

Although no quantitative survey of the front position of Moreno Glacier was made in the 1993−94 season, a part of the glacier front was touching and landing on the opposite bank with a tunnel draining water from the south (Brazo Rico) to the north (Canal de los Tēmpanos). This condition was almost similar to that in 1990. Aniya and Skvarca (1992) summarized the frontal variations from 1947 to 1990 based on the analyses of aerial photographs and satellite images. It is shown that Moreno Glacier has been fluctuating frequently by reaching (advancing) and leaving (retreating) the opposite bank. However, the range of fluctuations during the last 45 years is smaller than several hundreds of meters. Among 22 calving glaciers in the NPI and SPI analyzed (Aniya, 1992b ; Aniya *et al.*, 1992), nine glaciers have been fluctuating within 1 km and 12 glaciers have been retreating in a range from 1 km to 13 km (O'Higgins Glacier) during the last 50 years. Considering these figures of the variation rates of Patagonian glaciers, the front of Moreno Glacier can be regarded to have been almost stationary during the last half century.

Ice thickness in the ablation area of Moreno Glacier was found to have been unchanged during three years from 1990. On the other hand, during the same period, considerable thinning rates of 11 m/a (Skvarca *et al.*, 1995) and 3.1 m/a (Nishida *et al.*, 1995) were obtained near the terminus of Upsala Glacier and at the upper reach of the ablation area of Tyndall Glacier, respectively. At the latter glacier, a thinning rate between 1985 and 1990 was 4.0 m/a (Kadota *et al.*, 1992), and at Soler Glacier (NPI) the rate between 1983−85 was 5.2 m/a (Aniya and Naruse, 1987). Frontal positions of these thinning glaciers have been receding largely (Naruse *et al.*, in press ; Wada and Aniya, 1995).

From the results of the frontal variation and thickness change at Moreno Glacier, we can conclude that this glacier, at least its ablation area, is currently in a steady state.

4.2. Seasonal and short-term flow variations

A steady decrease in the flow velocity was found from late spring or early summer (November) to mid-summer (January, February) at Moreno Glacier (Fig. 4). This result is identical with a seasonal variation in flow reported from many glaciers in the northern hemisphere, in which the velocity reaches its maximum in late May or June (e.g. Hanson and Hooke, 1994), not in July and August (e.g. Andreasen, 1985b). This phenomenon can be explained as follows. After the beginning of the melting season, melt water starts to percolate through veins or channels to the glacier bed. Then the basal water pressure gradually increases so that the basal sliding velocity is enhanced. During the high melting season, since the basal water network has been fully developed and more melt water would be drained away, the basal water pressure becomes lower and the sliding velocity decreases.

From a laboratory experiment, it has been suggested that, when pure water of 0.0°C flows through a vein by gravity, a 1 mm wide vein in ice develops into a water channel of an order of 10 cm in diameter after one month as a result of melting of ice due to the heat converted from the potential energy of flowing water (Koizumi and Naruse, 1994). If the water temperature is higher than 0.0°C due to the absorption of global radiation at the surface, the rate of enlargement of a vein becomes larger. Therefore, at temperate glaciers in Patagonia, water networks within and under glaciers may attain such a condition in late spring to early summer that the basal water pressure becomes highest.

Velocity variations within a few hours (Fig. 5) should also be resulted from the basal sliding variations. After the measurements at four glaciers in the Alps (Iken, 1978), extensive studies on short-term variations in flow have been made (e.g. Iken and Bindschadler, 1986). In these works, the effect of basal water pressure on the sliding velocity was discussed. Especially, during the mini-surges of Variegated Glacier in Alaska, strong correlations were observed between the velocity and the pressure (Kamb *et al.*, 1985 ; Kamb and Engelhardt, 1987). At Soler Glacier (NPI), a good correlation was obtained between the velocity and the amount of water discharge from the glacier terminus (Naruse *et al.*, 1992). From the present study of flow variations at Moreno Glacier, the importance of basal sliding on the glacier dynamics has been further confirmed in Patagonia.

