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Recent thinning, retreat and flow of Upsala Glacier, Patagonia

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Abstract

In late November 1993, the surface elevation of Upsala Glacier, southern Patagonia, was remeasured along a transverse profile located about 1 km from the present glacier front. Repeated geodetic measurements show a significant average surface lowering of 33 m during the period 1990–93, namely a mean thinning rate of 11 m/a. The position of the glacier terminus, calving into the western arm (Brazo Upsala) of Lago Argentino, was also surveyed in the field. The comparison with the position in 1990 indicates a large recession of around 1200 m (400 m/a), except at the western margin that remained almost stationary. This shows a recent accelerated rate of the retreat initiated in 1981.

Between November 22 and 28, surface ice flow velocities were measured along approximately the same transverse profile at hourly and daily time intervals. Velocities ranged from 1.56 m/day near the east margin, increasing to 4.44 m/day towards the glacier center line. No significant changes in velocities were observed for the different time intervals. Ablation rates measured during the six days at seven points yielded a mean value of 5.8 cm/day.

1. Introduction

Excluding the Antarctica, the Southern Patagonia Icefield (SPI) is by far the largest ice body in the Southern Hemisphere, with 13,000 km^2 in extent (Aniya *et al.*, 1992). Despite this fact and though these glaciers represent the most typical temperate glaciers in the world due to large accumulation and ablation rates (Naruse and Aniya, 1992), the knowledge of basic glaciological features in Patagonia is still very poor (Warren and Sugden, 1993).

The contribution of melting of temperate glaciers and ice caps or icefields is of importance to the eustatic sea-level change. Meier (1985) pointed out almost absolute lack of mass balance data from the Patagonian icefields. The mass loss from these icefields is without doubt significant, considering a decrease of 500 km^2 in the SPI area and the surface lowering of more than 100 m at ablation areas of some glaciers from 1945 till 1986 (Aniya *et al.*, 1992). Moreover, the knowledge on run-off from the SPI and its outlet glaciers to the east is essential for future water management in the Patagonian semi-desert regions, where precipitation is on the order of only a few hundred millimeters per year. Therefore, the contribution of glacier melting, estimated for Moreno Glacier at about 11 m/a in water equivalent (Naruse *et al.*, 1995), is very significant in terms of water resource for this region.

The Glaciological Research Project in Patagonia (GRPP), initiated in 1990 between Japan, Argentina and Chile (Naruse and Aniya, 1992), with aims to clarify the processes and mechanisms of temperate glacier variations in response to climatic changes, has provided valuable data related to the above mentioned aspects. As part of the GRPP, glaciological studies began at Upsala Glacier (Fig. 1) in November 1990. The glacier calving into Brazo Upsala of Lago Ar-

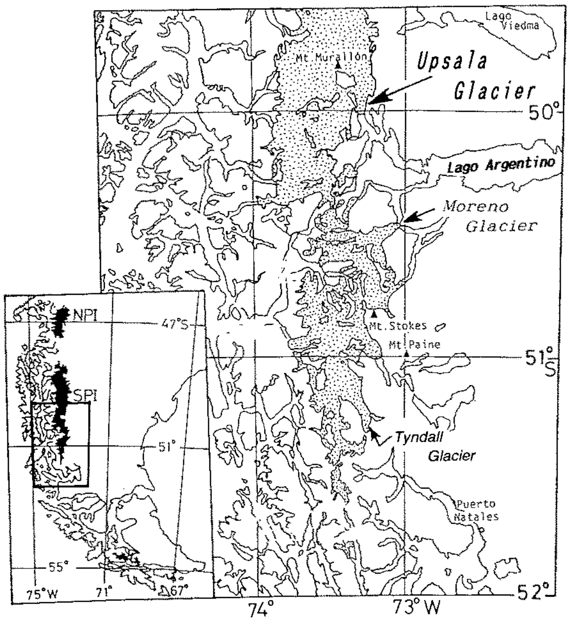

Fig. 1. Map of the southern part of the Southern Patagonia Icefield and location of Upsala Glacier. Dotted area indicates the icefield or outlet glaciers.

gentino as shown in Fig. 2, is a major SPI outlet glacier with 870 km^2 in the drainage area. The glacier variation from 1960 to 1990 and their characteristics have been described by Aniya and Skvarca (1992), and Naruse *et al.* (in press), suggesting that this glacier is very sensitive to climatic changes according to the present position of the equilibrium line altitude (ELA) on a hypsometric curve.

