Monitoring changes of Norwegian glaciers close to the Arctic Circle

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Abstract

During the twentieth century Norwegian glaciers close to the Arctic Circle have become smaller, but in recent decades some have advanced whilst others have continued to retreat. Changes of length do not necessarily reflect overall changes of mass. Extrapolating glacier net mass balance from areas of maritime climate to areas further from the ocean is difficult, partly because a glacier's response to regional climate is influenced by its area:altitude ratio. Detailed three-dimensional data can be acquired rapidly by Differential Global Positioning System surveying, which has potential utility for mass balance studies. Synthetic Aperture Radar imagery, which is unaffected by cloud cover and darkness, offers opportunities for monitoring changes of many glaciers in a particular area, and may provide an indication of the altitudes of their equilibrium lines.

Key words

Glaciers, mass balance, surveying, remote sensing, Norway.

Introduction

Glaciers play an important role in the Norwegian economy, as meltwater issuing from them in summer makes a significant contribution to hydropower generation. The glaciers are a natural reservoir of water. During the second half of the twentieth century most of the glaciers of northern Norway have become smaller, but changes have varied from one glacier to another (Theakstone 1988).[1] Glacier volumes may further decrease if, as is widely predicted, the global atmosphere becomes warmer. Monitoring the changing size of Norway's glaciers therefore is an important exercise. Some General Circulation Models suggest that future warming will be particularly pronounced around the latitude of the Arctic Circle (Hansen *et al.* 1988). Against this background, this paper examines the changes experienced by Norwe-gian glaciers close to the Arctic Circle during the last one hundred years, and indicates some of the techniques used there in current glacier monitoring programmes.

Svartisen and Okstindan, which lie close to the Arctic Circle (Figure 1), are amongst the largest ice-covered areas of Norway. The West Svartisen ice cap covers about 220 km^2, the East Svartisen ice cap almost 150 km^2 and Okstindan, which is some 60 km south of Svartisen, about 46 km^2. The two Svartisen ice caps, which are separated by a narrow valley, Vesterdalen – Glomdalen, supply 60 outlet glaciers, and there are 19 glaciers in the Okstindan area (Østrem *et al.* 1973). The water issuing from all the glaciers passes through hydroelectric power stations.

Early observations of the glaciers of Svartisen and Okstindan

Until the last part of the nineteenth century, the only glacier of Svartisen about which much was known was Engabreen (Figure 1), an outlet of the West Svartisen ice cap, which terminated at the head of Holandsfjord and was accessible from the sea. Rabot (1899), who explored Svartisen between 1881 and 1885, took the earliest known photographs of several of the glaciers. Rekstad (1893) spent six weeks at Svartisen in 1890, undertaking a reconnaissance of the area's glaciers. He returned in 1891 for a visit of similar duration, spending the last part of the period measuring surface velocity variations at Engabreen. The first survey of Svartisen was carried out by the Norwegian Topographic Survey (NGO) between 1894 and 1905; the resulting 1:100,000 scale maps were not replaced until 1974, when 1:50,000 scale maps based on aerial photographs taken in 1968 were published. Marstrander (1911) made detailed observations of many of the Svartisen glaciers in 1910, but few other studies were carried out in the area during the first half of the twentieth century (Theakstone 1965).

In 1908, Hoel (1910) carried out the first detailed investigation of Okstindan glaciers and set up cairns in front of several of them. The distances between these markers and the glacier fronts were measured every summer between 1908 and 1922, and the observations of the changes in length of the glaciers were restarted in 1934, continuing until 1944 (Hoel 1962). Aerial photographs of Okstindan were taken in 1962 and 1965, but few field observations of the glaciers were recorded between 1944 and 1970.

