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Thickness change and flow of Tyndall Glacier, Patagonia

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Abstract

In December 1993, we measured surface elevations and ice flow-velocities in the upper part of the ablation area of Tyndall Glacier, southern Patagonia. The measuring points were almost same as those in previous measurements in 1990. Comparing the results with those in 1990 and in 1985, we estimated average annual change of the surface elevation between 1990 and 1993 to be －3.1 m/a, which was close to that between 1985 and 1990 of －4.0 m/a. Therefore, we see that this part of the glacier has been thinning continuously during the last eight years. The rate is large compared to other retreating glaciers in the world. Flow velocities obtained by the measurements at an interval of nine days were 0.065 m/day to 0.61 m/day near the eastern margin. They were larger than those obtained in December 1990. Displacements of painted stones which were left on the glacier surface in 1990 gave annual flow velocities of 16.6 m/a to 47.3 m/a. From measurements of a strain grid, annual emergence velocity was estimated to be about 10 m and a brief discussion on mass balance was made.

1. Introduction

Patagonia Icefield in South America is the third largest ice-covered area on the earth and is considered to play an important role in the global climate and environment. However, few glaciological studies had been made in this area until early 1980s. Our group has been studying the glaciological and the meteorological aspects of Patagonian glaciers since 1983 (Nakajima, 1985 ; 1987 ; Naruse and Aniya, 1992 ; 1995). As a part of the study, surveys at Tyndall Glacier were carried out in 1985 (Naruse *et al.*, 1987) and in 1990 (Kadota *et al.*, 1992). Tyndall Glacier is located at the southern end of the Southern Patagonia Icefield and flows southward from the icefield (Fig. 1).

In December 1993, we carried out a field survey in order to investigate the variation of Tyndall Glacier putting the main interest on thickness changes of the glacier. To this end, we chose almost the same survey points as those used in 1990 and measured the surface elevations at those points. Surface ice flow-velocities for nine days were measured there as well. Besides long-term flow velocities were obtained from the displacements of painted stones which were left at the survey points in 1990. Emergence velocity, one of the important factors to explain the lowering of the surface, was obtained through the measurements of a strain grid.

2. Methods

Except for some measurements of the painted stones, the measurements were carried out with an electronic distance meter (EDM : TOPCON ET-2, minimum reading 1").

We utilized the same control point α and azimuth point β established on the left bank in 1990 (Fig. 2). In order to obtain surface elevation changes from 1990

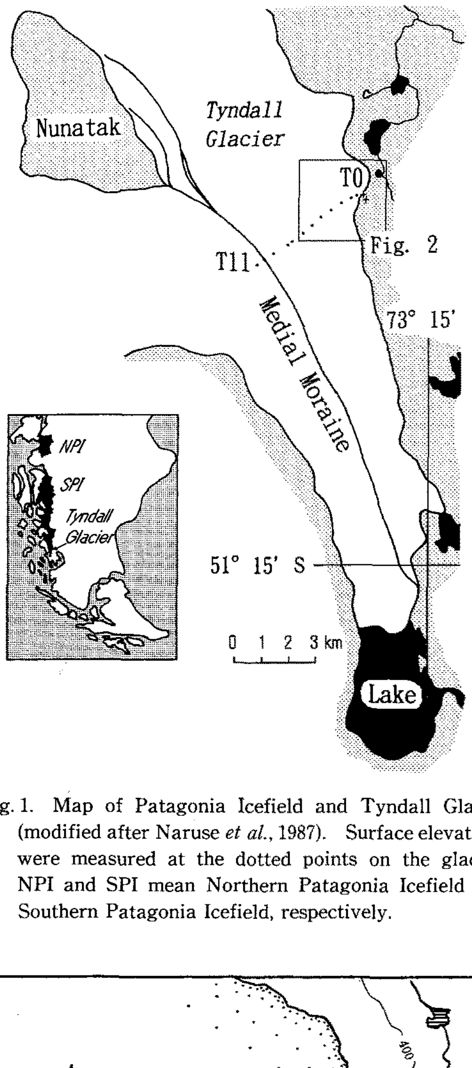

Fig. 1. Map of Patagonia Icefield and Tyndall Glacier (modified after Naruse *et al.*, 1987). Surface elevations were measured at the dotted points on the glacier. NPI and SPI mean Northern Patagonia Icefield and Southern Patagonia Icefield, respectively.

