Report 10

Flow of Soler Glacier and San Rafael Glacier

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Abstract. Measurements of glacial flow were made by a triangulation survey on Soler and San Rafael Glaciers in the Patagonia Northern Icefield during November and December, 1983. Surface flow velocities obtained for Soler Glacier are 2.3 m/d at the upper reach of the ablation area and 0.23 m/d near the terminus of the glacier; those for San Rafael Glacier are 13 m/d at the point 1 km from the terminus and 17 m/d at the calving front. Velocity distributions are discussed on the basis of the continuity equation. Decreasing velocity down-glacier in Soler Glacier is a typical pattern in the ablation area of a valley glacier. Increasing velocity down-glacier in San Rafael Glacier is considered to result mainly from the increase in number and spacing of crevasses toward the glacial front.

1. Introduction

Flow velocities of Patagonian glaciers are expected to be much greater than those of high mountain glaciers and polar glaciers, because in Patagonia the warm ice temperature, possibly 0°C throughout the year, causes a high rate of plastic deformation of ice, and abundant water from melting and rainfall should accelerate the basal sliding. Both effects contribute to rapid glacial flow, resulting in a large discharge of ice from the accumulation area in the icefield to the ablation areas of the glaciers.

For studies on the characteristics of mass balance and glacial variations in Patagonia, it is necessary to obtain much information on the glacial flow for the various types of glaciers. Only few data of flow velocities have been obtained in Patagonian glaciers to date (e.g. Lliboutry, 1956; Naruse and Endo, 1967; Enomoto and Abe, 1983). Two glaciers were investigated in November-December, 1983: Soler Glacier and San Rafael Glacier. Morphological features of Soler Glacier are described in Report 11.

2. Method of measurement

On Soler Glacier a base line was established on the rocks at the left and right banks of the glacier near the terminus, as indicated by α and β in Figure 1. The distance between two datum points was measured using an optical-wave distance meter, and corrected to a horizontal distance of 1693 m. Wood stakes were set up as markers for the survey in drilled holes 0.5–0.8 m deep over the regions from the terminus to the foot of the icefall. Angle measurements were made with a Wild T2 theodolite from both datum points α and β. Triangulation surveys were carried out from December 13 to 26, 1983. To investigate day by day variations in the flow velocity, angles were measured every two days from one datum point.

On San Rafael Glacier a base line 296 m long was established on the right bank and a small island near the glacier terminus. Because of heavy crevasses and seracs on the surface near the terminus, it was not possible to set up stakes. Then the tops of several remarkable seracs served as markers for the triangulation surveys. The measurement method was the

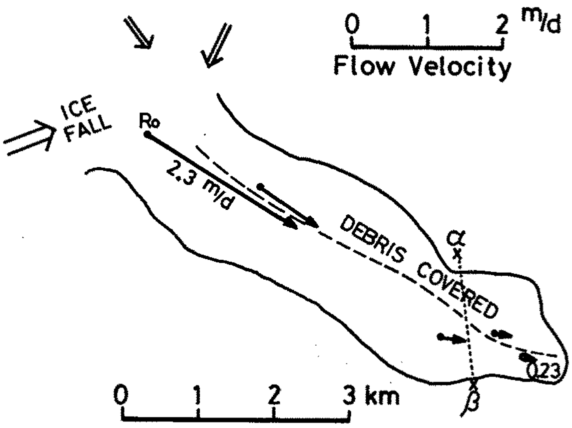

Fig. 1. Velocity vectors of ice flow on Soler Glacier in December, 1983.

same as on Soler Glacier. The surveys were carried out from November 25 to 28, 1983. Since the surface profile of each serac varies day by day as a result of ice melting and deforming, angles were measured every day from one datum point.

Distance measurements on both glaciers were carried out with the help of M. Aniya, and angle measurements were made with G. Casassa on Soler Glacier and J. Vargas on San Rafael Glacier.