Recent changes of glacier size

Members of the Svartisen Research Project[1] established photographic stations at many of the Svartisen glaciers in the late 1950s and early 1960s. Photographs taken between then and the early 1980s showed that several of the smaller glaciers advanced, whilst the larger ones continued to retreat (Knudsen and Theakstone 1997). Terrestrial photogrammetric surveys of three of the principal outlet glaciers of the East Svartisen ice cap between 1970 and 1990 documented their continued retreat (Knudsen and Theakstone 1984; Theakstone 1989). Changes of surface elevation of the ice cap and its outlets were determined from a comparison of aerial photographs taken in 1968 and 1985 (Knudsen and Theakstone 1997). The thickness of the lowermost 3 km of Fingerbreen, the longest outlet glacier of the East Svartisen ice cap (Figure 1), decreased by more than 10 m in the seventeen-year period. In 1990, the glacier was more than 350 m shorter than in 1968 and its front was about 1.5 km from the

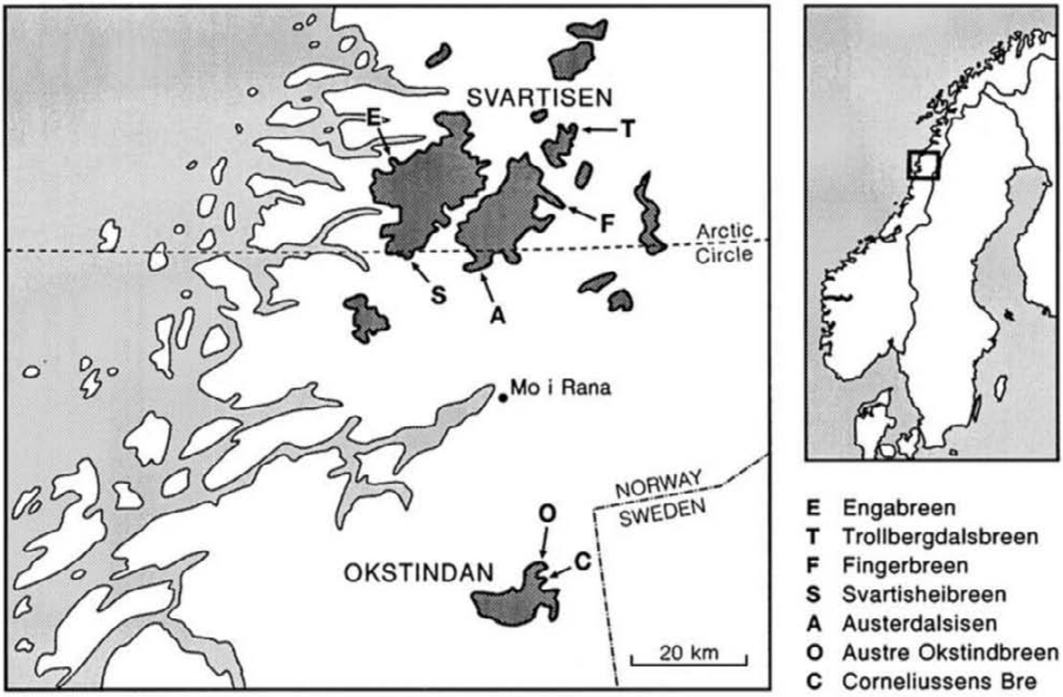

Figure 1: The Svartisen and Okstindan areas, Norway. The locations of seven specific glaciers are indicated.

position which it had occupied at the time of Marstrander's visit in 1910. East Svartisen's largest glacier is Austerdalsisen. Between 1940 and 1987, its retreat was dominated by calving into a marginal lake (Theakstone 1989), but the glacier has terminated on land since 1987, and the rate of retreat has slowed considerably.

At Okstindan, photographic stations established in front of several glaciers in 1934 and 1941 were used by the Okstindan Glacier Project in the early 1970s to record the changes which had taken place. All the glaciers had retreated. Terrestrial photogrammetric surveys of the largest of the Okstindan glaciers, Austre Okstindbreen, documented its retreat between 1970 and 1996, when its front was about 1.5 km from the position recorded by Hoel in 1908 (Knudsen and Theakstone 1997). A similar programme at the small (2 km^2) glacier Corneliussens Bre, which is close to Austre Okstindbreen (Figure 1), has provided detailed information about the progress of an advance which began in 1970. In 1994, the extent of some of the smaller glaciers at the southern part of Okstindan was little different from that which had been recorded twenty years before.

