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Scientific Paper

RECENT TRENDS IN THE MASS BALANCE OF GLACIERS IN SCANDINAVIA AND SVALBARD

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Abstract: Mass balance measurements of glaciers in the subarctic areas of Scandinavia show a different trend compared to the glaciers of the high arctic area of Svalbard, European Arctic. The longest continuous mass balance time series in Norway is from 1948. Since 1963 six glaciers have been monitored continuously in a profile from west to east in South Norway (61–62°N). Both winter and summer balance have been measured every year. The results show a different trend on the western, maritime glaciers compared to the more continental glaciers 200 km inland. In the west the glaciers have been increasing in volume, while in the east the glaciers have had a decreasing trend up to 1988. In the period from 1989 up to the present day conditions have changed towards a more positive net balance for all glaciers, mainly due to increasing winter precipitation. The volume growth has resulted in a glacier front advance of several outlets from ice caps in western South Norway.

In northern Sweden annual mass balance measurements have been carried out on Storglaciären (68°N, 18.5°E) since 1947. During a nearly 50 years period; 1947–1994, the average annual winter precipitation has shown a clear positive trend and increased about 0.5 m water equivalents with the strongest increase after 1988 as observed in southern Norway. The summer ablation has shown a negative trend and decreased about the same amount resulting in a change in net balance from negative to positive.

One of the longest continuous mass balance observation series in the Arctic is from the Svalbard archipelago where mass balance measurements were started in 1967 in the north-western part of the island Spitsbergen (79°N, 12°E). In general no dramatic changes have occurred in Svalbard during the last 28 years. Winter accumulation is stable or slightly increasing with small annual variations. The mean summer ablation is stable with no significant trend, but with large annual variations. There is no sign of increased melting during the observation period. The net balance depends on area/altitude distribution. Low altitude glaciers are steadily shrinking but with a slightly less negative net balance than 28 years ago. Glaciers with high altitude accumulation area are close to equilibrium.

1. Introduction

Glacier changes are among the clearest signals of ongoing warming trends existing in nature (Haeberli, 1995). There are, however, great uncertainties in the knowledge of the mass balance of the worlds ice masses, and not only of the great ice sheets of Greenland and Antarctica. Lack of continuous observations are the main cause of uncertainty in the knowledge of glacier mass balance. The observations in Scandinavia and Svalbard are of great importance in this context because these are among the few areas where the series are long enough to start analysis of the climatic impact. In this paper some main results from these mass balance investigations will be presented.

Only very few areas of the Arctic have detailed mass balance time series over a number of years. Such data exists mainly from the west coast of Spitsbergen and from the Canadian high Arctic (Meighen Ice cap, Devon Island Ice Cap). Circumpolar studies of Arctic glaciers are likely to give an early warning of the effect of climate change (DOWDESWELL, 1995). The archipelago Svalbard is located between 76 to 81°N and 10 to 33°E (Fig. 1). It is the northernmost landmass in the European Arctic and is a typical area with small and medium size glaciers. The total volume of ice is about 7000 km^3 (HAGEN *et al.*, 1993). Svalbard is particularly sensitive to climate change due to its position at the northern extremity of the strong transfer of heat through the Norwegian Sea. Climatic change at the beginning of the century, particularly an increase of atmospheric temperatures, acted drastically upon mass balances and retreat of calving fronts (LEFAUCONNIER and HAGEN, 1990).

