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Glacier changes in southern Spitsbergen, Svalbard, 1901–2000

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ABSTRACT. High-resolution ground-penetrating radar surveys at 50 MHz on the polythermal glaciers Hornbreen, Hambergbreen and several surrounding glaciers in southern Spitsbergen, Svalbard, are presented and interpreted. Accurate positioning was obtained using differential global positioning system (DGPS). Digital elevation models (DEMs) of the bedrock and surface were constructed. Comparison of DGPS data and surface DEMs with data from the topographic mappings from 1936 oblique stereoscopic aerial photographs and from Mission Russe in 1899–1901 shows that the Hornbreen and Hambergbreen surfaces are about 60–100 m thinner today in the upper part than at the beginning of the 20th century. Hornbreen has retreated by 13.5 km from the central part of the front, and Hambergbreen by 16 km. All the fronts of the nearby east-coast glaciers in this area have retreated. The bedrock DEM shows that the Hornbreen and Hambergbreen beds lie at −25 to 25 m a.s.l. The combination of sub-sea-level fronts and increasing steepness of the glaciers suggests that the low-lying glaciated valley filled by Hornbreen and Hambergbreen may become a partially inundated ice-free isthmus within perhaps 100 years.

INTRODUCTION

The future of glaciers in the Arctic will be primarily one of shrinkage, although it is possible that in a few cases they will grow as a result of increased precipitation (IPCC, 2001). In the Arctic, extensive land areas show a 20th-century warming trend in air temperature of as much as 5°C (Dowdeswell and others, 1997; IPCC, 2001). As result of the warming since the end of the Little Ice Age, and the associated shift towards consistently negative glacier mass balance in Svalbard (Hagen and Liestøl, 1990; Lefauconnier and Hagen, 1990), some glaciers that formerly surged are now apparently unable to build up the reservoir-area mass and geometry for a new surge (Dowdeswell and others, 1995; Dowdeswell and Williams, 1997). Those glaciers that undergo a great reduction in accumulation area will experience ever-increasing melting, and over some time that depends on altitude, thickness, speed and size they will eventually become ice-free areas.

Large glacier systems are rarely studied on Svalbard, but such vast low-inclination ice masses are typical of the archipelago. Some of them are low-altitude, thin glaciers such as the Hornbreen–Hambergbreen glacier system. Geomorphologic and remote-sensing evidence shows that they are of surge type. There are no mass-balance records from the Hornbreen–Hambergbreen area, but it was mapped by the Russian–Swedish expedition, Mission Russe, in 1899–1901. Our objective was to map the bedrock and surface of Hornbreen and Hambergbreen and adjacent glaciers and compare changes in surface elevations, glacier extents and volumes with maps from Mission Russe to get an idea of what has happened in this area in the past 100 years. We also used the bedrock data to determine if Sørkappland would become an island if the ice of Hornbreen and Hambergbreen were removed.

STUDY AREA

Hornbreen and Hambergbreen are grounded tidewater glaciers situated between Torell Land and Sørkappland in southern Spitsbergen, Svalbard (Fig. 1). Hornbreen flows to Brepollen in the Hornsund fjord, and Hambergbreen in the opposite direction to Hambergbukta and Storfjorden. The Hornbreen area was estimated to be 179 km^2 and the total ice volume 35.0 km^3 in 1980, while Hambergbreen was estimated to cover 144.0 km^2, with a volume of 27 km^3 (Hagen and others, 1993). Interpretation of aerial photographs suggests that in 1961 the equilibrium line on Hornbreen was at ~250 m a.s.l. (Jania, 1988) and on Hambergbreen at ~210 m a.s.l. (Hagen and others, 1993). Geomorphologic evidence from the area shows that Hornbreen and Hambergbreen are surge-type glaciers, so the retreat might be driven by surge cycles

EQUIPMENT AND METHODS

In April 2000 a Ramac ground-penetrating radar (GPR) (Malå Geoscience) was used to map Hornbreen bedrock topography and inner structure. The route was a zigzag profile covering Hornbreen and the adjacent glaciers Hambergbreen, Flatbreen, Skjoldfonna and northern parts of Sykorabreen (Fig. 1). The small valley glaciers Markhambreen, Crollbreen and Davisbreen on the east coast were mapped using additional profiles (the global positioning system (GPS) route is plotted in Figure 3b). We used 50 MHz antennas mounted on a plastic pulka, which was pulled 7 m behind

