Mass balance observations at Mittivakkat Gletscher, Southeast Greenland 1995–2002*

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Received 15 November 2003; accepted in revised form 2 June 2004

Abstract During the period 1995–2002 mass balance observations were made at Mittivakkat Gletscher, Southeast Greenland. The results comprise observations of winter, summer and net balance. The means of measured winter, summer and net balance were 1.25 m, 1.91 m and − 0.66 m water, respectively. Mass balance changes are related to meteorological observations at the weather station in the nearby coastal village of Tasiilaq, about 20 km south of the glacier. The results establish a significant linear correlation between accumulation and measured precipitation during the winters 1995/96–2001/02 and a poor relation between summer balance and temperature during the summers 1996–2002. During the period of mass balance measurements the glacier lost about 4% of the ice volume determined in 1994.

Keywords Glacier mass balance; glacier variation; Southeast Greenland

Nordic Hydrology **Vol 35 No 4–5 pp 381–390** © IWA Publishing 2004

Introduction

During the last 100–200 years, the melting of small ice caps and glaciers has contributed significantly to sea-level rise. Future climate warming associated with changes in atmospheric gas composition might be more intense in the Arctic. This will probably increase the amount of water produced by melting from high latitude glaciers. Knowledge of recent and previous mass balance of glaciers is therefore important.

The aim of this investigation was to determine the mass balance of the glacier in order to create detailed information to model the relation between climate and glacier development in Southeast Greenland.

The study area

Mittivakkat Gletscher (65°41′ N, 37°48′ W) is the largest single glacier in a snow- and ice-covered area on Ammassalik Island, Southeast Greenland (Figure 1). From a map constructed from aerial photographs taken in 1981 at 1:20 000 with 10 m contour intervals, the size of the glacier was determined to be 17.6 km^2. During the most recent years the equilibrium line altitude (ELA) has been situated between 500–550 m a.s.l. The ablation area is about 3.5 km long and 1.5–2.5 km wide, covering an area about 7.5 km^2. The accumulation area is 1.5–2 km wide in an east–west direction and about 5.5 km from north to south, covering an area of about 10 km^2. This indicates an accumulation area ratio (AAR) value of 0.57, which is well in agreement with observations at other glaciers (Torsnes *et al.* 1993). Using radio-echo sounding the volume of the glacier was determined as $2024 \times 10^6\,m^3$ in 1994. The mean ice thickness was 115 m and the maximum thickness

*Paper presented at the 14th Northern Research Basins Symposium/Workshop (Kangerlussuaq, Söndre Strömfjord, Greenland, 25–29 August 2003).

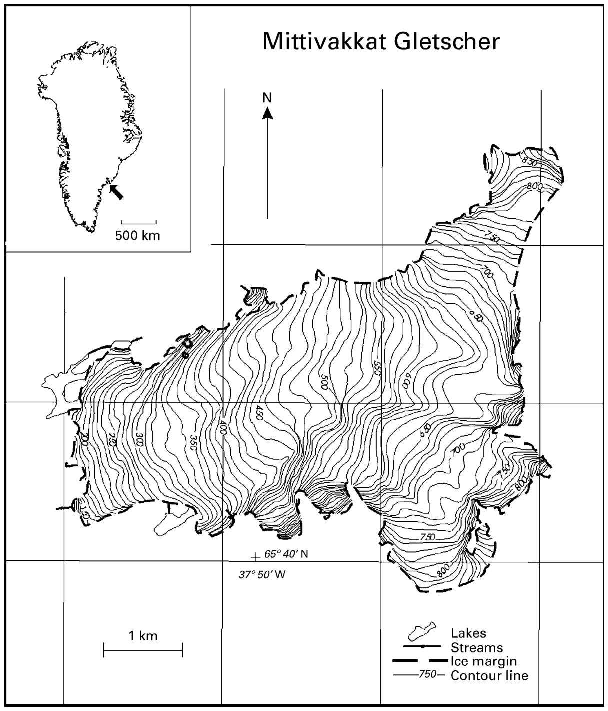

Figure 1 The location of Mittivakkat Gletscher on Ammassalik Ø, Southeast Greenland. The surface topography, glacier margin, lakes and rivers of the glacier are shown. The ELA is close at 500–550 m a.s.l. during recent years

measured was 245 m (Knudsen and Hasholt 1999). Changes in the size of the glacier since 1933 are well documented (Valeur 1959; Fristrup 1960; Hasholt 1986, 1992; Knudsen and Hasholt 1999).

