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Source: Arctic, Antarctic, and Alpine Research, 35(2) : 170-174

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2003)035[0170:MVIFVA]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 35, No. 2, 2003, pp. 170–174

Multiday Variations in Flow Velocity at Glaciar Soler, Northern Patagonia, Chile

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Abstract

Ice flow speeds were measured at Glaciar Soler in northern Patagonia during the middle of the melt season (November–December) in 1998 and compared to data from 1985. In 1998 the surface flow speed was greater at all survey points, yet the ice was about 40 m thinner; the greater melt rate in 1998 probably explains these differences because of the effect of melt rate on basal sliding speed. Multiday variations in surface speed were well correlated with daily variations in surface water input, which is the sum of melt rate and rainfall. Although the basal sliding speeds vary from place to place, we obtained similar linear relationships between basal sliding speed and surface water input. This result indicates the possibility of taking account of basal sliding as a function of surface water input.

Introduction

It has long been thought that temperate glaciers must be sensitive to global warming because their annual mass exchange rates are generally large (Meier, 1984); hence, they are good indices for climate change. In addition, even though their total area is much smaller than that of polar ice sheets, much attention has been given to the contribution of alpine glaciers to recent global sea-level rise (Dyurgerov and Meier, 1997; Gregory and Oerlemans, 1998). The mass exchanges of such glaciers are closely linked to their dynamics.

Basal sliding is considered to play an important role in the dynamics of temperate glaciers. Measurements using boreholes suggest good correlations between borehole water-level changes and surface flow variations at some temperate glaciers (e.g., Iken and Bindschadler, 1986; Boulton and Hindmarsh, 1987). According to Jansson (1995), similar exponential correlations between surface velocity and effective water pressure were shown at Storglaciären and Findelengletscher, and he argued that velocity variations on both glaciers had similar causes. On the other hand, the survey results during advancing and retreating periods at Findelengletscher suggested a possibility of change in basal sliding conditions between these two periods because of change in the subglacial drainage systems (Iken and Truffer, 1997). Further, at Storglaciären, Hanson et al. (1998) stated that large water-input events (e.g., rainstorms) produced coherent, lagged surface velocity responses. However, they did not find a consistent relationship between surface speed and water pressure. Some studies have indicated that other effects on glacial dynamics, such as change in longitudinal stress gradient (e.g., Hanson et al., 1998) and till deformation at the bed (e.g., Boulton and Hindmarsh, 1987; Blake et al., 1994; Iverson et al., 1994; 1995) play important roles in variations in basal sliding. Thus, because factors controlling basal sliding are complex, there are still unsolved problems in evaluating basal sliding.

The Patagonia icefields are an important area to study because, with a total area of 17,200 km^2 (Aniya et al., 1996), they are the largest temperate ice mass in the Southern Hemisphere (Warren and Sugden, 1993). Furthermore, most outlet glaciers from these icefields have been retreating (Aniya, 1992; Aniya et al., 1997), and the Patagonia icefields' ice-volume loss is estimated to represent 3.6% of the total sea-level change since 1944–1945 (Aniya, 1999). Therefore, knowledge of glacial dynamics in Patagonia is important to better understand the influence of global warming on glaciers.

Flow measurements have been carried out at several glaciers in Patagonia (e.g., Naruse, 1987; Nishida et al., 1995; Skvarca et al., 1995; Skvarca and Naruse, 1997). Naruse et al. (1992) empirically derived a correlation between surface flow speed and water discharge from the terminus at Glaciar Soler. Recently, extensive studies using radar interferometry of satellite images have been made (Rignot et al., 1996; Michel and Rignot, 1999; Forster et al., 1999). These studies pointed out the importance of basal sliding in Patagonia, but little attention has been paid to variations in basal sliding (Naruse et al., 1992; 1995). The purpose of this paper is to show the results of the ice-flow measurements, with 2- to 5-d intervals on the ablation area of Glaciar Soler, and to discuss variations in basal sliding.