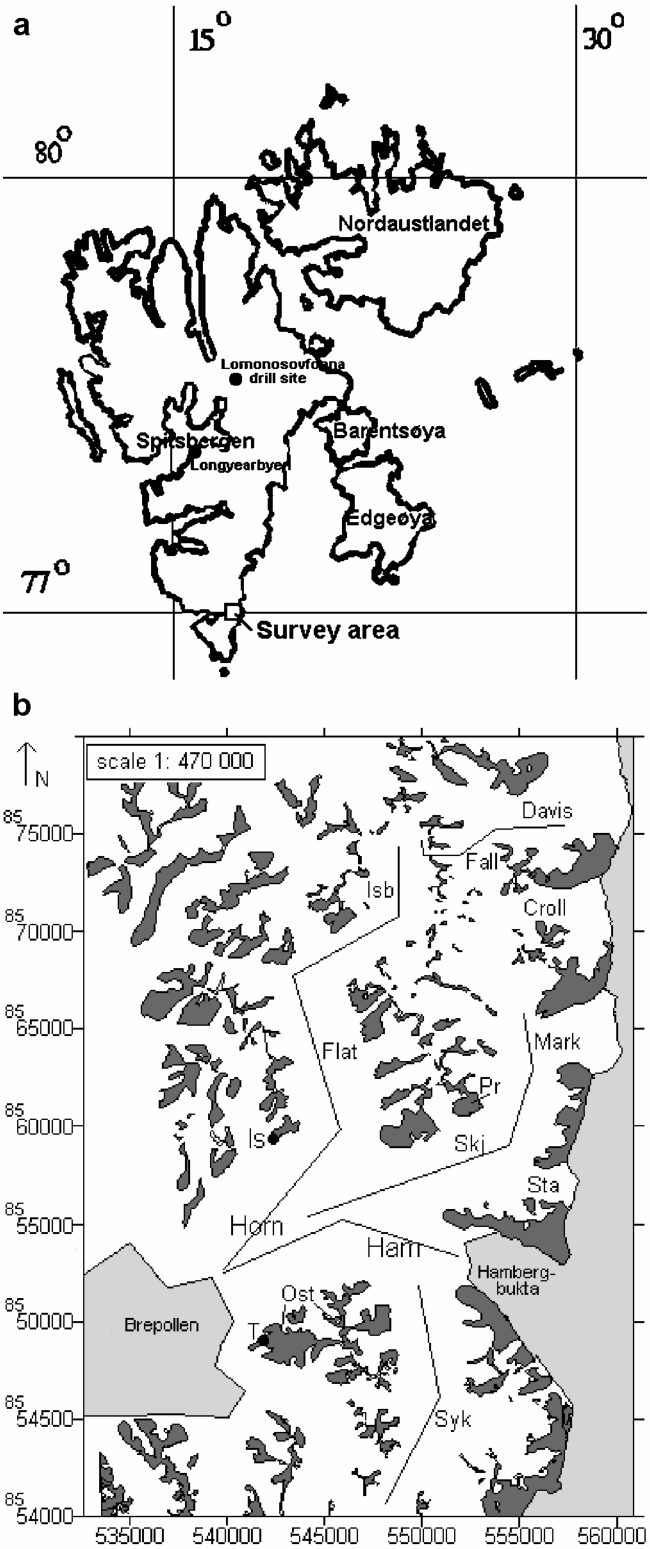

Fig. 1. (a) Location map of Svalbard with the survey area (black outlined rectangle) and the Lomonosovfonna drill site (black circle). (b) Detail with place names and surface elevation profiles for Figure 4. Horn, Hornbreen; Ham, Hambergbreen; Syk, Sykorabreen; Flat, Flatbreen; Isb, Isbroddbreen; Skj, Skjoldfonna; Sta, Staupbreen; Mark, Markhambreen; Croll, Crollbreen; Fall, Fallbergisen; Davis, Davisbreen; Ost, Ostrogradskifjella; Pr, Preikestolen. DGPS base stations at Is (Isingfjellet) and T (Tviryggen) shown by black dots.