The period since the first observation in 1933 has been one of almost continuous recession. A comparison between the topographic map surveyed by the Danish Geodetic Institute in 1932/33 (Geodætisk Institut 1938) and a map constructed from aerial photographs taken in 1972 showed that the glacier below about 300 m a.s.l. had melted down as much as 100 m at the 1972 margin. Above 300 m a.s.l. the change was smaller and at higher levels an increase was observed in places (Hasholt 1986). At higher elevations a comparison between the 1972 map and a map constructed from aerial photographs taken in 1981 showed a mean surface change of −5.8 m ice corresponding to −5 m water or −0.5 m a^{-1} in the altitudinal interval 250–650 m a.s.l. Mass balance measurements on the glacier during 1986/87 showed a net balance of −0.12 m water (Hasholt 1988). Since 1981, a further decrease of ice thickness has been measured close to the terminus, which has also receded. A comparison between a surface map constructed from 450 measurements of surface elevation on the glacier made in 1994 in connection with a survey of ice thickness on the glacier and the 1981 map indicated little change in most of the accumulation and ablation areas, except for the terminus, where values of more than −20 m were determined. In general, variations were within ±10 m, of which a part is explained by errors in the maps (Knudsen and Hasholt 1999).

Meteorological data were provided from the weather station operated by the Danish Meteorological Institute (DMI) in the coastal village of Tasiilaq some 20 km south of the glacier.

Mass balance measurements

Mass balance is generally measured using techniques described by Østrem and Stanley (1969). Procedures have been modified somewhat compared to the recommendations given by the International Hydrological Decade (IHD 1970) and later by Mayo *et al.* (1972), who advise a method combining mass balance measurements in either a stratigraphic or annual (fixed date) system of individual points to compute the mass balance of the entire glacier. The main concern is that the formation of reference surfaces takes place at different times at various parts of the glacier. The reason for modifications in this study is mainly logistic as the glacier is only visited twice a year: early in the summer (late May) before ablation and run-off commence and in August before the ablation season has actually ended.

In late May and early June the amount of snow accumulated during the winter is measured along probing transects at evenly spaced intervals of 50–100 m in both the accumulation and ablation areas. The distance between transects is about 500 m. The network used during most years is shown in Figure 2. The network is most dense in the ablation area and the northern part of the accumulation area. In some years the accumulation in the southern part of the accumulation area was only inferred. At visible stakes the length of the protruding stake and the snow thickness were measured. The length of the period during which snow accumulates in the upper and lower parts of the glacier probably differs by up to as much as 1–2 months. In the ablation area an ice surface is present except where there are many deep crevasses.

The density of the snow was determined in pits dug at 250 m, 500 m (close at the ELA) and 750 m during most years. The mean value of snow density measured in the pits was used to convert snow thickness measured at each individual probing in the ablation area (below about 400 m a.s.l.), close to the ELA and in the accumulation area (above 600 m a.s.l.)