Regional Setting

Glaciar Soler is located on the eastern side of Hielo Patagónico Norte (46°56′ S; 73°11′ W) in Chile, South America (Fig. 1). The glacier extends from about 350 m a.s.l. at the terminus to over 3000 m a.s.l.; the equilibrium line has been estimated at 1350 m a.s.l. (Aniya and Naruse, 1987). The 7-km-long outlet part has one source through an icefall from the icefield (1200–1500 m a.s.l.) and another source from Cerro Hyades (3078 m a.s.l.) (Aniya et al., 1988). The southern half of the ablation area is debris-free ice because its source is the icefield, whereas the northern half is covered with thin debris carried down by avalanches from Cerro Hyades (Fig. 1).

Surface flow measurements made in 1983 and 1985 at Glaciar Soler showed that the velocities near the terminus are dominated by basal sliding (Naruse et al., 1992). According to Naruse et al. (2000), the mean thinning rate of the glacier between 1985 and 1998 was 3.2 ± 0.5 m yr^{-1}, and the receding rate shows spatial variations from 15 m yr^{-1} to 40 m yr^{-1}. These authors suggested that recent remarkable thinning might be caused by the combined effects of a decrease in mass flux through the icefall and an increase in the ablation rate. The response time to climate changes was estimated at about 150 yr using a glacier flow model; hence, a possible decrease in mass flux is probably the integrated influence of climate change during the last

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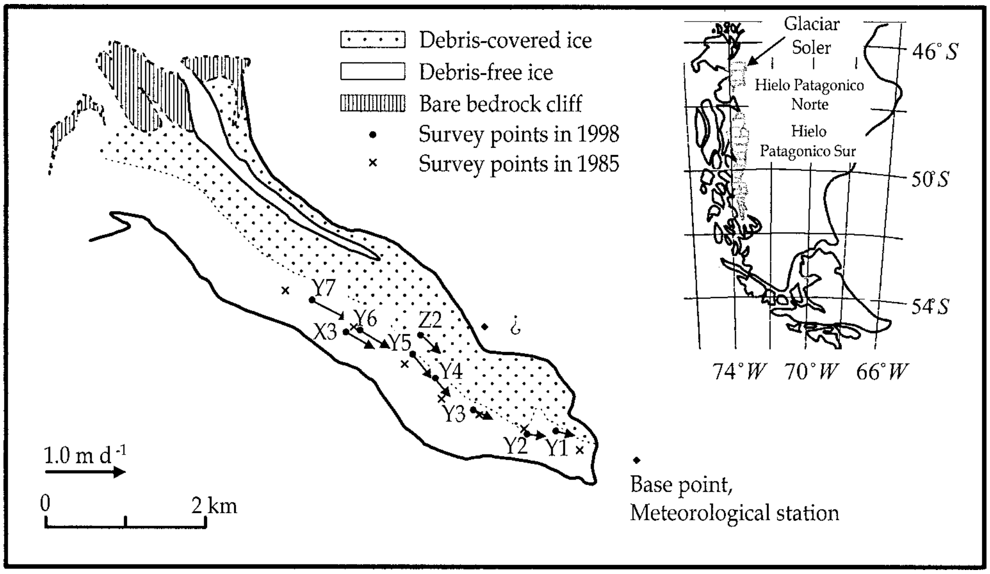

FIGURE 1. Map of the ablation area of Glaciar Soler with the survey points and mean horizontal velocities measured in November–December 1998.

century. On the other hand, according to the climate data at Puerto Aysen, about 150 km north of Glaciar Soler, no clear trends appear in either the annual mean air temperature or the yearly precipitation that would predict such glacier thinning.

