



Post-“Little Ice Age” retreat rates of glaciers around Billefjorden in central Spitsbergen, Svalbard

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Abstract: Twelve glaciers, representing various types, were investigated between 2000 and 2005, in a region adjacent to the northern reaches of Billefjorden, central Spitsbergen (Svalbard). On the basis of measurements taken using reference points, DGPS and GPS systems, analyses of aerial photographs and satellite images, geomorphological indicators and archival data their rates of deglaciation following the “Little Ice Age” (LIA) maximum were calculated variously on centennial, decadal and annual time scales. As most Svalbard glaciers have debris-covered snouts, a clean ice margin was measured in the absence of debris-free ice front. The retreat rates for both types of ice fronts were very similar. All studied glaciers have been retreating since the termination of the Little Ice Age at the end of 19th century. The fastest retreat rate was observed in the case of the Nordenskiöldbreen tidewater glacier (mean average linear retreat rate 35 m a^{-1}). For land-terminating glaciers the rates were in range of 5 to 15 m a^{-1} . Presumably owing to climate warming, most of the glacier retreat rates have increased several fold in recent decades. The secondary factors influencing the retreat rates have been identified as: water depth at the grounding line in the case of tidewater glaciers, surging history, altitude, shape and aspect of glacier margin, and bedrock relief. The retreat rates are similar to glaciers from other parts of Spitsbergen. Analyses of available data on glacier retreat rates in Svalbard have allowed us to distinguish four major types: very dynamic, surging tidewater glaciers with post-LIA retreat rates of between 100 and 220 m a^{-1} , other tidewater glaciers receding of a rate of 15 to 70 m a^{-1} , land terminating valley polythermal glaciers with an average retreat of 10 to 20 m a^{-1} and small, usually cold, glaciers with the retreat rates below 10 m a^{-1} .

Key words: Arctic, Svalbard, deglaciation, retreat rate, glacial geomorphology, “Little Ice Age”.

Introduction

The Arctic has experienced significant environmental changes during the last few centuries (Overpeck *et al.* 1997), many related to fluctuations of glacier mass

balances and ice front positions especially in the high Arctic area of Svalbard (Dowdeswell *et al.* 1997; Hagen *et al.* 2003a, b; Oerlemans 2005). About 60% of this archipelago is covered by glaciers, which are known to have been in retreat since the termination of the “Little Ice Age” (LIA) at the end of the 19th century (*e.g.* Hagen *et al.* 1993; Svendsen and Mangerud 1997). It is documented that both rate of glacial advance or retreat (of frontal or areal type) are key factors for terrestrial landscape evolution (*e.g.* Boulton 1972; Karczewski 1982; Bennett *et al.* 1996; Rachlewicz and Szczuciński 2000; Sletten *et al.* 2001; Lønne and Lyså 2005) and for fjord bottom relief in the case of tidewater glaciers (*e.g.* Plassen *et al.* 2004; Ottesen and Dowdeswell 2006). Glacier retreat may also have significant consequences for erosion rates (Koppes and Hallet 2006), the availability of easily transported unconsolidated sediments (Meigs *et al.* 2006), and, ultimately, changes of sediment accumulation rates in the fjords (Szczuciński 2004; Zajączkowski *et al.* 2004); in turn it also had a significant impact on the benthic communities (Włodarska-Kowalczyk and Węślawski 2001; Włodarska-Kowalczyk *et al.* 2005). Deglaciation also exerts influence on changes in water drainage pattern, plant communities succession, soil evolution, changes in coastline length (owing to recession of tidewater glaciers), local climate and others (*e.g.* Ziaja 2004; Moreau *et al.* 2005).

Implicitly, ice front position changes are excellent indicators of glacier mass balance and climate changes, and, as the glacier mass balance record is scarce for the glaciers in Svalbard (Lefauconnier and Hagen 1990; Dowdeswell *et al.* 1997; Hagen *et al.* 1993, 2003a, b) the glacier reaction to climate change might be indirectly studied by analysis of glacier geometry changes (Pälli *et al.* 2003; Hagen *et al.* 2005; Navarro *et al.* 2005), especially in respect of fluctuations in the ice front position. However, defining an ice front position is sometimes problematic. On Spitsbergen, most of the onshore snouts of glaciers are covered with debris or change into adjacent ice-cored moraines. It causes serious problems in detection of a “real” ice front position and often requires advanced geophysical techniques to trace the actual extent of the glacial ice underneath the debris cover (*e.g.* Everest and Bradwell 2003; Gibas *et al.* 2005). Certainly this problem has recently been a part of a heated scientific discussion (Ziaja 2001, 2002; Humlum 2002; Lønne and Lyså 2005; Lukas *et al.* 2005, 2006; Lønne 2007).

The present study analyzes both glaciers with clearly defined ice fronts and those with debris covered margins. In case of the latter, a “clean ice border” (*i.e.* the border of an area, which is not blanketed by a permanent debris cover) measurement was applied and tested in relation to results obtained from nearby glaciers which do have a well defined ice margin which are not mantled by debris. Although this, it is not a measurement of the true glacier retreat, it is undoubtedly equally important. Using the real ice edge covered with a thick mantle of debris does not always reveal the extent of the retreat since the LIA maximum position. Nevertheless it may be very useful providing that landscape development, plant

succession, surface albedo changes and glacier surface ablation are taken into account. Those parts of glaciers which are covered by a thick debris blanket (>1 m) are in a permafrost zone, and they are not undergoing rapid changes (*e.g.* Etzel-müller and Hagen 2005; Gibas *et al.* 2005). Hence, the debris cover above them actually develops like of the non ice-cored deglaciated areas.

The main objective of the study is to present new data on variations in glacier retreat rates with time scales of annual and decadal periodicities using quinquennial field measurements for the period 2000–2005, together with remote sensing and archive data of the 12 glaciers located in the vicinity of Petuniabukta, central Spitsbergen. Since many of the glaciers studied have debris covered snouts, thereby making the reliability of the real ice margin measurements uncertain, a reliability of the “clean ice border” was tested on similar glaciers with debris covered snouts and debris-free ice fronts. The comparison of the retreat rates here with those from other regions of Svalbard, and possible controlling factors are also discussed.

