Recent changes of McCall Glacier, Alaska

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ABSTRACT. Detailed surveys of McCall Glacier in the Alaskan Arctic reveal changes from 1972 to 1993. The ice surface dropped everywhere, by amounts ranging from about 3 m in the highest cirques to more than 42 m near the present terminus. The total volume loss was $5.5 \pm 0.2 \times 10^7 \, m^3$, resulting in an average mass balance of $-0.33 \pm 0.01 \, m \, a^{-1}$. The terminus has retreated by about 285 m at a rate of $12.5 \, m \, a^{-1}$. Results from photogrammetry for an earlier period, 1958–71, were $1.16 \times 10^7 \, m^3$ and $-0.13 \, m \, a^{-1}$ for volume change and mass balance, respectively; the mean terminus retreat rate was then $5.7 \, m \, a^{-1}$. The changes have to be seen in the context of McCall Glacier's low mass-exchange rate; annual accumulation and ablation, averaged over the years 1969–72 were only $+0.16$ and $-0.3 \, m \, a^{-1}$. Cross-profiles in the ablation area, surveyed at intervals of a few years, show an increased drop rate since the late 1970s. The volume-change data suggest a climate warming in the early 1970s. Enhanced thinning of the lower ablation region and accelerated terminus retreat seem to lag this climate change by not more than 10 years. This indicates a reaction time of McCall Glacier that is considerably shorter than its theoretic response time of about 50–70 years.

INTRODUCTION

Greenhouse warming of the atmosphere should affect the Arctic regions first and most strongly. The large fluctuations of annual weather make it difficult to detect an ongoing climate change from meteorological records alone. In this paper we present recent changes in surface elevation and volume of McCall Glacier in Arctic Alaska.

Kelly and others (1982) give a good summary of the changes in seasonal and annual air temperatures in the Arctic from 1881 to 1980. Warming after 1890 culminated in the 1930s with winters and summers being warmer by about 2.5° and 1.3°C, respectively, than during the 1880s. The warming started in the Barents and Kara Seas and became most pronounced in the northwest Greenland region. The Arctic cooled in the 1950s and stayed cold during the 1960s, with annual temperatures about 0.85°C less than in the 1930s. Warming began to affect the Arctic anew in the 1970s, again starting in the Barents and Kara Seas and spreading westward. In contrast with the 1930s, the warming is most pronounced in the Alaskan regions where annual temperatures rose by about 1°C (Fig. 1). The overall warming trend since the end of the 19th century is clearly exhibited by the glaciers in Arctic Alaska; they have retreated by 150–700 m from their "Little Ice Age" moraines (Hamilton, 1965; Calkin, 1988). Our goal is to identify more recent changes in climate against this background, by using high-resolution data from McCall Glacier.

To link climate changes to glacier changes two things have to be considered:

(i) Changes in climatic variables such as precipitation, solar radiation and temperature must not cancel in their combined effect on the mass balance of a glacier. On McCall Glacier, a general warming throughout the year would increase summer melt, but winter climate is too
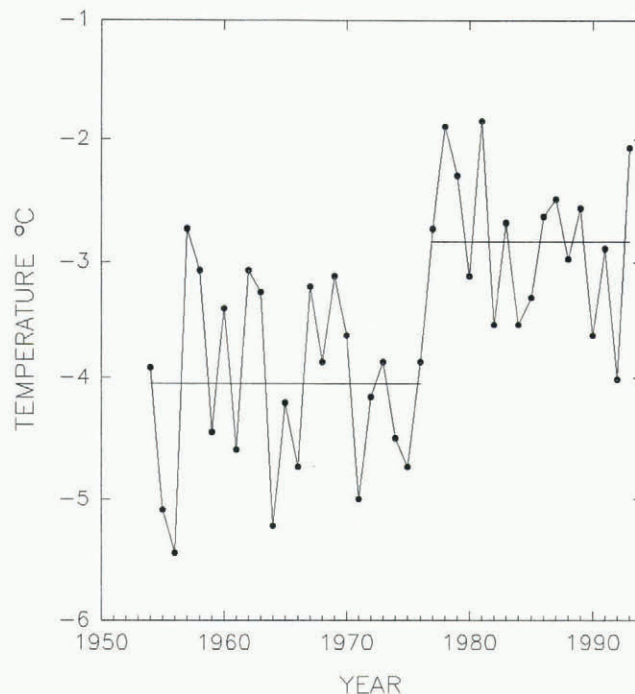

Fig. 1. Annual mean temperature, average of Anchorage, Barrow, Fairbanks and Nome (adapted from Bowling (1991)).

cold and dry for winter precipitation to increase significantly. This makes McCall Glacier a sensitive indicator of climate warming.

(ii) Advance/retreat or thinning/thickening of the glacier snout is greatly amplified by ice flux but lags the original mass-balance change in an intricate way (Nye, 1965; Jóhannesson and others, 1989). Measuring the total volume change of a glacier, by photogrammetry or surveying, is more difficult than observations near the terminus. The advantage is that a mass-balance change can be readily detected by a corresponding volume change without time lag.