Glacier mass balance variations

Although changes of length provide some indication of a glacier's change of size, they may be misleading. The thickness of a retreating glacier may be increasing before it starts to advance: its volume is increasing despite its decreasing length. In order to determine changes of size with reasonable accuracy, it is necessary to determine the mass added to a glacier each winter and the mass which is lost in summer. A positive mass balance, with the additional snow outweighing the loss of snow and ice during a particular year, means that the glacier is becoming larger; a negative net mass balance results in the glacier being smaller at the end of the balance year than at the beginning. Because the meltwater from both snow and glacier ice are used to generate electricity, the Norwegian Water Resources and Energy Administration carries out an extensive programme of annual glacier mass balance studies. In addition to monitoring the year-to-year variations of snow accumulation and snow and ice melting, the programme produces data about the changing size of the studied glaciers. Since 1970, Engabreen has been included in the programme.

Engabreen has a surface area of 38 km^2 and ends only 20 m above sea level; its highest parts are more than 1600 m above sea level. In the quarter-century since it was selected as the sample glacier for observations in the Svartisen area, net accumulation of snow has result in an increase of its mass equivalent to about 20 m of water over its entire area: the glacier's volume has increased by 780 million cubic metres (Elvehøy *et al.* 1997). The glacier has a maritime climate, and more snow accumulates on it in winter than on the glaciers of East Svartisen and of Okstindan. Recognition that the increase of stored water represented by the long-term positive mass balance at Engabreen is not representative of the area as a whole led to the establishment of comparative mass balance studies of other glaciers at Svartisen and Okstindan.

Austre Okstindbreen has a surface area of 14 km^2 and ends at 730 m above sea level. Mass balance studies were started there in 1986, as part of the Okstindan Glacier Project.[1] Since 1991, the results have been included in the Norwegian national programme (Elvehøy *et al.* 1997). Comparison of the winter, summer and net mass balance values for Engabreen and Austre Okstindbreen reveals that, over a period of nine years, the mean winter balance at Austre Okstindbreen was 74% of that at Engabreen, whilst the mean summer balance was almost the same at the two glaciers (Table 1). The net mass balance between 1986-87 and 1994-95 was positive at both glaciers, but the mean net balance (and thus the cumulative balance) at Engabreen was more than five times that at Austre Okstindbreen (Table 1). The mean altitude of the equilibrium line (ELA), at which the winter and summer balances are equal at the end of the balance year, was some 300 m higher at Austre Okstindbreen than at Engabreen. Changes of the ELA are a good indi-

Year	bw (E)	bw (A)	Ratio (w)	bs (E)	bs (A)	Ratio (s)	bn (E)	bn (A)
1986-87	2.57	2.30	0.89	1.63	1.60	0.98	+0.94	+0.70
1987-88	2.26	1.50	0.66	4.05	3.40	0.84	-1.79	-1.90
1988-89	4.62	3.70	0.80	1.45	2.20	1.52	+3.18	+1.50
1989-90	3.49	3.00	0.86	2.64	2.70	1.02	+0.85	+0.30
1990-91	2.83	1.78	0.63	2.14	2.30	1.07	+0.69	-0.52
1991-92	4.05	2.88	0.71	1.71	1.65	0.96	+2.34	+1.23
1992-93	3.06	2.20	0.72	2.02	2.01	1.00	+1.04	+0.19
1993-94	1.95	1.45	0.74	1.53	1.62	1.06	+0.42	-0.17
1994-95	3.50	2.25	0.64	1.76	1.79	1.02	+1.74	+0.46
1986-95	3.15	2.34	0.74	2.10	2.11	1.00	+1.05	+0.20

Table 1: Winter (bw), summer (bs) and net (bn) mass balance values at Engabreen (E) and Austre Okstindbreen (A), with ratios of the winter and summer balances for each year. The last row shows mean values for the nine-year period. Values are in metres of water.

cation of annual changes of climate, and early signs of more significant climate change may be detectable by long-term ELA monitoring.

For two short periods (1970-74 and 1990-94), annual mass balance measurements were made at Trollbergdalsbreen, a small (1.6 km^2) glacier with an altitudinal range from 900 m to 1270 m above sea level, situated to the north of the East Svartisen ice cap (Figure 1). During each of the ten years, the winter balance at Trollbergdalsbreen was lower than that at Engabreen and the summer balance at Trollbergdalsbreen was higher than that at Engabreen. The ELA generally was 50-100 m higher at Trollbergdalsbreen than at Engabreen. From a comparison of aerial photographs, Elvehøy *et al.* (1997) found that the surface elevation of Trollbergdalsbreen decreased by 5-25 m between 1968 and 1985, equivalent to a mean annual value of 0.9 m water for the 17-year period. Using a correlation established between the winter balances of Engabreen and Trollbergdalsbreen, they calculated a cumulative loss of ca 12 m, equivalent to about 0.7 m yr^{-1}.