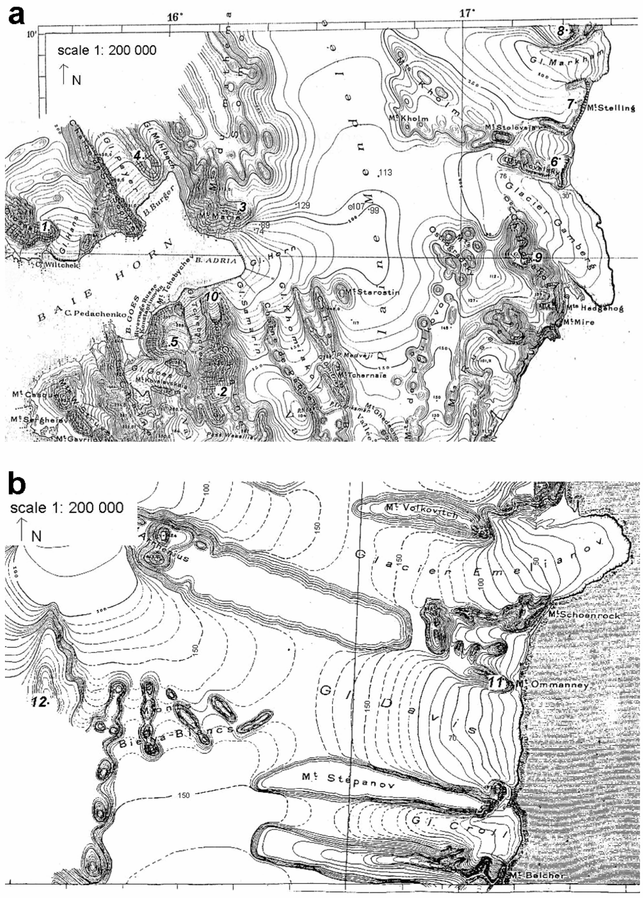

Fig. 2. (a) Mission Russe map of the southern area based on the 1899–1901 survey. The summits (see Table 1) are: 1. Fugleberget; 2. Hornsundtind; 3. Urnetoppen; 4. Lugeontoppane; 5. Tsjebysjovfjellet; 6. Kovalskifjella; 7. Stellingfjellet; 8. Stepanofjellet; 9. Kamtoppane; 10. Traunkammen. (b) Mission Russe map of the northern area. 11. Ommanneyfjellet; 12. Blåhø.

a snow scooter. The control unit together with a laptop was mounted on the snow scooter, along with a mobile GPS antenna. We used Javad differential GPS (DGPS) with base stations at Isingfjellet and Tviryggen (Fig. 1). Elevation surveys of the glacier surface over a wider area were made using two Ashtech Z receivers (the trajectories of these profiles are not marked in Figure 1).

The radar data were collected as 2048 samples in a 4.19 μs time window at 0.4 s intervals with no stacking during collection. Post-processing used the Haescan program (Roadscanners Oy). The amplitude zero-level correction was applied, background noise was removed and vertical high-pass and low-pass filtering was done. The data were of good quality, and reflections from bedrock were clear even in places with a thick, warm ice layer, where water content significantly attenuates the signal.

Digital elevation models

Bed elevation data from GPR measurements produced 30 973 measured points from the whole area. We failed to collect bed data from part of Davisbreen and all of Crollbreen, because the radar transmitter failed. The bed-elevation errors were estimated to be $\pm$5 m. Surface elevation data were collected using the DGPS record for each GPR measurement point. The surface elevation errors were estimated to be $\pm$1.5 m. Boundary data for the area were taken from the Norwegian Polar Institute (NP) map 1 : 100 000. The GPR bedrock and GPS surface datasets were linearly interpolated onto 100 × 60 grids, and boundary files were used to "blank" the interpolated data beyond the area limits.

Maps from Mission Russe and 1936 aerial photos

As a result of the Russian–Swedish expeditions in 1899–1901, several geographical maps, including one from the Hornbreen–Hambergbreen area (Fig. 2), were constructed. These large expeditions were devoted to a survey of the meridian arc length in the polar region. They used a triangulation net method and accurate astronomically fixed points along the eastern coast of Spitsbergen and the western coast of Edgeøya and Barentsøya to construct the 1 : 200 000 maps (Vasiliev, 1915). Plane errors relative to the ED50 ellipsoid used in later maps are difficult to estimate, but given the quality of surveyors, and the location of the study area in the centre of the fixed points, we estimate errors of order 10–100 m in both latitude and longitude. The elevation measurement unit used on the map is a Russian unit, the "sazhen" (similar to the English fathom), and equals approximately 2.13 m. The methods used for height measurements were mainly barometric, but also trigonometric (Vasiliev, 1915). We compare the heights of the summits from Mission Russe maps to the NP map (topographic map of Svalbard 1 : 100 000, sheet Markhambreen, 1953 and 1994) and the Silesian University map (Hornsund geomorphology 1 : 75 000, 1984) (Table 1). The height accuracy of the measured points on the Mission Russe maps is estimated to be ±25 m.