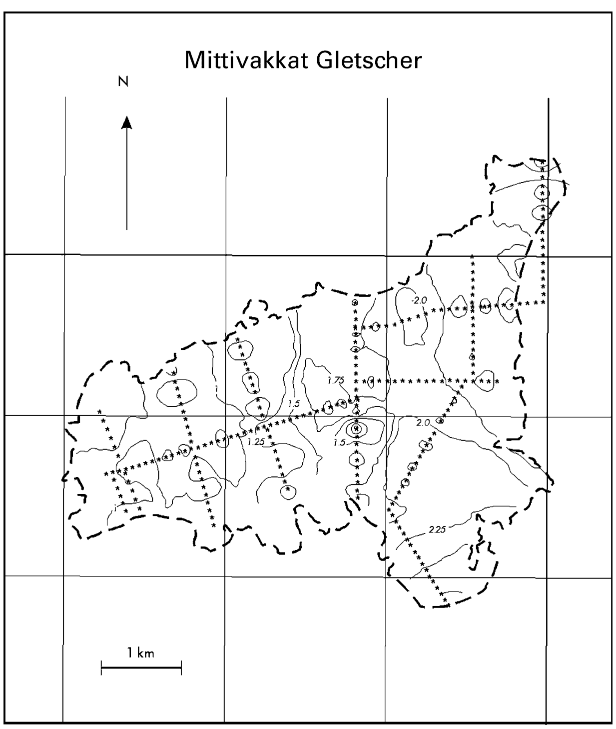

Figure 2 The distribution of the winter balance 1995/96 on Mittivakkat Gletscher determined from snow depth soundings and density measurements in pits in late May and early June 1996. On the map are shown the individual measuring points. Values are in m water

respectively into metres of water. Actually, the net accumulation of snow deposited on the glacier since the time of minimum mass at each measuring point since the previous summer, irrespective of when the minimum position was reached, was determined. This value is termed the measured winter snow balance, b_{mw}, which can be different from the winter balance, b_w, which should have been measured (Mayo *et al.* 1972). Further it is anticipated that no water had left the snow pack during the spring period because of melting before the observations were made. This was confirmed in most cases by negative temperatures at the ELA and in accumulation area pits. In the ablation area in most years isothermal temperatures were measured in the snow pack, but it is believed that any melt water was temporarily stored in the snow or was refrozen as superimposed ice, as almost no water was observed leaving the glacier margin nor was water dammed in lakes at the margin. The superimposed ice was not included in the accumulation, but was included in ablation, thereby lowering the ablation melt rate.

Ablation was measured at the stakes drilled into the glacier in both the accumulation and ablation areas. Observations were based on measurements at individual stakes along snow profiles spaced at a distance between stakes of 200–250 m and were usually determined as the change in exposed length of the stake and taking the density of the material melted in consideration. The ablation during the late part of the summer was usually determined as the change in length of the stake between the last summer measurement and the measurement of exposed length and snow thickness in the spring at the stake. Ablation was determined as the change of length of the stake above the glacier surface between the time when the winter accumulation was measured and the end of the measuring period in the summer. Ablation during the late summer was determined by the spring observations of stake length, the snow thickness and an added value of 20 cm superimposed ice, which was usually found at the ice–snow interface in the excavated pits. As the minimum in mass on the glacier is reached at different times, there is again a difference between the measured summer balance, b_{ms}, and the true summer balance, b_s.

The net balance is determined as the difference between measured winter accumulation and summer ablation. As the values determined probably vary from the "true" values an uncertainty holds for the determined net balance of the glacier. This is probably true in most cases where mass balance is measured. Pelto (1997) mentions that the North American Committee on Climate and Glaciers (1991) recommends that the actually adopted procedures are well explained.

Results

Generally, accumulation increased with elevation, reflecting the longer accumulation period and precipitation increasing height. Further, the accumulation was relatively large on flat sections, in lee-sides and against west-facing slopes, which reflected strong snow redeposition by wind (Hasholt *et al.* 2003). A computer generated map using all available snow soundings from late May to early June 1996 shows variations of accumulation with an isoline interval of 0.25 m (Figure 2). The highest values were determined in the southern accumulation basin, where values higher than 2.25 m were measured in places, and on the slopes below the highest parts of the glacier to the north. Measurements of snow thickness below the ELA during 1995/96 and 1996/97 (Figure 3) show similar patterns indicating that accumulation is controlled not only by height but also by the topography of the glacier.