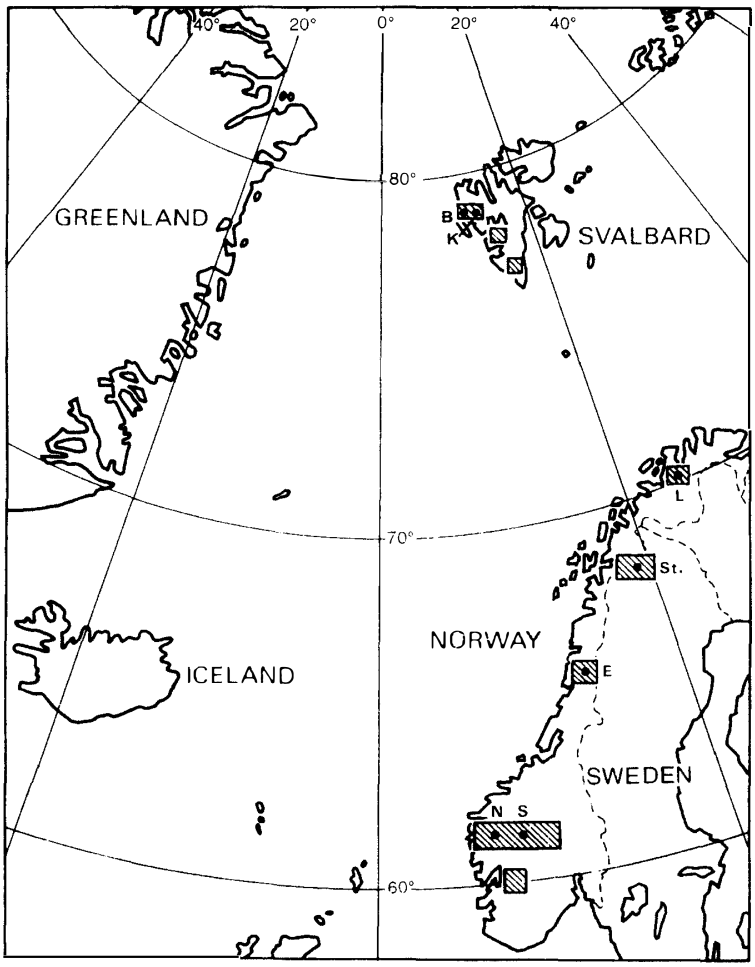


Fig. 1. Shaded areas showing main glaciated areas in Scandinavia and Svalbard where mass balance data exist. N: Nigardsbreen, S: Storbreen, E: Engabreen, St: Storglaciären, L: Langfjordjøkulen, B: Brøggerbreen, K: Kongsvegen.

2. Climate

The climate, both in Scandinavia and in Svalbard, is strongly influenced by the North Atlantic Drift, a branch of the Gulf Stream.

In Norway glaciers exist at low altitudes on the west coast due to a maritime climate with high winter precipitation. The mean annual precipitation in mountains on the west coast is about 4000 mm/year, giving up to 10–15 m of snow during the winter, decreasing gradually to a more continental climate of about 1500 mm/year in the high mountain areas 200 km from the coast. Thus the equilibrium lines of the glaciers increase from about 1200 m a.s.l. in west to about 2000 m a.s.l. in east.

On the western coast of Spitsbergen the average annual temperature is about –6°C, and slightly colder and more continental further inland. The warmest month, July, has an average temperature on the western coast about 5–6°C, while the coldest period, January–March has about –15°C. Precipitation is normally low, about 400 mm annually on the western coast and half as much in the central inland areas. Precipitation is higher on the glaciers due to the orographic effect, but seldom exceeding 2–4 m of snow. The frequent easterly winds caused by low pressures passing through the Barents Sea brings the highest precipitation to the eastern and southern parts of the islands. About 60% of Svalbard is covered by glaciers of various types. The equilibrium line altitude, ELA, is only 200 m a.s.l. in the south-east of Spitsbergen, but more than 800 m a.s.l. in the central northern part reflecting a more continental climate (LIESTØL, 1993).

3. Mass Balance Measurements

Mass balance investigations have been conducted for longer and shorter periods in a transect from south Norway to Svalbard, from 61°N to 80°N in a sector between 10°E to 25°E (Fig. 1). Measurements are currently carried out on glaciers in southern Norway (61–62°N—maritime and continental), in the Svartisen area (66–67°N—maritime) and in northern Sweden in the Kebnekaise area (68°N—continental). There are no ongoing measurements further north, although there are large glacier areas. One glacier at 70°N was however measured for a five year period (1989–1993). In Svalbard the longest ongoing mass balance series is carried out at 80°N. On all investigated glaciers both accumulation and ablation have been measured by direct glaciological, stratigraphic, method: snow sounding profiles, density measurements and stake readings.

3.1. Norway

Systematic measurements of glaciers have a long tradition in Norway. Since the beginning of this century frontal positions have been measured annually, with small gaps, on about fifteen glaciers, and for shorter periods on several other glaciers. Mass balance measurements started in 1948 on Storbreen in Jotunheimen, Southern Norway, by the Norwegian Polar Research Institute (LIESTØL, 1967). Both winter and summer balance have been measured every year since then.

The Hydrology Department under the Norwegian Water Resources and Energy Administration (NVE) initiated long-term mass balance studies on selected glaciers in southern Norway (61–62°N) in 1962 and 1963. Glaciers regarded as representative for certain areas were selected. In this paper Nigardsbreen (48 km^2, 61.5°N, 7°E) will be used as an example of the glaciers in south Norway.

The second longest mass balance series in Northern Scandinavia is from Engabreen, (38 km^2) close to the polar circle at 66.5°N, 14°E and situated in a maritime climate on the west coast of Norway. This glacier has been studied since 1970. In addition some glaciers have been studied for 3 to 5 years. In 1989 a five year measurement series was initiated on Langfjordjøkulen (70°N), one of the northernmost glaciers in Norway. In 1994 mass balance investigations were carried out on 12 Norwegian glaciers—7 in southern Norway and 5 in northern Norway. Most of the investigations are related to water power development.