We also use data from a 1936 survey based on oblique (30 grad) stereoscopic aerial photographs (Luncke, 1949a,b). The 1 : 100 000 scale maps were constructed in 1953 (topographic map of Svalbard 1 : 100 000, sheet Markhambreen) from the aerial photos. Some of these data are also used in making the latest maps, so a different error analysis is required. The route flown followed the coast at 3500 m a.s.l., so the scale of the photos changes from 1 : 20 000 (near distance) to 1 : 120 000 (far distance). The main source of error during elaboration of stereo models is inaccurate ground-control points (GCPs). The accuracy of GCPs used for absolute orientation of the stereo model was ~5–10 m in plane and 3–5 m in height (personal communication from L. Kolondra 2002). The final accuracy is slightly worse due to observer errors. The final accuracy in height of the GCP is estimated to be ±7 m. The accuracy of the map is best at the coast closest to the line of flight, and decreases with distance from the coast. The 1936 surface data were picked by digitizing the 1953 map. The 1900 surface data were collected from Mission Russe maps by hand for profiles shown in Figure 1b. These "old" data were compared to 2000 surface data from the same location. The coordinate system of the GPS data and the 1936 data (maps constructed in 1953) was UTMN ED-50.

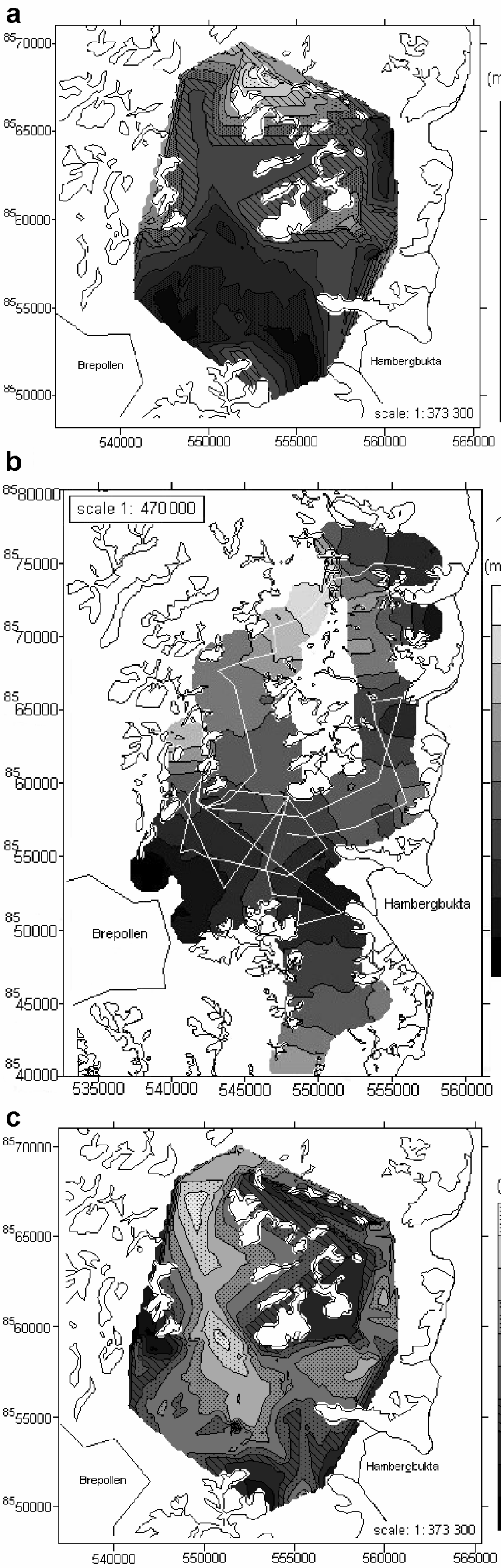

Fig. 3. (a) Subglacial topography DEM from the area. Data from Isbroddbreen, Davisbreen and Crollbreen are not included. Hornbreen–Hambergbreen bedrock is mostly <25 m a.s.l., but there is no continuous sub-sea-level channel between Torell Land and Sørkapp Land. (b) Surface DEM from the area. GPR profiles are marked in white. Hornbreen, Hambergbreen, Markhambreen and Sykorabreen (Fig. 1b) are situated below 200 m a.s.l. (c) Thickness DEM from the survey area.