Mass balance measurements were made at Svartisheibreen (5.8 km^2), the southernmost outlet of West Svartisen (Figure 1), between 1987-88 and 1993-94. The glacier's surface extends from 770 m to 1420 m above sea level. During the seven-year period, the ELA generally was lower at Svartisheibreen than at Engabreen. The mean winter balance was similar at the two glaciers, but the mean summer balance was somewhat higher at the southern glacier.

The mass balance observations indicate that the glaciers which are nearer to the ocean receive more snow during the accumulation period than those which are further from it: the mean winter balance exceeds 3 m water equivalent (W.E.) at Engabreen and Svartisheibreen, whilst it is less than 2.5 m W.E. at Trollbergdalsbreen and Austre Okstindbreen. Of course, the winter balance is influenced by other factors, such as the duration of the accumulation period (which is an indirect function of altitude), the degree of exposure to winds (which remove and re-deposit snow) and local topography (Theakstone 1988). The summer balance is related to a glacier's area: altitude ratio – the mean summer balance is less than 2.5 m at Engabreen and Austre Okstindbreen, at which, respectively, 74% and 86% of the surface area is above 1100 m. At Svartisheibreen, where 61% of the surface area is below 1100 m, the summer balance is about 2.5 m, and at Trollbergdalsbreen, where 92% is below 1100 m, it is more than 2.5 m.

Annual mass balance data are not collected at any of the East Svartisen glaciers. Pettersson (1981) used river discharge data to calculate their mass balances and concluded that the winter balance of the East Svartisen

Winter balance	Summer balance	Net balance	Cumulative net balance	Glaciers
+2.91	-2.32	+0.59	+10.15	Engabreen
+2.32 (0.80)	-2.79 (1.20)	-0.47	-7.99	East Svartisen
+2.32 (0.80)	-2.90 (1.25)	-0.58	-9.86	East Svartisen
+2.47 (0.85)	-2.55 (1.10)	-0.08	-1.36	East Svartisen

Table 2: Mean observed glacier mass balance (metres water equivalent) at Engabreen, 1968-85, and values calculated for the glaciers of East Svartisen. The East Svartisen data are calculated from the Engabreen data, using the ratios indicated in parentheses.

glaciers was 80-85% of that of Engabreen, whilst the summer balance was 110-125%. Knudsen *et al.* (1992) used maps based on aerial photographs taken in 1968 and 1985 to determine glacier change at East Svartisen and found that the mean change of thickness of the ice cap in the seventeen years was equivalent to a loss of about 8 m of water. The cumulative net mass balance of Engabreen for the same period was positive (equivalent to 10.15 m of water). Extrapolating the Engabreen data to the East Svartisen glaciers using the ratios suggested by Pettersson (1981) provides a range of values for the cumulative mass loss there (Table 2). Although the observed net change at East Svartisen falls within the range of the predicted values, it is evident that the error in the predictions may be substantial. This indicates the difficulties involved in extrapolating observed glacier changes within areas of maritime climate to changes in areas with a more continental regime.

Glacier surveying using a Global Positioning System

Terrestrial photogrammetry requires little time in the field, but the time taken to produce the contoured glacier maps limits the number of glaciers in any one area which can be surveyed on a regular basis. The programme of annual mapping undertaken each summer from 1981 until 1992 at Austre Okstindbreen is unique – elsewhere, terrestrial photogrammetric glacier monitoring programmes involve fieldwork every second year, or even less frequently (Reid and Charbonneau 1979). The cost of taking aerial photographs means that surveys of this type generally can be repeated only at intervals of several years: aerial photographs of the whole of the Svartisen area were taken in 1968 and 1985, and a further programme is planned for 1998. Clearly, neither terrestrial nor aerial photogrammetric programmes afford opportunities for monitoring year-to-year changes at a large number of glaciers.