Study area

The study area is located in central Spitsbergen near Petuniabukta (Petunia Bay) in the northern part of Billefjorden (Fig. 1). The climate of the region is modified by the warm West Spitsbergen Current, which considering its northern location makes it relatively mild. The average annual temperature is about 6.5° C. The warmest months are July and August (with usual temperatures of 5–6° C, although recently above 7° C, see Rachlewicz 2003b). The precipitation is very low – about 200 mm annually (Hagen *et al.* 1993), *i.e.* half that on the western coast of the island. The period of air temperatures above 0° C normally starts in June and lasts until the end of August or mid-September (Hanssen-Bauer *et al.* 1990). The temperature record on Svalbard since the end of 19th century documents an abrupt warming up to the 1930s, and a cooler period from then, with minimum temperatures in the 1960s, followed by a continuous warming till today (Nordli *et al.* 1996). The mean annual temperature on the western Spitsbergen has increased by *c.* 4° C since the LIA. During the same period, the precipitation has increased by about 2.5% per decade (Førland and Hanssen-Bauer 2003). Førland and Hanssen-Bauer (2003) predict further increases in temperature and precipitation for this region. Recently, the record of former climate conditions has been extended backwards in time by high resolution analysis of ice cores (Isaksson *et al.* 2001, 2003), which proved the LIA to be the coldest period in the late Holocene. Apparently the LIA ended rapidly at the turn of the 19th and 20th century with an increase in the annual average temperatures by several degrees.

Twelve glaciers were selected for the analysis (Figs 1–5). These glaciers represent different sizes, thermal types and associated marginal landforms. Their pro-

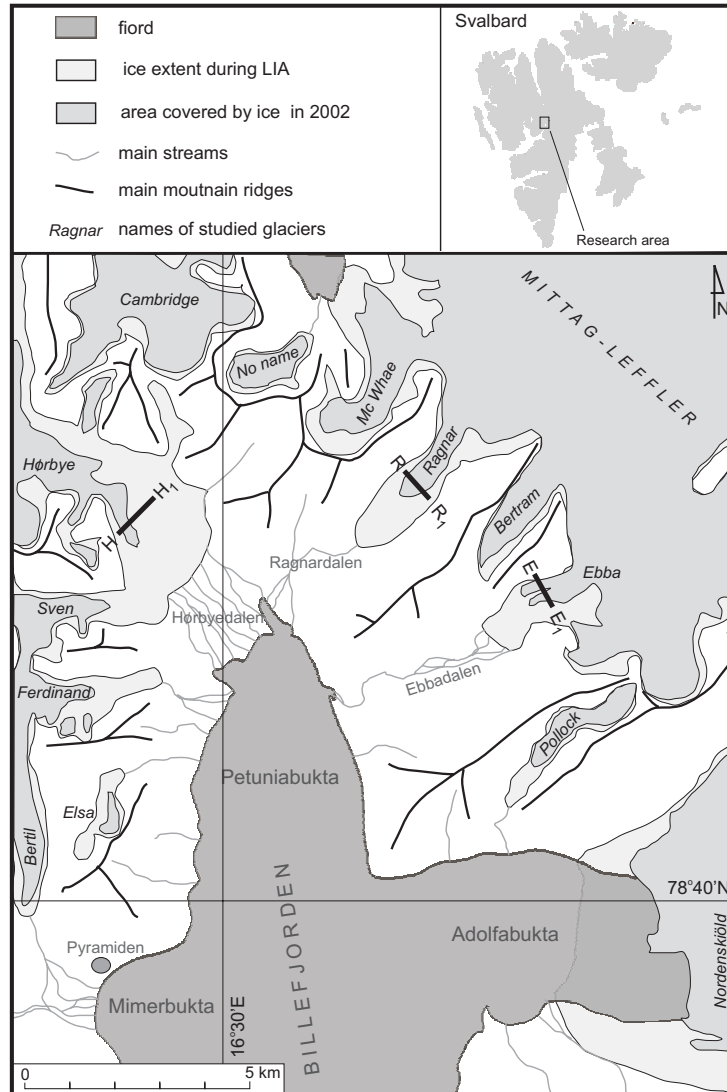


Fig. 1. The study area showing all the glaciers described in the text, including their LIA and 2002 ice front positions. Transects H-H₁, R-R₁ and E-E₁ are shown in Fig. 10.

properties are listed in Table 1. The largest investigated glacier is the only tidewater glacier in Billefjorden – Nordenskiöldbreen. Ragnarbreen and Bertrambreen represent outlet glacier type terminating on land. The remaining glaciers: Ebbabreen, Mc Whaebreen, Pollockbreen, Bertilbreen, Elsabreen, Ferdinandbreen, Svenbreen, the No name glacier and Hørbyebreen are all valley glacier types. The last mentioned is considered to have surged in former times – probably around the LIA maximum (Croot 1988; Karczewski 1989; Gibas *et al.* 2005). All these glaciers have negative mass balance and have been in retreat since the LIA (Fig. 1). Their

Table 1

Basic data on the investigated glaciers. Glacier type and code follows the glacier classification in Hagen *et al.* (1993). In this glacier code the following digits define: 1st – glacier type (4 – outlet glacier, 5 – valley glacier), 2nd – accumulation zone (1 – more than one composite firn area, 2 – composite firn area, 3 – single firn area), 3rd – ice front (0 – glacier front terminating on land, 4 – calving) and 4th – ice front dynamics (2 – slight retreat). The glacier areas and lengths are given for year 2002. The glacier thermal type is defined by the presence or absence of naled ice and/or fluted moraine, evidence of its polythermal state (based on the authors’ observations). The glacier lengths depend on the assumed centre flowline, so in some cases two values are presented.