RESULTS AND INTERPRETATION

DEMs

The subglacial topography DEM of Hornbreen and its surroundings is shown in Figure 3. Most of the Hornbreen and Hambergbreen bed lies at −25 to 25 m a.s.l. (Fig. 3). Beneath the lower glacier centre lines and near the snouts, both the beds are below sea level. These glacier beds connect Torell Land and Sørkapp Land and form a valley that slopes

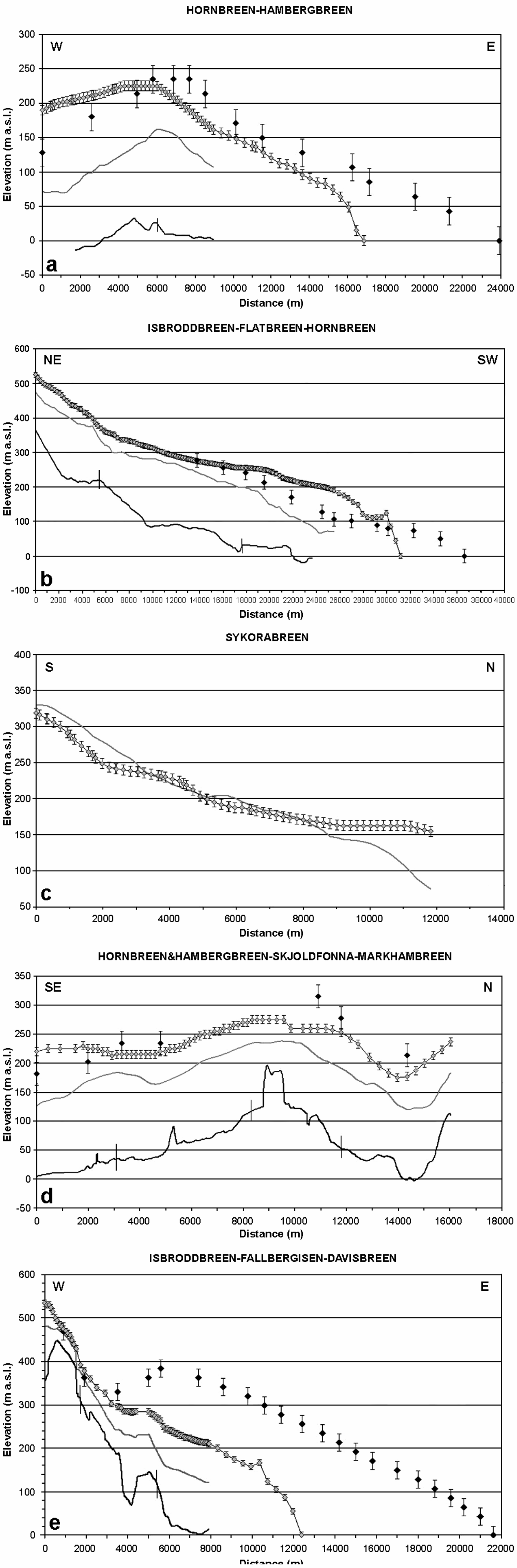

Fig. 4. Changes in surface elevation between 1900 (black squares), 1936 (grey squares) and 2000 (grey solid line). Bedrock data are marked with black solid line, with turns in the profiles (Fig. 1b) marked with vertical black lines. (a) Surface and bedrock profiles from Hornbreen to Hambergbreen. (b) Surface and bedrock profiles from Isbroddbreen to Flatbreen and Hornbreen. (c) Surface profiles from Sykorabreen, going towards Hambergbreen. (d) Surface and bedrock profiles from Hornbreen to Hambergbreen, Skjoldfonna and Markhambreen. (e) Surface and bedrock profiles from Isbroddbreen to Fallbergisen and Davisbreen.