The results from the mass balance investigations in Norway are published in annual reports by Norwegian Water Resources and Energy Administration (NVE) (HAAKENSEN, 1982, 1995; ØSTREM *et al.*, 1991; ELVEHØY and HAAKENSEN, 1992).

3.2. Sweden

In North Scandinavia winter, summer and net balance have been measured annually on Storglaciären in Sweden since 1946. This is the longest continuous series in the world, two years longer that Storbreen in South Norway. The two glaciers have the same name, Storglaciären in Swedish and Storbreen in Norwegian. They are also of similar size (*c.* 5 km^2) and are well defined cirque glaciers. Storglaciären is situated in the mountain ridge area close to the border of Norway at 68°N in a continental type of climate. Mass balance results have been published and analysed by Swedish scientists (SCHYTT, 1981; HOLMLUND, 1987, 1993, 1996; HOLMLUND *et al.*, 1996).

3.3. Svalbard

One of the longest continuous mass balance observation series in the Arctic is from Svalbard. In 1966 investigations were started in the Kongsfjord area on Brøggerbreen (6.1 km^2) (HAGEN and LIESTØL, 1990). The basin is close to the research station Ny-Ålesund (79°N, 12°E) on the north-west coast of Spitsbergen. Observations on some other glaciers have been carried out by Russian and Polish scientists in shorter periods in other parts of the island both before and during the period 1967–1993 giving a good supplement to the continuous series. Long term mass balance data has also been obtained by detection of radioactive reference layers by French scientists (LEFAUCONNIER *et al.*, 1993, 1994).

Both the Norwegian and the Russian mass balance measurements have been carried out on relatively small (2–6 km^2) cirque or valley glaciers close to the coast. The main parts of these glaciers are below 500 m a.s.l. Only sporadic measurements have been made on larger glaciers and ice caps. Mass balance investigations were therefore started on Kongsvegen (105 km^2) in 1987. Kongsvegen is in the inner part of Kongsfjorden about 30 km east of Ny-Ålesund. The glacier extends from sea level up to 800 m a.s.l.

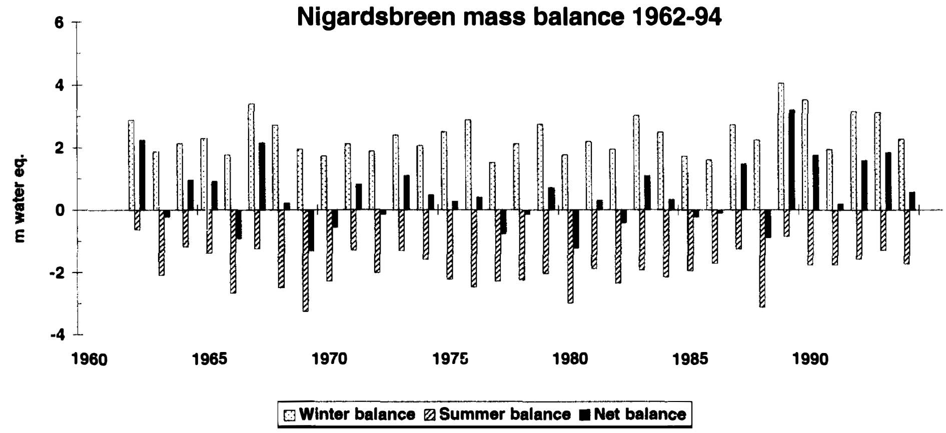
Most of the glaciers in Svalbard are of the surge type. It is therefore difficult to use the front position of a single glacier as a climate indicator. Since the motion of most glaciers in Svalbard is very slow, the front will shrink and retreat in periods between surges. The front position does therefore give little information on whether the ice mass is growing or shrinking. Mass balance measurements are therefore necessary to tell the true story of volume change.

4. Results

4.1. Scandinavia

From the start of mass balance measurements in Southern Norway in the beginning of the 60's and up to 1988, the mass balance results show a more or less constant tendency with a different trend on the western, maritime glaciers compared to the more continental glaciers 200 km inland. The westernmost and most maritime glaciers had a positive net balance whereas the continental glaciers further east had a negative net balance. This period terminated in 1988 with an extremely negative net balance for all glaciers in Southern Norway.