Glacier name	Type	Glacier code	Area (km ²)	Length (km)	Elevation of ice front [m a.s.l.]	Thermal type	Flow velocity	Type of ice margin
Bertilbreen	valley glacier	5302	3.91	4.69	240	polythermal?		debris covered snout
Bertram-breen	outlet glacier	4302	3.81	5.42	430	cold?		debris covered snout
Ebbabreen	valley glacier	5202	20.4	6.2 (7.6)	110	polythermal	to 10.8 m a ⁻¹ (Rachlewicz 2004)	debris covered snout and ice front
Elsabreen	valley glacier	5302	0.36	1.16	290	cold?		debris covered snout
Ferdinandbreen	valley glacier	5202	1.60	2.56	270	polythermal?		ice front
Hørbyebreen	valley glacier	5102	13.9	6.75 (7.39)	55	polythermal	3.0-12.1 m a ⁻¹ (Rachlewicz 2004)	ice front
Mc Whaebreen	outlet glacier	5302	4.26	3.92	180	?		debris covered snout
Nordenskiöldbreen	tidewater outlet glacier	4242	242	26	0	polythermal	60-150 m a ⁻¹ (Hedfors unpublished after Isaksson <i>et al.</i> 2001 and Hagen <i>et al.</i> 2005)	ice cliff in fjord and ice front on land
Pollockbreen	valley glacier	5302	0.96	2.81	360	polythermal?		debris covered snout
Ragnarbreen	outlet glacier	4202	6.65	4.92	130	polythermal	3.8-11.1 m a ⁻¹ (Rachlewicz 2004)	marginal lake
Svenbreen	valley glacier	5302	3.42	3.63	200	polythermal		ice front
No name glacier	valley glacier	5302	1.01	1.64	275	cold?		debris covered snout

marginal zones are developed in several different ways (Figs 2–5), as: tidewater cliff, steep ice front, gentle ice front, debris cover glacier snout, ice cored moraine or marginal lake.

Materials and methods

Field measurements. — Glacier extent was surveyed in the years 2000–2003 and 2005. Three methods were applied:

- measuring of a glacier retreat by tape in relation to stakes installed in the first season (2000) in front of Ebbabreen, Ragnarbreen and Hørbyebreen. These measurements were used for the GPS results calibration. Owing to the sliding and debris flow on ice margins only a few of the stakes were preserved for longer than one year.
- mapping of all ice margins with a handy GARMIN GPS. The accuracy of this measurements reached 1.0–1.5 m. McWheabreen and the No name glacier were measured in 2000, Bertilbreen, Elsabreen, Ferdinandbreen and Pollockbreen were measured twice (in different years) and all the remaining glaciers (Nordenskiöldbreen, Ebbabreen, Bertrambreen, Ragnarbreen, Hørbyebreen and Svenbreen) at least annually and sometimes several times a year. The measurements are shown in Table 2.

Table 2

Dates of the ice margin GPS measurements

Glacier name	Dates of measurements
Bertilbreen	2001.09.05; 2002.08.12
Bertrambreen	2000.08.08; 2005.09.08
Ebbabreen	2000.07.16; 2002.08.02*; 2003.08.11*; 2005.08.22*
Elsabreen	2000.07.31; 2001.08.22; 2005.09.05
Ferdinandbreen	2000.07.31; 2005.09.05
Hørbyebreen	2000.07.14; 2002.08.30*; 2003.07.18*; 2005.08.29*
Mc Whaebreen	2000.07.25
Nordenskiöldbreen	2000.07.12; 2001.08.22
Pollockbreen	2000.07.19; 2005.09.16
Ragnarbreen	2000.07.10; 2001.07.07; 2001.09.12; 2002.08.05*; 2002.09.25*; 2005.08.14
Svenbreen	2000.07.31; 2005.09.11
No name glacier	2000.07.25

* – measured using high precision differential GPS

- detailed mapping with a differential GPS A500 by LEICA. This method was implemented to document the ice fronts of Ebbabreen (in years 2002, 2003 and 2005), Ragnarbreen and Hørbyebreen (in 2002 and 2003). For each glacier a separate permanent reference collocation was utilized. The precision obtained was 0.01–0.03 m. This tool was also used to map the glacier surface elevations of Ebbabreen, Hørbyebreen and Ragnarbreen.

