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# Characteristics of ice flow of Soler Glacier, Patagonia

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## Abstract

Glacial flow was measured by a triangulation survey on Soler Glacier in the Northern Patagonia Icefield during October to November, 1985. Surface flow velocities showed 1.5 m/d at the upper reach of the ablation area and 0.2 m/d near the glacier terminus. Velocity distributions obtained at 21 points are discussed on the basis of the continuity condition with the ice thickness profiles and ablation data. The difference of ice discharges through vertical cross sections between the upper and the middle reach was evaluated as approximately the same value as the total amount of surface melting in the area between the two cross sections. This result implies that the glacier thickness did not change with time in the observation period from the end of October to early December.

Short-term variations of the flow velocity were also obtained near the glacier terminus : the maximum flow rate was found to be three times the minimum value. These results indicate a major contribution of basal sliding to the glacier flow.

## 1. Introduction

For studies on the mechanism and characteristics of mass balance and glacial variations in Patagonia, much information is required on ice flow for various types of glaciers. Only few data of flow velocities have been estimated for Patagonian glaciers, by using areal photographs (Lliboutry, 1956), or by simple survey methods (Marangunić, 1964 ; Naruse and Endo, 1967 ; Enomoto and Abe, 1983). Naruse (1985) made triangulation surveys on Soler Glacier and San Rafael Glacier in the Northern Patagonia Icefield in the summer of 1983. He showed that the surface flow velocities ranged from 0.23 m/d to 2.3 m/d over the ablation area of Soler Glacier and from 13 m/d to 17 m/d near the calving front of San Rafael Glacier. Extraordinarily high rates of flow of the latter glacier were found to be just the same order as 8 m/d to 18 m/d obtained near the calving front of Columbia Glacier, Alaska, in the summer of 1984 (Vaughn *et al.*, 1985).

More extensive studies of ice flow were carried out on Soler Glacier during October to November, 1985. The ablation area where the measurements were made forms a valley-type glacier about 8 km in length and 1.5 km in mean width. Ice is supplied from the Northern Icefield through a big icefall and also from the southeastern face of Mt. (Cerro) Hyades (3078 m) by ice avalanching (Kobayashi and Naruse, 1987). Detailed features of the morphology and structure of Soler Glacier are presented by Aniya and Naruse (1987).

## 2. Method of measurements

Two stations, $\alpha_1$ and $\beta$, were established as control points on the left and right banks, respectively, in the lower reach of Soler Glacier. The oblique distance between these two stations was measured using an electronic distance meter (Topcon EDM-Theodolite Guppy GTS-2), and corrected to a horizontal distance of 1692.59 m. Almost the entire surface of the ablation area of the glacier was visible from $\alpha_1$ (550 m a.s.l.) and $\beta$ (382 m). For some surveys, additional control stations $\alpha_2$ (559 m a.s.l.) and M2 (324 m) were also used. Locations of these stations are indicated in Fig. 1. Elevations of all the stations were determined by triangulation surveys on the basis of an elevation of 277 m a.s.l. at Base Camp (M4), 1 km downstream from the terminus of Soler Glacier.