The aim of this paper is to describe the glaciological field survey carried out at Upsala Glacier in late November 1993, and to present the results on surface lowering and glacier retreat which occurred between 1990 and 1993, as well as the ablation rates and short-term velocity fluctuations measured at hourly and daily time intervals during six days.

2. Field measurements

2.1. Surface elevations and flow velocities

Field surveys were carried out between November 21 and 29, 1993. As the weather condition was excellent on November 21, the first survey was devoted to remeasure the elevation of the glacier surface along the transverse line near the glacier

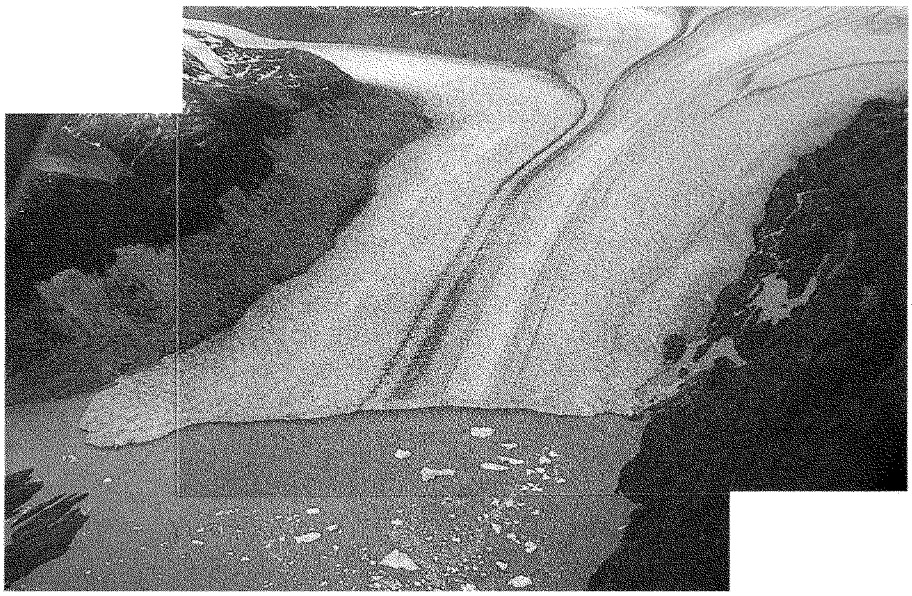

Fig. 2. Oblique aerial photograph of Upsala Glacier taken on January 8, 1993. The tributaries from west (right glacier margin) to east (left margin) are : Bertacchi Glacier, Cono Glacier, Murallón Glacier and the main ice inflow from the Upsala -Viedma divide. Volcanic ash bands are visible on the upper right corner of the picture.

front. Of a total of eight points (U1 – U8) surveyed on November 14, 1990 (Naruse *et al.*, 1992), seven points (U1' – U7' : shown in Fig. 3) were relocated by conventional survey methods. The measuring procedure and the instrument (EDM : TOPCON ET – 2) were the same as in 1990. A team stationed with an EDM at the Control Station (CS), located on an eastern high ridge about 134 m above the present lake level, guided another team over the glacier to place an EDM reflector. Due to severely broken glacier surface (Fig. 4), the re-setting of the 1990 coordinates was not an easy task. When the exact location of the 1990 points could not be reached as they were located within crevasses (points U5', U6' and U7'), the reflector was set on the top of the crevasse edges as close as possible to the 1990 position. The height difference between the edge and the bottom of the crevasse was estimated in situ. A striking feature observed was a ridge protruding the glacier surface (Figs. 4 and 5), that was not visible in 1990, and was now flanked on its western side by the glacier and a wide water channel developed along its eastern side.

On November 22, seven stakes for velocity and ablation measurements were installed on the top of ridges along the above survey line. Despite the very complicated terrain, the markers were visited and measured every day until November 28, except for one rainy day. As a steam drill was available, a hole more than 13 m deep was drilled on November 24, for long-term ablation and ice flow measurements. Aluminum stakes of 2.5 cm in diameter, connected in 2 m sections and painted in different colors were left at a station Px (Fig. 3).