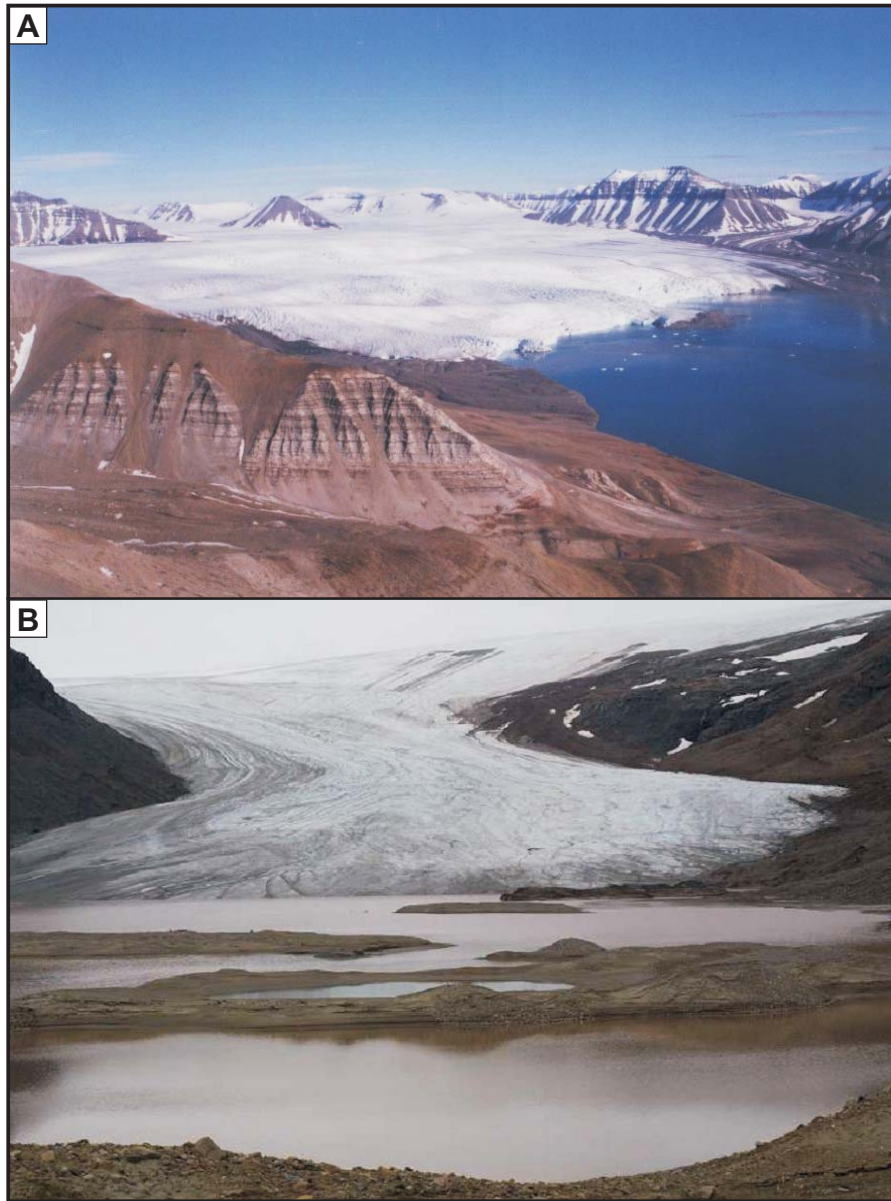


Fig. 2. Examples of the investigated glaciers marginal zones. **A.** Ice cliff of the tidewater glacier Nordenskiöldbreen. The ice cliff is approximately 3 km wide. **B.** Marginal lake in front of Ragnarbreen. The lake is 1 km long.

Where determination of the real ice edge was hindered by the existing debris cover, the “clean ice border” measurement was taken. Such a border is easily determined in field as well as recognized on cartographic material, aerial photographs or satellite images – even applying an automatic spectral analysis.

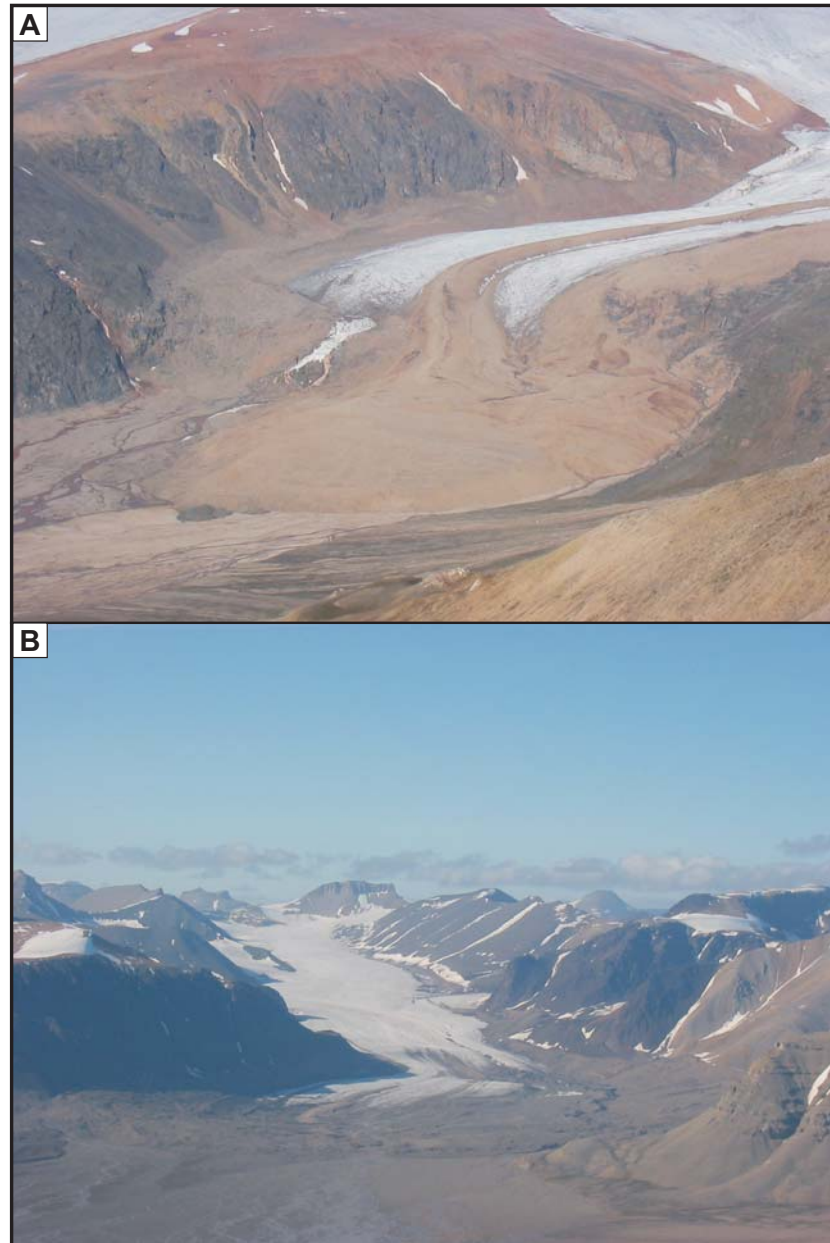


Fig. 3. Examples of the investigated glaciers marginal zones (continued). **A.** Marginal zone of Ebbabreen composed of ice cored moraine on the southern part (right) and free of debris cover ice front on the northern part (left). **B.** Hørbyebeen with its wide marginal zone.

Maps and remote sensing data. — Several kinds of data were used to carry out the analysis of former glaciers extents: topographical maps, black-and-white aerial photography, color aerial photography, Aster satellite images and older sci-



Fig. 4. Examples of ice margins of the studied glaciers. **A.** A steep ice front at southern end of the Nordenskiöldbreen ice cliff. **B.** Ice margin of Ragnarbreen with its marginal lake.

entific reports. These were integrated into one geographical information system using TNTmips software. UTM projection on WGS84 datum was chosen as the main projection of the system. The source data contained different reference sys-

tems, so re-projecting methods were used where needed. The following sources and methods were applied:

- topographical maps 1:100 000 by Norwegian Polar Institute (Norsk Polar-institutt 1978, 1984, 1988) were scanned and registered to the UTM projection using corner points and intersections grid line,
- black-and-white aerial photographs from the year 1961, (by Norwegian Polar Institute) at 1:50 000 scale were registered using ground control points (GCP) measured with GPS,
- color aerial photographs from the year 1990 (by the Norwegian Polar Institute) at 1:15 000 scale, registered using ground control points (GCP) measured with GPS,
- Aster image from the year 2002, with pixel ground resolution of about 15 m; the Aster image has internal orientation so there was no need to georeference it.