Table 1. Summit heights from Mission Russe maps and NP map (topographic map of Svalbard 1 : 100 000, sheet Markhambreen, 1953, 1994). The summits are numbered as in Figure 2

Summit	Height in 1900 saz	Height in 1953 m	Difference m
1	262	569	−10
2	647	1431	−51
3	380	813	−3
4	337.5	695	+25
5	425	907	0
6	210.1	453	−5
7	216.1	457	+3
8	281.8	600	0
9	260	570	−16
10	176	421	−46
11	180	415	−32
12	342	740	−12

Note: 1 saz = 2.13 m.

gently towards the northern and southern edges. The results show that there is no continuous sub-sea-level channel between Torell Land and Sørkapp Land (Fig. 3).

All the glaciers surveyed, except Isbroddbreen, are situated at low altitudes: Hornbreen and Hambergbreen below 200 m a.s.l., and Flatbreen, Skjoldfonna, Markhambreen, Crollbreen and Davisbreen below 275 m a.s.l. (Fig. 3). The Hornbreen and Hambergbreen beds are below sea level in their lower parts. The Markhambreen and Davisbreen beds are at 0–25 m a.s.l. in the lowest parts accessible with GPR, and, though data from the snouts are lacking, we believe that their beds are also below sea level closer to the snout. The upper parts were mostly <100 m a.s.l., and the slope from upper to lower parts is steep. All the glaciers are thin, their thickness in general varying between 100 and 200 m, and none of them is frozen to its bed. Hornbreen was only frozen to the bed in two narrow places on the sides: a small area on the southern upper side of Hornbreen close to Ostrogradskifjella, and a small narrow area on the northern upper side of Hornbreen on the northeast side of Flatbreen's snout. A narrow area next to Preikestolen close to Markhambreen was also frozen to the bed.

Comparison with maps from Mission Russe

The topographical Mission Russe map of the area is shown in Figure 2. In Figure 4 we present individual profiles (Fig. 1b) from the area, with bedrock data and surface positions in 1900, 1936 and 2000.

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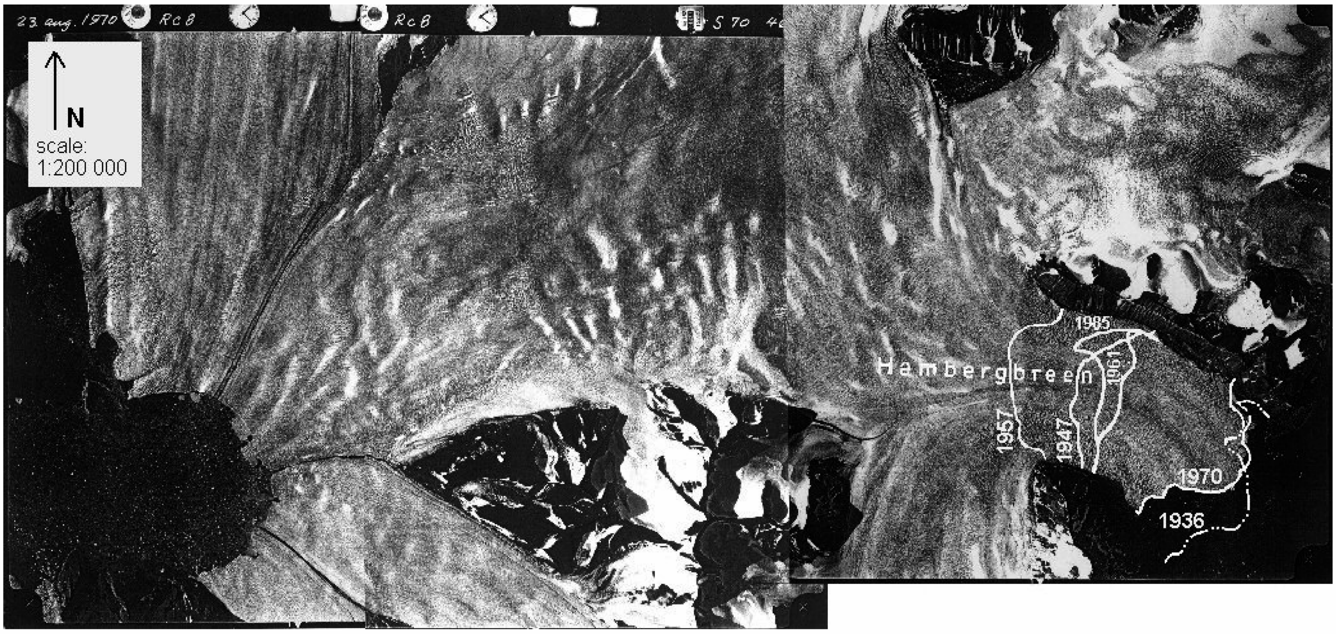