In the period from 1989 up till now, conditions have changed towards a more positive net balance for all glaciers. The maritime glaciers have had higher positive net bal-



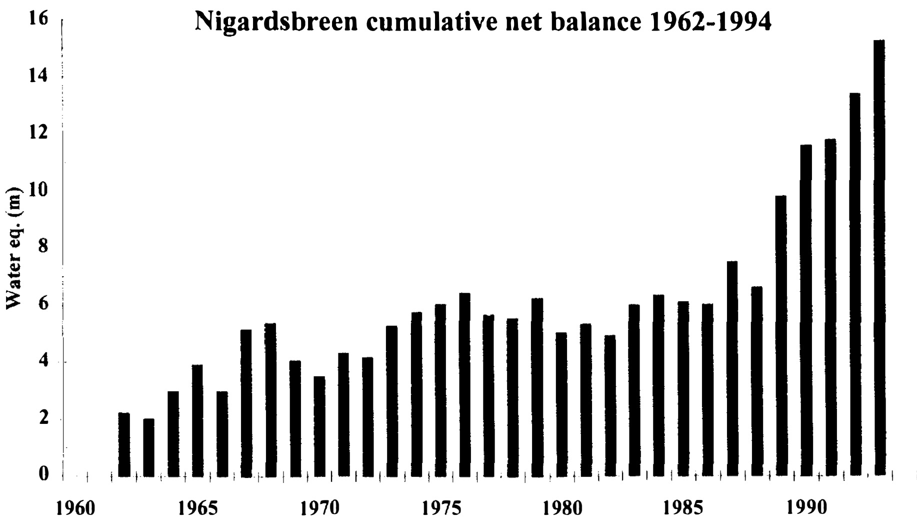


Fig. 2. Annual mass balance results from Nigardsbreen (48 km², 61.5°N, 7°E) in South Norway given in specific values (upper) and cumulative net mass balance (lower) showing the increasing trend since 1989 typical for glaciers in south Norway.

ance. Even the continental glaciers have had mass surplus in this period. Most of the glaciers in southern Norway had their most positive net balance ever measured in 1989. Apart from 1967 three or four of the most positive years were measured in the period 1989–1994. On Nigardsbreen (48 km^2), one of the main outlet glaciers from Jostedalsbreen, the mean winter balance for the period 1962–1994 has been $b_w = 2.39$ m ± 0.61 m water eq. The mean summer balance has been $b_s = -1.91 \pm 0.63$ m water eq. The high values show that this is a glacier influenced by a maritime climate. The net mass balance has shown a positive trend since 1962 with a cumulative mass increase of 6.5 m water eq. in the 26 year period 1962–1988. During the last six years, 1989–1994, the cumulative growth has been an additional 9.1 m water equivalents (Fig. 2). The main reason for the change in net balance is the increase of the winter precipitation with values up to 180% of the average for the whole period of measurements, but also partly to slightly cooler summers than normal. Normally the net balance of the glaciers in western Norway is controlled by the winter precipitation while the more continental glaciers are controlled mainly by the summer temperature. The change since 1989 is, however, mainly explained by increasing winter precipitation also for the more continental glaciers. The change is also seen in the meteorological data from western Norway where the increasing precipitation is clear. Figure 3 shows the summer temperature and the winter precipitation in Bergen (60.4°N) at the west coast of Norway 1900–1994. The