Moreover, additional data on former glacier extent and marginal zone features were obtained from the works of: De Geer (1910); Slater (1925); Feyling-Hanssen (1955); Kłysz (1985); Karczewski (1989); Kłysz *et al.* (1989); Stankowski *et al.* (1989); Karczewski *et al.* (1990) and Hagen *et al.* (1993).

From these sources the glacier front positions were interpreted and manually digitised for four time horizons:

- maximum “Little Ice Age” (LIA) – using aerial photographs and topographical maps to detect moraine ridges from which an interpretation of the former ice margin was possible. The interpretation was supported by some previous reports (De Geer 1910; Slater 1925), which also included maps and positions reported by various researchers from the beginning of the 20th century. The interpretation was confirmed by field observations;
- 1961 – outlined from black-and-white aerial photography;
- 1990 – identified on color aerial photography;
- 2002 – obtained from an Aster image, later verified by field GPS measurements.

Additionally, based on field data, changes within the period 2000–2005 were taken into account. The calculation of the glacier area changes for each of the studied periods of time was made using GIS.

Results

Decadal changes in ice front positions (LIA–1961–1990–2002). — The decadal fluctuations of the glacier coverage and the linear retreat rates are presented in Fig. 6, Table 3 and Figs 7–8, Table 4, respectively. All of the glaciers studied were in recession during this period. The associated reduction of the glacier sur-



Fig. 5. Examples of ice margins of the studied glaciers (continued). **A.** Land-terminating part of Nordenskiöldbreen with its steep ice margin. **B.** Clean ice margin on Ebbabreen.

face area from the LIA to 2002, varied from about 3000–5000 m² a⁻¹ for the smaller glaciers at higher altitudes (Pollockbreen, Elsbreen, No name glacier) to

Table 3
Reduction of glacier cover after the LIA, and for particular periods: LIA–1961, 1961–1990 and 1990–2002, as well as related average aerial retreat rates for the glaciers studied

Glacier	LIA–1961	1961–1990	1990–2002	Sum	Mean	Decrease from LIA to 2002
	m ²				m ² a ⁻¹	%
Bertilbreen	390 550	223 440	197 450	811 440	7955	17.2
Bertrambreen	317 340	129 730	100 430	547 500	5368	16.4
Ebbabreen	544 750	402 300	162 290	1 109 340	10876	5.2
Elsabreen	136 600	134 340	142 480	413 420	4053	53.5
Ferdinandbreen	685 830	465 760	99 390	1 250 980	12265	43.9
Hørbyebreen	2 694 900	1 534 100	1 109 370	5 338 370	52337	27.7
Mc Whaebreen	283 430	684 350	408 120	1 375 900	13489	30.1
Nordenskiöldbreen	9 340 600	3 915 850	231 360	13 487 810	132233	5.3
Pollockbreen	427 400	69 690	48 630	545 720	5350	36.2
Ragnarbreen	502 420	445 190	215 760	1 163 370	11406	14.9
Svenbreen	935 730	184 460	81 320	1 201 510	11780	26
No name glacier	136 250	114 140	80 300	330 690	3242	24.7

more than 132 400 m² a⁻¹ for the tidewater Nordenskiöldbreen (Table 3). Among the group of land-terminating glaciers, the largest reduction in ice cover was observed in the case of Hørbyebreen, which is suspected to have undergone a surge in the past. In regard to temporal changes in an aerial retreat rate [m² a⁻¹], seven glaciers (the No name, Bertilbreen, Bertrambreen, Elsabreen, Mc Whaebreen, Ragnarbreen and Hørbyebreen) indicated an increase in their recession during the last decade. The rate is stable in the case of Ebbabreen and lower for the other glaciers. The decrease in the aerial retreat rate is particularly severe in the case of tidewater Nordenskiöldbreen (from about 153 000 m² a⁻¹ for the period LIA to 1961 to 19 000 m² a⁻¹ in the last decade). The total reduction of the glacier cover since the LIA in the study area is about 25 km². However, with respect to the total percentage decrease of the clean ice surface (Table 3), the biggest losses are observed in the case of the smaller glaciers – Elsabreen (53.5%), Ferdinandbreen (43.9%) and Pollockbreen (36.2%). The reduction of the cover in respect of large glaciers is much smaller – about 5% in the case of Nordenskiöldbreen and Ebbabreen. The linear post-LIA mean retreat rates in respect of all glaciers ranges between 5 and 15 m a⁻¹, except in respect of Nordenskiöldbreen, where the average for the tidewater ice cliff is about 35 m a⁻¹ (Table 4). Figures 7–8 show the decadal variations of the retreat rates; this reveals a significant increase in the recent retreat rate – as much as several fold. In respect of Bertilbreen, Elsabreen, Mc Whaebreen, Hørbyebreen, Ragnarbreen, the No name glacier and a part of the Ebbabreen. In the case of the northern part of the Nordenskiöldbreen, Pollockbreen and