Fig. 5. Aerial photograph of Hambergbreen and Hornbreen, 23 August 1970 (courtesy of Norwegian Polar Institute, Tromsø, Norway; published by permission). The Hambergbreen front positions of 1936, 1947, 1957, 1961, 1970 and 1985 are marked with white dashed lines (after Lefauconnier and Hagen, 1991).

Figure 4a shows that, according to the maps, Hornbreen was greatest in thickness in 1936. The greatest differences in thickness between 1900, 1936 and 2000 are observed in the lower parts. In 1900 the upper part appears the same as in 1936. The upper parts have thinned 70–80 m since 1936, and the lower parts by about 110–130 m. Hambergbreen has experienced less thinning than Hornbreen. The highest position of the surface was in 1900. The thinning in 100 years has been about 80–100 m. Figure 4b shows a profile extending from the lower parts of Hornbreen to its main tributary, Flatbreen, and continuing uphill northeast to Isbroddbreen. Flatbreen has thinned very little since 1936 compared with Hornbreen. Sykorabreen, a tributary of Hambergbreen in the south, has built up mass in the upper parts but experienced thinning in the lower parts (Fig. 4c). The thinning is greatest (about 80 m) where Sykorabreen flows into Hambergbreen.

The northeast tributary of Hambergbreen and Hornbreen, Skjoldfonna, does not appear in the Mission Russe maps. Figure 4d shows that the 1900 surface was lower than the 1936 surface on Hornbreen, but higher than the 1936 surface on Hambergbreen and Markhambreen. The greatest thinning since 1936 has been in the upper parts of Hornbreen and on the northern sides of Skjoldfonna and Markhambreen (60 m), while there has been fairly constant thinning of 45 m on Hambergbreen and Markhambreen's southern side. Figure 4e shows a profile from Isbroddbreen via the lower parts of Fallbergisen to the southern side of Davisbreen. The southern side of Davisbreen had a steeper slope in 1900 than in 1936. From 1936 to 2000 the profile has remained constant, and the thickness difference is 60–80 m.

DISCUSSION

At the beginning of the 20th century, Hornbreen and Hambergbreen were large ice caps, having both accumulation and ablation areas. The Hornbreen and Hambergbreen fronts then were about 13.5 and 16 km, respectively, from their present positions. The Hornbreen front position is determined not only from Mission Russe maps but also from geomorphologic evidence. The limit of fresh basal moraine sediments in the form of hummocky moraine (created by basal crevasses filled by moraine) was mapped on the Treskelodden peninsula (Marks, 1981). The strong surge of Hambergbreen a few years before 1900 is marked by morainic deposits on the northern shore of Hambergbukta (Lefauconnier and Hagen, 1991).

Today both glaciers are situated well beneath the equilibrium line at 250–300 m a.s.l. Hornbreen is steeper than in 1936 (Fig. 4). Both glaciers are thin, and their beds in their frontal parts are below sea level. All these facts make Hornbreen and Hambergbreen very sensitive to climate change. The only building or maintaining source would be large additional mass input from the adjacent Flatbreen or Sykorabreen with surge-type behaviour.

In 100 years the total volume of Hornbreen and Hambergbreen has decreased by 37–50%. Svalbard and the Russian High Arctic have undergone warming over the last 100 years or so, associated with the end of the cold Little Ice Age, which in Scandinavia occurred around 1920 (e.g. Govorukha, 1988; Jania and Hagen, 1996). The maximum extents of Hornbreen and Hambergbreen were reached before the end of the 19th century, as a result of surging (Lefauconnier and Hagen, 1991). The enormous retreat of both glaciers may be explained by climatic warming at the end of the Little Ice Age, resulting in large mass loss by calving of the sub-sea-level glacier fronts. Dowdeswell and others (1996) reported that some low-elevation ice caps in Franz Josef Land, Russian High Arctic, may be undergoing rapid decay with little or no net accumulation even at their crests, and this is probably linked to the end of the cold Little Ice Age. The Longyearbyen temperature record shows a ~2–4°C rise between 1911 (when records began) and 1920 (Førland and others, 1997), and models of the temperature profile in the Lomonosovfonna ice core indicate that temperature has risen between the 19th century and the present by about 2.5°C (Van de Wal and others, 2002). Assuming a lapse rate of 0.44°C $(100\,\mathrm{m})^{-1}$ (Pohjola and others, 2002a), and assuming no significant change in snow accumulation at that time, as observed in the Lomonosovfonna ice core (Fig. 1; Pohjola and others, 2002b), the equilibrium-line altitude (ELA) would have been about 100 m lower in the Little Ice Age than at present.