McCall Glacier is located at 69°18′ N, 143°48′ W in the northernmost chain of the Romanzof Mountains, northeastern Brooks Range, Alaska (Fig. 2 inset). The
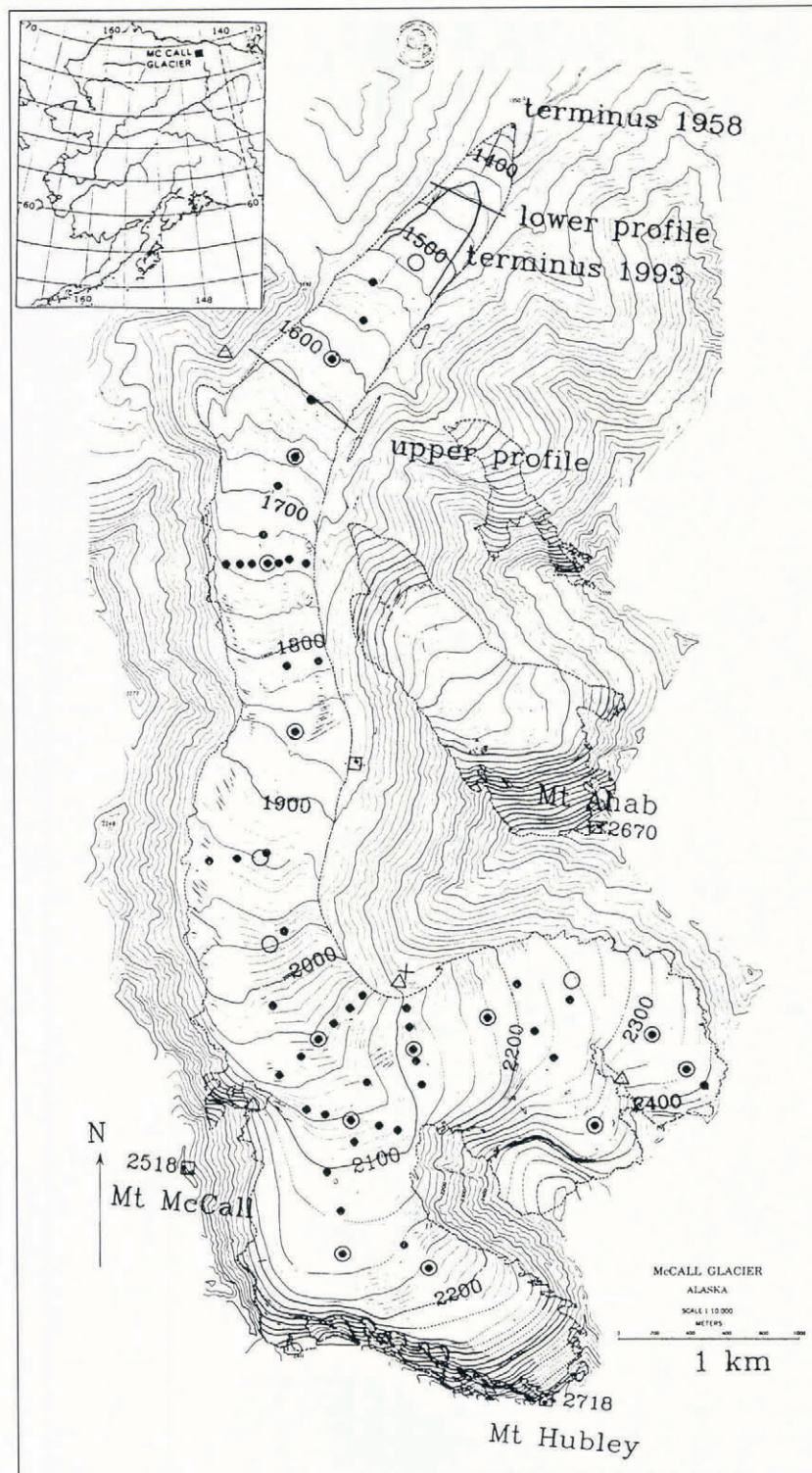

Fig. 2. Map of McCall Glacier, showing 1972 pole positions resurveyed in 1993 (black dots); control monuments (triangles); 1993 mass-balance stakes (open circles); upper and lower detailed-transverse profiles; and position of 1993 camp (cross).

glacier occupies a north-facing valley. It is about 8 km long, has an average width of 640 m and covers an area of 7.4 km^2. The ice originates in three cirques (referred to, from east to west, as upper, middle and lower cirque) and extends from more than 2700 m on the north face of Mount Hubley to the terminus at 1350 m. The glacier surface forms a series of bulges and treads with slopes of up to 15° and as low as 3°; the average ice slope is 7.5°. Figure 3 is a view of the lower ablation area, about 1.5 km up-glacier of the terminus, looking towards the confluence of the three cirques.

Benson, 1986). Maximum ablation at the terminus was 2.1 m a^{-1} in 1957/58 and 1.6–2 m a^{-1} in the 1970s. (All mass-balance values are given as water equivalent unless noted.) On McCall Glacier all the ablation and about 75% of the accumulation occur during June–September. Internal accumulation accounted for up to 54%, and superimposed ice for up to 5%, of the total accumulation (Trabant and Benson, 1986). McCall Glacier has a low-mass-exchange rate; annual accumulation and ablation, averaged from 1970 to 1972, were $+0.16$ and -0.3 m a^{-1}, respectively. The mean equilibrium-line altitude from

Fig. 3. Looking up-glacier from the upper detailed-transverse profile. Note "Hanging" Glacier to the left and snow-capped Mount McCall in the right background.