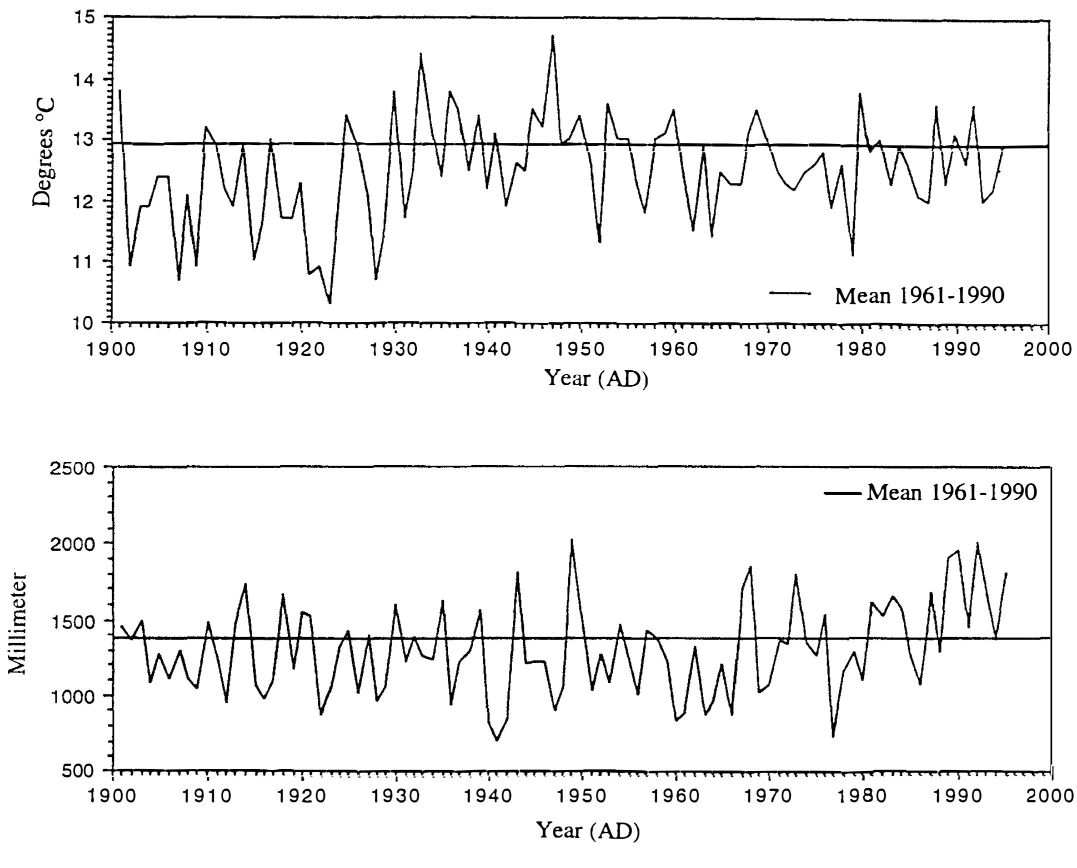
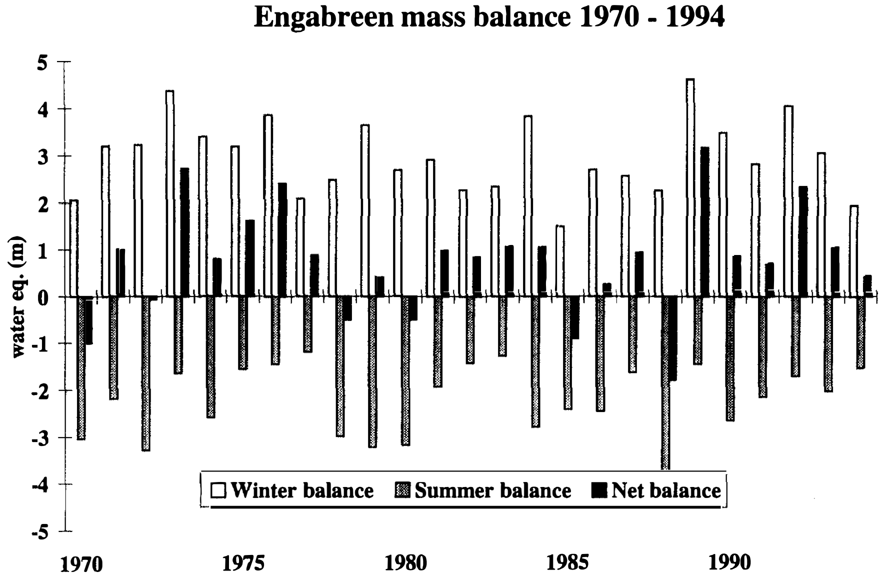


Fig. 3. Summer temperature and winter precipitation in Bergen (60.4°N), west coast of Norway 1900–1994.

volume growth has resulted in a glacier front advance of several outlets from ice caps in western South Norway (NESJE *et al.*, 1995). Some of these small outlets have a reaction time of only a few years (< 5 years).

In northern Norway conditions are more variable. The tendency is more difficult to point out due to the lack of long series of measurements. The glacier Engabreen, located very close to the ocean, has however been measured since 1970. It has shown a considerable positive mass balance amounting to 18 m of water equivalent, which is more than on any of the glaciers in southern Norway (Fig. 4). The maritime climate influence is shown in the high values of specific mass balance components, the mean winter balance b_w = 2.98 m ± 0.80 m water eq. and summer balance b_s = –2.23 m ± 0.76 m, resulting in