2.2. Ice-front and lateral channel topographies

Because no aerial photographs or satellite images are available since 1986, the present front position was measured by means of a conventional resection survey to prominent points at the glacier terminus and the east margin water channel on November 26, 27 and 29. All selected features were clearly identifiable from each end of the extended baseline located at the

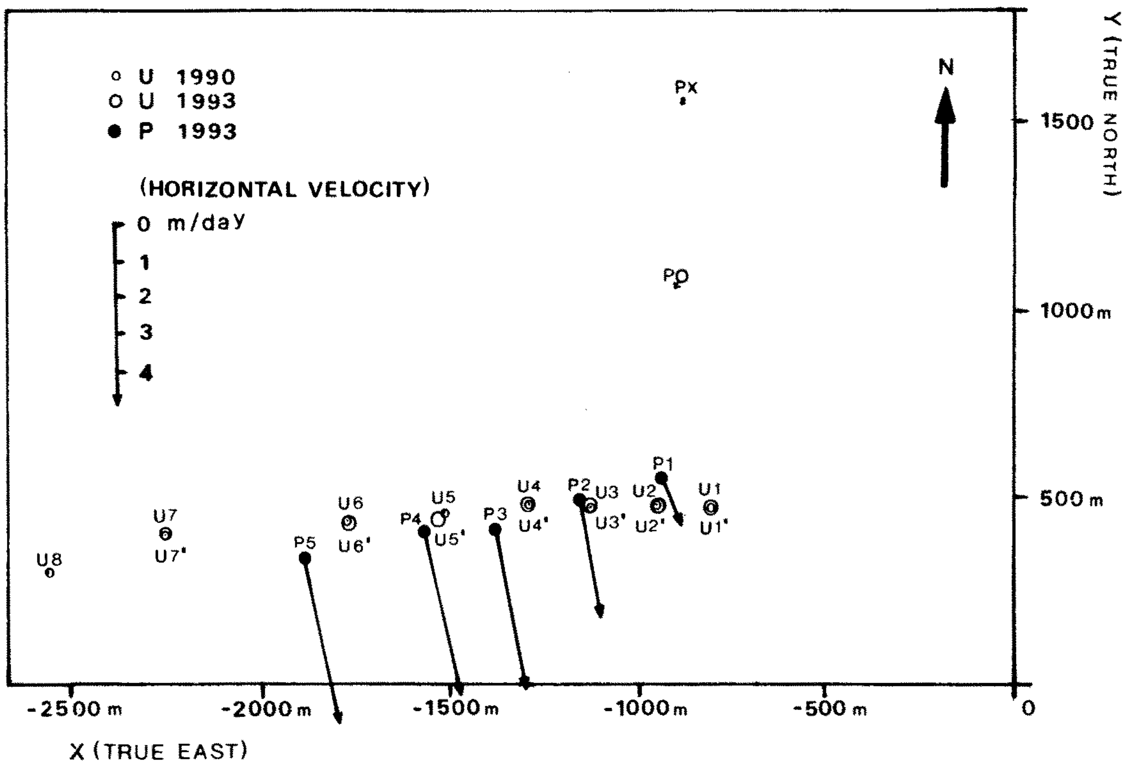

Fig. 3. Locations of profile survey points (U), and mean daily ice-flow velocities during November 22 – 28 at the seven points (Px, P0, and P1 – P5). The origin of the coordinates is taken at the Control Station on the left (eastern) bank.

Upsala Glacier, Left Margin

November 16, 1990

November 27, 1993

Fig. 4. Photographs of the lower reach of Upsala Glacier taken from the Control Station on the eastern bank in 1990 and 1993 (Photos by M. Aniya). Note a wide water channel developed since 1990 between the left glacier margin and the eastern bank, and also a bare-rock ridge seen along the left glacier margin in 1993, which was almost covered by ice in 1990.

eastern margin along a ridge running south-north. The true North was obtained by a compass and the magnetic declination correction. The absolute positions of the CS and two points along the lobe-like western margin were measured on November 29 by a GPS, Trimble Pathfinder Basic receivers. The same receivers were used in the differential mode (1−5 m accuracy) to measure the relative positions of Px, top of the ridge (R in Fig. 5) and the ice-rock contact at the easternmost front. The WGS−84 coordinates were transformed into the local Datum System.

A significant retreat between 1990 and 1993 occurred probably during the austral winter 1992. Luciano Pera (personal communication), during a flight to Estancia Cristina, observed big icebergs almost totally covering all Brazo Upsala. This information prompted the first author to make a field trip to the area in January 1993. An attempt to enter by a boat into Canal de las Amēricas was frustrated due to very heavy broken ice and icebergs. On the next day it was only possible to reach the eastern side margin after several attempts. On January 8 the aerophotographic reconnaissance survey allowed to obtain the oblique photographs shown in Fig. 2.

