SEASONAL SURFACE-VELOCITY VARIATIONS ON A SUB-POLAR GLACIER IN WEST GREENLAND

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ABSTRACT. Eight stakes situated in the ablation and the accumulation areas of a sub-polar glacier in West Greenland were surveyed at intervals of 10 days during the summers of 1982 and 1983. The horizontal velocity in both the ablation and the accumulation areas increased distinctly during the short summer season. This indicates that melt water reaches the bed and that the glacier is sliding. It is proposed that melt water produced in the ablation area is forced up-glacier through a subglacial water system. The vertical displacement of stakes showed variations indicating an apparent uplift of the glacier during the summer. However, this is interpreted as the result of seasonal variation in atmospheric refraction.

INTRODUCTION

Seasonal variations in surface velocity of glaciers, showing higher velocities during the summer period, have been known for more than a century. Variations of surface velocity in temperate glaciers have been noted by numerous observers, e.g. Meier (1960), Paterson (1964), Hodge (1974), Iken (1978), and Iken and others (1983). Few investigations have been made on sub-polar glaciers, e.g. Battle (1951), Müller and Iken (1973), and Brzozowski and Hooke (1981). (The term "sub-polar" is used to denote that the temperature over parts of the glacier is negative, even during the short summer season. This indicates that melt water reaches the bed and that the glacier is sliding. It is proposed that melt water produced in the ablation area is forced up-glacier through a subglacial water system. The vertical displacement of stakes showed variations indicating an apparent uplift of the glacier during the summer. However, this is interpreted as the result of seasonal variation in atmospheric refraction.)

METHODS

The surface velocity and the direction of movement of the stakes in 1982-83 were determined by intersection from fixed points (A0, A1, B0, and N; Fig. 2) on bedrock or on stable moraine along the periphery of the glacier. The seasonal variation in surface velocity was determined by measuring the angle between a fixed point and the stake in 1982-83. The transient snow line was at about 1050 m at the end of the summer of 1983. "Kitdlerssuaq glacier" advanced approximately 10 m in 1982-83. The glacier is coded No. 1 DG 16166 in the West Greenland Inventory and is located at lat. 66°07' N., long. 50°10' W.

The standard deviation of angle measurements was determined using directions of sight to two fixed points. One point was located on the same side, the other point on the opposite side of the glacier (B, and F, respectively) relative to the survey point A. At a given time, the accuracy of the vertical angle from A to F was determined as ±0.00038° (n = 30). When readings to fixed points were taken during the summer, at the same time as readings to stakes, the accuracy of vertical angles was determined as ±0.00008° (n = 33) and ±0.00138° (n = 26) for points on the same side (B, ) and on the opposite side (F) of the glacier, respectively. The discrepancy between the accuracy at a given time and the accuracy during the summer is interpreted as a result of changes in refraction over snow and ice surfaces (Andreasen, 1985). The standard deviation of horizontal angle measurements was determined using the fixed angle between the two points B, and F. Readings were taken during the summer, at the same time as readings to stakes. The accuracy of horizontal angles was in this way determined as ±0.0118° (n = 25).

RESULTS AND DISCUSSION

Horizontal velocity

Stake positions and the direction and magnitude of ice velocity are shown in Figure 2. In Figure 3, seasonal horizontal velocity variations in 1982 and 1983 are presented together with the daily mean temperature measured at the base camp and the discharge of the main melt-water outlet (E1). Ice and snow at the gauging station at the beginning of the melt season prevented reliable discharge measurements in June. A reasonable relation between daily ablation and temperature exists at Qumaniarsaap sermia, about 185 km south of "Kitdlerssuaq glacier" (Braithwaite and Olesen, 1982). An indication of daily ablation at "Kitdlerssuaq glacier" is given by the daily mean temperature at the base camp.

At stakes 950 and 980, ice velocity decreased by an order of 30–40% from July to September 1982. In June, temperatures were rather high, and the ice velocity may have been higher in June than in July, but no velocity measurements were made during that month. Apparently, the decrease in velocity was interrupted by a small increase in the period 24–31 July.

At stakes 1050 and 1100, situated in the lower part of the accumulation area, the glacier velocity reached a maximum 3 weeks later, in the period 24 July–2 August 1982, immediately followed by a marked decrease in ice velocity. At stake 1100, maximum velocity was more than twice the annual velocity.

Although the glacier was completely snow-covered during the summer season of 1983, and both temperatures and discharge were much lower in 1983 than in 1982, marked velocity variations were observed. In the middle of July a distinct increase in velocity was found at stakes 900, 950, 980, 1050, and 1100. Two weeks later, the velocity decreased markedly at stakes 900, 950, and 980, whereas the velocity at stakes 1050 and 1100 remained high for another week. At stakes 1150 and 5, the velocity increased through July to a maximum in the period 25 July–2 August.