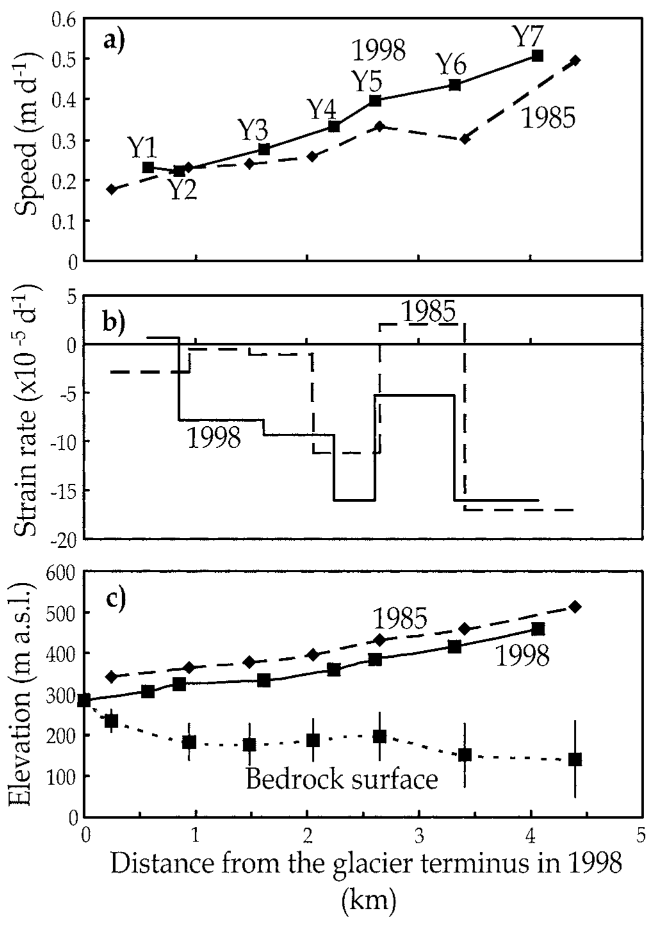

FIGURE 2. (a) Distribution of surface flow speed. (b) Distribution of longitudinal strain rate. Positive sign indicates extension and negative sign contraction. (c) Surface and bedrock profiles with error bars. Solid lines indicate the results in 1998, and broken lines the results in 1985. For locations of the survey points from Y1 to Y7, refer to Figure 1.

Measurements Procedure

Between November 15 and December 10, 1998, we monitored 9 survey points for flow velocities on the outlet part of Glaciar Soler. We set one of a pair of GPS receivers (Topcon model GP-SX1) at a fixed base point near the meteorological station, 400 m below the glacier terminus in 1998 (Fig. 1). We measured positions of the survey points on the glacier with another receiver for 30 min at a time, using the rapid-static method. Altitudes of the survey points were determined with reference to the known altitude of base point α on the left lateral bank. Eight of the flow survey points were set on the debris-free surface zone, and the remaining one (Z2) was on the thin, debris-covered surface zone (Fig. 1). At each survey point, we set up a plastic pipe to be used as an ablation stake. To withstand very strong winds, we buried all pipes in drilled holes, leaving only about 10 cm above the ice surface. Each pipe's position and height were measured at 2- or 3-d intervals. Daily melt rates were obtained from the difference of the pipe heights divided by interval days at Y1, Y2, Y3, and Y4.

Mechanical measurement errors of horizontal and vertical positions of the GPS depended on their distance from the base point. The most uncertain position was Y7, with an error estimate of ± 10 mm in the horizontal and ± 20 mm in the vertical. Errors of stake positions owing to surface melting and stake leaning were estimated to be at most ± 10 mm.

The meteorological station was established on a terminal moraine to measure various conditions, including air temperature and rainfall. The air temperature was measured 1.5 m above the ground and recorded automatically at 1-h intervals. Rainfall was measured several times a day using a "rain gauge" composed of a bottle and a 21-cm-diameter funnel (Ushiyama and Matsuyama, 1995).