3. Results of measurements

Resurveys were accomplished at five stakes among a dozen stakes placed on the surface of Soler Glacier. Other stakes were lost by heavy melting of ice and strong winds. Distributions of velocity vectors of ice flow obtained are shown by arrows in Figure 1. They are mean values over two days. The velocity decreases gradually toward the terminus, being 2.3 m/d at the foot of the icefall (marked R_0) and 0.23 m/d near the terminus. The value of 0.4 m/d was obtained at the middle part of the glacier in the austral summer of 1967 (Naruse and Endo, 1967). This tendency of the velocity decrease toward the terminus is normal in the ablation area of a valley glacier, because the difference of discharge mass in the upper part and that in the lower part is usually ablated by ice melting between these two parts. The estimated ice discharge through a vertical cross section at R_0 is about 700 kt/d, taking the mean velocity as 2 m/d, the width as 1500 m, the mean ice thickness as 250 m (assumed from Report 11) and the ice density as 900 kg/m^3. The total amount of melting estimated over the surface below R_0 is also about 700 kt/d, with the width of 1500 m, length of 6500 m and mean surface melting rate of 70 kg/m^{2}d (Report 7).

Flow velocities obtained in San Rafael Glacier are shown with the surface profile in Figure 2. They are mean values over three days. Although measurements were restricted to the lower part of the glacier, flow velocities show such large values as 13 m/d at point (e) 1 km from the terminus and 17 m/d at the calving front (points a and b) of the glacier. This high flow velocity can probably be attributed to the effect of rapid basal sliding due to abundant subglacial water. It is noted that the velocity increases toward the terminus, opposite to Soler Glacier.

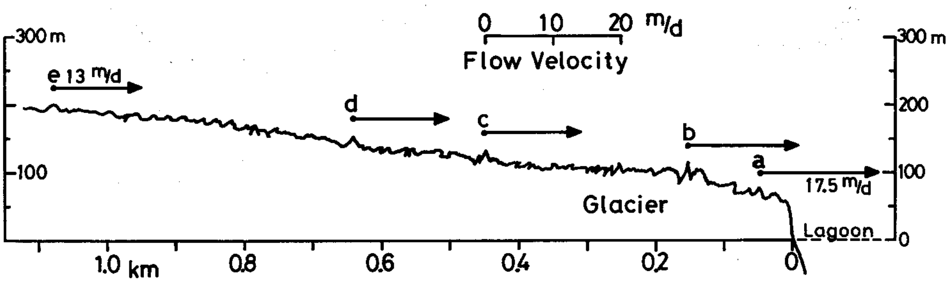

Fig. 2. Flow velocities and the surface profile of San Rafael Glacier in November, 1983.

Observational errors affecting the velocities are estimated at less than a few percent in Soler Glacier and less than about 10 percent in San Rafael Glacier.

4. Discussions

4.1. Velocity distributions over a glacier

We consider a thin prism of ice bounded on two faces by vertical side walls of a glacier and two other faces by the top and subglacial surfaces, as shown in Figure 3. The x axis is taken to be the mean flow direction and the z axis to be the transverse direction of the glacier. We neglect the existence of water on and in the glacier, and melting on side walls.

If the strain rates $\dot{\varepsilon}_x$ and $\dot{\varepsilon}_z$ do not vary with depth, the continuity condition (mass conservation) requires

$$\rho VWh = (V+\Delta V)(W+\Delta W)(h+\Delta h)(\rho+\Delta\rho)+[A+B+(\rho+\Delta\rho/2)\dot{h}](W+\Delta W/2)\Delta x, \quad (1)$$

where ρ is the bulk density of the ice body and V is the flow velocity, both being averaged

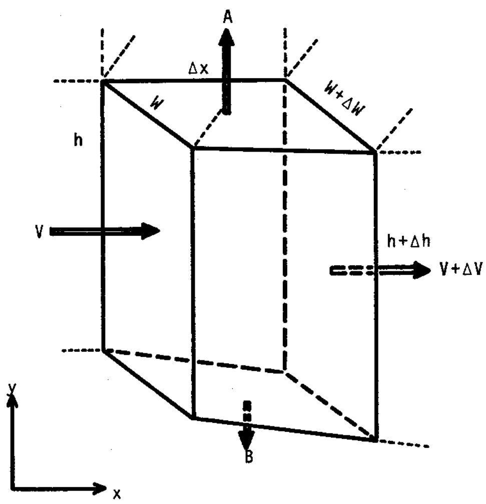

Fig. 3. A portion of a glacier.
A and B: melting rates at the top and bottom surfaces of a glacier; h and W: the thickness and the width of the glacier; V: the flow velocity averaged over the depth and the width.

values over the vertical cross section (Wh); W and h are the width and thickness of the glacier, respectively; and A and B are melting rates of ice expressed by mass per unit area per unit time at the top and bottom surfaces, respectively. When accumulation occurs at the top surface, the sign of A is negative; when freezing occurs at the bottom, B is negative. The term $\dot{h}$ indicates the thickening rate (negative for thinning) of the glacier.