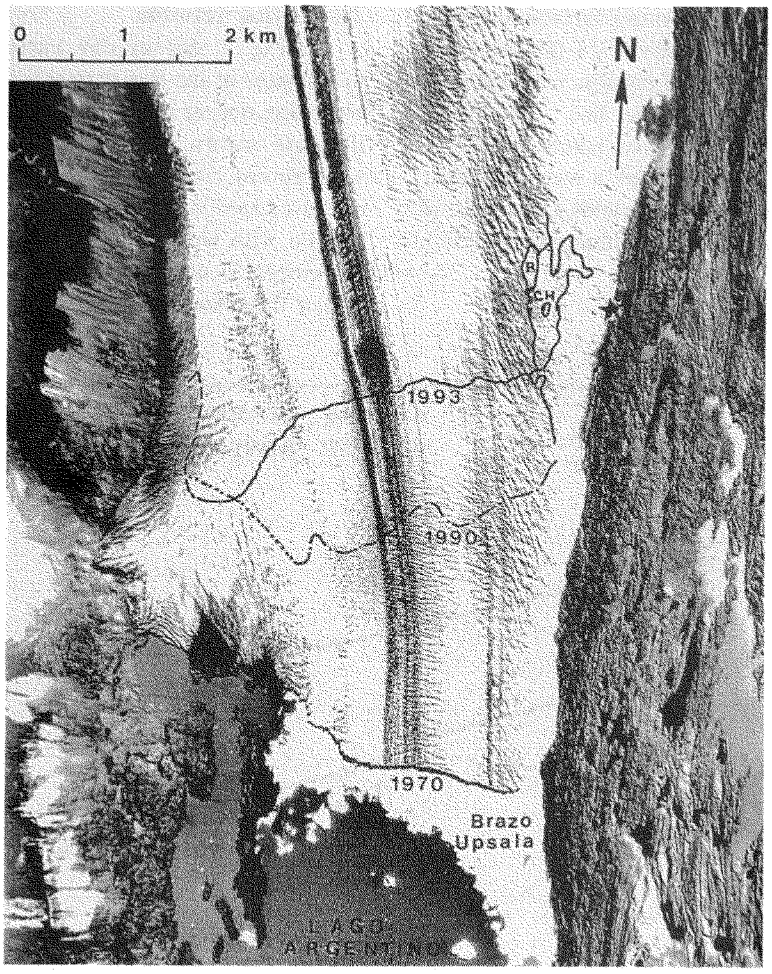

Fig. 5. Vertical aerial photograph obtained in March 1970 by Instituto Geogrāfico Militar (IGM), Argentina. The approximate 1990 terminus position was obtained in the field during GRPP−1990. The 1993 terminus position, the lateral channel (CH) developed recently along the eastern glacier margin, and the ridge (R) were surveyed by the conventional methods with the aid of GPS receivers. An asterisk at the border between the eastern bank and the 1970 side margin of the glacier indicates the Control Station (CS) used for surveys in 1990 and 1993.

3. Results of measurements

3.1. Surface lowering

The surface cross-profiles as measured on November 14, 1990 and on November 21, 1993, are plotted in Fig. 6. A dashed line of 1993 represents elevations of the points, of which exact relocations were impossible since they were located within crevasses. Therefore their vertical coordinates are estimates. The solid line of 1993 shows elevations measured at crevasse edges, which were used for calculating the average change of the surface level between the two dates. The comparison of the 1993 and 1990 profiles indicates more pronounced surface lowering (on the order of 40 m) at the points U1−U1' and U2−U2' that are close to the glacier margin, with a steady decrease towards the glacier center line. Though an arithmetical mean over the seven points is 35.5 m difference between the two profiles, a weighted mean with spacings between the points yields a decrease of 33.3 m during three years, *i.e.* a thinning rate of 11.1 m/a.

3.2. Front retreating

Survey results of the frontal position of Upsala Glacier were transferred onto the 1970 aerial photograph, and the frontal fluctuations between 1970 and 1993 are shown in Fig. 5. Since the frontal position near the western margin in 1990 (Aniya and Skvarca, 1992) was estimated from ground photographs, it may not be accurate and is, therefore, shown with a dotted line. A large frontal retreat of around 1200 m (400 m/a) on average was found during the last three years, except at the western margin which probably remained stationary.