Results

DISTRIBUTION OF FLOW VELOCITIES

The direction and relative magnitudes of surface flow velocities at the nine points, averaged over the survey period, are shown by vectors in Figure 1. Figure 2 shows (a) the mean daily flow speeds, (b) strain rates, and (c) surface profiles along a flow line in 1998. This data is compared to measurements made between October and November 1985 (Naruse et al., 1992; Aniya and Naruse, 1987). Also

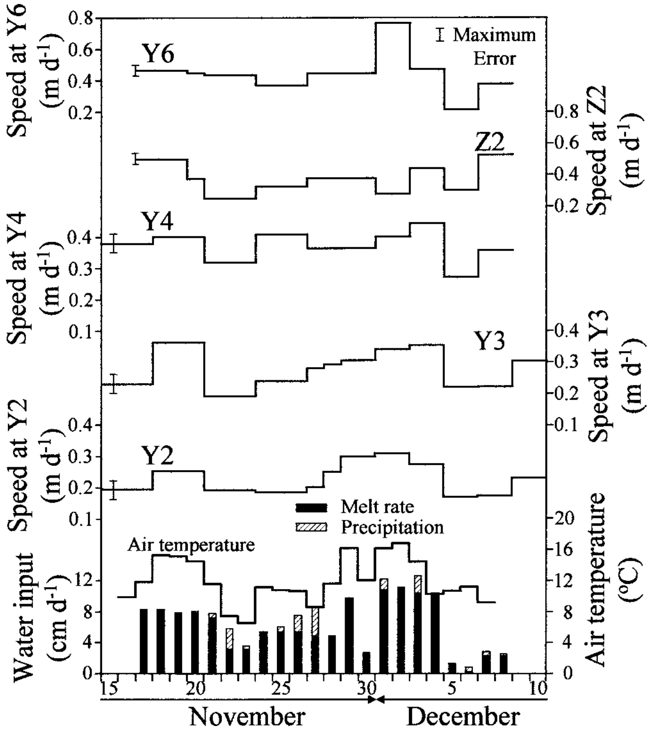

FIGURE 3. Multiday variations in surface flow speed with error bars at five survey points and meteorological data in November–December 1998.

shown in Figure 2c is the bedrock profile inferred from the gravity survey made in 1985, in which the ice thickness has ±25% error (Casassa, 1987).

Figure 2a shows that the flow speeds increase gradually with the distance upglacier. The trend in 1985 is similar, but the speeds in 1998 were greater by up to 0.13 m d^{-1}, although the ice has thinned by approximately 40 m on average since 1985 (Naruse et al., 2000).

Figure 2b shows a comparison of the longitudinal strain rates between 1985 and 1998; the rates were obtained from the gradients in Figure 2a. In both years, the strain rates were mostly negative, indicating a longitudinally compressing flow in this region of the ablation area. In both years, the strain rate was high about 2.5 to 3 km from the terminus, becoming positive in 1985. The reason may be related to the glacier geometry but is unclear owing to insufficient data regarding the bedrock topography. The strain rate near the terminus was also positive in 1998, which was considered to be an effect of calving into a newly formed proglacial lake.

COMPARISON OF MULTIDAY VELOCITY VARIATIONS AND METEOROLOGICAL CONDITIONS

Figure 3 shows multiday variations in flow speed at 5 points (sufficiently frequent data were not obtained at Y1, Y5, X3, and Y7 to discuss multiday variations) as well as daily mean air temperature and surface water input. Hereafter, surface water input is the sum of daily melt rate averaged over Y1, Y2, Y3, and Y4 plus daily rainfall, both of which factors are considered to affect surface flow speed (e.g., Hooke et al., 1989; Hanson and Hooke, 1994; Jansson, 1995).

Every point exhibited significant variations in flow speed, which implied that basal sliding was dominant because it is unlikely that such large variations would occur in the internal ice deformation rate. Although the amplitudes of variations of flow speed are different from point to point, each trend of variation has two similar peaks: one appeared from November 18 to 20 and another from December 1 to 4.

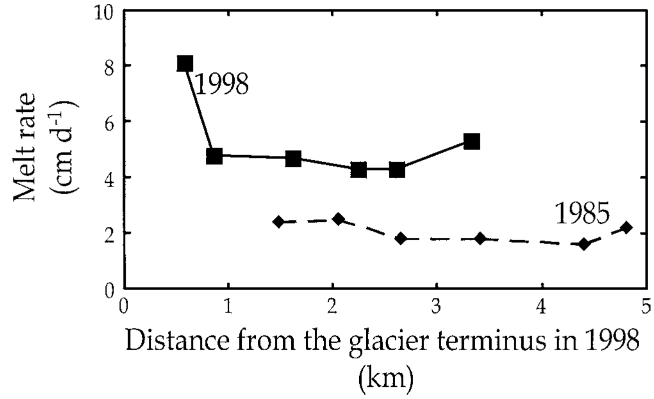

FIGURE 4. Mean melt rate over the ablation area. Solid line indicates the results in November–December 1998 and broken line the results in October–November 1985.