The labour involved in programmes of mass balance determination is considerable. The observations of the winter balance at Austre Okstindbreen include more than 170 snow depth soundings along about 6 km of profiles, carried out on skis (Knudsen 1995). In order to convert the measured snow depths to water equivalent values, several pits have to be excavated to the previous summer's surface, which may be at a depth of 5 m or more. At Engabreen, the maximum snow depth measured in April 1995 was 9.3 m, and determination of the winter balance necessitated 90 snow depth measurements above 920 m (Elvehøy *et al.* 1997). The use of recently-introduced Differential Global Positioning System surveying techniques offers possibilities of determining a glacier's winter balance without the need for such a substantial number of at-a-site snow depth measurements.

Global Positioning System (GPS) surveying can be carried out quickly with high precision. At Austre Okstindbreen, GPS surveys were made at the same time as the late winter mass balance observations in 1995, 1996 and 1997. Differential GPS surveying makes use of two receivers, which receive information transmitted by satellites (Jacobsen and Theakstone 1997). One of the geodetic-quality receivers is maintained at a fixed reference site whilst the other is moved from one place to another. At Austre Okstindbreen, the roving receiver was mounted on a snow scooter, which was driven over the snow-covered surface of the glacier at a speed of about 20 km h^{-1}. With the three-dimensional position of a site being fixed every 10 seconds, the along-track separation of the sites is about 56 m. By driving along a series of profiles from one side of the glacier to the other, the surface topography of a large area can be determined in a few hours.

Repeating kinematic GPS surveys at the same time during successive mass balance years permits the change of snow surface level to be determined. This change results from two components: the addition of snow to the surface (or the loss of snow and ice from it) between the surveys, and the glacier's 'emergence velocity'. The latter is the vertical rise or subsidence of the ice at a given horizontal position. In general, the surface rises as a result of glacier thickening where the glacier is in longitudinal compression, whilst the surface becomes lower where longitudinal stretching (extension) occurs. At Austre Okstindbreen, longitudinal extension occurs as the glacier steepens into an icefall at about 1200 m above sea level. At the foot of the icefall, as the slopes of both the glacier's bed and its upper surface decrease, upward-directed emergence velocities accompany longitudinal compression (Jacobsen *et al.* 1997). In the area above the icefall, emergence velocities are low in comparison with the change of surface level which results from the addition of snow each winter. When due correction is made for emergence, the snow cover thickness can be converted to a water equivalent value by measuring the density of the snow at a small number of sites, as is done in mass balance determination based on manual snow depth sounding. The results of GPS surveys can be incorporated directly into a computer, and a detailed digital terrain model of the surveyed surface can be constructed without difficulty. Such a model has great utility as it incorporates detailed information about the variations of both the gradient and the aspect of the surface (Theakstone and Jacobsen 1997).

Remote sensing of glaciers

Satellite remote sensing offers opportunities for monitoring the changes of a large number of glaciers through time. The first Earth Resources Technology Satellite (ERTS 1/Landsat 1) was placed in orbit in 1972. Landsat images provide a record of the Earth's surface, and images acquired at different times can be used to measure spatial (two-dimensional) changes. Recognition of the utility of Landsat images for providing an inventory of the world's glaciers led the United States Geological Survey to decide, in 1979, to produce a 'Satellite Image Atlas of Glaciers of the World'. The Atlas was to make use of Landsat images from the period 1972-82 to provide a global 'snapshot' of glacier extent, for comparison with historical information, such as maps and photographs, and with post-1970s data (Williams and Ferrigno 1993).

Two glacier atlases of Norway had been published before satellite images were widely available (Østrem and Haakensen 1980). In their report on the glaciers of Norway published as part of the Satellite Image Atlas of Glaciers of the World, Østrem and Haakensen (1993) noted that "Landsat images have limited value in Norway for most glaciological studies". The images do not provide as much information as do high-quality aerial photographs. The areas in which many of Norway's glaciers are located experience frequent cloud cover; satellite systems which operate in the visible and infrared wavelengths, including Landsat, are unable to penetrate cloud cover and darkness. However, those difficulties of remote sensing of glaciers which are associated with the weather conditions common to mountain and high-latitude areas can be overcome by means of Synthetic Aperture Radar (SAR) imagery. Satellite SAR sensors include those on the European Space Agency's Remote Sensing satellites, ERS-1 and ERS-2, NASA's Spaceborne Imaging Radar C (SIR-C) and the Canadian Space Agency's RADARSAT.