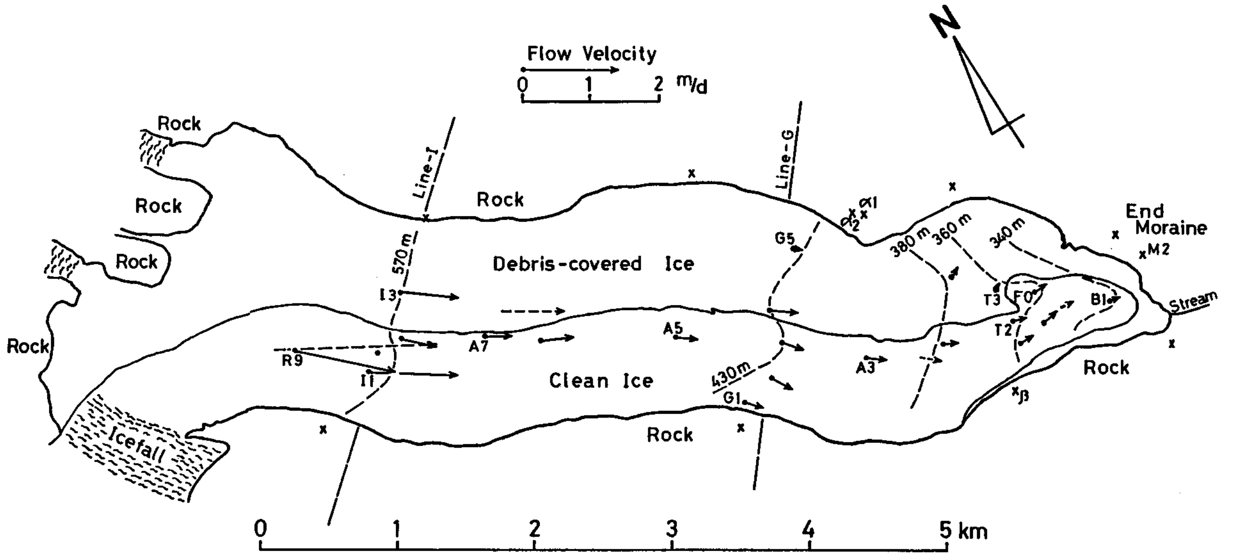

Fig. 1. Distribution of velocity vectors of the surface flow over the ablation area of Soler Glacier.
Solid arrows indicate velocities obtained in October-November, 1985 ; broken arrows in December, 1983. Contours of the surface elevation (m, a.s.l.) were drawn by broken lines with arbitrary intervals.

Twenty one points were distributed over the region from near the terminus to the foot of the icefall. Wooden stakes about 3 cm in diameter with red flags were set up as markers for the survey in drilled holes 0.7-1.0 m deep on the clean ice surface, the right half of the glacier. Stakes were reset approximately every week to prevent tilting of stakes due to heavy melting of surface ice (Fukami and Naruse, 1987). Rocks covered with red cloth were also used as markers on the debris-covered area in the left half of the glacier.

The horizontal and vertical angles for each marker were measured mainly from stations $\alpha_1$ and $\beta$ with a Wild T2 theodolite (a minimum reading: 1 second) and also with the EDM theodolite (a minimum reading: 10 seconds). The surveys were carried out from October 21 to November 18, 1985. By means of triangulation calculations, coordinates and relative elevations of surveyed points were determined. Then horizontal displacement and its azimuth were calculated at each point from the difference of its coordinates obtained on different days.

Short-interval measurements of ice flow were carried out for points A2, A3, T2 and T3 from Station $\beta$ with a theodolite, and for F0 from Station M2 with a distance meter. The former were made at half-day intervals during November 1 through 3, and the latter every three to several hours from November 10 to 18, 1985. Since the direction from F0 to M2 coincides approximately with that of the ice flow, the horizontal velocity at F0 can easily and accurately be obtained by correcting the directly measured distance to the horizontal component in the flow direction.

## 3. Results and discussion

### *3. 1. Distribution of flow velocities*

Horizontal component of the flow velocity and its direction obtained at 21 points are compiled in Table 1, together with the period over which the velocity was averaged and the surface elevation of the station. Figure 1 shows the distribution of horizontal vectors (thick arrows) of the surface flow over the ablation area of Soler Glacier. Also indicated by broken arrows are the results obtained in the middle of December, 1983 (Naruse, 1985).

The maximum velocity in the upper reach of the glacier was found not near the center line but in the central area (R9 and I1) of clean ice on the right half of the glacier. This tendency has been predicted from the shape of ogive patterns (Aniya and Naruse, 1985; 1987). However, in the middle and lower reaches of the glacier differences of flow velocity between the clean ice and the debris-covered ice are not seen clearly. It is also noted that the flow direction diverges slightly on the lower reach.

