Bulletin of Glacier Research 10 (1992) *55 − 62*

Flow of Upsala and Moreno glaciers, southern Patagonia

Renji NARUSE[1], Pedro SKVARCA[2], Tsutomu KADOTA[3] and Ken KOIZUMI[1]

1. Institute of Low Temperature Science, Hokkaido University, Sapporo 060 Japan
2. Instituto Antártico Argentino, Cerrito 1248 Buenos Aires, Argentina
3. Water Research Institute, Nagoya University, Nagoya 464-01 Japan

(Received December 24, 1991 ; Revised manuscript received February 28, 1992)

Abstract

Ice-flow velocities were obtained in November 1990 at two glaciers located on the eastern side of the Southern Patagonia Icefield. Near the terminus of Upsala Glacier, flow-velocity was 3.5 m/d and 3.7 m/d, while at Moreno Glacier, it ranged from 1.9 m/d to 2.1 m/d along a longitudinal line in the middle reach of the ablation area, and was about 5 m/d at the calving front. Distributions of velocities and strain rates were discussed with the topographic features of Moreno Glacier. Based on the surface patterns of medial moraines on Upsala Glacier, the dynamical behavior of the tributary Cono Glacier was analyzed and deduced to be in a nearly stagnant condition.

1. Introduction

Only few studies have ever been attempted on the flow of glaciers in the Patagonia Icefield (Hielo Patagônico) which covers the southern part of the Andes from 46°30'S to 51°30'S over South America. By simple survey methods, measurements of glacier flow were made at some selected glaciers (*e.g.* Raffo *et al.*, 1953 ; Marangunić, 1964 ; Naruse and Endo, 1967 ; Enomoto and Abe, 1983). Detailed surveys of flow-velocity using an electronic distance meter were first carried out in 1983 at Soler and San Rafael glaciers in the Northern Patagonia Icefield (Naruse, 1985). During the early summer of 1985, ice-flow velocities were again measured on the ablation area of Soler Glacier (Naruse, 1987), with the results including down-glacier decrease in the velocity from 1.5 m/d at the foot of the icefall to 0.2 m/d near the terminus. Short-term variations in flow velocity were also obtained at intervals of a few hours or a few days. The maximum flow rate was found to be about four times the minimum value. Naruse *et al.* (1992) concluded that the velocity variations should have resulted from variations in basal sliding velocity which was strongly controlled by the subglacial water pressure.

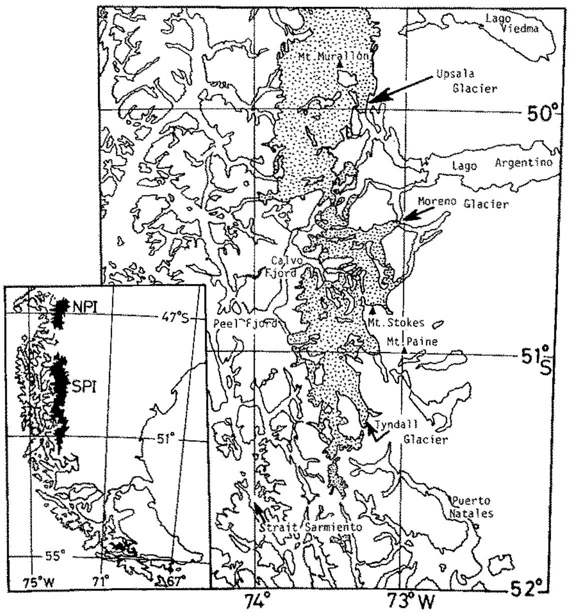

Fig. 1. Map of the southern part of the Southern Patagonia Icefield in South America.

Upsala Glacier flows southward from the eastern part of the Southern Patagonia Icefield (SPI : Hielo Patagônico Sur) and calves into the northwestern bay of Lago (Lake) Argentino at 50°S and 73°20'W (see Fig. 1). Moreno Glacier flows eastward from the eastern part of the SPI and calves into the southwestern bay of Lago Argentino at 50°30'S and 73°W. Topographic characteristics and recent variations of these glaciers are described in detail in the separate reports (Naruse and Aniya, 1992 ; Aniya and Skvarca, 1992).

The purpose of this paper is to present the results of the ice-flow velocities measured during a short period of a few days in November 1990 at Upsala and Moreno glaciers, and to discuss the dynamical characteristics of these glaciers.