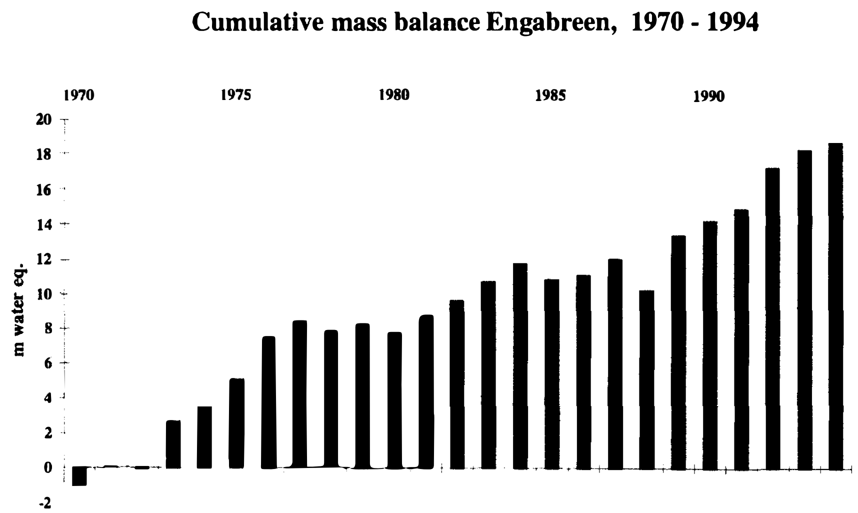
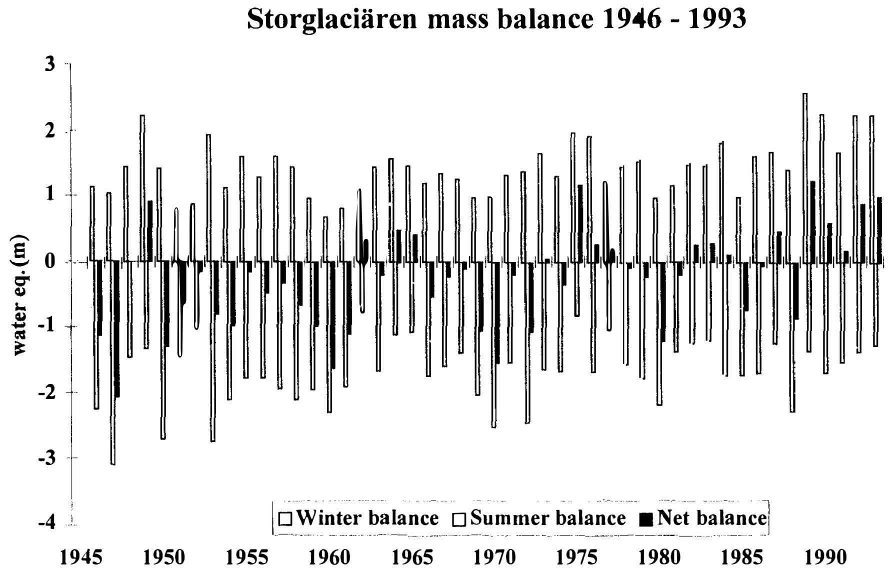


Fig. 4. Annual mass balance results from Engabreen (38 km²) close to the polar circle at 66.5°N, 14°E, and cumulative net mass balance showing an increasing ice mass.

a stable increasing ice volume. Engabreen has not shown any increasing trend after 1988 such as the South Norwegian glaciers. Short measurement series from other glaciers in northern Norway indicate that the more continental ones are close to equilibrium or have been slightly decreasing.

During the nearly 50 years period 1947–1993 of measurements on Storglaciären in northern Sweden the mean winter accumulation was $b_w = 1.44$ m ± 0.43 m and the summer ablation $b_s = 1.69$ m ± 0.51 m resulting in a decreasing ice mass. The values are typical of a more continental climate with lower specific values compared to the Norwegian glaciers closer to the west coast. However, the average annual winter precipitation



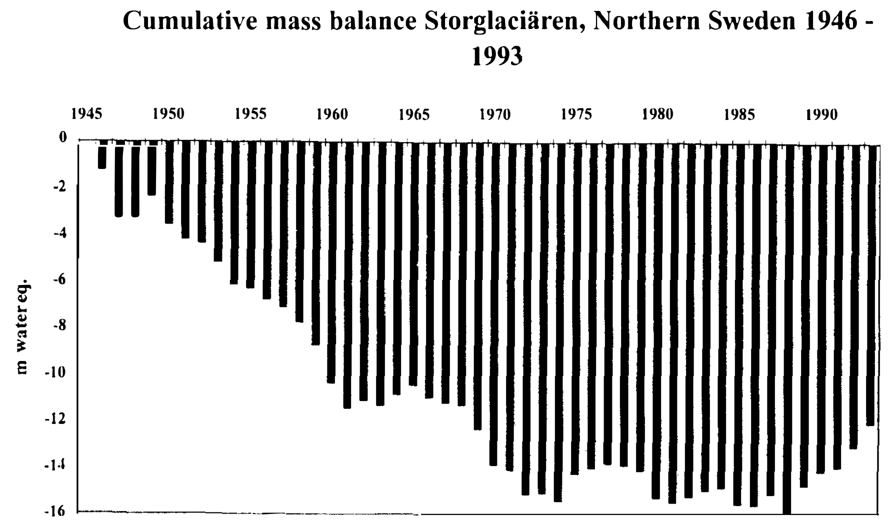


Fig. 5. Annual (upper) and cumulative (lower) mass balance results from Storglaciären (3.1 km², 67.9°N, 18.6°E), in northern Sweden showing the change from a stable decreasing glacier to lesser decrease and then an increasing trend since 1989.

has shown a clear positive trend and increased about 0.5 m water equivalents while summer ablation has shown a negative trend and decreased about the same amount resulting in a change in net balance from negative to positive (HOLMLUND *et al.*, 1996). Figure 5 shows the annual values of the winter, summer and net balance. The changing trend is clearly seen in the lower part of Fig. 5.