3.3. Ice-flow velocities

In Fig. 7, day-by-day variations in horizontal coordinates of the five survey points along the transverse line during a period from November 22 to 28, 1993 are shown. The directions of displacements were almost constant with time. Daily flow velocities are listed in Table 1. Except for the data at Px and Po with small velocities, and at P2 and P4 on November 26 obtained with short time-intervals of two or three hours, the day-by-day fluctuations were

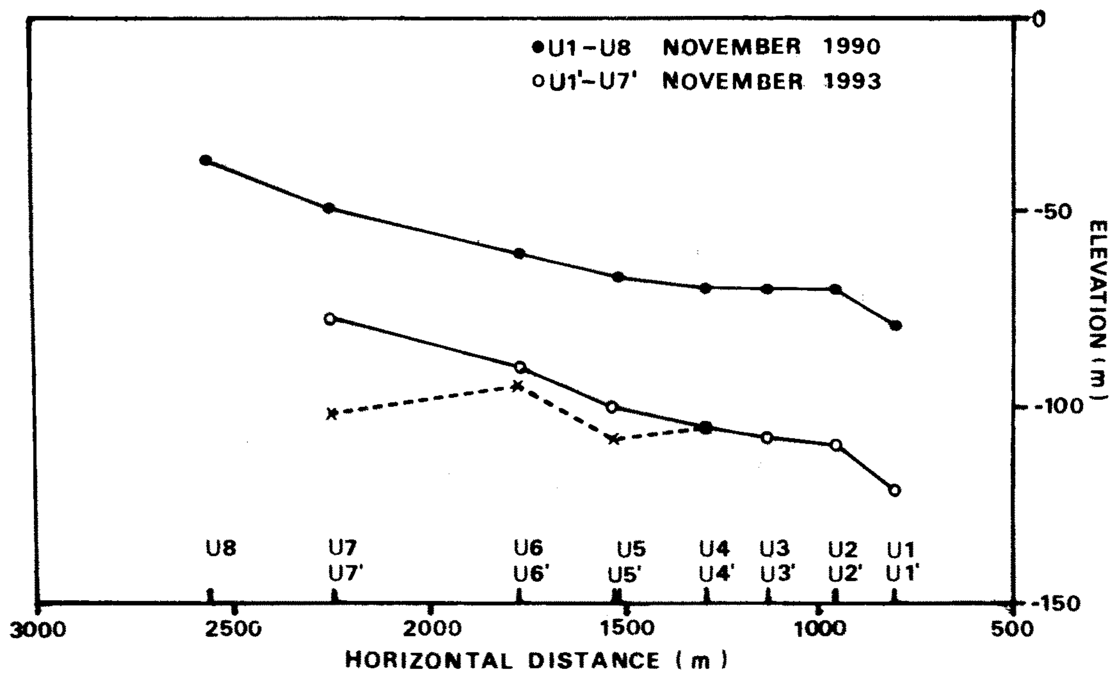

Fig. 6. Changes in surface elevations at Upsala Glacier between November 14, 1990 (solid circles) and November 21, 1993 (open circles). The ordinate indicates the relative elevation to the Control Station (CS) and the abscissa the horizontal distance from the CS.