SAR imagery is unaffected by cloud, and provides images by night as well as by day. Thus studies which make use of sequential SAR imaging – repeat-track observations – have great potential for long-term investigations of glaciers. Multiple SAR images are of value in detecting very small changes of elevation over very large areas, and both topographic mapping and studies of glacier change and dynamics have made use of repeat-track ERS-1 and SIR-C interferometry (Joughin *et al.* 1996; Rignot *et al.* 1996). However, processing SAR images of mountainous areas must take account of the effects of the terrain, which may be considerable.

Microwaves are scattered from snow and glacier ice surfaces by both sub-metre scale roughness and larger undulations. As the microwaves penetrate snow, further scattering occurs at inhomogeneities, such as grain surfaces and boundaries between strata, and as a result of absorption (Rott *et al.* 1993). Whilst the precise influence of snow temperature, density, hardness and liquid water content, particle size and shape, and stratigraphic variations on the backscattering still is not known, it is recognised that dry and wet snow have different effects. In winter, newly-fallen snow with a temperature below the melting point may cover wet snow which was exposed at the surface during the preceding summer. The difference means that it may be possible to use SAR imagery acquired in winter to locate the position of the ELA at the end of the previous melt season (Dowdeswell *et al.* 1994). Thus, it is likely that the ELA of glaciers at which mass-balance data are not acquired in the field can be determined from SAR imagery. The potential value of SAR data in studies of glacier mass balance therefore is high. In order to verify the effect of near-surface snow temperature on SAR imagery, the European Multi-sensor Airborne Campaign (EMAC), which was carried out at Okstindan in 1995, included measurements of temperature.

The European Multi-sensor Airborne Campaign

It is essential to test new SAR sensors before they are used on satellites. The European Space Agency's Multi-sensor Airborne Campaign provided support for the preparation of future remote sensing programmes. In 1995, EMAC included snow and ice experiments in northern Europe. Okstindan was one of the test-sites for snow, and Austre Okstindbreen was the single test-site for land ice (glaciers). The EMISAR imaging radar developed at the University of Copenhagen Electromagnetics Institute was mounted in a Gulfstream G-3 aircraft of the Royal Danish Airforce, which flew over the test-site at an altitude of 41000 feet on 22 and 23 March, 1 and 3 May and 5 and 6 July 1995. ERS-1 SAR data also were acquired during the campaign.

Plans were made to observe snow temperature, grain-size distribution and liquid water content, surface roughness and topography at Austre Okstindbreen at the times of the EMISAR flights in March, May and July, and to make observations of the exposed ice at Austre Okstindbreen, including the glacier margin, at the time of the July flight. Unfortunately, weather conditions at ground level were poor during each period. Results of the 1995 research programme at Austre Okstindbreen are reported elsewhere (e.g. Raben and Theakstone 1997) and only observations of snow temperature made in late winter as part of the EMAC programme are outlined here.

On 22 March the snow on the centre-line of Austre Okstindbreen at an altitude of 825 m was 2.17 m deep. The temperature within the lowest metre was above -1°C, but the uppermost snow was colder. Strong winds prevented observations at higher sites selected for study during the EMAC programme, and blizzard conditions on 23 March made all work at the glacier impossible. On 24 March, however, the weather was excellent and a pit was excavated through the 2.13 m of snow which covered the glacier centre-line at 1230 m above sea level. Close to the surface, the temperature of the snow reflected the low air temperature, but it increased with depth to -5°C at 1 m (Table 3).

Date	Time	Site	Ta	Ts
22 March	11.15	825	-3.0	-0.2
26 April	10.15	825	-2.3	-1.2
29 April	17.50	825	-5.7	-1.3
1 May	09.50	825	-5.2	-1.3
3 May	10.50	825	+3.6	-0.7
24 March	16.00	1230	-11.6	-5.0
27 April	10.00	1230	-10.3	-5.2
1 May	11.10	1230	-6.4	-5.1
3 May	15.30	1230	+1.2	-6.3
28 April	13.30	1300	-8.3	-8.9
30 April	09.30	1350	-12.9	-7.6
1 May	14.30	1350	-6.4	-7.4
29 April	11.15	1470	-9.6	-8.2
1 May	15.55	1470	-7.3	-8.2
3 May	17.15	1470	-8.6	
30 April	15.50	1500	-7.6	-9.5

Table 3: Air temperature (Ta) and temperature of snow (Ts) at a depth of 1 m during the EMAC programme at Austre Okstindbreen in 1995. Temperatures are in °C. Site altitudes are in metres above sea level.