During the last five years all glaciers have shown a surplus due to high winter precipitation except Langfjordjökulen (5 km^2) at 70.5°N, 22°E, one of the northernmost glaciers in Scandinavia where mass balance measurements have been carried out. This glacier was studied in the period 1989–1993. The result shows a glacier close to equilibrium, the cumulative net balance for the five year period was –0.11 m water eq.

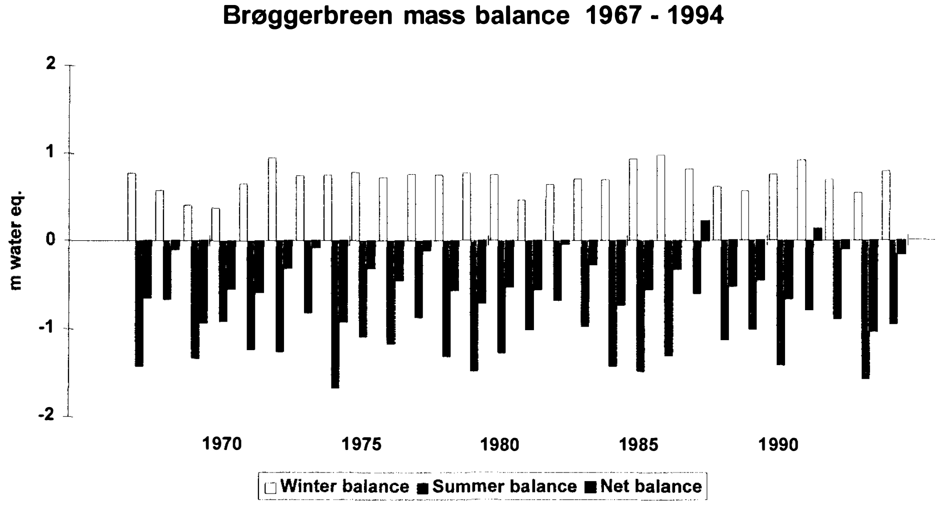
4.2. Svalbard

Reliable spot measurements of precipitation are difficult because most of it comes in connection with strong winds and snow drift. In Ny-Ålesund the meteorological station is situated only 5–6 km from the central areas of the glaciers. However, the correlation between the measured winter precipitation from September to June at the station and the snow accumulation measured by sounding profiles over the entire glacier surface is not high. During the 14-year period 1974–1975 to 1987–1988 the correlation coefficient was 0.63 (HAGEN and LIESTØL, 1990).

The mean winter accumulation on Brøggerbreen during the period 1967–1993 is b_w = 0.71 m ± 0.16 m in water equivalent. As can be seen in Fig. 6 the annual variations are fairly small. The low values reflects the cold arctic climate with much less precipitation and ablation than in Scandinavia. The altitudinal increase of snow accumulation has a fairly constant gradient $db_w/dz = 1$ kg $m^{-2}m^{-1}$, or 100 mm/100 m. Trend analysis of the measured winter balance shows a slight increase of the winter accumulation through this period.

During the observation period (1967–1993) the mean summer ablation has been b_s = –1.15 ± 0.31 m water equivalent on Brøggerbreen. Annual ablation values show more fluctuations than the winter balance values (Fig. 6). There is no sign of increased melting. There is no significant trend of the summer ablation during the whole observation period.

The glaciers are not in balance with the existing climate since the summer ablation has been greater than the winter accumulation in nearly all observed years, resulting in steadily decreasing ice masses. The mean annual specific net mass-balance is –0.43 m water equivalent on Brøggerbreen. Only two balance years, 1986/87 and 1990/91, had positive net balances during these twenty-seven years, respectively +0.22 m and +0.13 m, mainly due to cold summers with less melting than in an average year. The net balance deficit decreased slightly from 1967 to 1993, mainly because of slightly increasing trend in the winter balance, but also due to a front retreat and decrease of the area in lower altitudes of the glacier. The decreasing area in lower altitudes is partly caused by the climatic conditions with high melting, and partly because the flow and the emergence velocity of the glacier is very small due to the cold glacier ice. In the lower part of the glacier, below 200 m a.s.l., the horizontal velocity is only about 0.5 m/year, and thus the emergence velocity is only a few centimetres per year. Based on air photos from 1977, a glacier map was constructed at the scale of 1:20000 with a contour interval of 10