Normally, ice is regarded as incompressible, so ρ is taken as constant. But we now leave ρ as a variable parameter with distance x, because the existence of large crevasses should vary the bulk density of the ice body. Eliminating products of small quantities, equation (1) reduces to

$$\rho V\frac{\partial h}{\partial x}+hV\frac{\partial \rho}{\partial x}+\rho h(\dot{\varepsilon}_x+\dot{\varepsilon}_z)+A+B+\rho\dot{h}=0\,, \tag{2}$$

where $\dot{\varepsilon}_x$ is the longitudinal strain rate ($\partial V/\partial x$) and $\dot{\varepsilon}_z$ is the transversal strain rate. If the glacier width is constant, $\dot{\varepsilon}_z=0$. Since the amount of A is usually much larger than B, we put $B=0$.

We now examine the sign of each term in equation (2), for Soler Glacier and San Rafael Glacier in summer.

For Soler Glacier: it is considered approximately that $\dot{\varepsilon}_z=0$, and ρ is constant. If we assume the ice thickness h is constant along the glacier, it follows that,

$$\rho h\dot{\varepsilon}_x+A+\rho\dot{h}=0. \tag{3}$$

Since $A>0$ in summer, equation (3) gives

$$h\dot{\varepsilon}_x+\dot{h}<0. \tag{4}$$

Thus, $\dot{\varepsilon}_x<0$, namely the velocity should decrease with x down-glacier, if the glacier is assumed to be in a steady state ($\dot{h}=0$).

For San Rafael Glacier: $\dot{\varepsilon}_z\simeq 0$, $A>0$, and the obtained result showed $\dot{\varepsilon}_x>0$ (increasing of velocity with x). Then, equation (2) gives,

$$\rho V\frac{\partial h}{\partial x}+hV\frac{\partial \rho}{\partial x}+\rho\dot{h}<0. \tag{5}$$

This relation implies that the ice thickness or the bulk density decreases with x, or the glacier is thinning in this observational period. The most probable cause seems to be decreasing density; namely, numbers and spacings of crevasses increase toward the terminus of the glacier so that the bulk density decreases to much lower than 900 kg/m^3 approaching the calving front.

4.2. Glacial variations

Frequent fluctuations of the front of San Rafael Glacier have been reported (e.g. MERCER, 1962). The present author observed a retreat of about 1.5 km from 1967 to 1984. Frequent variations are also observed at Pio XI Glacier on the western side of the Southern Icefield (LLIBOUTRY, 1956; IWATA, 1983). As for Soler and Nef Glaciers, they seem to be almost stable.

We should carefully discuss the glacial variations taking account of the different mechanisms between standard valley glaciers such as Soler Glacier and calving glaciers such as San Rafael and Pio XI Glaciers. If the climate changes, the surface mass balance (total amount of accumulation and melting) will change; then the shape of the glacier gradually approaches a new steady state taking a time of the order of 10^1–10^2 years for a valley glacier. Consequently, both the thickness and frontal position of the valley glacier should change.

For a glacier calving into a fjord or lake, the frontal position of the glacier is determined by the balance of the amounts of the following parameters near the glacier terminus: total ice discharge from up-glacier to the terminus (denoted by Q), ice melting on the top surface, and on the side and front walls of the terminus (A), ice melting on the bottom surface of the glacier (B), and calving of ice blocks (C). The height of the front of San Rafael Glacier was measured as about 60 m above the water level of Lagoon San Rafael, as shown in Figure 2. Then the front must be grounded at present, since the depth of the lagoon is not much deeper than about 100 m. If the glacier terminus floats in the fjord or lake, i.e. like an ice shelf, the amounts of (A) and (B) become greater due to the large amount of heat transfered from the water of several degrees in centigrade (see Report 15). The amount of (C) may be controlled by such mechanical properties of ice as how big or how many cracks and crevasses to be formed in the vicinity of the glacier terminus, and also by the effects of (A) and (B). If we suppose that calving does not take place, the front of San Rafael Glacier should advance on the order of a hundred meters annually. If calving of large ice masses occurs from the ice shelf, the front may be recognized to have retreated greatly.