Seasonal variations in glacier velocity in the ablation area of "Kitdlerssuaq glacier" (stakes 900, 950, and 980) are as expected, because they agree with results of earlier investigations on sub-polar glaciers. On White Glacier, Axel Heiberg Island in the Canadian Arctic Archipelago, Müller and Iken (1973) found that the summer velocities were about 10–60% greater than the winter velocities and, on Storglaciären in northern Sweden, Hooke and others (1983) found that the maximum summer velocity was 40% greater than the mean winter velocity. At both White Glacier (Iken, [1973]) and Storglaciären (Hooke and others, 1983), negative temperatures were measured in the ablation area but the ice was temperate near the bottom, and velocity variations were explained as variations in glacier sliding.

In Greenland, too, glacier–velocity variations have been measured in the ablation area. In West Greenland, a century ago, Steenstrup (1883) investigated seasonal velocity...
Variations on glaciers on Nugssuaq and he concluded that "the velocity ... decreases through winter and spring". Seasonal velocity variations have been reported from Nordbogletscher (Clement, 1983) and from Qamanatsermi (Andreasen, 1982). In East Greenland, Paterson (1961) measured decreasing velocity on Sefstrøms Gletscher through August and, on Berørkerbreen, Friese-Greene and Pert (1965) found a correlation between the rate of flow and rate of ablation during the period 7 July–25 August.

Temperature measurements are not available from the ablation areas of the above-mentioned glaciers or from "Kitdlerssuaq glacier". However, previous investigations at nearby glaciers suggest that ice temperatures in the ablation area of "Kitdlerssuaq glacier" are below zero. At Isua, close to the margin of the inland ice and approximately 90 km south of "Kitdlerssuaq glacier", Colbeck and Gow (1974) found negative temperatures in the whole ice body, but they extrapolated the temperature at the ice/rock interface to be 0°C. In the ablation area of Sukkertoppen Iskappe, 50–100 km to the west of "Kitdlerssuaq glacier", negative temperatures have been measured (Henry and White, 1964; Hooke and Koci, 1978).

It seems safe to conclude that the temperature of the ice in the ablation area of "Kitdlerssuaq glacier" is negative down to a certain depth. This is supported by the fact that all stakes on "Kitdlerssuaq glacier" were frozen into the ice throughout the year.

In 1982, a maximum in glacier velocity in the ablation area occurred at the beginning of July. The entire glacier was snow-covered with large slush areas and the glacier-drainage system was poorly developed. This can be seen from the discharge curve; although discharge was high, diurnal amplitude was small. Probably, large amounts of water went into storage in and below the lower part of the glacier, causing high subglacial water pressure and subsequent high sliding velocity. As the drainage system developed, the temporarily stored water gradually drained and the ice velocity decreased.

In 1983, temperatures were lower than in 1982 and the maximum in glacier velocity in the ablation area was delayed a couple of weeks compared with 1982. In both 1982 and 1983, a maximum in glacier velocity occurred while the glacier was still snow-covered.

Velocity variations in the ablation area were as expected, whereas velocity variations measured in the accumulation area proper are quite surprising. In the accumulation area, variation in glacier velocity is normally either not significant or shows a maximum velocity in late winter, and it is then explained as the result of changes in ice thickness. At Hintereisferner in the Alps, Schimpf (1958) measured the maximum velocity in the firm area in late April/early May, whereas Brecher (1966) found no significant differences from the mean seasonal surface velocity in the accumulation area of Kaskawulsh Glacier, Yukon Territory, Canada.

In 1982, the maximum surface velocity occurred one month later at stake 1050 (at the equilibrium line) and at stake 1100 in the ablation area. In 1983, a distinct rise in surface velocity at stakes 1050 and 1100 occurred at the same time as at the lower situated stakes, but the velocity remained high. At stakes 1150 and 5, at higher levels in the accumulation area, the maximum was reached in late July–early August.

As the maximum in glacier velocity was observed in late July, it is not plausible to explain it by winter accumulation. It is more likely caused by subglacial storage of melt water at the glacier bed beneath the accumulation area.

As noted, the increase in velocity in the ablation area during summer is probably explained by the variation in sliding velocity. This in turn implies that the basal ice is at the melting point and that melt water can penetrate to the bed, even though the ice is below the melting point to a certain depth. Cold ice must be impermeable on the intergranular scale. Paterson (1981) mentioned that water might reach the glacier bed by penetration from the sides, if they are not frozen to the bed, whereas Iken (1972) argued that moulins on White Glacier are connected to the subglacial drainage system. However, water at the bed of sub-polar glaciers may also originate from the accumulation area in the accumulation area, melt water percolates down through the firm until it reaches layers with a negative temperature, where it refreezes and releases latent heat.