The calculated net winter balance in 1995/96, $26.59 \times 10^6\,m^3$, corresponded to a mean specific value of 1.51 m water. This was the largest value measured during seven years of observations, for which a mean accumulation and standard deviation of 1.25 ± 0.18 m water was determined (Table 1). Preliminary results indicate that winter accumulation is highly correlated to the observed winter precipitation at the meteorological station in Tasiilaq.

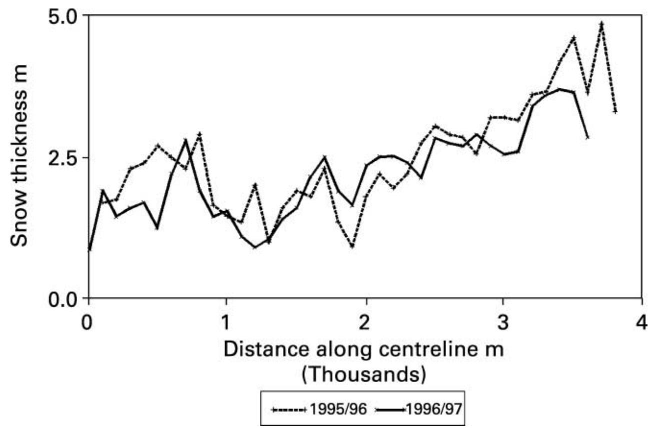

Figure 3 Snow accumulation along the centre line from the terminus to the equilibrium line in late May 1996 and 1997. A comparison shows that the accumulation pattern is very similar with accumulation generally increasing towards the equilibrium line and with little accumulation on the top of steep slopes and high accumulation at the bottom of the slopes. Larger deviations are mainly caused by measurements over crevasses

Table 1 Measured winter, summer and net balances during the balance years 1995–2002 as water equivalent

Year	Winter balance b_{mw} m	Summer balance b_{ms} m	Net balance b_{mn} m
1995/96	1.51	1.50	0.01
1996/97	1.41	1.81	−0.40
1997/98	1.14	2.31	−1.17
1998/99	0.98	1.75	−0.77
1999/00	1.23	2.06	−0.83
2000/01	1.18	2.14	−0.96
2001/02	1.28	1.78	−0.50
1995/96–2001/02	1.25	1.91	−0.66

A linear relation based on 7 years of observations of winter precipitation during October–May 1995–2002 (Figure 4) showed a correlation coefficient of $r = 0.77$ ($p = 0.023$) and a relation of the form

$$X_{acc} = Y_{prec} \times 0.86 + 0.62\,\text{m water}$$

where X_{acc} is the measured accumulation on the glacier in late May and Y_{prec} is the measured precipitation in Tasiilaq during October to May. Using the 30-year mean measured winter precipitation (Table 3) in Tasiilaq (1961–1990) a mean net accumulation and standard deviation of $1.27 \pm 0.17\,\text{m a}^{-1}$ is determined, which resembles the value measured during the period of observations.

Ablation generally decreased with height reflecting a longer ablation period at low altitude and a decreasing energy flux into the surface with height (Karlsen 1998). Figure 5 shows the change in ablation with height during summer 1998, when the largest summer balance during the observation period was measured. It is seen that ablation decreases strongly with altitude up to about 500 m (the level of ELA during recent years), and that variation at a given elevation is large, probably reflecting mainly variations in the length of time with snow cover influencing the albedo at the stakes. In the accumulation area the ablation still decreased but much less with height, which is mainly caused by the shorter period of ablation and the albedo of snow reducing ablation caused by radiation compared with ice. The summer balance was