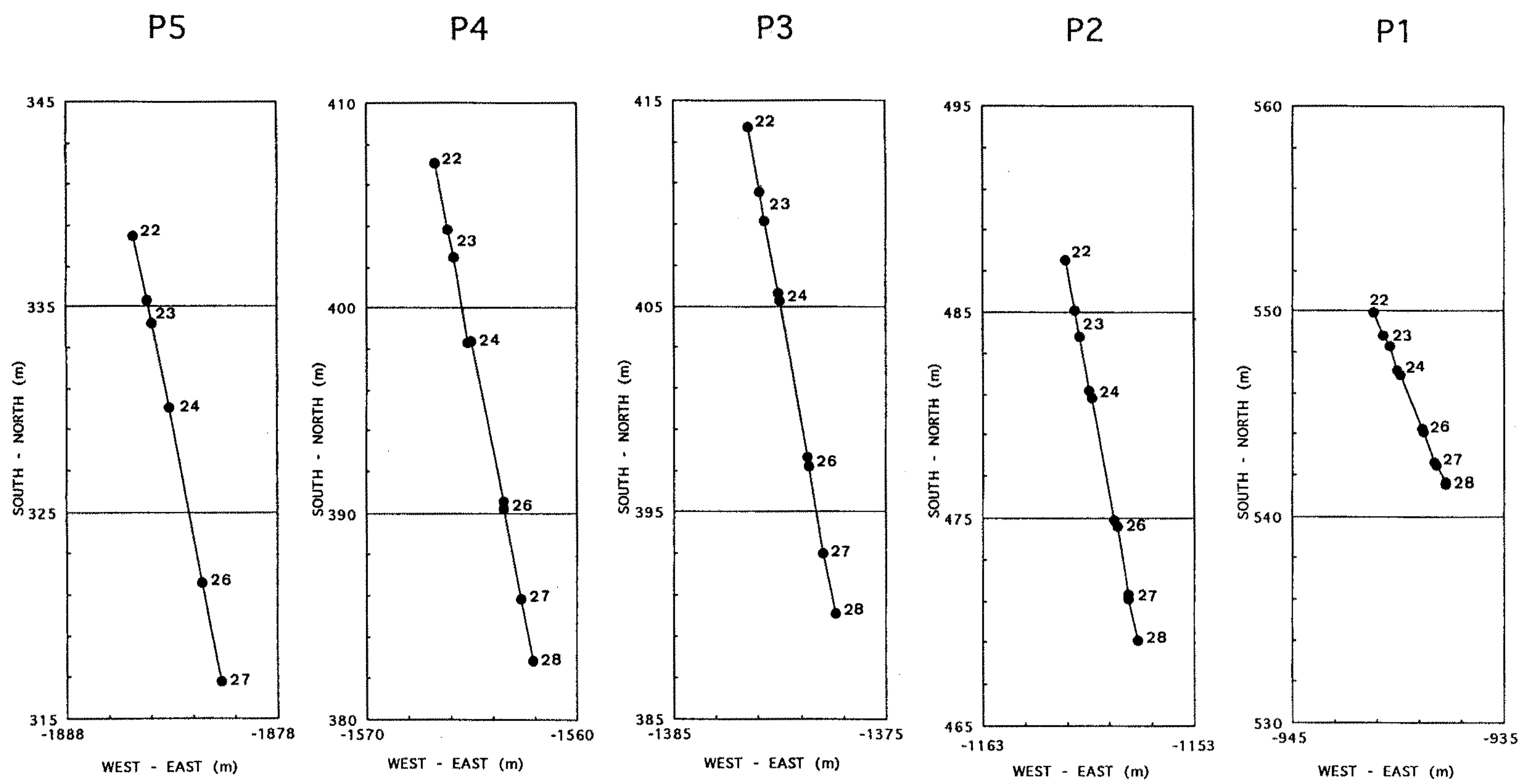

Fig. 7. Variations in positions of points in local X – Y coordinates (0, 0 : at the Control Station) along a transverse profile on Upsala Glacier from November 22 to 28, 1993. Numbers attached to solid circles indicate dates in November.

Table 1. Ice-flow velocities measured at Upsala Glacier between November 22–28, 1993.

Point	Day 22–23	Day 23	Day 23–24	Day 24–26	Day 26	Day 26–27	Day 27–28	Day 22–28
	Horizontal surface velocity (m/day)							
	Dates (November, 1993)							
Px				0.06		0.30	0.19	0.08*
Po				0.06		0.16	0.08	0.12*
P1	1.46	1.53	1.59	1.58	1.51	1.61	1.49	1.56
P2	3.18	3.44	3.32	3.35	2.71	3.35	3.08	3.26
P3	4.04	4.42	4.21	4.29	4.08	4.19	3.96	4.18
P4	4.16	4.46	4.89	4.37	3.68	4.36	4.07	4.30
P5	4.24	4.57	4.44	4.52		4.42		4.44

*Day24–28

found to be small, being less than 10% of the means of the whole period. Mean daily flow velocities during the six days are shown by arrows in Fig. 3.

3.4. *Ablation rates*

Ablation rates were measured almost every day at the seven points of the velocity survey. The cumulative amount of ablation during the six days in late November ranged from 20 cm to 55 cm in ice thickness. A mean for the seven points during the period amounts to 5.8 cm/day.

4. Discussions

4.1. *Comparison of thickness changes with other glaciers*

At the upper reach of the ablation area of Tyndall Glacier, southern part of the SPI (Fig. 1), thinning rates of ice were also obtained as 4.0 m/a from 1985 to 1990 (Kadota *et al.*, 1992), and 3.1 m/a from 1990 to 1993 (Nishida *et al.*, 1995). On the other hand, the middle reach of the ablation area of Moreno Glacier, located some 50 km southerly, has been in an equilibrium state between 1990 and 1993 (Naruse *et al.*, 1995).