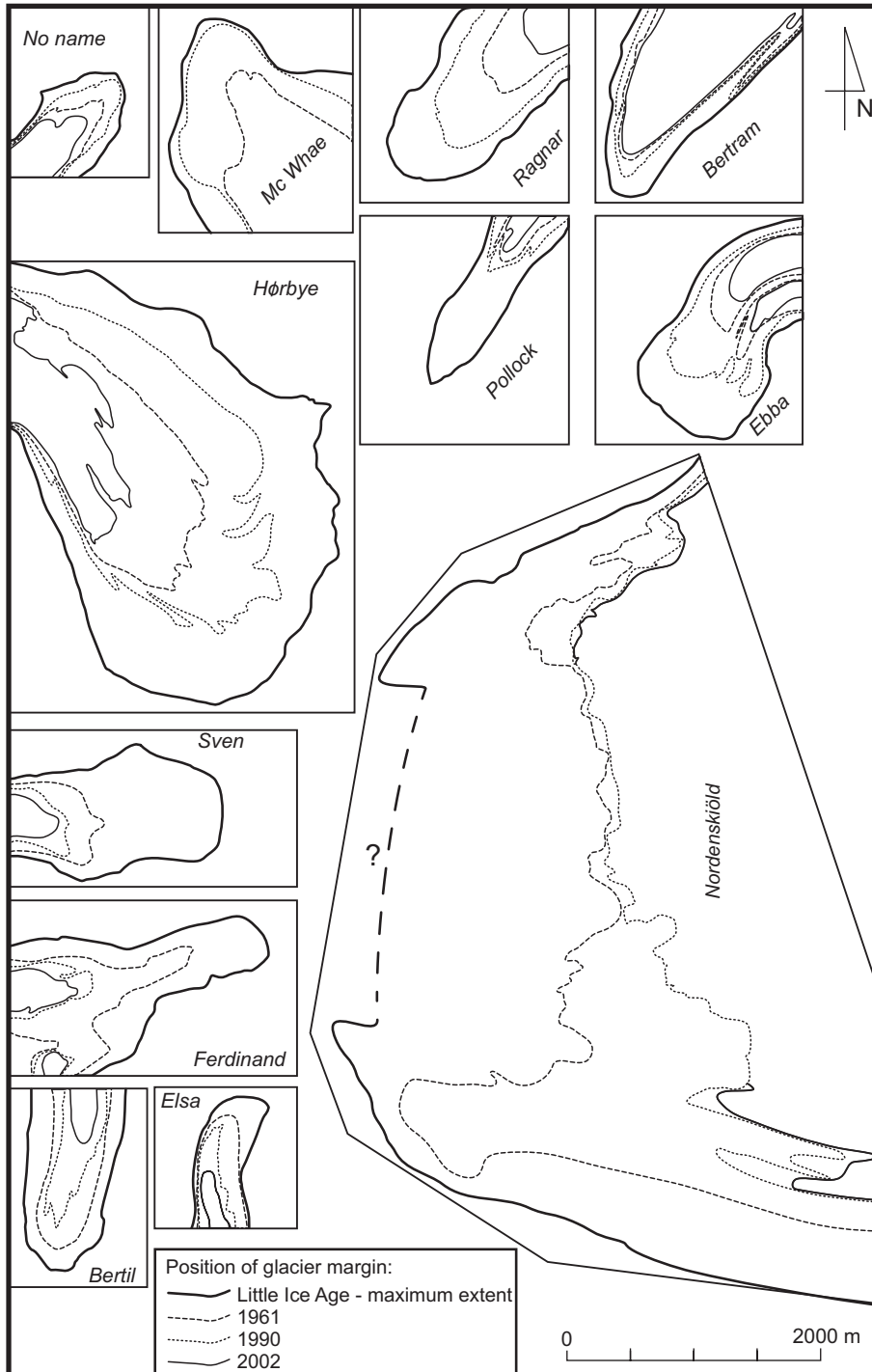


Fig. 6. Glacier ice limits subsequent to the end of the LIA (about 1900), 1961, 1990 and 2002.