2. Method of measurements

At Upsala Glacier, a control station and an azimuth point were established at about 600 m a.s.l. on the eastern (left-side) bank about 2.5 km from the present glacier terminus. An electronic distance meter (Topcon EDM-Theodolite Guppy) was set up at the control station, and an EDM reflector was placed temporarily at survey points in the ablation area. From the control station, distances and horizontal/vertical angles to survey points were measured. The first survey was made on 14 November 1990 at six points along a transversal line from the left margin to the medial moraine located at about one half of the glacier width of about 4 km, as shown in Fig. 2. Heavy crevasses and seracs were distributed almost all over the ablation area. Hence all the survey points were selected on the top of relatively flat ice ridges. Stakes 1.5 m long were installed in drilled holes at survey points. During the period from 15 to 17 November, it was occasionally rainy with extremely strong winds and poor visibility due to low clouds. The second survey was made on 18 November, although winds were still so strong to set stably the tripod with EDM at the control station. Among the six survey points, four stakes were blown away and lost. Two stakes were found to lay down on the glacier surface, but the relics of the drilled holes were recognized near the stakes. Two sets of coordinates of the two points were determined with an interval of four days.

At Moreno Glacier, a control station and an azimuth point were established at about 420 m a.s.l. on the southern (right-side) bank about 5 km from the median tip of glacier terminus which reaches the

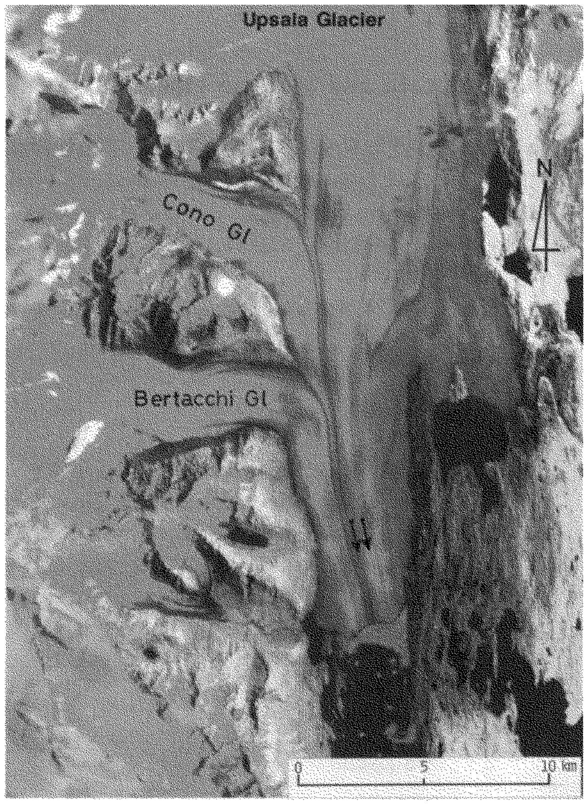

Fig. 2. Landsat TM image of the middle and lower reach of Upsala Glacier taken on 14 January 1986. Two medial moraines are clearly recognized along the bouders of three ice bodies, i.e. the main Upsala Glacier, the tributary Cono Glacier and Bertacchi Glacier.

Arrows marked near the glacier terminus indicate surface flow velocities, 3.5 m/d and 3.7 m/d, measured with an interval of four days in November 1990.

opposite bank (Península Magallanes). Method and procedure of surveys were the same as those at Upsala Glacier. The first and the second surveys were successfully made on 25 and 26 November, respectively. A chain of six survey points was set up along a transversal line 1.5 km long from the right margin to the median line and another 1.5 km long chain of six points was set up longitudinally along the median line where a thin medial moraine developed. There were no large crevasses along the survey lines ; however, the glacier surface was undulating with the range from 10 to 20 m and several water ponds existed on the ice surface. Two sets of coordinates of all points were determined with an interval of about 24 hours.

Also a short base line, about 160 m long, was established on the southern beach of the lake into which Moreno Glacier discharges. Aiming at distinguished tips of seracs on the surface of the frontal portion of the glacier, flow velocities were also measured by the triangulation method. The first and the second surveys were carried out in the morning and in the afternoon of 28 November with an interval of about 8 hours.

3. Results of measurements

3.1. Upsala Glacier

Surface flow velocities at two points near the medial moraine are shown by arrows in Fig. 2. Velocities of 3.5 m/d and 3.7 m/d are considerably large, compared with values from 0.2 m/d to 2 m/d measured in summer at Soler Glacier (Naruse, 1987) and at Tyndall Glacier (Naruse *et al.*, 1987). The high flow velocity of Upsala Glacier may be attributed to the rapid basal sliding enhanced by the existence of abundant water at the glacier bed which was supplied by extensive melting of surface ice. Actually, during the observation period from 14 to 18 November, it was very warm with air temperatures from +6°C to +20°C near the glacier terminus, and was extremely windy and rainy as well.