Data on ice-thickness changes were compiled by IAHS/UNEP/UNESCO (1993) for 28 glaciers in Europe, Asia and North America. Thickness changes at intervals of 100 m in elevation are tabulated for each glacier. Among 28 glaciers, 25 glaciers have been thinning during the last 5 to 29 years. The thinning rate averaged over the entire glacier ranges from 0.05 m/a to 1.18 m/a and a mean of the 25 thinning rates is 0.49 m/a. When we examine the local thinning rate in detail at each glacier, the largest rate is found to be 1.8 m/a obtained at the frontal area of Careser Glacier in Italy during 1980–90, and at the lower part of Hintereis F. Glacier in Austria during 1979–91. Most values of the maximum thinning rate for each glacier are more or less 1 m/a. Considering these data, the thinning rate of 11 m/a at Upsala Glacier may be the largest rate recorded during the last 30 years on the earth, and is about one order of magnitude larger than the other, common thinning rate of the thinning glaciers.

4.2. *Features of the recent variations of the glacier*

It was reported recently that a retreat of 1000 m has occurred at the eastern half of Upsala Glacier sometime between March 1992 and 1993 (Warren *et al.*, in press). The rapid recession of the Upsala calving front has initiated in 1981 (Aniya and Skvarca, 1992). According to the field drawing in 1990 and the topographic survey in 1993, a recession of more than 1200 m on the average was obtained at almost the entire front. This gives a retreat rate of 400 m/a for the last three-year time interval. It can be observed that the western side has undergone almost no change since 1990 (Fig. 5), probably following the general recessional pattern in which the western section has receded at slower rates. The glacier near the western margin seems to be partially grounded, judged from the presence of elongated islands appearing in front of the lobe-like margin.

Due to the significant surface lowering, coincident with a recent fast retreat, the width (area) of the lower reach of Upsala Glacier has been also reduced considerably as shown in Fig. 5. Also an isolated bare rock at the eastern margin (Fig. 4) has been exposed during the last three years.

4.3. Recent climatic trend

There is no meteorological station in the Upsala Glacier region. A nearest station with a long record is the Station Lago Argentino (220 m a.s.l.), about 80 km southeast of the glacier front. Although the station is located in a different climate (dry condition) from that in the glacier region, meteorological data are available from 1937.

Ibarzabal (unpublished) has recently analyzed the meteorological data at 39 stations in the southern part of Argentina. According to the work, the general climatic trend at Station Lago Argentino is as follows : during the last 50 years, the annual mean air temperature (T) has increased by about 0.5°C from 7.2°C, and the annual precipitation (P) has decreased considerably from about 220 mm to 180 mm. Extreme values were found in the recent years as 82 mm/a in 1986 and 60 mm/a in 1988. The same trends of positive T and negative P are also clearly seen at Río Gallegos on the Atlantic coast of southern Argentina. However, it does not necessarily follow that these trends are dominant in this region ; for example, positive T and positive P at San Julian, and stable T and positive P at Puerto Santa Cruz are recognized.

Although the detailed and quantitative discussion cannot be made for the moment on the relationship between variations of glaciers and the climate, the recent warming and a decreasing trend in precipitation observed at Lago Argentino may have affected somewhat the recent thinning and retreating of Upsala Glacier.

4.4. Characteristics of flow velocity and ablation

During the previous survey in November 1990, also very high velocities of 3.5 m/day and 3.7 m/day were measured at U6 and U7 (Fig. 3), respectively (Naruse *et al.*, 1992). At P5, the closest point to U6–7, an average value of 4.4 m/day (1,600 m/a) was obtained in November 1993, which was about 20% higher than the 1990 value (3.6 m/day). This velocity difference seems to be small, considering a significant contrast in weather conditions between the two survey periods. In 1990 it was a very warm, extremely windy and rainy weather, whereas in 1993 a relatively cool, calm and sunny weather with little rain. As mentioned in the section 3.3, significant daily variations in the flow velocity that were observed at Moreno Glacier (Naruse *et al.*, 1995) were not recognized at Upsala Glacier (Fig. 7). From these results, we can infer that Upsala Glacier is flowing at almost constant speed in summer, mostly by the rapid basal sliding due to sufficient water at the bed supplied from the vast upstream area.

A mean ablation rate of 5.8 cm/day in ice thickness measured during November 22–28 is in a good agreement with 5.4 cm/day obtained from the eight points at Moreno Glacier during the same period (Takeuchi *et al.*, 1995). At Moreno Glacier, based on the amount of ablation measured during 110 days in summer, the annual ablation was estimated as about 12.5 m in ice thickness at 350 m a.s.l. (Naruse *et. al.*, 1995). Hence, it is suggested that the comparable, large annual ablation rate may be occurring near the terminus of Upsala Glacier.