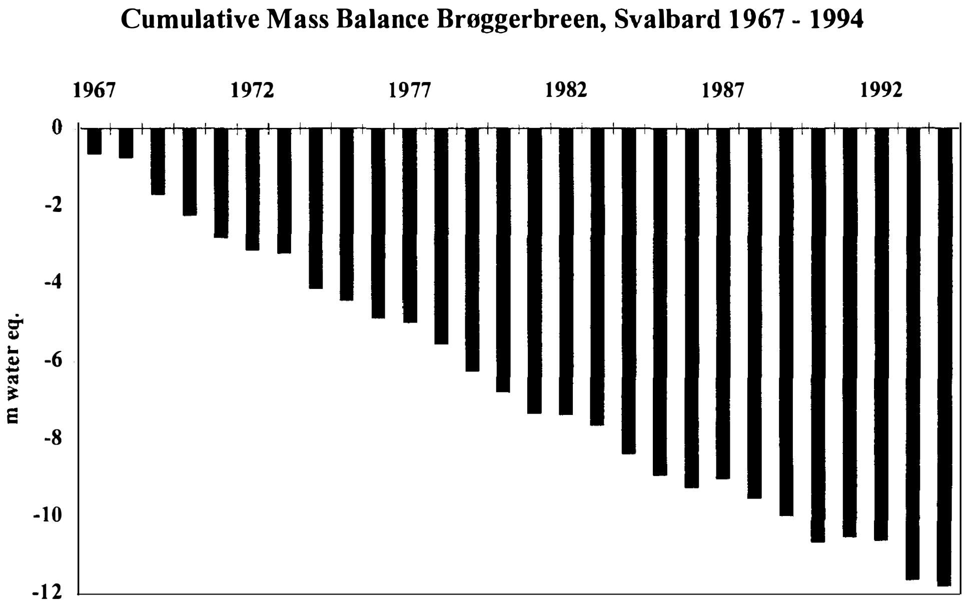


Fig. 6. Annual (upper) and cumulative (lower) mass balance results from Brøggerbreen (6.1 km², 79°N, 12°E), Svalbard showing a stable decreasing ice mass with no significant change during the last years.

m. One of the ablation stakes was resurveyed in 1985. The vertical difference on the glacier surface was 5.20 m compared to the 1977 map. The cumulative net balance at this point over the same period was 4.95 in water equivalent, which is 5.45 m of ice. Direct measurements from the map and the surveying thus agreed well with the annual mass-balance measurements (HAGEN and LIESTØL, 1987). This is typical for these small subpolar valley glaciers in Svalbard where the thin and outermost parts of the glacier are frozen to the ground.

More than 10% of the total volume of Brøggerbreen has been lost in the period 1967-1993. The average equilibrium line is about 100 m higher than the level that gives zero net balance. Based on a simple degree-day model of the summer ablation steady state would be obtained if the average summer temperature was lowered by 1 °C or if the winter precipitation increased about 50% (HAGEN and LIESTØL, 1990).

The mass balance investigations on Kongsvegen are well correlated to the nearby Brøggerbreen, but due to the different area/altitude distribution it shows different results. The mean accumulation has been 0.79 m ± 0.14 m and the mean summer ablation has been –0.73 ± 0.28 m of water equivalents. The summer ablation includes in average 0.05 m of calving since the glacier front ends in the sea. Estimates of the calving rate is made from velocity measurements in the lower part of the glacier together with radio-echo soundings of profiles in the lower part. The summer balance is lower than the values measured on Brøggerbreen mainly because the main part of Kongsvegen covers higher altitude areas. The result is that the mean net balance of Kongsvegen is slightly positive, b_n = +0.06 m. Thus, the results from seven years indicate that glaciers covering higher accumulation areas are closer to a steady state than the lower cirque glaciers closer to the coast.

5. Conclusions

In south Norway (61–62°N) the results show a different trend on the western, maritime glaciers than on the more continental glaciers 200 km inland during the period 1962–1988. In the west glaciers have been increasing in volume, while in the east glaciers have had a decreasing trend up to 1988. In the period from 1989 up till now (1995) conditions have changed towards more positive net balance values for all glaciers. This is mainly due to higher winter precipitation with snow precipitation up to 50% more than the average value. The volume growth has resulted in a glacier front advance of several outlets from ice caps in western South Norway.

The main trend for the glaciers in Northern Scandinavia is towards a more positive net mass balance in the area between 66°N to 68°N, mainly due to higher winter precipitation, similar trend to the observed in southern Norway. Further north on Langfjordjökulen at 70°N, there is however no sign of a changing trend during the last years.

In general no dramatic changes have occurred in Svalbard during the last 28 years. The winter accumulation is stable or slightly increasing with small annual variations. The mean summer ablation is stable with no significant trend, but with large annual variations. There is no sign of increased melting during the observation period. The net balance depends on area/altitude distribution. Low altitude glaciers are steadily shrinking but with slightly less negative net balance than 28 years ago. Glaciers with high altitude accumulation area are close to equilibrium.

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