3.2. Moreno Glacier

Distribution of flow velocities is shown by arrows in Fig. 3. The longitudinal profile of the glacier surface, the flow velocity and the longitudinal strain rate are shown in Fig. 4. The longitudinal strain rates were obtained from the gradients of surface velocities along the glacier flow. A positive sign indicates an extension and a negative sign a contraction. The mean velocity of 2.0 m/d was obtained in this longitudinal survey line.

Also, the transversal profile of the glacier surface, the flow velocity and the transverse strain rate are shown in Fig. 5. Since the survey points were aligned approximately transversal to the flow direction, the transverse strain rates were calculated from the

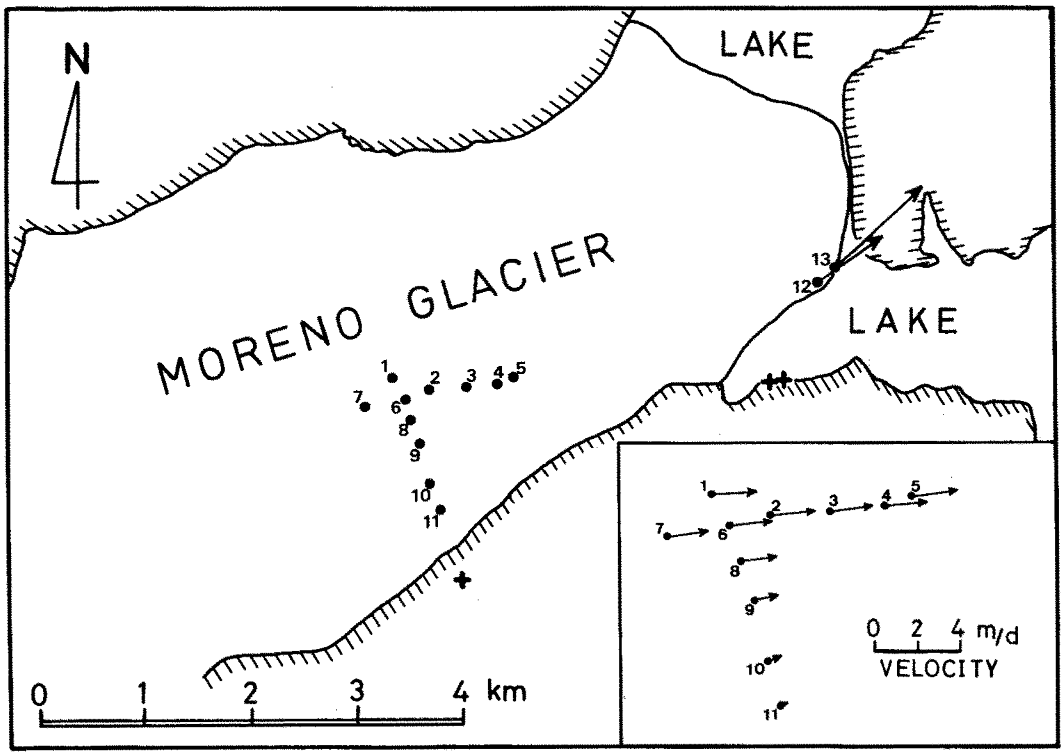

Fig. 3. Lower reach of Moreno Glacier. Solid circles with numbers 1 to 13 indicate the survey points M1 to M13. Arrows show surface flow velocities measured with an interval of one day in November 1990. Marks + indicate control stations.