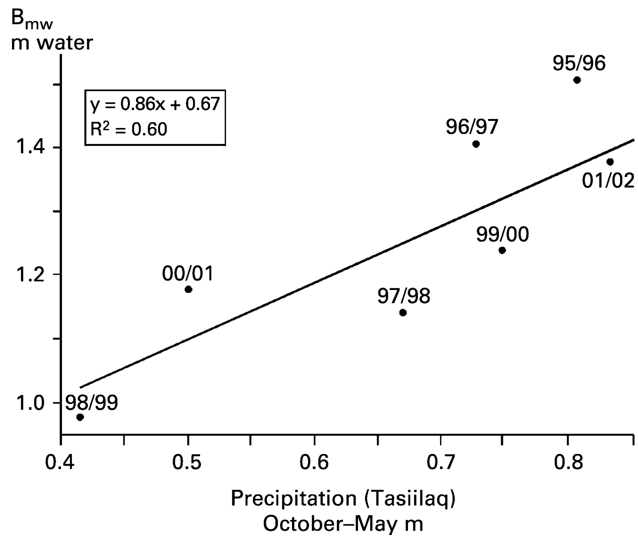

Figure 4 Relationship between the observed winter precipitation (October–May) in Tasiilaq and the measured winter balance at Mittivakkat Gletscher during the balance years 1995–2002

calculated using the mean value determined in each 100 m height interval and the area within the corresponding height interval determined by the area distribution curve. Using this procedure a summer balance of 2.31 m water, corresponding to a volume of $40.56 \times 10^6\,m^3$, was determined during the summer 1997/98 (Table 1). During the summers 1996–2002 a mean value and standard deviation of 1.91 ± 0.27 m water was determined.

A comparison between the mean temperatures in the months June to September in Tasiilaq during the summers 1996–2002 (Table 3) and measured ablation show a poor

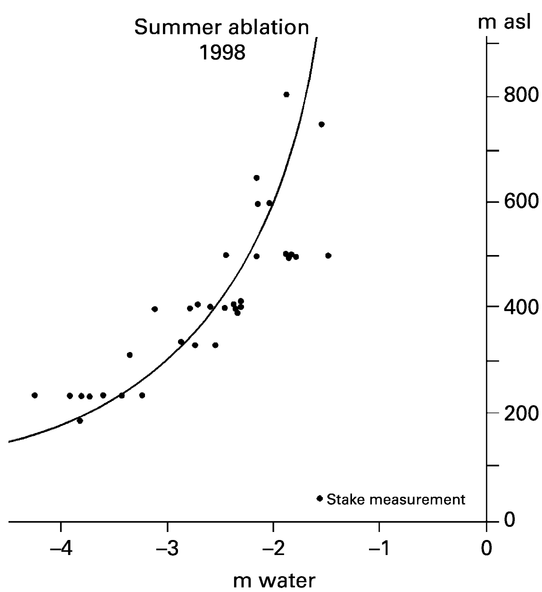

Figure 5 Summer balance during the balance year 1997–98. The highest ablation was measured close to the terminus and decreased rapidly with height. Some variation of ablation at a given level was typical. The winter of 1997/98 had low accumulation

relationship (Figure 6). Actually, in 1998, the summer with the lowest mean temperature, ablation was the largest measured. The summer of 1996, with the lowest ablation measured, had one of the highest mean temperatures recorded. This, on the other hand, was a summer preceded by the highest recorded winter balance. Obviously, winter balance could well influence ablation just as snow cover could persist longer by lowering the ablation. Further, 1998 was the summer where the lowest summer precipitation was measured. This indicates that the measured summer balance is also influenced by summer precipitation (Figure 7), which in this environment could well fall as snow over most parts of the glacier, especially at both ends of the summer period.

The net balance was determined as the difference between the measured winter and summer balance. The winter, summer and net balances measured during the balance year 1995–96 are shown in Figure 8 and Table 2. The table shows that the largest volume of snow was accumulated between 600–700 m, and the largest volume of ice was lost between 400–500 m. The largest net gain was between 700–800 m, and the largest net loss was between 200–300 m.

During the period a mean net balance of -0.66 ± 0.39 m water was found. The highest value measured was 0.01 m water and the lowest -1.17 m water (Table 1). The accuracy of the balances measured is assumed to be within $\pm 10\%$, as the measurements were made generally using the methods described by Østrem and Stanley (1969).