MEASUREMENTS PRIOR TO 1993

McCall Glacier is the only glacier in the U.S. Arctic with a glaciological record of several decades. Shorter records exist for some of the small cirque glaciers of the central Brooks Range (Calkin and others, 1985). McCall Glacier was studied during the International Geophysical Year (IGY) in 1957/58, and from 1969 to 1975 as a contribution to the International Hydrological Decade (IHD). As part of the IGY field program, a photogrammetric map of scale 1:10 000 was produced (Brandenberger, 1959). Observations of the IGY team on the equilibrium and firn-line position are also compiled in this map. Another photogrammetric mission was carried out in 1971 by Dorrer and Wendler (1976).

Keeler (1958) mapped mass balance on lower McCall Glacier during the IGY. Mass-balance maps of the whole glacier exist for the balance years 1968/69, 1969/70, 1970/71 and 1971/72 (Wendler and others, 1972; Trabant and

1969 to 1972 was 2050 m; mountain shadowing and preferred snow deposition on the west side of the glacier make the equilibrium line run normal to topographic contours over an elevation range of 350 m (Wendler and Ishikawa, 1974).

The extensive mass-balance network of the 1970s was surveyed each year, giving good definition of the ice surface and the surface velocity field at that time (unpublished information from Trabant, 1969–72). Maximum annual velocity was about 16 m a^{-1}. Two detailed transects of the ice surface in the lower ablation area (Fig. 2) were surveyed for several years starting in 1969 (unpublished information from Benson, 1969–75). The upper profile was resurveyed in 1987. Maps of a perennial aufeis field below McCall Glacier show the outline and elevation contours of the terminus in 1970. These data sets give accurate base lines for measuring changes in glacier volume and terminus position.

Meteorological observations were carried out in the

upper cirque at about 2300 m during 1957/58 (Orvig, 1961). An automated weather station operated from 1969 to 1972 on the rock ridge between upper and middle cirque. Sparse data were obtained during the winters. Comparison with weather stations of interior Alaska and the Arctic coast revealed a distinct mountain climate dominated by the proximity of the Arctic front in the region of McCall Glacier (Wendler and others, 1974). Approximate mean annual temperatures were about −12°C at 1700 m (Trabant and others, 1975). Annual precipitation averaged over the glacier was estimated as 500 mm a^{-1}. During summer, winds are mainly from the southwest (Wendler and others, 1974).

A polythermal temperature regime is suggested for McCall Glacier. In the accumulation zone the glacier is at about −1°C throughout its thickness (Orvig and Mason, 1963), while the ablation zone is cold at the surface (−8°C at 10 m depth) but is probably underlain by a layer of temperate ice at the bed (Trabant and others, 1975).

1993 FIELD WORK

The data presented in this paper were gathered from 26 June to 10 August 1993 as part of a 3 year study of recent changes of McCall Glacier. Surveying the glacier surface, using optical methods and airborne and ground-based GPS methods, was the key tool for defining the glacier surface in 1993. The new data set allows comparison with past surveys in 1958 and the 1970s. Most of the control monuments used for the 1970s survey were recovered, and the more stable ones were selected for the 1993 survey. A GPS base line about 15 km long ties the glacier-control network to a survey benchmark that is fixed to the United States Coastal Geodetic Survey network of northern Alaska.

From the 1972 survey of the IHD mass-balance network 55 reliable pole coordinates were selected (Fig. 2). On the glacier a person was iteratively directed into the known horizontal position using a theodolite with an electronic distance measurer. Most horizontal coordinates were recovered to within 0.1 m radius, and the changes in vertical coordinate ΔZ since 1972 were recorded. At some positions, stakes were drilled into the ice for mass-balance and velocity measurements. The upper and lower detailed cross-glacier profiles (Fig. 2) were resurveyed in 1993 using the bedrock markers of the previous surveys.

A complete center-line profile was obtained using ground-based stop-and-go kinematic GPS from near the pass of the upper cirque down to the terminus. A detailed outline and elevation profile of the 1993 terminus up to about 150 m up-glacier were determined both optically and by kinematic GPS methods.

The most important correction to the elevation-change data came from the different dates of the surveys in 1972 and 1993. From readings of all 1993 mass-balance stakes (Fig. 2), we interpolated ice and snow ablation for the period 29 June–5 August 1993 as a function of elevation (see Fig. 4a inset). Lower and upper cirque have somewhat different ablation, possibly due to non-uniform mountain screening. The maximum value of the ablation correction was −1.38 m at stake 2 about 550 m from the terminus; the average for all points was about −1.0 m. Repetitive surveys about a month apart of several

1993 mass-balance stakes gave horizontal and vertical velocities. The vertical movement between 29 June and 5 August is smaller than +0.01 m and can be neglected.