Air temperature ranged from 6°C to 16°C and showed two peaks: one from November 18 to 20 and another from November 29 to December 3. Variations in melt rate had almost the same trend as air temperature; that is, melt rate was greater in warmer air temperatures. There were four rainy periods: November 20–23, November 25–27, December 1–3, and December 6–8.

It seems that variations in surface speed synchronized with variations in surface water input because flow speeds were greater during the high surface water input periods (November 17–20 and December 1–4) and lower during the low surface water input periods (November 21–23 and December 5–6).

Discussion

CAUSE OF THE DIFFERENCE IN SURFACE SPEED BETWEEN 1985 AND 1998

Surface speed due to internal ice deformation should be smaller in 1998 than in 1985 because of thinner ice in 1998. Figure 4 shows that melt rates at all points were larger in 1998 than in 1985, which may be because the mean air temperature during the survey period in 1998 was about 2°C higher than in 1985. Thus, the higher surface speed despite the thinner ice in 1998 at Glaciar Soler can be attributed to the fact that the basal sliding was much greater in 1998 than in 1985 owing to differences in the subglacial water system and the higher melt rate in November–December 1998 than in October–November 1985. The effect of those factors was sufficiently greater than the decrease in ice deformation rate because of ice thinning in 1998.

CORRELATION BETWEEN FLOW SPEED AND WATER INPUT

We have not attempted to measure subglacial water pressure, which is considered to be one of the principal factors in basal sliding, so far. However, it is likely that subglacial water pressure is linked to water input. Figure 5 indicates relationships between surface flow speed and surface water input. Good correlations are seen between the two parameters, except Z2, although the proportionality varies with position.

A possible reason for the poor correlation at Z2 is the effect of thin debris cover, which sometime promotes surface melting. In fact, daily melt rates at Z2 were larger than the average over Y1, Y2, Y3, and Y4, which were on debris-free ice surface. Hence, it is possible that a subglacial drainage system may have developed fully under Z2, and the water storage at the bed may not have been affected much by surface water input.

In Figure 6, a relation was shown between daily basal sliding speeds at four points (Y2, Y3, Y4, and Y6) and the daily surface water

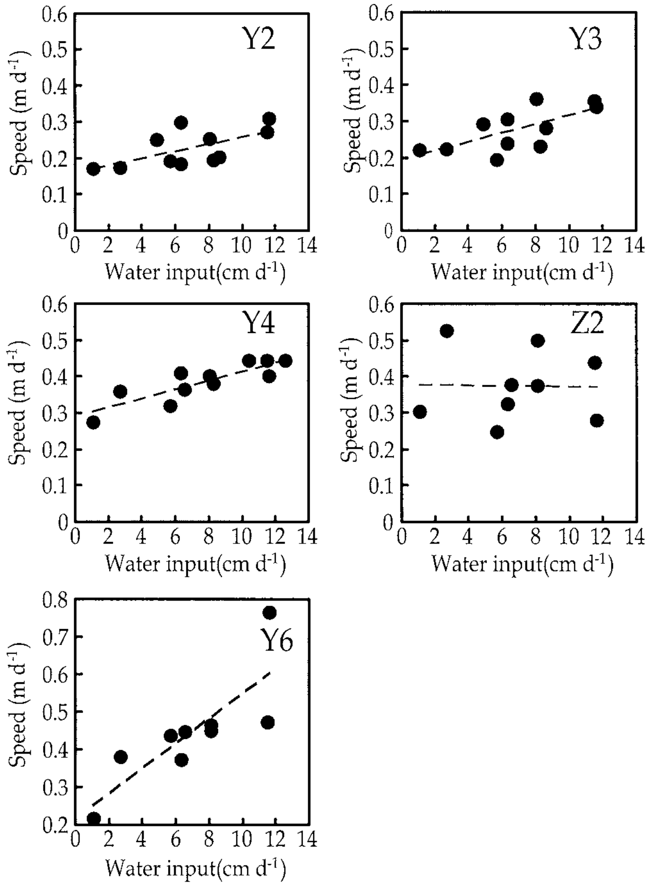

FIGURE 5. Correlations between daily surface flow speed and daily surface water input at five survey points.