Discussion

The retreat of the glacier margin since 1933 is well documented and indicates that ice movement driven by input of mass through accumulation has been unable to replace ice loss by ablation at the margins. This has been demonstrated by comparison of topographic maps from 1933 and 1972, which indicates ice loss up to as much as 100 m in the ablation area at

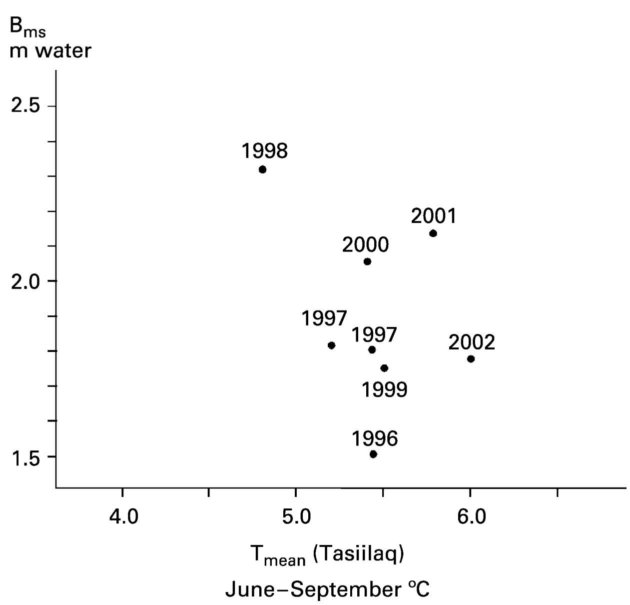

Figure 6 Relationship between mean summer temperature (June–September) in Tasiilaq and the measured summer balance at Mittivakkat Gletscher during the summers 1996–2002. The highest summer balance was measured during the summer with the lowest mean temperature. It is obvious that there is only a weak relationship between the summer balance and the summer temperature

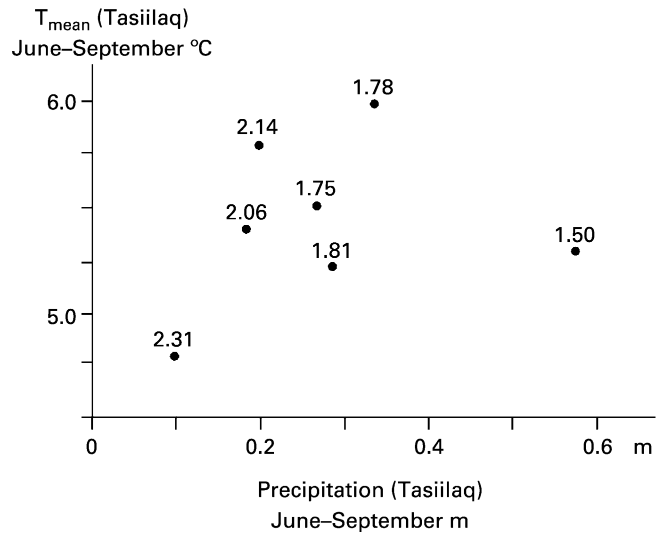

Figure 7 The relationship between summer temperature (June–September) and summer precipitation (June–September) at Tasiilaq and the measured summer balance at Mittivakkat Gletscher during the summers 1996–2002