The 1993 vertical coordinates were corrected for refraction and earth curvature. This correction increased the 1993 elevations by less than 0.2 m for most base lines (< 1.7 km). A few exceptionally long base lines had larger corrections (0.63 m for the longest base line of 2.8 km). A similar correction was also calculated for the 1972 vertical coordinates. Due to shorter base lines, however, it was smaller than the inherent error of the 1972 survey (about 0.3 m). The final error in the 1993 elevation data is ±0.05 m; similar accuracy exists in the horizontal coordinates. The error in the elevation change from August 1972 to August 1993 is dominated by the accuracy of the 1972 survey which was 0.3 m in vertical and 2 m in horizontal.

In the context of a future long-term monitoring program that includes glaciers from all over Alaska, center-line elevation profiles of McCall Glacier and two other glaciers in the northeastern Brooks Range — Esetuk and Okpilak Glaciers, about 20 km southeast and 15 km south, respectively — were obtained using a lightweight, airborne-laser ranging system. These data will be presented elsewhere.

CHANGES IN ELEVATION, VOLUME AND TERMINUS POSITION

Figure 4a–c illustrate elevation change from 1972 to 1993. The surface dropped everywhere from a minimum of 1 m at the head of middle cirque to over 42 m near the terminus. The 1 m minimum is exceptional; the average drop in the accumulation areas of the three cirques is more like 3–3.5 m. This can best be seen from Figure 4a, where the elevation change, ΔZ, for all available positions is plotted against 1972 elevation, Z, regardless of the horizontal coordinates. The scatter represents variations in ΔZ both across the glacier and between different cirques. Figure 4b shows elevation change for selected transverse profiles. Cross-glacier variation of ΔZ ranges from about 0.5 m at the transects near the confluence of the cirques (Fig. 2) to about 5 m at the lower detailed-transverse profile. This cross-glacier variation is about 10% of the mean surface drop for each profile. No clear large-scale pattern, such as the glacier's sides dropping more than the center, is evident. Meandering surface streams which incise channels a few meters deep into the ice are a ubiquitous feature on McCall Glacier. Some of the recovered pole locations from 1972 were in or near such streams in 1993, indicating that a shift of the surface drainage network may be responsible for cross-glacier variations in elevation change.

The ice surface along the two detailed transects on the lower glacier is shown in Figure 5 for a number of years. The surface topography is almost uniformly lowered between successive dates, making transverse variation of elevation change comparatively small. The characteristic indentation in the middle of the upper profile is preserved from year to year. A second interesting detail in Figure 5 is the constant angle of the side-moraine slope as the apparent width of the glacier diminishes over time. Direct
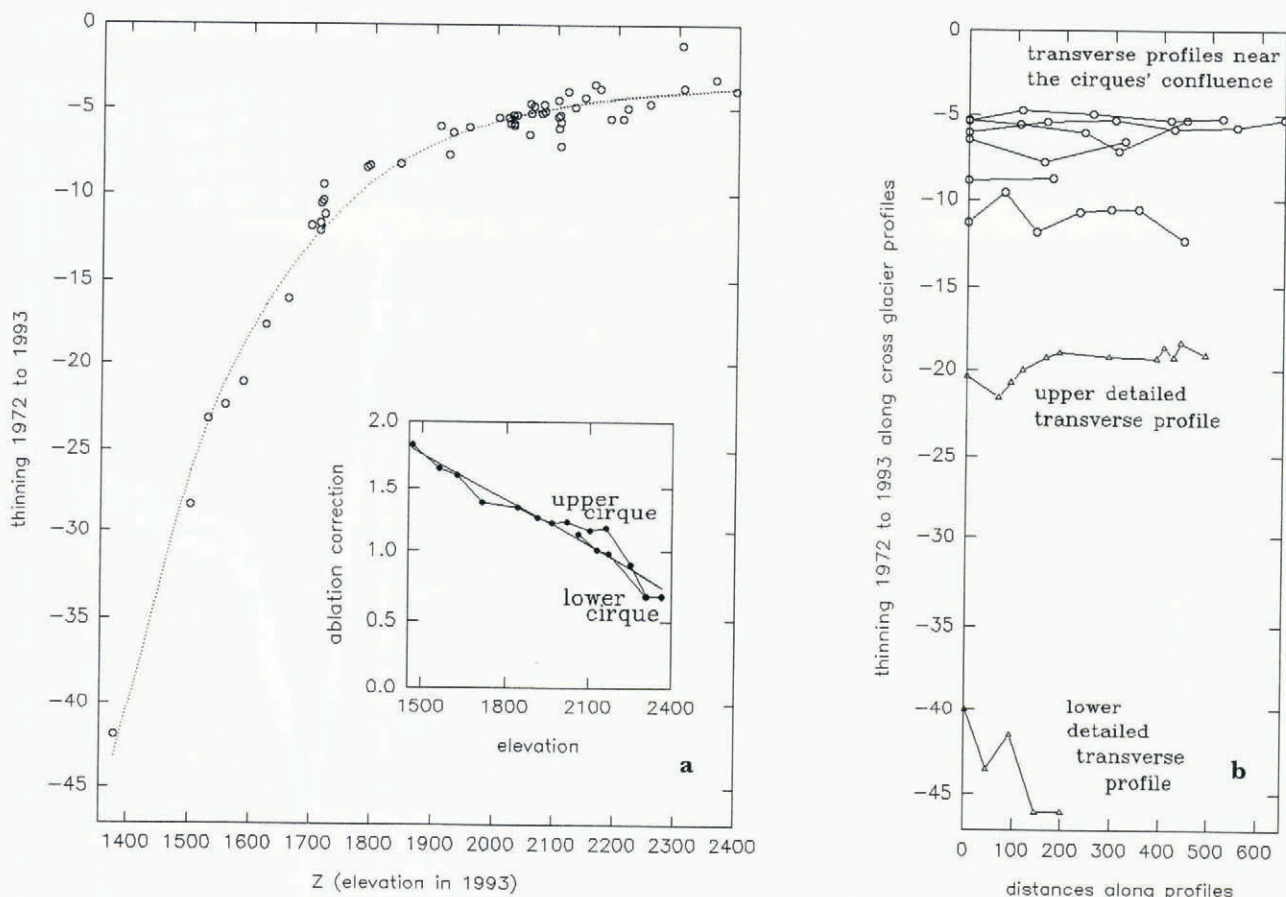
Fig. 4. Elevation change, 1972–93: a. vs elevation, b. cross-glacier variation, c. contour map.