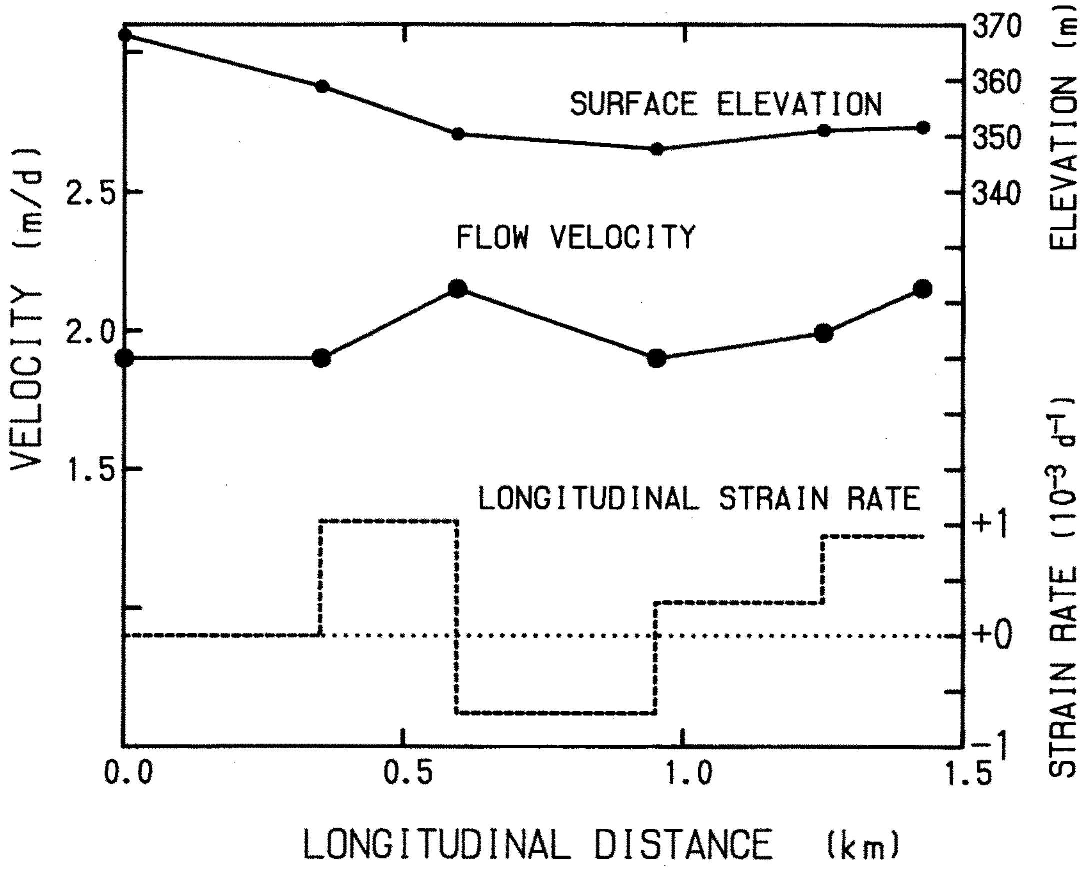

Fig. 4. Longitudinal profiles of the glacier surface, the surface flow velocity and the longitudinal strain rate measured in November 1990, along the median line in the middle reach of the ablation area of Moreno Glacier. From left to right, survey points M7, M6, M2, M3, M4 and M5.

changes in the distance between the neighboring survey points. The surface is almost flat in the survey line from M1 to M11 (about 0.5 km from the right margin), and from M11 it lowers steeply toward the right margin. The flow velocity decreased linearly with distance from the median part to the right margin.

As indicated in Fig. 3, large velocities of 5.4 m/d and 3.4 m/d were obtained near the calving right-hand edge of the glacier front. However, these values may contain much larger errors than those measured at the middle reach, because of the difficulty in correct positioning of targets (tips of seracs), very narrow triangles used for the triangle calculations, and a considerably short time interval between measurements. Heights of the two measured points were obtained to be 55 m and 57 m, respectively, above the present lake level.

4. Discussion

4.1. Distribution of flow velocities and strain rates at Moreno Glacier

The survey lines in the middle reach of Moreno Glacier were selected on the bare ice with less crevasses. The surface slopes are relatively gentle as seen in Figs. 4 and 5. It is noticed from Fig. 4 that the surface slope from points M7 to M2 is about 1/30, whereas that from M2 to M5 is nearly zero or even upslope to the downglacier direction. The surface velocity increases slightly from 1.90 m/d at M3 to 2.15 m/d at M5, which indicates a longitudinal extension