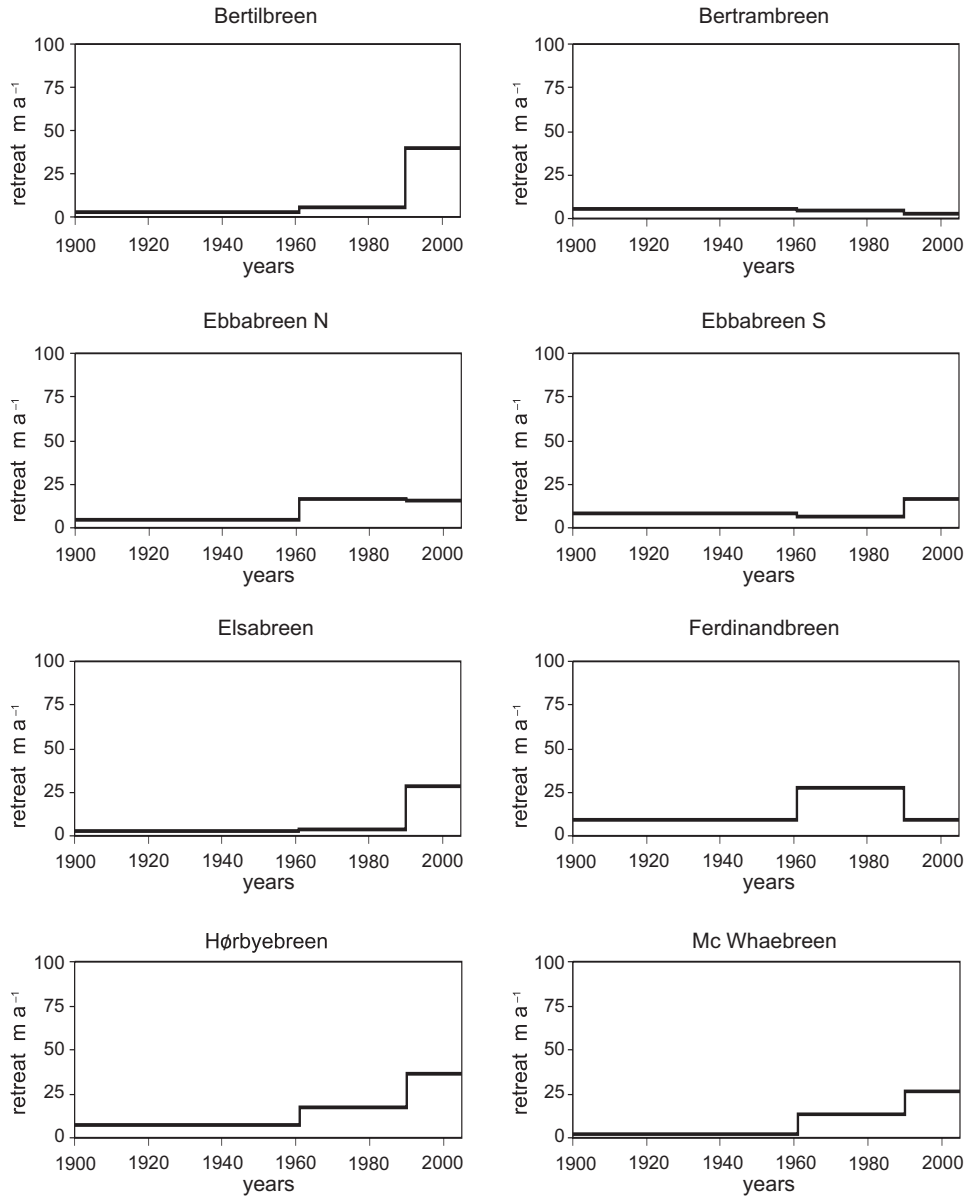


Fig. 7. Linear mean retreat rates of glaciers in Billefjorden region for following periods: 1900–1961, 1961–1990 and 1990–2002.

Svenbreen the present retreat rate is slower than in the first half of the 20th century. Between 1961 and 1990 Ferdinandbreen and the western part of Nordenskiöldbreen show maximum retreat rates whereas the southern part of Ebbabreen had the slowest. Bertrambreen has retreated at a steady rate throughout the study period.

Table 4
Distances of glacier retreat (or clean ice border retreat) and mean rates of linear retreat for the post-LIA period

Glacier	LIA–1961	1961–1990	1990–2002	Sum	Mean
	m				m a ⁻¹
Bertilbreen	161	162	599	922	9
Bertrambreen	316	136	40	492	5
Ebbabreen N	291	502	237	1 030	10
Ebbabreen S	499	199	241	939	9
Elsabreen	192	105	421	718	7
Ferdinandbreen	551	835	142	1 528	15
Hørbyebreen	460	520	545	1 525	15
Mc Whaebreen	77	388	402	867	9
Nordenskiöldbreen N	820	362	67	1 249	12
Nordenskiöldbreen W	379	2498	651	3 528	35
Pollockbreen	986	139	77	1 202	12
Ragnarbreen	471	603	394	1 468	14

Table 5
Annual and seasonal changes in glacier area and ice front position due to retreat for Hørbyebreen, Ragnarbreen and Ebbabreen glaciers

Years	Area of ice extinction	Clean-ice margin retreat
	m ²	m a ⁻¹
Hørbyebreen		
2000–2002	–	from 46 to 59
2002–2003	66 590	from 12 to 44
2003–2005	145 030	from 18 to 154
Ebbabreen		
2000–2002	–	39
2002–2003	–	19
2003–2005	7 328	from 7 to 23
Ragnarbreen		
2000.07.10–2001.07.07	12 362	From 14 to 37
2001.07.07–2001.09.12 (67 days)	10 325	From 7 to 35
2001.09.12 – 2002.08.05	9 202	From 14 to 32

Annual changes in ice front positions 2000–2005. — The annual retreat rates were studied for Hørbyebreen, Ragnarbreen and Ebbabreen glaciers (Table 5 and Fig. 9). The areal retreat of the glaciers studied for the period 2000–2005 varies from c. 3,500 m² a⁻¹ to > 70,000 m² a⁻¹. The linear rate of ice front (or clean ice bor-

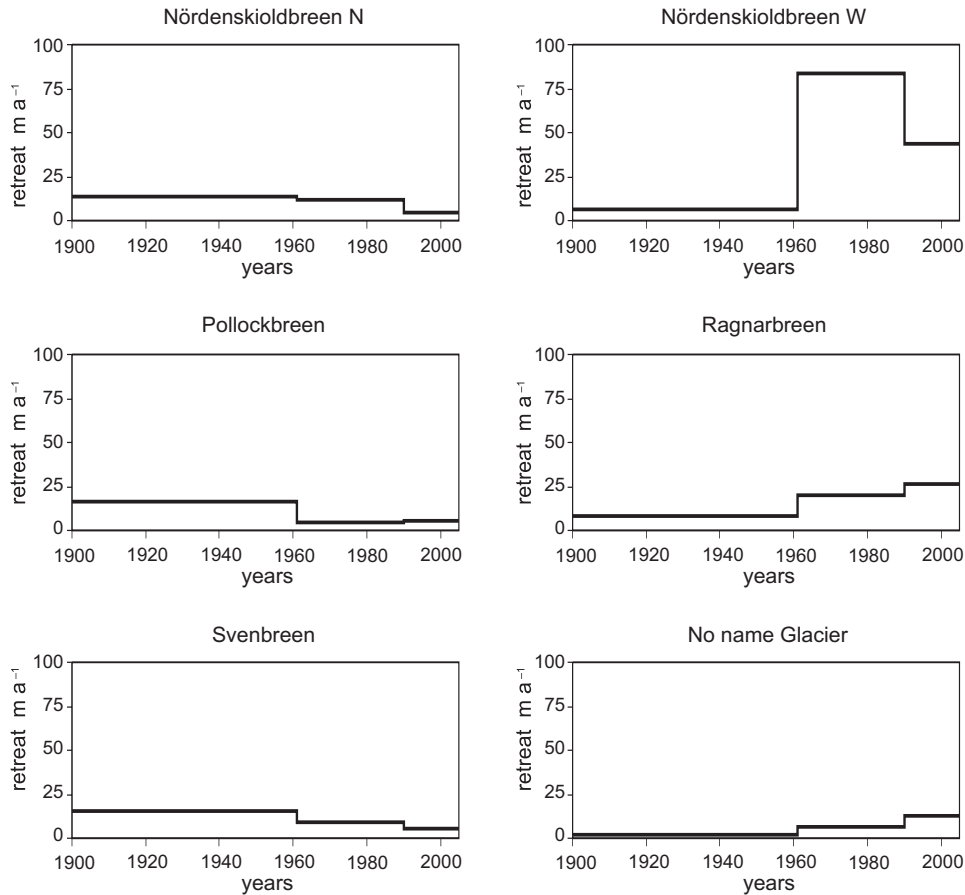


Fig. 8. Linear mean retreat rates of glaciers in Billefjorden region for following periods: 1900–1961, 1961–1990 and 1990–2002 (continued).

der) retreat is also irregular: 13 to 16 m a⁻¹ for Ebbabreen, 17 to 35 m a⁻¹ for Ragnarbreen and 15 to 51 m a⁻¹ for Hørbye-breen. These rates are slightly higher than the decadal mean values. The values of the retreat distances differ among particular years up to an order of magnitude, as exemplified by Ragnarbreen (Table 5, Fig. 9), where the retreat distance due to the ablation in July and August is virtually the same as that for the whole year.