The velocity decreases gradually downglacier, being 1.5 m/d at the foot of the icefall (marked R9),

Table 1. Horizontal component of surface flow velocity, its azimuth measured clockwise from the true north, the period over which the mean velocity was obtained, and the elevation of station.

| Station | Velocity (m/d) | Azimuth (degree) | Period (days) | Elevation (m) |
|---|---|---|---|---|
| B 1 | 0.18 | 101 | 5 | 344 |
| B 2 | 0.24 | 80 | 5 | 356 |
| F 0 | 0.22 | 90 | 6 | 363 |
| T 1 | 0.23 | 90 | 5 | 352 |
| T 2 | 0.21 | 110 | 8 | 364 |
| T 3 | 0.13 | 61 | 16 | 362 |
| T 4 | 0.17 | 64 | 5 | 377 |
| A 2 | 0.24 | 118 | 16 | 378 |
| A 3 | 0.29 | 130 | 16 | 396 |
| G 1 | 0.28 | 141 | 6 | 407 |
| G 2 | 0.33 | 151 | 6 | 411 |
| G 4 | 0.40 | 128 | 6 | 430 |
| G 5 | 0.16 | 133 | 10 | 435 |
| A 4 | 0.33 | 142 | 6 | 432 |
| A 5 | 0.30 | 128 | 6 | 459 |
| A 6 | 0.49 | 116 | 6 | 514 |
| A 7 | 0.39 | 121 | 6 | 535 |
| I 1 | 1.27 | 124 | 8 | 577 |
| I 3 | 0.81 | 130 | 8 | 573 |
| R 8 | 0.54 | 134 | 6 | 564 |
| R 9 | 1.48 | 135 | 10 | 613 |

0.30 m/d at A5 in the middle of the glacier and 0.18 m/d at B1 near the terminus. The longitudinal distribution of flow velocities along the center line from R9 through B1 is shown in Fig. 2. The velocity fluctuates slightly from place to place. To make clear this pattern, mean longitudinal strain rates $\dot{\varepsilon}_x$ at the glacier surface were estimated from $\dot{\varepsilon}_x = \partial u/\partial x$, where $u(x)$ indicates the horizontal velocity and $x$ is the horizontal distance taken downglacier. Distribution of $\dot{\varepsilon}_x$ is illustrated in Fig. 2. Positive strain rate indicates an extension, negative a compression. Negative strain rate is a normal mode in the ablation area of the glacier. From Fig. 2, mean longitudinal strain rate was given to be approximately $-3\times10^{-4}$(1/d), which corresponds to $-0.1$(1/a). The value coincides well with $-0.1$ to $-0.01$(1/a) obtained generally in valley glaciers (Paterson, 1985). Also shown in Fig. 2 are the surface profile and the bedrock profile which was deduced from gravimetric surveys (Casassa, 1987). To elucidate the causes for positive strain rates recognized around A7-A6 and A5-A4, more data are necessary on the detailed topography of the bedrock undulation and distribution of the longitudinal and transverse strain rates in the region along the center line.

A transverse profile of the surface velocity along Line-G (see Fig. 1) is shown in Fig. 3, with the surface and bedrock profiles (Casassa, 1987). The bedrock profile represents a subglacial ridge in the clean ice body near the boundary with the debris-covered ice. It is noticed that the velocity profile does not show a symmetric one, namely almost a linear profile on the left half of the glacier covered with debris, and a nearly flat profile on the right half. The maximum velocity is found near the center line (around G4), coinciding with the maximum ice thickness. Decreased velocity seen at A4 may have resulted from the effect of a subglacial ridge. A large shear force is expected in the region between G1 and the right margin; actually numerous crevasses exist there (Aniya and Naruse, 1987). Judging from the topography around the left margin, ice to the left-hand side from G5 might be almost stagnant.

### *3. 2. Discharge of ice mass (Continuity condition)*

Transverse profiles of the flow velocity and bedrock were also obtained along Line-I in the upper reach, as marked in Fig. 1. We now discuss the continuity condition for a portion of the glacier cut by two vertical cross sections at Line-I and Line-G. The mean distance between the two sections is 2750 m, the whole surface area is 4.59 km$^2$, and the mean surface slope is about 1/20 (*i. e.*, 2.9 degrees). We estimate the amounts of discharge through both cross sections, and compare the difference with the amount of surface