4.3. Annual ablation

An empirical relationship was derived at Moreno Glacier between the cumulative amount of ablation and the cumulative daily mean air temperature. A ratio (k) between these two quantities was obtained as

7.6 (mm-water/°C·day) during 14 days in November 1993 (Takeuchi *et al.*, 1995b). As the ablation was successfully measured over a complete summer, it is expected to derive a more useful relation for a longer period. However, since no temperature data are available in other period than November 1993, temperature data at the meteorological station Lago Argentino (LA) are utilized.

The station LA is located in Calafate (220 m a.s.l.), about 60 km east of the front of Moreno Glacier. Firstly, a correlation of air temperature was examined between LA and the station MS on the glacier (330 m a.s.l.) during the period from 12 to 27 November 1993. A good linear relationship was obtained, in which the daily mean temperature at MS was systematically lower than LA with a mean of about 4°C. This temperature difference is much larger than that due to the elevation difference (110 m). It should be caused by the fact that LA is situated in an arid climate with few cloud-cover conditions while MS is on a large-scale ice of 0°C at all the times.

Secondly, using the above linear relationship, air temperatures at LA was rectified and converted into those at MS from 28 November to 1 March 1994. The cumulative daily mean air temperature was thus obtained and plotted on the abscissa in Fig. 6. A gradient of the solid line in Fig. 6 gives the ratio k. The ratio during 110 days in summer was derived as 6.9 (mm-water/°C·day) which was close to the short-term value of 7.6.

Thirdly, also by rectifying air temperatures at LA throughout the year, the annual cumulative temperature at MS was calculated as 1630°C·day. Then, extrapolating the solid line up to this degree-day value, the annual amount of ablation at 350 m a.s.l. was estimated at about 11.2 m ($\pm$ 1 m) in water equivalent, that is 12.4 m in ice thickness. Because Moreno Glacier is in a steady-state condition, this ablation thickness is compensated by an emergence velocity, that is a velocity component normal to the glacier surface, and the accumulation of new snow. If we can regard the latter to be negligibly small in the ablation area of the temperate glacier, a mean emergence velocity is estimated from the ablation thickness (12.4 m/a) as about 35 mm/day. This speed approximately coincides, accidentally, with the emergence velocity of 40 mm/day at Tyndall Glacier, that was derived from a product of the vertical strain rate and the ice thickness (Nishida *et al.*, 1995).

Assuming that the annual ablation rate decreases linearly with the elevation increase up to the equilibrium line, the total annual amount of ablation in the whole ablation area (75 km^2) of Moreno Glacier is calculated as about 0.59 km^3/a (Naruse *et al.*, in press), which corresponds to a mean ablation rate of about 8 m/a in water equivalent. The annual calving amount of the glacier was roughly estimated as comparable with the annual ablation amount in the ablation area. Then, from a mass-balance consideration of the glacier, the annual net accumulation rate averaged over the whole accumulation area (182 km^2) is estimated as from 6 m/a to 9 m/a in water equivalent, which are much larger than 1.2 m/a in water derived from an analysis of a 13 m deep firn-core obtained at 2 km a.s.l. near the divide of the Moreno Glacier drainage (Aristarain and Delmas, 1993). We consider this low accumulation rate from the firn-core is not representative for the plateau of the icefield.

5. Conclusions

1) Moreno Glacier has been in a steady state during the last half century.
2) Flow velocity is larger in late spring or early summer than mid-summer.
3) Flow velocity shows a maximum value in the afternoon and a minimum in the morning. These flow variations 2) and 3) are resulted from variations in the basal sliding speed.
4) The amount of ablation during 110 days in summer is about 6 m in water equivalent at the middle reach of the ablation area. The annual ablation is estimated as about 11 m in water.

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