observations show that the side moraines are ice-cored. The overlying till slides down at some angle of repose when the glacier thins, protecting more glacier ice from ablation. The bedrock valley walls are much steeper than the constant angles of repose revealed by Figure 5.

Average elevation drop of the upper profile as a function of time is plotted in the inset of Figure 5a. Around 1975 the drop rate increased from about 0.3 to about $1 \, \mathrm{m \, a^{-1}}$. The elevation drop of the upper detailed transect from 1972 to 1993 provides an independent check of the elevation change obtained at the 1972 pole positions. A pole position about 20 m up-glacier from the upper detailed transect has an elevation drop of 21.1 m while the nearby part of the upper transect dropped 20.9 m.

A map of elevation change from 1972 to 1993 has been constructed by smoothing and interpolation (Fig. 4c). Total volume change was $5.5 \pm 0.2 \times 10^7 \, \mathrm{m}^3$ of ice. The error was estimated from the interpolation statistics and the 0.3 m error in elevation change of the 1972 locations. Mean mass balance from 1972 to 1993, i.e. volume loss divided by mean glacier area, was $-0.33 \pm 0.01 \, \mathrm{m \, a^{-1}}$.

COMPARISON OF THE PERIODS 1972–93 AND 1958–72

Dorrer directly compared stereo-photo pairs from 1971 and 1958 to deduce volume loss during this period (Dorrer, 1975; Dorrer and Wendler, 1976). Due to the
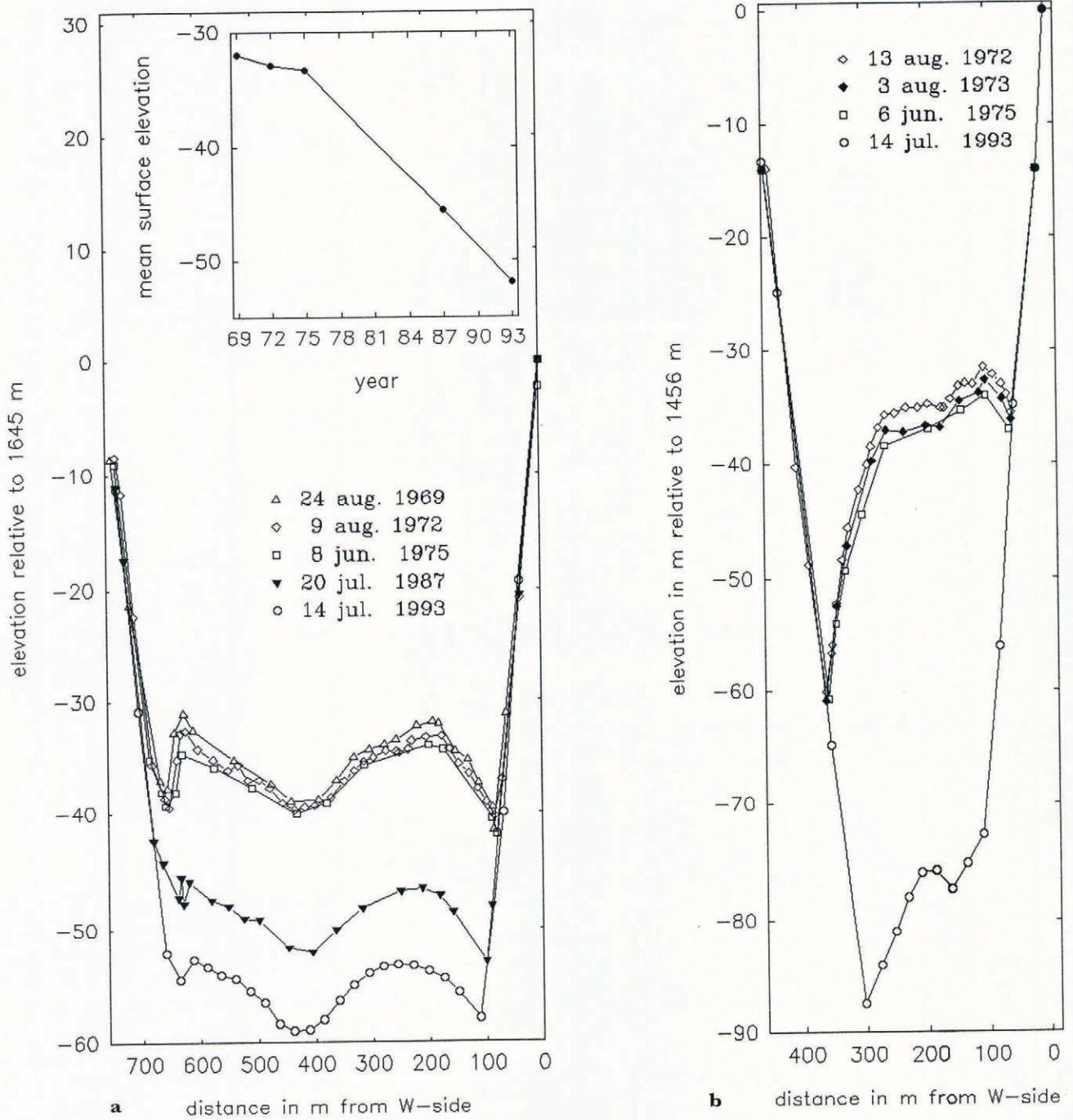
Fig. 5. Time evolution of ice surface along a. upper and b. lower detailed-transverse profile.