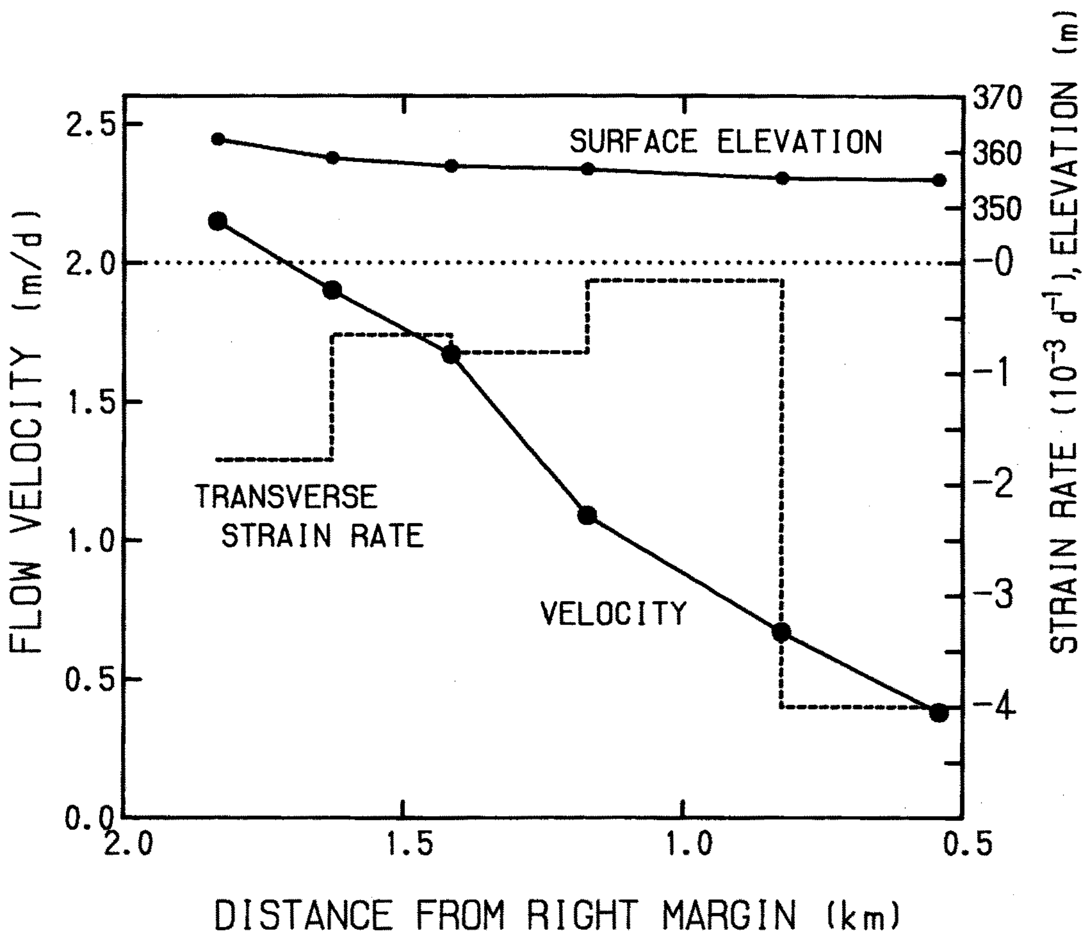

Fig. 5. Transversal profiles of the glacier surface, the surface flow velocity and the transverse strain rate measured in November 1990, in the middle reach of the ablation area of Moreno Glacier. From left to right, survey points M1, M6, M8, M9, M10 and M11.

as shown in Fig. 4. In the area downglacier from M5, it was observed that the surface slope becomes steeper with numerous large crevasses. Based on this information, we can infer a step in bedrock around point M5.

A large transverse compression was observed between points M10 and M11 as shown in Fig. 5. This may be due also to the bedrock topography. The existence of many large crevasses just upglacier from M10-M11 is considered to be related to this strain pattern.

Points M7, M1, M2 and M8 form a quadrangle with an approximate center at M6. A mean longitudinal strain rate of $+0.51\times10^{-3}$ d^{-1} was obtained along M7-M6-M2 and a mean transverse strain rate of -1.2×10^{-3} d^{-1} was obtained along M1-M6-M8 (see Figs. 4 and 5). Since we can assume the incompressibility of glacier ice, the vertical strain rate is calculated from the above values to be $+0.69\times10^{-3}$ d^{-1}, which corresponds to $+0.25$ a^{-1} when we convert it to the annual strain rate. This vertical extension results in an emergence component of ice flow. If we assume that vertical strain rate does not vary with depth, the strain rate is equal to the annual ablation amount divided by the thickness of glacier in a steady state condition (see subsection 4.3.). So if we know one of the two parameters, the other can be estimated.

4.2. Comparison with previous measurements at Moreno Glacier

Forty years ago, the surface movement of Moreno Glacier was measured (Raffo *et al.*, 1953), along a transversal profile located at approximately 5.5 km from the glacier front, *i.e.* less than 1 km further upglacier from the present survey line. Of the 22 stakes set up and measured in the end of November 1948, covering about two-thirds of the glacier width starting from the northern (left) margin, only 10 stakes were found and their positions were re-measured 491 days later. These measurements cover two complete summers (1948−49 and 1949−50) and one winter (1949). Therefore, the data obtained seem to be more representative than the present results measured within a short time interval of one day. Although we cannot evaluate the accuracy or reliability of their results, because there are unfortunately no descriptions about how the stakes were maintained during more than one year and which instruments and methods were used for the velocity measurements, we attempt a crude comparison with our results.