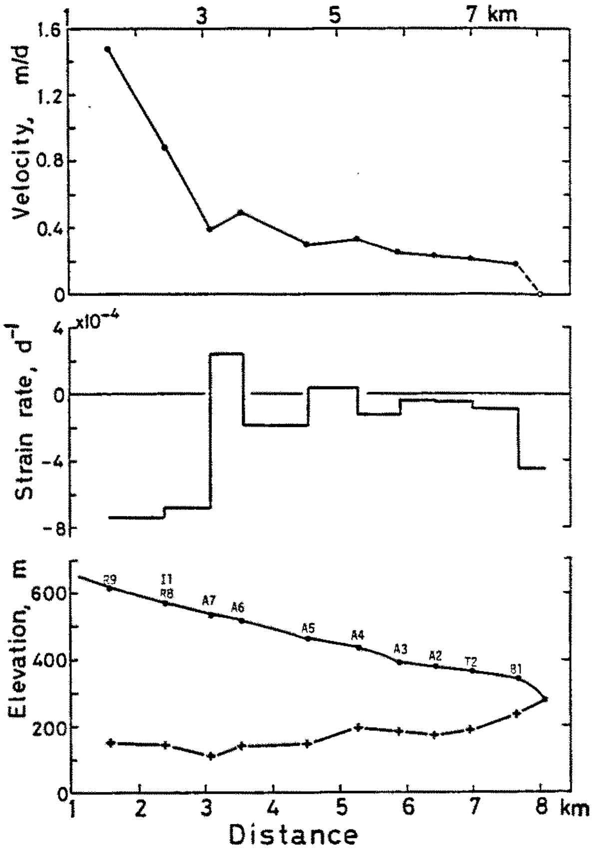

Fig. 2. Longitudinal profiles of the surface flow velocity, the longitudinal strain rate, the glacier surface and the bedrock surface, along the approximate center line of Soler Glacier.

Horizontal distance is measured downglacier from the foot of icefalls.

ablation.

Vertical cross-sectional areas were estimated as 0.53 km$^2$ at Line-I, and 0.31 km$^2$ at Line-G. The depth mean of flow velocity was assumed to be 90% of the surface value, since basal sliding is predominant in this glacier, as is mentioned in the next section. The mean flow velocities through the cross sections at Lines-I and −G were thus calculated as 0.50 m/d and 0.23 m/d, respectively. Then the discharge amounts of ice were given as 2.7x10$^5$ m$^3$/d and 0.70x10$^5$ m$^3$/d, respectively, the difference of ice discharge being 2.0x10$^5$ m$^3$/d.

Daily amounts of surface melting were measured with stake methods from the end of October to early December, 1985 (Fukami and Naruse, 1987): the daily mean rates were 3.0 cm in ice thickness over the clean ice surface, and 6.0 cm over ice covered with debris. By calculating the melting rates and the whole surface area between Lines-I and −G, the total volume of surface melting was obtained as 2.1x10$^5$ m$^3$/d, Although melting of ice must occur at the glacier sole due to frictional heat produced within basal water streams, it is negligibly small compared with surface melting.

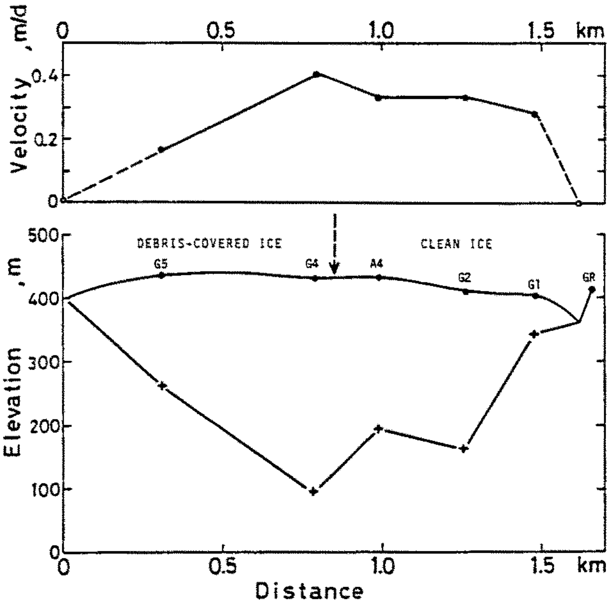

Fig. 3. Transverse profiles of the surface flow velocity, the glacier surface and the bedrock surface, along Line-G (see Fig. 1).