Hence, an obvious fluctuation of a calving glacier, in terms of advance or retreat of the glacial front, cannot be automatically considered to be the result of direct response to recent climatic change. There remain more complex mechanisms to be solved on the mass balance and the dynamics of glaciers.

Day to day variations in the flow velocity on the order of several tens percent were observed in Soler Glacier, and of several percent in San Rafael Glacier. These results are to be presented in a separate paper.

References

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, 11–14.

IWATA, S. (1983): Further advance of Pio XI Glacier. 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, 14–17.

LLIBOUTRY, L. (1956): Nieves y Glaciares de Chile. Ediciones de la Universidad de Chile, Santiago, 471 p.

MERCER, J. H. (1962): Glacier variations in the Andes. Glaciological Notes, No. 12, New York, 9–31.

NARUSE, R. and ENDO, T. (1967): Glaciological investigations of northern Patagonian glaciers, Chile. Seppyo, **29**, (6), 167–176.

Resumen. Flujo de los Glaciares Soler y San Rafael

Se realizaron mediciones de flujo glaciar por triangulación en los Glaciares Soler y San Rafael en Noviembre y Diciembre de 1983.

En el Glaciar Soler, se instaló una línea base sobre rocas en los márgenes derecho e izquierdo del glaciar cerca del frente. Se midió la distancia usando un distanciómetro óptico de onda, siendo el valor horizontal de 1693 m. Se instaló balizas de madera en hoyos perforados

de 0,5–0,8 m de profundidad en un área cercana al frente glaciar y hasta el pie del salto de hielo. Se hizo mediciones de ángulo con un teodolito Wild T2 desde los dos puntos origen.

La distribución de vectores de velocidad de flujo de hielo obtenidos a finales de Diciembre se muestra con flechas en la Fig. 1. Es de notar que la velocidad decrece gradualmente hacia el frente, siendo de 2,3 m/d al pie del salto de hielo marcado R_0, y 0,23 m/d en la cercanía del frente. Esta tendencia es la usual que se observa en el área de ablación de un glaciar de valle, dado que el exceso de masa de descarga en la zona superior con respecto a aquella de la zona inferior, debería eliminarse por fusión de hielo. Se estimó la descarga de hielo a través de una sección transversal en R_0 aproximadamente igual a 700 kt/d a base de valores de velocidad media de 2 m/d, ancho de 1500 m, espesor medio supuesto de hielo de 250 m y densidad de hielo de 900 kg/m^3; mientras que la fusión total sobre la superficie bajo R_0 se estimó también aproximadamente igual a 700 kt/d a partir de un valor de 1500 m de ancho, 6500 m de largo y 70 kg/m^{2}d de tasa superficial de fusión.

En el Glaciar San Rafael, una línea base de 296 m de largo fue instalada sobre el borde derecho y una isla cercana al frente del glaciar. No se pudo instalar ninguna baliza debido a la gran cantidad de grietas y séracs en superficie cerca del frente. Consecuentemente, las cúspides de varios séracs prominentes sirvieron como marcas para el levantamiento por triangulación. Las velocidades de flujo obtenidas a fines de Noviembre se muestran en la Fig. 2. A pesar que las mediciones se limitaron sólo al sector inferior del glaciar, se obtuvo valores considerablemente altos de velocidad que fluctuaron entre 13 y 17 m/d. Esta alta velocidad de flujo de hielo puede ser explicada por efectode altas velocidades en la base debido a la existencia de gran cantidad de agua entre el glaciar y la roca subyacente.

La tendencia observada de un aumento de velocidad hacia el frente puede ser producida por un menor espesor o un angostamiento del glaciar a medida que el hielo fluye hacia el frente. En el caso del Glaciar San Rafael sin embargo, se considera que la distribución de velocidades es principalmente producto de un mayor espaciamiento en las grietas a medida que el hielo del glaciar se aproxima al frente; así, la densidad aparente del cuerpo de hielo no es constante a lo largo de la dirección del flujo, y puede disminuir a un valor mucho menor que 900 kg/m^3 cerca del frente.