different illumination, scales and snow coverage prevailing during the two photogrammetric missions, elevation change could be obtained for only three regions in the ablation area, around 1500, 1715 and 1900 m elevation. Mean elevation changes in these regions were 4.5±0.4, 2.9±0.6 and 2.0±0.4 m, respectively. In Figure 6, mean annual thinning rates for the periods 1958–71 and 1972–93 are compared. In both cases a suitable exponential was fitted to the data (cf. Weidick, 1968; Dorrer and Wendler, 1976). Two features are immediately obvious: (i) in the earlier period the accumulation area is only very slightly affected while in the later period it is characterized by a noticeable surface drop; and (ii) the difference in mean annual elevation change between the two periods increases drastically down-glacier. Extrapolation of

Dorrer's curve to the region close to the terminus gives rise to rather large uncertainties. According to his error bars, annual thinning of the ice there was between –0.5 and –0.85 m a^{-1} during 1958–71, while from 1972 to 1993 the terminal region thinned by almost 2.4 m a^{-1} (2.1 m a^{-1} w.e.), a value in excess of the maximum ablation at the terminus during the 1970s. Mean mass balance during 1958–71 was –0.13 m a^{-1} as compared to –0.33 m a^{-1} for the period 1972–93.

Elevation change between 1958 and 1972 can also be calculated by locating the 1972 pole positions on the 1958 IGY map. The result is shown in Figure 6: surface drop from 1958 to 1972 based on the IGY map differs greatly from Dorrer's estimate. Mean annual balance would be –0.45 m a^{-1}, which is more than three times Dorrer's value.
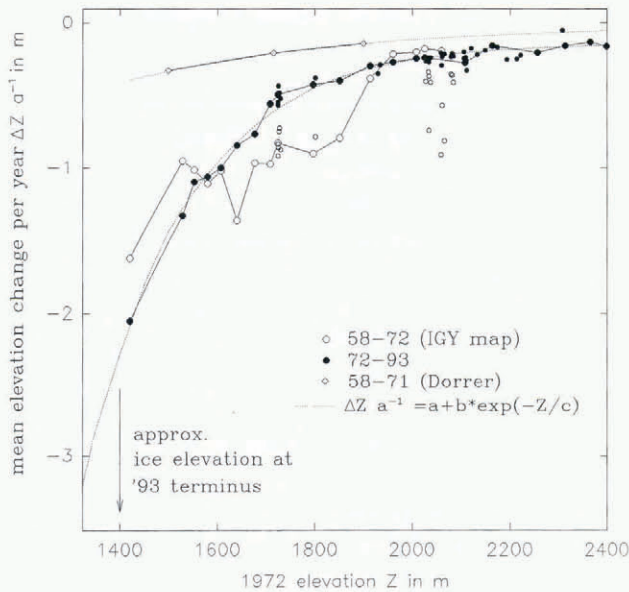
Fig. 6. Mean annual thinning vs elevation: 1972–93 (this paper), 1958–72 based on the IGY map, and 1958–71 from Dorrer and Wendler (1976). Positions along the center line of the glacier are connected by lines.

Strong thinning would occur not only close to the terminus but also about 1.5 km up-glacier. This irregular pattern of elevation change and two further arguments make us believe that there are systematic errors in the 1958 map considerably exceeding the expected error of ±2.5 m.