A boundary between the debris-covered ice and the clean ice is indicated by a broken arrow.

The amount of total melting was found to be approximately the same as the difference of ice discharges between two cross sections. This result indicates that equilibrium of the mass balance held, namely the glacier thickness did not change with time in this 50-day observation period. Therefore, we can consider that the deficit of ice masses resulting from surface melting was compensated by the emergence velocity, $v'$, (upward, normal component of the ice flow velocity; see Fig. 4). The mean value of $v'$ is then estimated as about 4.5 cm/d, while the mean $u'$ (velocity component parallel with the surface) is 36 cm/d in this area.

We cannot, however, regard the glacier to be in a steady state, because the glacier may thicken in winter when the melting rate would be small and may thin in mid-summer. Actually thinning of 5.2 m/a took place at the lower reach of the glacier from 1983 to 1985 (Aniya and Naruse, 1987). To elucidate the de-

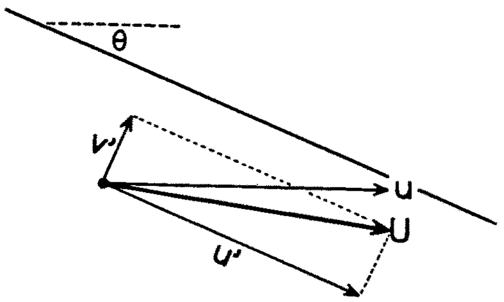

Fig. 4. Velocity components of the ice flow.

The thick arrow, $U$, indicates a velocity vector of ice at (P) near the glacier surface in the ablation area. $u$ is the horizontal component of $U$, which was measured by triangulation survey and is shown in Figs. 1, 2, 3, and 5. Thin arrows, $u'$ and $v'$, represent the components of $U$ parallel to and normal to the surface, respectively ; upward $v'$ is called emergence velocity, downward $v'$ submergence velocity. $\theta$ indicates the surface slope.

tailed behavior of growth or shrinkage of the glacier, long-term measurements on the mass balance and ice flow are necessary.

### 3. 3. *Short-term fluctuation of glacier flow*

Results of short-term fluctuation of the glacial flow obtained at point F0 are shown in Fig. 5. Also shown are a hydrograph of an outlet stream of Soler Glacier observed at 1 km downstream from the terminus (Fukami and Escobar, 1987), and variations in air temperature and precipitation observed at a Base Camp near the glacier terminus (Fukami *et al.*, 1987).

Clearly noticed is the strong correlation between the peaks of the ice flow velocity and of the water discharge. And one can find a time lag of several hours in the discharge peaks. The larger flow rates (*i. e.* about 15 mm/h) are regarded as about three times the minimum rates (*i. e.* about 5 mm/h).

The flow velocity to be measured at the glacier surface is the sum of the integral of shear strain rates from the bottom to the surface, and the basal sliding velocity of the glacier. The former, that is the plastic deformation of ice, is greatly affected by the surface slope, ice thickness and ice temperature ; whereas the latter is affected by the surface slope, ice thickness and the amount of water (*i. e.*, water pressure and/or thickness of water layer) at the glacier bed. Parame-