According to Raffo *et al.* (1953), the mean annual flow velocity increases gradually from 100 m/a at 0.5 km from the left margin to 965 m/a as a maximum at the center of the glacier, 2.5 km from the margin. If we assume the steady flow throughout the year, the velocity at the center corresponds to 2.6 m/d which is slightly larger than the present value of 2.2 m/d. In general, the flow velocity decreases gradually along the flow in the ablation area of a valley glacier. Therefore, when we take into account the fact that the survey line 40 years earlier is closer to the equilibrium line, the difference in two velocities seems to be reasonable. From these estimative arguments, the flow regime of Moreno Glacier may not have changed remarkably during these several decades. This result supports glacier characteristics obtained by Aniya and Skvarca (1992) that Moreno Glacier itself has recently been almost in a stable condition and only the terminus portion of the glacier has fluctuated.

4.3. Dynamical behavior of tributary glaciers of Upsala Glacier

— Cono and Bertacchi glaciers —

In Fig. 2, we can notice a curious pattern of medial moraines on Upsala Glacier. One medial moraine originates from the junction of the main Upsala Glacier and Cono Glacier, and another medial moraine originates from the junction of Cono and Bertacchi glaciers. The spacing between the two moraines becomes remarkably narrower in the area 12 km to 9 km upglacier from the glacier front in 1986. A medial moraine is a belt of glacial till and debris on the glacier surface, which extends downglacier from a junction of two tributaries. A medial moraine is therefore considered to delimit the boundary between two tributary ice bodies, and to represent a surface streak line which coincides with a surface flow line if the glacier is in a steady state. If we assume that the boundary of the two ice bodies extends vertically underneath the medial moraine, a consideration based on the mass continuity along the glacier flow provides an interesting insight on the dynamical behavior of the two glaciers. If this assumption does not hold, namely the boundary of ice bodies inclines steeply to form an ice body being narrower in the upper layer and wider in the deeper layer, then the transverse stress patterns should be greatly different with the depth of the ice body. However, this situation is hard to imagine in general.

Widths of Cono and Bertacchi glaciers were measured from the spacings of medial moraines seen in Fig. 2, and their variations against the distance from the glacier front are shown in Fig. 6. Bertacchi Glacier shows a gradual variation in glacier width, whereas Cono Glacier exhibits a steep decrease in width at the midstream reach of the ablation area. The width changes from about 2700 m at 17 km to about 100 m at 9 km, that is a narrowing of about 1/30.

Here we take x axis along the glacier flow positive downglacier, y axis normal to the glacier surface positive upward, and z axis transverse to the glacier flow. The x and y components of the flow velocity are denoted by u and v. Now we assume that a transverse strain rate $\dot{\varepsilon}_z$ does not change with z, and a vertical strain rate $\dot{\varepsilon}_y$ does not change with y. This assumption holds approximately in glaciers, except for regions with steep surface and bedrock slopes or with large curvatures in flow directions. Then, strain rates $\dot{\varepsilon}_z$ and $\dot{\varepsilon}_y$ can be expressed by

$$\dot{\varepsilon}_z = \partial W/(W\ \partial t) = (u/W)(\partial W/\partial x), \tag{1}$$

$$\dot{\varepsilon}_y = v_s/I, \tag{2}$$

where W and I are the width and the thickness of a glacier at x, respectively, and v_s is the vertical velocity at the surface. We can assume the incompressibility of glacier ice, so that a longitudinal strain rate $\partial u/\partial x$ is given as