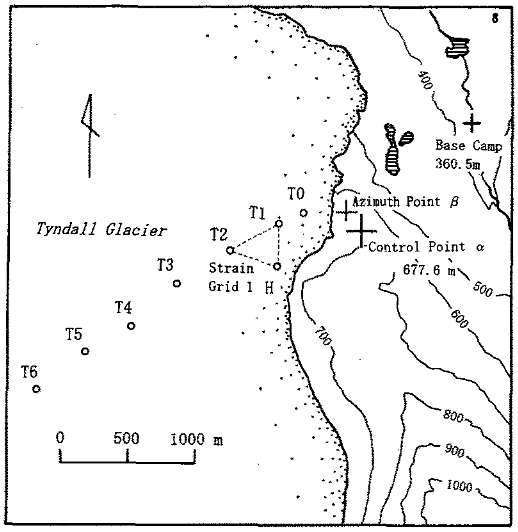

Fig. 2. Map indicating the points at which surface flow-velocities were measured (modified after Kadota *et al.*, 1992). Strain Grid 1 is also shown.

to 1993, we re-established about the same measuring points of 1990 named T0 to T11. They were set on a transverse line from the left margin to the medial moraine in the upper ablation area of the glacier, and were about 13 km away from the snout.

By measuring distances, horizontal angles and vertical angles of the measuring points from the control point, we obtained horizontal positions and elevations of T0 to T6 on December 9, 1993. Since the other points, T7 through T11, were too far to be directly measured from the control point in bad weather condition as occurred in that period, the relative positions of them were measured with a traverse survey method starting from T6 on December 11. The horizontal error of the positions of T0 to T11 between 1990 and 1993 was mostly less than a few meters. The error of the elevation caused by the horizontal error of positions were considered to be neglected, for the surface of the glacier was so flat.

After the measurement of the elevation of T0 to T11, a marking flag was set up at each point in order to obtain surface flow-velocities. The positions of flags at T0, T1 and T2 were re-measured on December 18. Unfortunately, new snow covered over crevasses between T2 and T3 and prevented us to go T3 and further than T3, thus only variations of the horizontal angles were measured at T3 and T5 from the control point. The flags at T4, T6 and the points further than T6 could not be found out. Assuming that the flow directions were almost the same as those in 1990, the surface flow-velocities at T3, T5 and T6 were estimated from the variation of the horizontal angles.

We had placed a painted stone with a diameter of about 30 cm at each measuring point in the previous survey in 1990. In the survey of 1993, we could find out some of them and re-measured their positions. However, precise measurements with the EDM were done only for the stones placed at T1 and T2. Due to bad weather, positions of stones left at T3 and T4 were simply measured with a rope and a compass from the corresponding 1993 points.

We established triangular strain grids around T2 (Strain Grid 1) and T6 (Strain Grid 2) so as to estimate emergence velocity, which is the flow velocity perpendicular to the surface. Because of the new-snow cover, only Strain Grid 1 was successfully re-measured. This grid consisted of the survey point T1, T2 and specially established point 'H' (Fig. 2). Relative positions of H and T1 were measured from T2 with the EDM and the area of the triangle was calculated on December 11 and 18.

From now on, we present a theoretical procedure to derive the emergence velocity from the data of the strain grid. Let A_1 and A_2 be the measured areas of the strain grid at the beginning and the end of the measurement, respectively. Taking the Cartesian coordinates with a z-axis normal to the surface of the glacier, a plane which contains x-axis and y-axis comes to be parallel to the glacier surface. Real directions of the x-axis and y-axis on the plane are not important in the following calculation. Let ε_x, ε_y and ε_z be the normal strain rates in x, y, and z directions, respectively. Assuming the incompressibility of the glacier ice, the total strain rate, $\varepsilon_x+\varepsilon_y+\varepsilon_z$, must be zero. Hence,

$$\varepsilon_z=-(\varepsilon_x+\varepsilon_y) \tag{1}$$

From

$$dA=(\varepsilon_x+\varepsilon_y)A\,dt, \tag{2}$$

$$\varepsilon_x+\varepsilon_y=\ln(A_2/A_1)/\Delta t \tag{3}$$

can be calculated from the measurements of A_1 and A_2. Here Δt indicates an interval of the measuring time. If the topography of bedrock does not change much along the flow, integration of ε_z from the bottom to the surface gives the emergence velocity W. Further, if we assume that ε_z does not change with z within the glacier, the integration comes to $\varepsilon_z h$. Here, h is the ice thickness. Accordingly,

$$W=\varepsilon_z h. \tag{4}$$

Therefore, the emergence velocity can be estimated from the measurements of A_1, A_2, Δt, and h by the following equation derived from the equations (1), (3), (4).