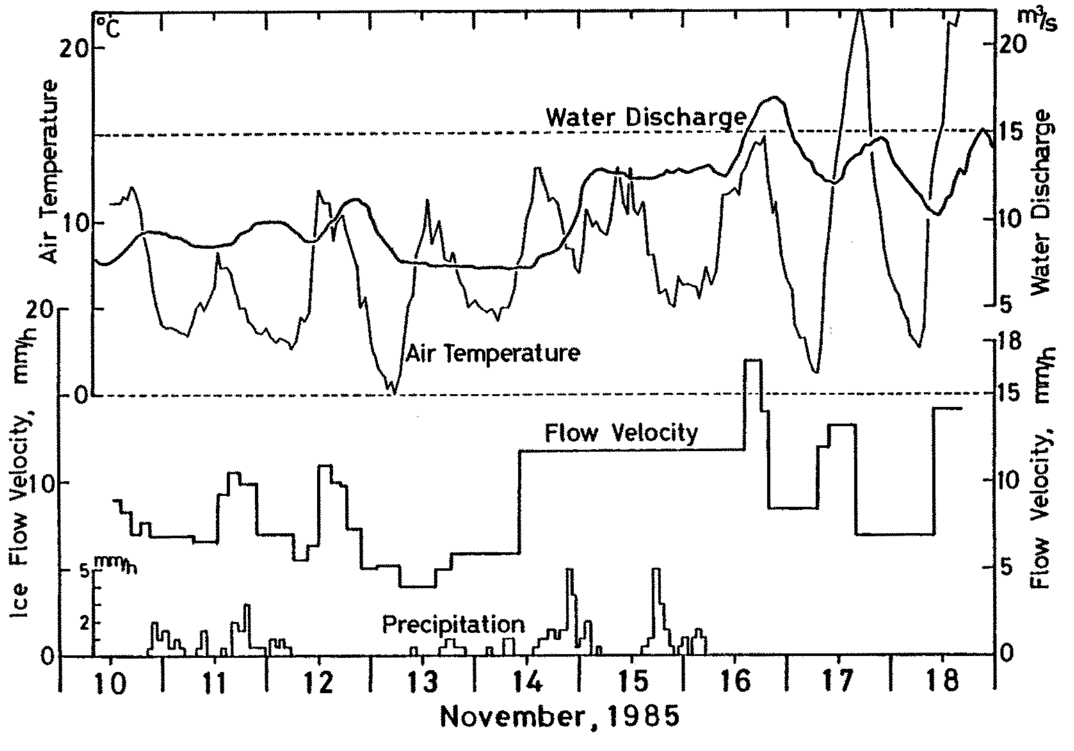

Fig. 5. Variations in the water discharge at the outlet stream of Soler Glacier, the air temperature and the amount of precipitation near the glacier terminus, and the surface flow velocity at F0 near the terminus.

ters which control the plastic deformation cannot be considered to change in a short period. Therefore, observed fluctuations of flow velocity are undoubtedly caused by variations in basal sliding, the same phenomenon as recently analyzed in Switzerland glaciers (Iken, 1977 ; Iken and Bindschadler, 1986), Columbia Glacier, Alaska (Vaughn *et al.*, 1985), and the surge-type Variegated Glacier, Alaska (Kamb *et al.*, 1985). The contribution of basal sliding is then estimated as more than 2/3 of the surface ice flow near the terminus of Soler Glacier in the spring season.

Seasonal variations of flow velocity are also recognized. The values obtained in the mid-summer of 1983 were greater than those in the spring of 1985 (see Fig. 1), and annual mean flow rates estimated from ogive spacings are smaller than the mid-summer velocity (Aniya and Naruse, 1985), yet larger than the spring velocity (Aniya and Naruse, 1987). These results support the high contribution of basal sliding in Soler Glacier.

Further analyses and considerations on these short-term velocity variations, with the hydrological and heat balance data, are to be presented in a separate paper (Naruse and Fukami, in preparation).

## 4. Concluding remarks

Triangulation surveys conducted at Soler Glacier in October and November 1985, gave information on the following dynamic properties of the glacier :

1 ) The velocity decreases gradually down-glacier, being 1.5 m/d at the foot of the icefall, 0.30 m/d at the middle part of the glacier and 0.18 m/d near the terminus. The mean longitudinal strain rate was then obtained to be approximately $-3\times10^{-4}(1/d)$, which corresponds to $-0.1(1/a)$ in compression mode. Although the magnitude of the velocity is larger than those of usual glaciers in the world, the pattern of longitudinal distribution of the velocity shows the typical features over the ablation area of a standard valley glacier.

2 ) Transverse profiles of the surface velocity do not represent symmetric ones. That is considered to be caused by the bedrock undulation, namely by the existence of a subglacial ridge running near the central axis of the glacier.

3 ) Calculations of the ice discharge through two vertical cross sections and the total amount of surface ablation between the two sections indicate that the glacier was in an equilibrium state in the observational period, *i. e.* from October to December.