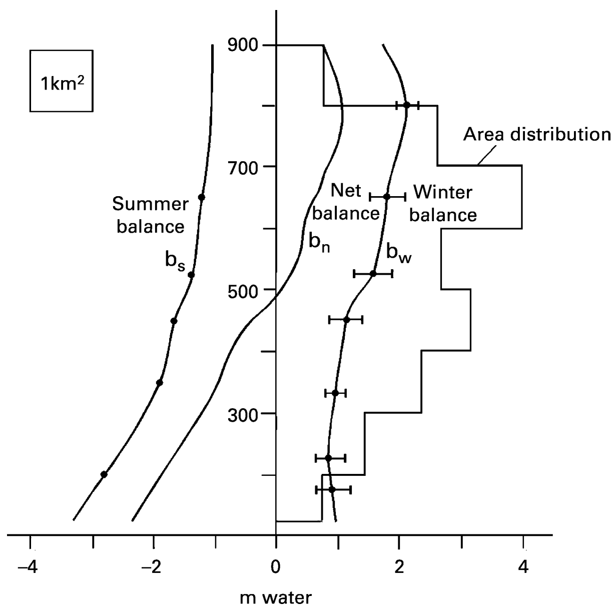

Figure 8 The mass balance diagram for Mittivakkat Gletscher for the balance year 1995/96. Values are in m water

about 200 m. Above 300 m the loss was small and in places an increase was observed. The net loss at the margin since 1972 has continued at a rate close to 1 m a^{-1}. Since then mass balance of parts of the glacier from comparing of maps has shown continued net loss. This indicates negative mass balance on the glacier during the last 70 years.

During the period of observations from 1995 to 2002 the glacier lost about 0.66 m a^{-1} of water, corresponding to about $11.6 \times 10^6 m^3\ a^{-1}$. Preliminary investigation shows a

Table 2 Winter, summer and net balances in relation to elevation and area distribution for each 100 m height interval, 1995–96

Altitude m	Area km^2	B_{mw} m	B_{mw} $\times 10^6$ m^3	B_{ms} m	B_{ms} $\times 10^6$ m^3	B_{mn} M	B_{mn} $\times 10^6$ m^3
>800	0.771	2.00	1.54	1.00	0.77	1.00	0.77
700–800	2.647	2.05	5.43	1.05	2.78	1.00	2.65
600–700	3.994	1.80	7.19	1.15	4.59	0.65	2.60
500–600	2.702	1.70	4.59	1.30	3.51	0.40	1.08
400–500	3.160	1.20	3.79	1.65	5.21	−0.45	−1.42
300–400	2.351	1.00	2.35	1.90	4.47	−0.90	−2.12
200–300	1.439	0.85	1.22	2.40	3.45	−1.55	−2.23
<200	0.536	0.90	0.48	3.00	1.61	−2.10	−1.13
130–899	17.600	1.51	26.59	1.50	26.39	0.01	0.20

Table 3 Mean values of winter precipitation, summer precipitation and summer temperature measured during selected periods by the Danish Meteorological Institute (DMI) at Tasiilaq. During 1971 and 1972 no observations were made

Period	Winter precipitation October–May mm	Summer precipitation June–September mm	Summer temperature June–September °C
1958–2003	694	236	5.01
1961–1990	707	237	4.88
1995/96–2002	673	256	5.46

significant positive correlation between measured precipitation in Tasiilaq and accumulation during the period. As winter accumulation calculated using long-term precipitation measurements in Tasiilaq resembles that measured during the period of observations, then the summer temperature increase during the period of observations compared to the long-term temperature indicates that the summer balance possibly has changed markedly towards even higher values.

Conclusions

During the period of observations 1995/96–2001/02 in 6 out of 7 balance years the glacier had a negative balance, and the cumulative balance during the period was −4.62 m water. The mass loss for the period 1995–2002 amounts to about 81×10^6 m^3 or 4% of the volume determined in 1994. A preliminary study indicates a high positive correlation between uncorrected precipitation measurements at the weather station in Tasiilaq and the measured winter accumulation. Between measured summer temperatures (June–September) and measured summer balance the correlation was poor. The summer balance to a high degree was influenced by both the summer temperature and precipitation.

Acknowledgements

The project is part of a frame programme on climate and arctic landscape processes carried out at the Department of Earth Sciences, University of Aarhus and Institute of Geography, University of Copenhagen and sponsored by the Danish Natural Science Research Council. We would like to thank Ruth Nielsen for figure design.

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