Surges play an important role in mass loss of surge-type low-elevation glaciers. The active phase of surge transports large volumes of ice to the ablation zone where the melt rate is higher. Massive calving of tidewater glaciers (during the active phase) is another important factor in mass loss. The Brepollen embayment is 90–100 m below sea level (personal communication from J. M. Weslawski, 2002), allowing massive calving to occur. In 1936, Hornbreen's surface was 60 m higher at the snout and 30 m higher in the middle parts than in 1900. Between 1936 and 2000 the glacier thinned by 100–120 m. The additional mass input, especially to the lower parts of Hornbreen, could be the result of a surge that occurred after 1936. The enormous mass loss and retreat of the front required huge calving. Similarly, tidewater glaciers oscillate enormously in length, largely independent of climate (Paterson, 1994, p. 376), as long as they retain large accumulation areas.

The radar data show Hornbreen and Hambergbreen presently have a cold ice layer 20–30 m thick in their lower parts and 30–70 m thick in their upper parts. Temperate ice patches found in the frontal parts of Hornbreen are evidence of transport from a previously temperate accumulation area by a surge. A further indication of Hornbreen surge behaviour is the muddy piles (the first stage in formation of hummocky moraine) found on the southern side near Ostrogradskifjella. These features are known to be formed as a result of a surge with incorporation of basal moraine into basal crevasses, i.e. sediment-filled thrust features (Murray and others, 1997). However, as mass balance is negative everywhere and no additional mass input can be expected from Flatbreen (Fig. 4a and b), thinning and collapse of the glaciers is more likely than a new active surge phase. Hambergbreen experienced a major surge a few years before 1900, which affected the entire basin. Figure 5 shows Hambergbreen front positions since 1936. It seems that the Hambergbreen front retreated hugely between 1936 and 1957, but advanced between 1957 and 1970. In the period 1961–70, Hambergbreen surged again and the surge also activated Sykorabreen (Lefauconnier and Hagen, 1991).

It seems that as a result of warming and the consequent rise in ELA since the end of the Little Ice Age, and the associated shift towards consistently negative glacier mass balance in Svalbard (Hagen and Liestøl, 1990; Lefauconnier and Hagen, 1990), Hornbreen and Hambergbreen are unable to build up the reservoir-area mass and geometry for a new surge. Calculating the rate of surface lowering as a function of elevation allows simple estimates to be made of how long the thickest ice will survive if fresh ice is not supplied. In this case, Hornbreen will become ice-free in 82 ± 20 years, and Hambergbreen in 150 ± 50 years.

CONCLUSION

There has been a major change in the area and volume of Hornbreen, Hambergbreen and adjacent glaciers during the past 100 years. The Hornbreen front has retreated by 13.5 km and Hambergbreen by 16 km. The total volume of these glaciers has decreased by 37–50%. Surging of particular ice tongues, with important mass loss due to calving, drives shrinkage of the large Hornbreen–Hambergbreen glacier system. The geomorphologic evidence of basal crevasses is a result of Hornbreen surge-type behaviour. Low-altitude, flat glaciers such as Hornbreen and Hambergbreen are sensitive to climate change and would not endure without receiving surges of tributary glaciers. However, the net balance in the area seems to be mostly negative, and there is no significant mass input to Hornbreen from adjacent glaciers. Therefore, in the present climate it would require a very long time for the glacier ever to surge. An exception to glacier thinning in the area is Sykorabreen, a southern tributary glacier to Hambergbreen, where a thickness increase of about 25–30 m in the higher-elevation accumulation area was noted for the period 1936–2000. The low-lying glaciated valley filled by Hornbreen and Hambergbreen is likely to become a partially inundated ice-free isthmus in the relatively near future.

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