4 ) Short-term variations in the flow velocity exhibit the strong effect of the basal water system on the glacial flow.The contribution of basal sliding of the glacier, *i. e.* more than 2/3 of the surface ice flow in the spring season, is estimated near the terminus of Soler Glacier.

These results should contribute to making clear the mechanism of glacial variations and mass balances in the Patagonia region. There are, however, a number of calving glaciers, in Patagonia, which directly discharge into fjords or glacial lakes. More studies are also necessary on the dynamics of such calving glaciers.

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## Resumen

### Características del flujo del Glaciar Soler, Patagonia

Desde Octubre a Noviembre de 1985 se realizó mediciones de flujo glaciar por triangulación en el Glaciar Soler, Hielo Patagónico Norte. Se distribuyó un total de veintiún estaciones sobre la zona de ablación del glaciar. En la zona de hielo limpio que constituye la mitad derecha del glaciar se instaló balizas de madera de unos 3 cm de diámetro con banderolas rojas, en hoyos perforados de 0,7-1,0 m de profundidad. En la mitad izquierda del glaciar cubierta por detritos se emplearon rocas con paños rojos como señales.

Por medio de un distanciómetro eléctrico se midió la distancia entre las estaciones de control $\alpha_1$ y $\beta$ (ver Fig. 1). Los ángulos horizontales y verticales hacia cada estación se midieron desde las estaciones de control con un teodolito Wild T2. Se determinó las coordenadas y cotas relativas a partir del cálculo por triangulación. Luego se calculó el desplazamiento horizontal y su azimut en cada estación, basándose en la diferencia de las coordenadas obtenidas en días distintos (ver Tabla 1 y Fig. 1).

Las principales características obtenidas del flujo del Glaciar Soler son las siguientes:.

1 ) La velocidad disminuye gradualmente hacia aguas abajo del glaciar, siendo de 1,5 m/d al pie del salto de hielo, 0,30 m/d en la sección media del glaciar y 0,18 m/d cerca del frente (Figs. 1 y 2). Se obtuvo entonces una razón longitudinal de deformación de $-3\cdot10^{-4}(1/d)$ que corresponde a $-0{,}1(1/a)$ en el modo de compresión. A pesar que la magnitud de la velocidad es mayor que aquella normalmente encontrada en otros glaciares del mundo, la distribución longitudinal de la velocidad muestra las características típicas de un glaciar de valle en su área de ablación.

2 ) Los perfiles transversales de la velocidad en superficie no son simétricos (Fig. 3). Se considera que esto es causado por ondulaciones del lecho de roca, en particular debido a la existencia de una arista subglacial que corre cerca del eje central del glaciar.

3 ) Se calculó que el gasto de hielo a través de dos secciones transversales verticales, lineas I y G (ver Fig. 1), es de 270 $\mathrm{k\cdot m^3/d}$ y 70 $\mathrm{k\cdot m^3/d}$ respectivamente. Desde fines de Octubre a principios de Diciembre se obtuvo un volumen total de ablación en superficie de 210 $\mathrm{k\cdot m^3/d}$ en promedio entre estas dos secciones. Este valor es aproximadamente igual a la diferencia de gasto de hielo entre ambas secciones. Se considera en consecuencia que el glaciar estaba en estado de equilibrio durante este período de observación de 50 días desde fines de la primavera hasta principios del verano.

4 ) Se realizó observaciones de corto plazo del flujo cerca del frente del glaciar, tal como se muestra en la Fig. 5. Tambien se presenta el hidrograma de un río de desagüe del Glaciar Soler registrado 1 km aguas abajo del frente, y las variaciones de la temperatura del aire y la precipitación observada en campamento base. Se nota claramente una marcada correlación entre los peaks de velocidad del glaciar y gasto del río, con un desfase de varias horas entre ellos. Se encontró que los valores altos de flujo glaciar son unas tres veces mayores que los valores bajos. Estos resultados muestran el efecto importante del drenaje de agua en el lecho sobre el flujo glaciar. Se sugirió que el deslizamiento basal es superior a 2/3 de la velocidad en superficie.