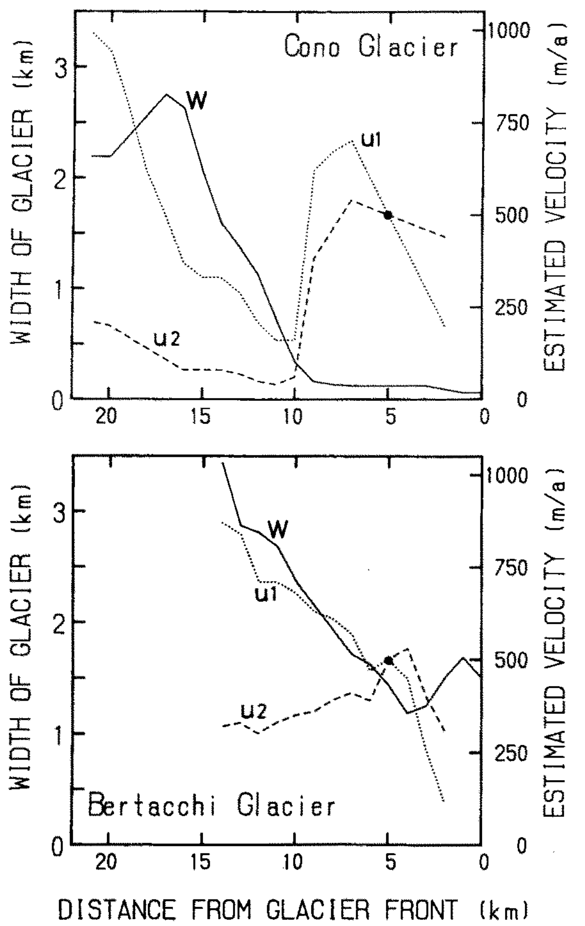

Fig. 6. Variations in the width of glacier (W) and calculated flow velocities (u_1 and u_2) plotted against the distance from the glacier front (in 1986) for Cono Glacier and Bertacchi Glacier. For u_1, the vertical strain rate (b/I) was assumed as $+0.1\ a^{-1}$; and for u_2, it was assumed as $+0.02\ a^{-1}$. Solid circle indicates the adopted boundary condition, that is $u=500$ m/a at 5 km from the glacier front.

$$\partial u/\partial x = -\dot{\varepsilon}_y - \dot{\varepsilon}_z. \tag{3}$$

If we assume a glacier is in a steady state, it follows that v_s is equal to the annual ablation rate b. Then, from equations (1), (2) and (3),

$$\partial u/\partial x = -b/I - (u/W)(\partial W/\partial x) \tag{4}$$

is obtained.

Now W and $\partial W/\partial x$ are known in both Cono and Bertacchi glaciers, as shown in Fig. 6. If we know one velocity value as a boundary condition, and if we regard b/I as a variable parameter, we can calculate the distribution of u with x by using equation (4).

The surface velocity 3.7 m/d measured near the medial moraine at a point 4 km up from the glacier front corresponds to 1350 m/a. However, this value was obtained in early summer and it should be much larger than the annual mean velocity. On the aerial photographs taken in November 1968 and March 1970, a distinguishable lump of debris was found on the medial moraine at about 4–5 km from the glacier front. Regarding the lump as a marker which moves with the surface ice, Aniya and Skvarca (1992) estimated the mean annual flow velocity as about 700 m/a. Then we assume here the boundary condition of u averaged over the depth to be 500 m/a at a point 5 km from the glacier front.

The parameter b/I is selected as follows, because we have no measurements of either b or I at Upsala Glacier. At the ablation area of Soler Glacier, the vertical strain rate was deduced from the velocity distribution to have a considerably large value of about $+0.1\ a^{-1}$ (Naruse, 1987), and the ice thicknesses were estimated by the gravity method to range from 100 m to about 550 m (Casassa, 1987). Assuming the mean thickness of the glacier as 300 m, the annual amount of ablation can be estimated to be on the order of 30 m/a. The thickness of Tyndall Glacier was measured by a radio-echo sounder to be 620 m at a point close to the median line (Casassa, 1992). Referring to these data, we can estimate the maximum and minimum values of b/I of Upsala Glacier. If we adopt 15 m/a as the annual ablation b and 800 m as the ice thickness I, then the vertical strain rate becomes $+0.02\ a^{-1}$. If we adopt 30 m/a as b and 300 m as I, then the vertical strain rate becomes $+0.1\ a^{-1}$. We now calculate the distribution of u both in Cono and Bertacchi glaciers, assuming the above two extreme values.

Results of calculations are shown in Fig. 6, by a broken line (u_2) and a dotted line (u_1) for both Cono and Bertacchi glaciers. The boundary value of $u=500$ m/a is indicated by a solid circle as an intersection of two lines. Although the range of velocity between u_1 and u_2 at Bertacchi Glacier is considerably wide in the region around 15–7 km from the glacier front, the longitudinal velocity variation seems to be relatively smooth and gentle. Therefore, this glacier is considered to be active. On the other hand, at Cono Glacier, the estimated velocities in two cases with the extreme values of b/I sharply drop below about 150 m/a in the region from about 12 km to 9 km, and rise again in the downstream area. This remarkable result indicates that the middle reach of the ablation area of Cono Glacier is now in a nearly stagnant condition. We can further speculate that the middle reach is now thinning and the upstream part of Cono Glacier may separate from the main Upsala Glacier in the near future.