The first argument is based on the time history of elevation along the upper detailed traverse (Fig. 5a inset). Elevation can be extrapolated for 1958 using the IGY map, and the thinning rate there from 1958 to 1972 is then about $1 \, \mathrm{m \, a^{-1}}$, just as from 1975 to 1993. This implies the research period in the 1970s was characterized by exceptionally low ablation (thinning rate $0.3 \, \mathrm{m \, a^{-1}}$). In contrast, mass balance calculated by Dorrer and Wendler (1976) from weather records of Barter Island, 110 km north at the Arctic coast, indicates that during the period 1969–75 the glacier thinned at a higher annual rate than the mean rate during the 1960s. A thinning rate of $0.3 \, \mathrm{m \, a^{-1}}$, on the other hand, would give a surface drop of 3.9 m for the 13 year period 1958–71. This is very close to what Dorrer's curve shows for an elevation of 1600 m, the 1972 elevation of the upper detailed traverse. Secondly, Trabant and Benson (1986) mention several IGY mass-balance stakes that reappeared in 1969 and 1972 after they had apparently crossed the mean equilibrium line. The mean equilibrium line reconstructed in this way coincided best with the 1972 equilibrium line, making the 1972 balance of $-0.19 \, \mathrm{m \, a^{-1}}$ a crude estimate of the mean balance in the period 1958–72. Dorrer's value of $-0.13 \, \mathrm{m \, a^{-1}}$ for the mean balance is within the error range of this estimate while the value of $-0.45 \, \mathrm{m \, a^{-1}}$ deduced from the IGY map is not.

Terminus retreat

Figure 7 shows reconstructions of the 1958, 1970 and 1993 termini together with the youngest end moraine
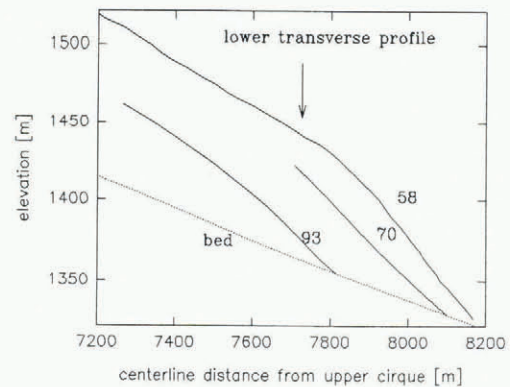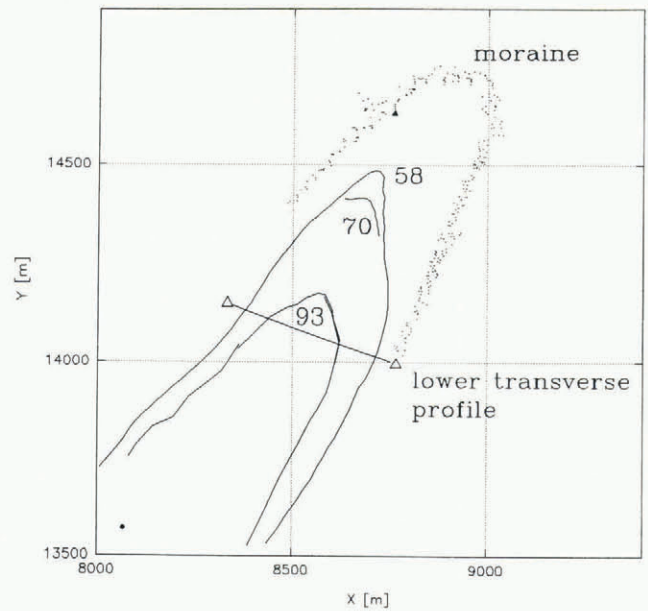

Fig. 7. The terminus of McCall Glacier for the years 1993, 1970 and 1958, and before the retreat from its "Little Ice Age" maximum (presumably around 1890).

that outlines the maximum extent of the glacier around 1890 (lichen date). Terminus altitudes were 1354 m in 1993, 1327 m in 1970 and about 1320 m in 1958. Changes of retreat rate and surface elevation at the terminus were derived from direct observation and geometric considerations, treating the terminus up to the lower detailed profile as a wedge with constant surface and bed slope (see Table 1). Implications are: (i) Terminus-retreat rate more than doubled between the time periods 1958–70 and 1970–93. (ii) Thinning from 1958 to 1970 is faster than Dorrer's curve suggests for the terminus (Fig. 6) but still within the expected error range. (iii) The thinning rate from 1970 to 1993 is less than the $2.4 \, \mathrm{m \, a^{-1}}$ interpolated from Figure 6; it is almost constant down-glacier of the lower detailed transverse, suggesting a stagnant, passively melting terminus for most of that period. (iv) Surveys from 1970 to 1972 of the lowermost mass-balance stake (about 40 m from the 1970 terminus) imply that thinning of the terminus accelerated more gradually compared to the step-like increase in thinning rate around 1975 documented at the upper detailed-transverse profile.

Table 1. *Retreat rate of the terminus for different time periods; thinning rate at terminus position corresponds to the end of each time period*

	Surface slope (°)	Bed slope (°)	Terminus retreat m	Retreat rate $m\,a^{-1}$	Thinning at terminus m	Thinning rate $m\,a^{-1}$
1890^r–1958	–	–	300	4.4	–	–
1958–70	$14.4^{1\,d}$	6^d	68^d	5.7	10	0.8
1970–71	$12.8^{t\,d}$	0–6	6–12	6–12	1.3^d	1.3
1971–72	–	–	–	–	1.4^d	1.4
1970–93	$14.0^{1\,d}$	5.3^d	285^d	12.5	41	2.0

^{d} Direct observations from surveys or photogrammetry.
^{1} Average surface slope measured from terminus to lower transverse profile.
^{t} Average surface slope measured from terminus to about 50 m up-glacier.
^{r} Lichen date.