input (average over Y1, Y2, Y3, and Y4). Basal sliding speeds were estimated from the surface speed minus ice deformation speed, which is calculated using data of ice thickness and surface slope, and flow parameter at 0°C (Paterson, 1994). Basal sliding speed and water input are normalized by dividing with the mean values over the observation period.

Though mean values of basal sliding depend on location, the same correlation exists between variations of sliding speed and surface water input at all locations. A linear regression equation between normalized basal sliding (U_{bm}) and normalized water input (W_m) was obtained as,

$$U_{bm} = 0.38 \times W_m + 0.62. \quad (1)$$

It has been suggested that the basal sliding speed is strongly affected by the subglacial water pressure (e.g., Iken and Bindschadler, 1986). In particular, Jansson (1995) proposed a power relationship between the surface velocity and the effective water pressure at the bed. Because we have no knowledge on the link between the surface water input and water pressure at the bed, we cannot discuss the matter further by comparing equation 1 with Jansson's equation.

Conclusions

Surface flow speeds measured using GPS in 1998 were larger than those in 1985, though ice thickness had thinned by approximately 40 m since 1985 at Glaciar Soler in northern Patagonia. This result indicates that basal sliding in 1998 was larger. A possible reason for this difference is that the melt rates were larger for the mid–melt season in 1998 than the early melt season in 1985; the difference in the subglacial water network may have been another factor.

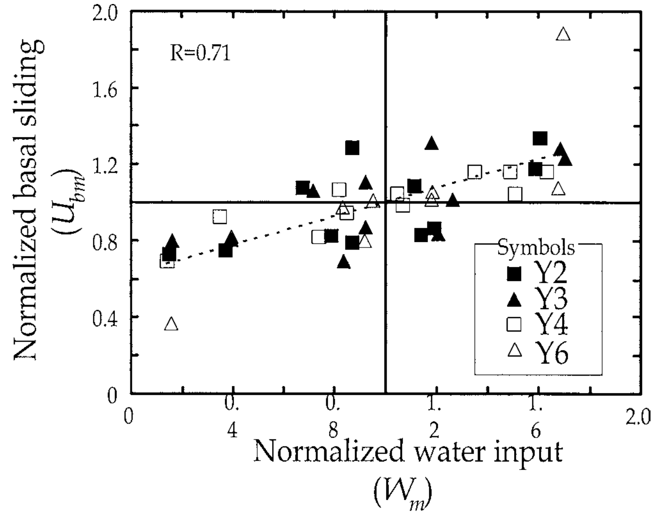

FIGURE 6. Correlation between normalized basal sliding speed and normalized surface water input for four survey points, with the correlation coefficient R.

We found a good correlation between variations in flow speed and surface water input. Though the values of basal sliding varied by location, the relationships between the normalized basal sliding speeds and normalized surface water inputs showed the same trends for all points, with a correlation coefficient of 0.71. Hence, basal sliding speed can be treated by a function of surface water input at Glaciar Soler, and a similar function may be applied to other temperate glaciers.

Acknowledgments

We thank Masamu Aniya, Institute of Geoscience, University of Tsukuba, and Kaoru Izumi, Research Institute for Hazards in Snowy Areas, Niigata University, who helped with field research and gave good suggestions. Detailed comments from Neil Glasser and an anonymous reviewer helped to improve this paper greatly. We are also indebted to Anselmo Soto for his logistical support in the field. This study was supported by grant #10041105 of the Ministry of Education, Science, Sports, and Culture, Japan

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Ms submitted June 2001
Revised ms submitted July 2002