We have no detailed information or estimation on the time when this near stagnation behavior of Cono Glacier has begun. However, based on the vertical aerial photographs of Upsala Glacier taken by the Argentine agency in November 1968 and March 1970, the spacing between two medial moraines was measured to be approximately 150 m around 5 km from the present glacier front. This result showed a narrowing from about 150 m to 100 m during the last two decades. These phenomena should be related with the recent remarkable retreat of Upsala Glacier revealed from ground survey and satellite data analyses (Aniya and Skvarca, 1992 ; Aniya and Naruse, 1991).

5. Concluding remarks

Flow velocities were firstly measured at Upsala Glacier, although only at two points. The relatively large velocity of 3.6 m/d in the early summer was considered to be caused by strong basal sliding of the glacier. At Moreno Glacier, the present results of velocity distribution were compared with previous values obtained 40 years ago, suggesting that the glacier has been more or less in a steady state. The surface pattern of medial moraines on Upsala Glacier enabled us to conclude that the tributary glacier (Cono) is at present close to a stagnant condition.

These results, though only preliminary ones, should provide basic information to further work on Patagonian glaciers in the future.

Acknowledgment

This study was supported by the grant of International Scientific Program (No. 02041004 : led by R. Naruse) of the Ministry of Education, Science and Culture, Japan.

References

1. Aniya, M. and Naruse, R (1991) : Studies on glacier and snow-cover variations in South America utilizing satellite data – Glacier variations in the Southern Patagonia –. In *Better Understanding of Earth Environment via Satellite,* the Second Symposium in the fiscal year of 1990, 174–179 (in Japanese).
2. Aniya, M. and Skvarca, P. (1992) : Characteristics and variations of Upsala and Moreno glaciers, southern Patagonia. Bulletin of Glacier Research, **10**, Japanese Society of Snow and Ice, 39–53.
3. Casassa, G. (1987) : Ice thickness deduced from gravity measurements at Soler Glacier, Nef Glacier and the Northern Patagonia Icefield. Bulletin of Glacier Research, **4**, Japanese Society of Snow and Ice, 43–57.
4. Casassa, G. (1992) : Radio-echo sounding of Tyndall Glacier, southern Patagonia. Bulletin of Glacier Research, **10**, Japanese Society of Snow and Ice, 69–74.
5. Enomoto, H. and Abe, Y. (1983) : Reconnaissance studies of meteorology and glaciology in Steffen and Jorge Montt Glacier, Patagonia. *Glaciological and Meteorological Studies in Patagonia, Chile, by Japanese Research Expeditions in 1967–1982.* Research Committee on Patagonian Glacier, Japanese Society of Snow and Ice (JSSI), 11–14.
6. Marangunić, C. (1964) : Observaciones glaciológicas y geológicas en la zona del Paso de los Cuatro Glaciares, Hielo Patagónico Sur. Tesis para optar al título de Geólogo, Universidad de Chile, Santiago, 125p (unpublished).
7. Naruse, R. (1985) : Flow of Soler Glacier and San Rafael Glacier. Glaciological Studies in Patagonia Northern Icefield, 1983–1984. Data Center for Glacier Research, JSSI, 64–69.
8. Naruse, R. (1987) : Characteristics of ice flow of Soler Glacier, Patagonia. Bulletin of Glacier Research, **4**, Japanese Society of Snow and Ice, 79–85.
9. Naruse, R. and Aniya, M. (1992) : Outline of Glacier Research Project in Patagonia, 1990. Bulletin of Glacier Research, **10**, Japanese Society of Snow and Ice, 31–38.
10. Naruse, R. and Endo, T. (1967) : Glaciological investigations of northern Patagonian glaciers, Chile. (in Japanese with English abstract). *Seppyo,* **29**, No. 6, 167–176.
11. Naruse, R., Fukami, H. and Aniya, M. (1992) : Short-term variations in flow velocity of Glaciar Soler, Patagonia, Chile. Journal of Glaciology, **38**, No. 128 (in press).
12. Raffo, J.M., Colqui, B.S. and Madejski, M.E. (1953) : Glaciar Moreno. Dirección General del Servicio Meteorológico Nacional, Publicatión No. 9, Buenos Aires, República Argentina, 293–311.