When the ablation is sufficiently great, this causes the winter cold wave to disappear. When the whole ice mass is at the pressure-melting point, melt water from the accumu-
south Greenland, Clement (1983) found that the discharge, all stakes were frozen in the firn. Only available from the cold 1983 summer, but also in 1982, the cold wave was not eliminated. Temperatures at stake 5 are not only from the accumulation area but all stakes were frozen in the firn temperature may have been higher in lower parts of the accumulation area and negative temperatures in the ablation area, is typical of sub-polar regions (Schytt, 1969).

As regards "Kitdlerssuaq glacier", most melt water in the ablation area (1982) disappeared into two moulins and only minor amounts of water discharged superficially. In the accumulation area, the temperature was measured in 1983 at stake 5 (1200 m a.s.l.) down to a depth of 10 m, and here the temperature was negative (below -3°C) throughout the summer. The temperature may have been higher in lower parts of the accumulation area but all stakes were frozen in the firn throughout the summer, and this indicates that the winter cold wave was not eliminated. Temperatures at stake 5 are only available from the cold 1983 summer, but also in 1982 all stakes were frozen in the firn.

Observations during Project Mint Julep (lat. 66°17' N., long. 47°46' W.) showed that the net ablation above the firn limit was nearly zero, as percolating melt water refroze in the firn layers (LaChapelle, 1955). On Nordbogletscher in south Greenland, Clement (1983a) found that the discharge, if any, from the accumulation area was very small. The sliding during summer, in both the ablation and the accumulation areas, must be caused by changes in the subglacial water pressure brought about by melt-water input from the ablation area to the subglacial water system. As the margin of the glacier is frozen to the bed at the beginning of the melt season (June), the melt water is confined behind cold ice in the ablation area, and water is forced up-glacier through the subglacial water system into the accumulation area. Here, the increased water pressure causes glacier sliding. Finally, the water (in July) breaks through the frozen margin and subglacial water is drained.

In both 1982 (on 8 July) and 1983 (on 21 July) turbid (presumably subglacial) water broke through the glacier at the southern side of the front and drained into stream E2. Although the subglacial water pressure in the vicinity of the outlet drops, melt-water input from ablation may still maintain a high water pressure over most of the ablation area, until ablation decreases or totally stops. Even when the subglacial water pressure in the ablation area decreases, the pressure gradient will still force water up-glacier. This explains the longer period with increased glacier velocity and the later maximum up-glacier.

**Vertical displacement**

The vertical positions of the stakes were determined from the fixed points A<sub>s</sub> and B<sub>s</sub>, and in Figure 4 the results from stake 950 are plotted as movements in the vertical plane, with a six-fold vertical exaggeration. The horizontal velocity at stake 950 and the vertical positions of the fixed point F, measured at the same time as the measurements to stake 950, are also shown. Apparently, measurements from point B<sub>s</sub> show an uplift of the glacier surface at the beginning of June, whereas the measurements from point A<sub>s</sub> show an uplift in the middle of July, at the same time as a sharp rise in horizontal velocity took place. However, it is notable that the measurements from A<sub>s</sub> to the fixed point F on the opposite side of the glacier also show an apparent "uplift" of the fixed point during the summer months.

It is known that atmospheric refraction varies systematically throughout the day, and Andreasen (1985) found that apparent regular vertical displacements through the day or for a few days were the result of variations in the refraction. In a similar way, the apparent discrepancy between the "uplift" at stake 950 determined from A<sub>s</sub> and B<sub>s</sub>, respectively, and the apparent uplift of the fixed point F is explained as a result of changes in atmospheric refraction throughout the period.

It is notable that the variations apparently show an annual trend, with low positions (corresponding to a small refraction coefficient) in the spring and in the autumn, and
high positions (i.e. high refraction coefficient) during the summer. In fact, this is to be expected from the temperature gradients in the near-surface air layer. During the daytime the snow surface is melting and the temperature at the surface is in general higher in the summer than in the spring or autumn, a more positive temperature gradient is found, and a higher refraction coefficient is to be expected.

It is concluded that the apparent uplift of the glacier at stake 950 is not real but is the result of a seasonal change in atmospheric refraction.

CONCLUSIONS

1. Horizontal velocity shows distinct seasonal variations in both the ablation and the accumulation areas. These variations can only be explained as variations in basal sliding. This, in turn, means that basal ice is at the melting point and that melt water reaches the bed, although the ice and snow temperatures in the ablation and accumulation areas are negative. Melt water from the ablation area is confined behind cold ice and the frozen margin, and water is forced up-glacier through a subglacial water system. The increased basal water pressure causes basal sliding in the accumulation area.

2. Measurements of the vertical displacement show an apparent uplift of the glacier surface. However, the uplift is not real but the result of a seasonal change in atmospheric refraction.

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REFERENCES