By 26 April, the thickness of the snowpack at the 825 m site had increased to 2.70 m, but the temperature one metre below the surface was slightly higher than on 22 March (Table 3). The 1230 m site was re-visited on 27 April, when the glacier ice was covered by 2.33 m of snow. The temperature of the snowpack increased with depth, from -10.0°C at 0.10 m depth to -6.2°C at 0.60 m, and then more slowly, to -5.2°C at 1 m, -4.5°C at 1.5 m, -4.2°C at 2m and -3.8°C at the contact with the glacier ice. On 28 April, observations centred on a transverse profile at about 1300 m. A site at 1470 m was examined on the following day. There, the accumulated snow from the 1994-95 winter was 7 m deep. A pit was excavated to a depth of 3 m; the temperature of the snow increased from -8.2°C at 1 m to -7.3°C at 3 m. At 825 m, the temperature at a depth of 1 m was only -1.3°C (Table 3). The study site at 1360 m on the centre-line of the glacier was visited for the first time on 30 April, and another 3 m pit was excavated. Under a clear sky, air temperatures were low, and snow temperatures of -7.6°C at 1 m, -6.8°C at 2 m and -6.0°C at 3 m were recorded. Temperatures also were measured at the high-est part of the glacier, at about 1500 m above sea level.

Detailed observations were made at Austre Okstindbreen on 1 May, when the first EMISAR flight of the second EMAC period took place. The glacier's snow cover still had not begun to melt. Heavy rain at lower altitudes, together with a low cloud base, prevented observations being made on 2 May. However, investigations were carried out on 3 May, to coincide with the second EMISAR flight, despite a low cloud base and precipitation. Air temperatures were higher than on 1 May. The thickness of the snow cover on the glacier at the 825 m site had decreased to 2.65 m and the temperature of the uppermost 0.5 m was close to the melting point. The minimum temperature was at a depth of 1 m, and the lower part of the pack also was close to the melting point. Snow was falling and drifting at higher sites, but the temperature of the accumulated pack remained low (Table 3).

Conclusions

Although glaciers close to the Arctic Circle in Norway have become smaller during the twentieth century, representing a net loss of stored water, the histories of individual glaciers have differed. Some, such as Engabreen at Svartisen and Corneliussens Bre at Okstindan, have experienced substantial advances in recent decades, whilst others, such as Fingerbreen at Svartisen and Austre Okstindbreen at Okstindan, have continued to retreat year after year. Changes of length are not necessarily an indication of overall changes of size or mass: the net mass balance of Austre Okstindbreen has been positive since 1986, despite its retreat, and the glacier's volume increased by 22.70×10^6 m^3 between 1986 and 1995.

Differences of winter balance are apparent between glaciers close to the coast and those further from the ocean, which receive less snowfall. The area:altitude ratio of a glacier has an important influence on the response of a glacier to the regional climate, and accurate maps or digital terrain models therefore are needed if attempts are to be made to estimate a glacier's future response to changing climatic conditions. Differential Global Positioning System surveying using geodetic quality receivers, such as that carried out at Austre Okstindbreen since 1995, results in the rapid acquisition of detailed three-dimensional data. Satellite remote sensing offers opportunities for monitoring changes of a large number of glaciers in a particular area, but only Synthetic Aperture Radar (SAR) imagery, which is unaffected by cloud cover and by darkness, has utility for detailed studies. The different response of SAR to wet and dry snow, which is at and below the melting point respectively, may permit identification of the Equilibrium Line Altitude, a useful surrogate for net mass balance determination.

Notes

1. Glacier studies have formed part of the work of the Svartisen Research Project since the mid-1950s. The Okstindan Glacier Project has monitored glacier changes since 1970. Personnel from the University of Manchester Department of Geography have played a major role in both Projects.

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