INTERPRETATION — EVIDENCE FOR RECENT CLIMATE CHANGE?

A significant climate change within the total observation period 1958–93 is strongly implied by the available data. Mean mass balance calculated from volume change became more negative by a factor of about two between the periods 1958–71 and 1972–93. If Dorrer's estimate of $-0.13\,m\,a^{-1}$ for the 1958–71 mean mass balance is accurate, this factor would be 2.5; a value of $-0.2\,m\,a^{-1}$, which is considered a minimum, would reduce the factor to about 1.7. The difference in mean mass balance between these two periods corresponds to the stepwise change in temperature in the 1970s (Fig. 1).

The terminus has doubled its retreat rate from 1970–93 as compared to 1958–70. Data from the early 1970s (last column of Table 1) favor a steadier increase in retreat rate beginning around 1970 rather than a step change. The similar relative increases of terminus-retreat rate, thinning rate of the lower ablation area and mean mass balance imply that all three are indicative of the same climate change.

Reaction and response times of McCall Glacier

Jóhannesson and others (1989) describe the delayed adjustment of a glacier's terminus to a change in mass balance by a response time $\tau_V \approx \langle h \rangle/(-b_T)$ where $\langle h \rangle$ is mean glacier thickness and b_T mass-balance rate at the terminus. For a step change in mass balance this is approximately the time it takes the glacier to change its volume by $1 - 1/e \approx 63\%$ of the total volume difference between the initial and final steady states. Temperate valley glaciers have a τ_V of 10–100 a (e.g. McClung and Armstrong, 1993). Application of the formula to McCall Glacier, $b_T = 2\,m\,a^{-1}$, $\langle h \rangle \approx 150\,m$, gives $\tau_V = 75\,a$, much longer than the observation record of McCall Glacier. On the other hand, the characteristics of the recent changes suggest that the amplified *reaction* of the lower ablation region of McCall Glacier lags the original climate change by not more than 10 years. As reaction time we define the

time after a mass-balance change when there is a strong increase or decrease in the rates of elevation change and terminus retreat. If the glacier was in steady state before the mass balance was disturbed the reaction time corresponds to the time of maximum retreat or advance of the terminus. Jóhannesson and others (1989) describe the time evolution of the ratio $f =$ average thickness change/thickness change at the terminus. They find a rapid decrease of f from its initial value of 1 to its long-term value of about $\Delta b/(-b_T)$ where Δb is the disturbance of the mass balance. This step-like change in f, which seems to occur at about 20–30% of τ_V (Jóhannesson and others, 1989, fig. 6), presumably defines the above reaction time of the glacier. In accordance with our findings for McCall Glacier, Sigurðsson and Jónsson (1995) observe reaction times of Icelandic glaciers to be much shorter than their response times.

There is also a pronounced asymmetry between advance and retreat of the glacier terminus which is often overlooked. If glacier ice were perfectly plastic, i.e. ice velocity scaled with a power $n \to \infty$ of the basal shear stress $u \sim (\tau/\tau_{yield})^{n+1}$, a positive mass-balance disturbance would lead to instantaneous advance of the terminus, while the retreat caused by a negative mass-balance disturbance would never be by active movement of the ice but only by melting of the stagnant terminus in finite time. According to suggested laws of ice deformation and basal sliding, n should be in the range of about 2–3 (e.g. Paterson, 1981, p. 87, 116). Both advance and retreat rates of the terminus are then finite, but terminus retreat still depends on passive melting. Therefore, most theories of glacier response strictly apply only to positive mass-balance disturbances and terminus advance. In a steady state, ice flux at the terminus equals ablation losses there. A uniform negative mass-balance disturbance therefore causes an initial retreat rate $\Delta b/\tan(\alpha_{surface} - \beta_{bed})$. Complete stagnation of the terminus leads to a maximum retreat rate $b_T/\tan(\alpha_{surface} - \beta_{bed})$. For McCall Glacier, minimum and maximum retreat rates are about 2 and 13–$14\,m\,a^{-1}$, respectively, the latter being close to the retreat rate actually observed.

CONCLUSIONS

(1) The increase in the rate of volume wastage by a factor of more than two from the earlier to the later time period indicates a severe change in mass balance, most likely near the border of the periods, i.e. in the early 1970s.

(2) The observed mass-balance change is probably mainly due to higher summer temperatures.

(3) The step-like increase in surface-drop rate of the lower ablation area between about 1975 and 1980, and the increase in terminus-retreat rate, appear to be correlated with the recent climate change. This suggests a fast reaction time of McCall Glacier of less than a decade.

(4) How representative the detected climate change is for the region cannot be decided at the moment. Limited data from other Brooks Range glaciers and an approach to modeling the mass balance of McCall Glacier from atmospheric data will be employed to answer this question in the future.

ACKNOWLEDGEMENTS

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