$$W=-h\ln(A_2/A_1)/\Delta t \tag{5}$$

3. Results and discussion

Figure 3 shows the changes in the surface elevations along T0 to T11 since 1985. The lowering of the surface between 1990 and 1993 ranges from 8.6 m at T7 to 14 m at T0. Averaging these values with weights of position intervals, an average lowering during these three years was calculated as 9.4 m, which is equivalent to the annual lowering of 3.1 m. Since the average annual lowering between 1985 and

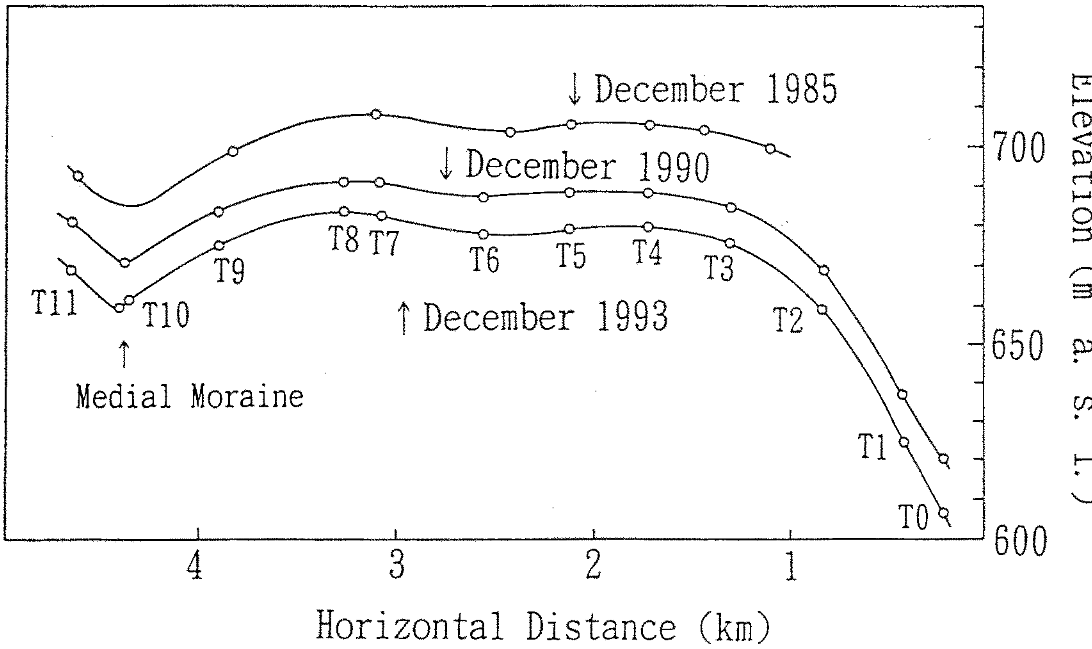

Fig. 3. Cross-section of the glacier surface showing changes in elevations along the measured points between 1985 and 1993 (new data added to those by Kadota *et al.*, 1992).