4.5. Dynamics of thinning Upsala Glacier

An annual rate of thickness change at the ablation area of a glacier is given as the remainder by subtracting annual net ablation rate from the annual emergence velocity, *i.e.* the velocity component normal to the glacier surface. Near the terminus of Upsala Glacier, a thinning rate of 11 m/a was obtained and an ablation rate of 12.5 m/a was estimated. Then, if we neglect the accumulation rate, the emergence velocity is obtained as about 1.5 m/a. This component is extremely small compared with the horizontal component of about 1500 m/a. The ratio is about 1/1000.

The emergence flow is generated by the longitudinal compression of ice, which is accompanied by the downglacier decrease in velocity for a glacier with parallel sides. For example, at Soler Glacier in northern Patagonia, the surface flow velocity decreased from 1.5 m/day at the upper reach of the ablation area to 0.2 m/day near the glacier terminus (Naruse, 1987). The mean emergence velocity there was estimated as about 4.5 cm/day, while the mean horizontal velocity was 36 cm/day ; thus the ratio is 1/8.

The very small emergence component at Upsala Glacier indicates that the glacier is moving almost without deformation ; namely the ice body is sliding on the bed as a rigid body. Because of very high velocity near the terminus and no deceleration of flow toward the terminus, an emergence flow may not occur in a significant degree at Upsala Glacier. If this dynamical condition persists, the thinning phenomenon may continue. However, the detailed mechanism remains unsolved.

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References

1. Aniya, M., Naruse, R., Shizukuishi, M., Skvarca, P. and Casassa, G. (1992) : Monitoring recent glacier variations in the Southern Patagonia Icefield, utilizing remote sensing data. International Archives of Photogrammetry and Remote Sensing, Vol. **XXIX**, Part B7, (Proc. of XVIIth Congress of International Society for Photogrammetry and Remote Sensing), 87–94.
2. Aniya, M. and Skvarca, P. (1992) : Characteristics and variations of Upsala and Moreno glaciers, southern Patagonia. Bull. Glacier Res., **10**, 39–53.
3. IAHS/UNEP/UNESCO (1993) : Fluctuations of Glaciers 1985–1990. Volume **VI**, Zürich : World Glacier Monitoring Service, 332pp.
4. Ibarzabal, T. D. (unpublished) : Preliminary analysis of climatic data in southern South America.
5. Kadota, T., Naruse, R., Skvarca, P. and Aniya, M. (1992): Ice flow and surface lowering of Tyndall Glacier, southern Patagonia. Bull. Glacier Res., **10**, 63–68.
6. Meier, M. F. (1985) : Mass balance of the glaciers and small ice caps of the world. Glaciers, Ice Sheets, and Sea Level : Effects of a CO_2-Induced Climatic Change. Report of a Workshop held in Seattle, Washington, September 13–15, 1984, 139–144.
7. Naruse, R. (1987) : Characteristics of ice flow of Soler Glacier, Patagonia. Bull. Glacier Res., **4**, 79–85.
8. Naruse, R. and Aniya, M. (1992) : Outline of Glacier Research Project in Patagonia, 1990. Bull. Glacier Res., **10**, 31–38.
9. Naruse, R., Skvarca, P., Kadota, T. and Koizumi, K. (1992) : Flow of Upsala and Moreno glaciers, southern Patagonia. Bull. Glacier Res., **10**, 55–62.
10. Naruse, R., Aniya, M., Skvarca, P. and Casassa, G. : Recent variations of calving glaciers in Patagonia, South America, revealed by ground surveys, satellite-data analyses and numerical experiments. Ann. Glaciol., **21** (in press).
11. Naruse, R., Skvarca, P., Satow, K., Takeuchi, Y. and Nishida, K. (1995) : Thickness change and short-term flow variation of Moreno Glacier, Patagonia. Bull. Glacier Res., **13**, 21–28.
12. Nishida, K., Satow, K., Aniya, M., Casassa, G. and Kadota, T. (1995) : Thickness change and flow of Tyndall Glacier, Patagonia. Bull. Glacier Res., **13** 29–34.
13. Takeuchi, Y., Naruse, R. and Satow, K. (1995) : Characteristics of heat balance and ablation on Moreno and Tyndall glaciers, Patagonia, in the summer 1993–94. Bull. Glacier Res., **13**, 45–56.
14. Warren, C. R. and Sugden, D. E. (1993) : The Patagonian Icefields : a glaciological review. Arc. Alpine Res., **25**, No. 4, 316–331.
15. Warren, C. R., Glasser, N. F. and Greene, D. R. : Upsala Glacier, Patagonia: rapid calving retreat in freshwater. Ann. Glaciol., **21** (in press).