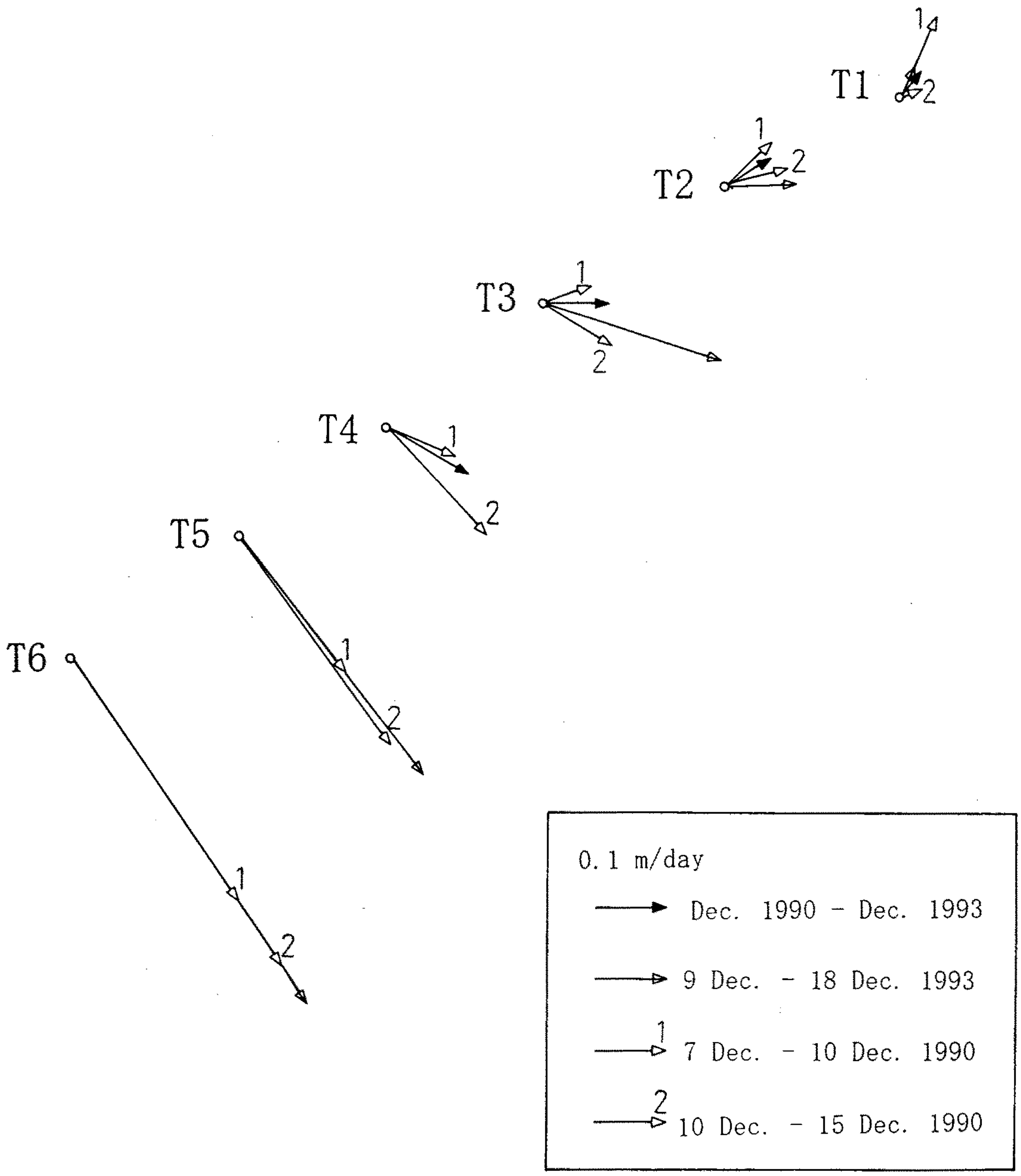

Fig. 4. Distribution of surface flow-velocities measured during early December 1990, mid-December 1990, mid-December 1993, and three years from 1990 to 1993. The directions of the flow at T5 and T6 during December 9 and 18, 1993 were supposed to be the average of two sets of the data in 1990.

1990 was 4.0 m (Kadota *et al.*, 1990), this part of the glacier has been thinning continuously during the last eight years. The rate is large compared to those of other retreating glaciers in the world (Skvarca *et al.*, 1995).

Mean surface flow-velocities measured between December 9 and 18 in 1993 (short-term velocities) are shown in Fig. 4, together with those measured in 1990. The solid arrows in Fig. 4 show the mean flow velocities obtained from the displacements of the painted stones for three years (long-term velocities) which can be regarded to represent the annual mean flow-velocities. Figure 4 indicates that the annual flow-velocities at T1, T2, and T3 are within the range of the short-term flow-velocities in early December and in mid-December 1990. The short-term flow-velocities in December 1993 exceed those in 1990 at all points except for T1. This suggests that the short-term flow-velocities increase rapidly and exceed the annual velocities in December.

The mean strain rate in z-direction ε_z between December 11 and 18 at Strain Grid 1 was calculated to be $-2.0 \pm 0.6 \times 10^{-4}$/day. On the other hand, radio-echo sounding shows the average ice thickness around the grid was 200 m (Casassa, 1992). Hence, using the equation (5), we estimate the emergence velocity as 4 cm/day or 15 m/a. However, the annual flow-velocities at T1 and T2 are 65 % and 70 % of the short-term flow-velocities measured in 1993, respectively. If the strain increases linearly with surface flow velocity, the annual mean emergence velocity would be also 65 % or 70 % of the short-term emergence velocity, that is about 10 m/a. So it is reasonable to estimate that the precise value of W should be between these two values, 10 m/a and 15 m/a.

Now we make a brief discussion on the mass balance at Strain Grid 1. To understand the mechanism of rapid thinning of Tyndall Glacier, knowledge of the mass balance is important. The average annual change in the surface elevation at T1 and T2 of -3.8 m should be equal to sum of the annual emergence of 10 m and annual balance. Accordingly, the annual balance would be about -3.8 m-10 m$=-14$ m or -3.8 m-15 m$=-19$ m in ice thickness (Fig. 5). It yields the daily ice ablation averaged thorough an year to be 4.7 cm/day. We measured an ice ablation rate of 6.9 cm/day at T2 with an ablation stake between December 9 and 17. The difference is probably due to acceleration of the ablation rate in summer time or melting of newly accumulated snow.

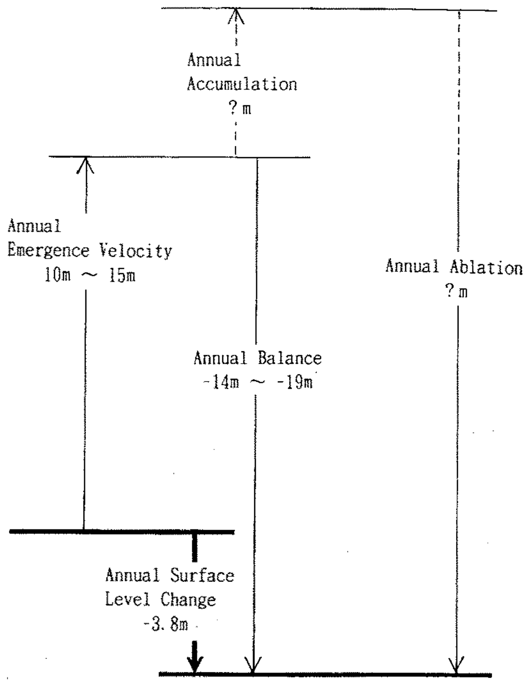

Fig. 5. Mass balance diagram at the Strain Grid 1.

The amount of the annual ablation cannot be directly estimated here, because the annual snow accumulation is unknown.

In the following, we compare these results on mass balance with those in Moreno Glacier (Naruse *et al.*, 1995), which is located at eastern side of the Southern Patagonia Icefield. At a point with the elevation of about 350 m above sea level on Moreno Glacier, the annual ablation is roughly estimated by a degree-day method as 11 m in ice thickness. It is close to the estimated annual balance at Tyndall Glacier by measurements of the strain and the surface level change. However, the estimated annual ablation in Moreno Glacier contains the melting of new snow and cannot be precisely equal to annual balance. Measurement on annual snow accumulation or annual ablation on Tyndall Glacier is necessary for more precise comparison.

In order to fully understand the thinning mechanism, all values discussed here should be measured during more than a year. Measurements at various parts on the glacier also should be carried out from now on.

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References

1. Casassa, G. (1992) : Radio-echo sounding of Tyndall Glacier, Southern Patagonia. Bull. Glacier Res., **10**, 69–74.
2. 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.
3. Nakajima, C. (1985) : Outline of the Glacier Research Project in Patagonia, 1983–1984. Glaciological Studies in Patagonia Northern Icefield 1983–1984 (ed. C. Nakajima), Data Center for Glacier Research, Japanese Society of Snow and Ice, 1–6.
4. Nakajima, C. (1987) : Outline of the Glacier Research Project in Patagonia, 1985–1986. Bull. Glacier Res., **4**, 1–6.
5. Naruse, R., Peña, H., Aniya, M. and Inoue, J. (1987) : Flow and surface structure of Tyndall Glacier, the Southern Patagonia Icefield. Bull. Glacier Res., **4**, 133–140.
6. Naruse, R. and Aniya, M. (1992) : Outline of Glacier Research Project in Patagonia, 1990. Bull. Glacier Res., **10**, 31–38.
7. 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.
8. Naruse, R. and Aniya, M. (1995) : Synopsis of glacier researches in Patagonia, 1993. Bull. Glacier Res., **13**, 1–10.
9. Skvarca, P., Satow, K., Naruse, R. and Leiva, J. (1995) : Recent thinning, retreat and flow of Upsala Glacier, Patagonia. Bull. Glacier Res., **13**, 11–20.