Changes in glacier thickness. — The changes of the ice thickness of Hørbye-breen, Ragnarbreen and Ebbabreen were assessed in 2002 by detailed elevation measurements taken in relation to the contour positions on the map of 1961, with the use of a differential GPS (Fig. 10). For the investigated transects in ablation zone of the glaciers (Fig. 1), the ice surface has lowered in the last four decades by as much as 40 m, 65 m and 15 m for Hørbye-breen, Ragnarbreen and Ebbabreen respectively.

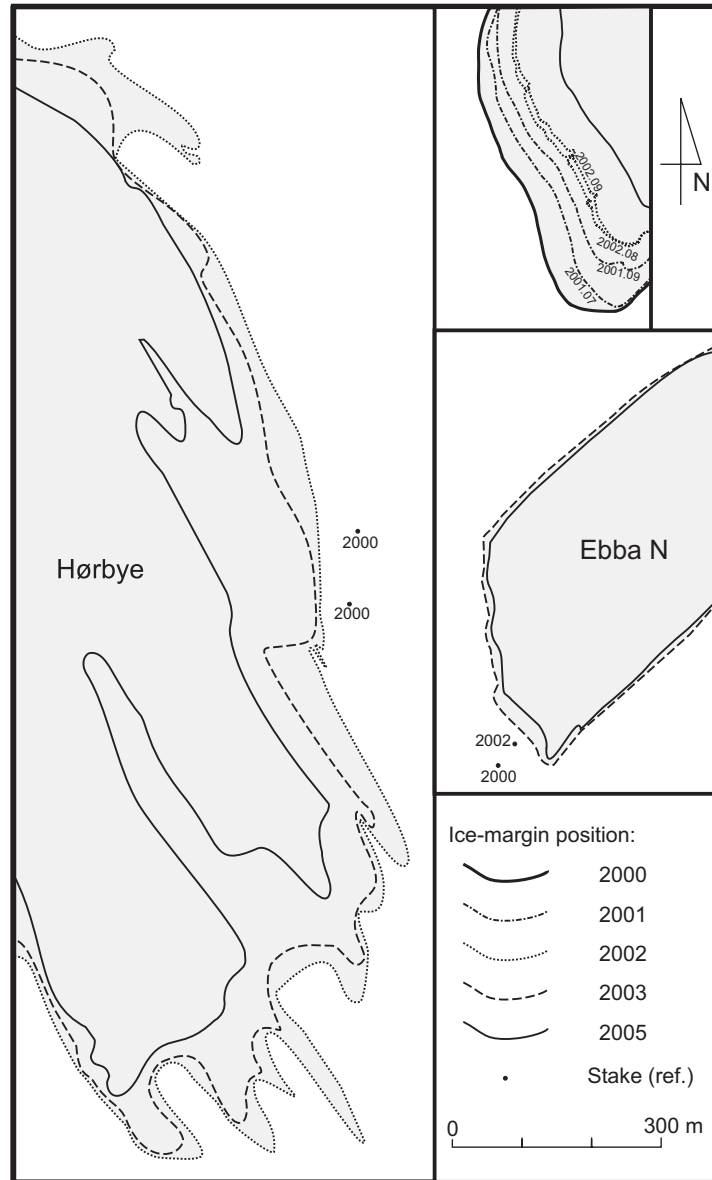


Fig. 9. Annual and seasonal changes in the glacier area and ice front position due to retreat in the case of Hørbyebreen, Ragnarbreen and Ebbabreen (for the northern part with debris free ice front).

Discussion

Comparison of real ice front and clean ice border. — For most of the land terminating glaciers in the study area, the observed retreat rates were of the same order of magnitude, regardless of the type of ice edge (whether debris covered,

marginal lake or ice front). With respect to Ebbabreen, the northern part of its margin is an ice front and the southern one is a debris-covered snout; however the post-LIA average retreat rates are very similar: 10 and 9 m a⁻¹, respectively. Notably, the real ice edge of the southern part is still covered with a thick layer of debris and seems to have lain at more or less the same position during the LIA (Gibas *et al.* 2005). This indicates that a clean ice border may be a valuable indicator of a glacier retreat, even more sensitive than a real ice edge which is covered by debris. Furthermore, the retreat rate values based on it are similar to the actual ice front retreat in the case of the debris-free ice front cover. Of course, detection of clean ice borders is relatively easy in field and on both aerial photographs and satellite images. Moreover, as already discussed, on numerous occasions a clean ice border may turn out to be a much more important marker than a true one which has a debris cover. This is obviously a useful concept in studies of landscape evolution, plant succession, surface albedo etc. but with regard of mass balance studies, such a simplification is of dubious usefulness. Changes in glacier mass thickness have to be taken into account, and in many cases are much better indicators of ice mass balance than retreat rates (*e.g.* Ziaja 2001; Pälli *et al.* 2003). Of course decrease in ice thickness also depends on presence or absence of a debris cover. For example, the clean ice surface on Ebbabreen was lowered about ten times faster than below its thick (>1m) medial moraine (Fig. 10).

Potential factors influencing retreat rates and their variations. — Glacier retreat rates result from the interaction of many factors related to climate (temperature, precipitation), the glacier itself (type, size, thickness, thermal state, mass balance, equilibrium line altitude, dynamics, debris content) and its location (elevation of its termination, subglacial morphology, aspect, water depth in case of tidewater glaciers, local climate, supply of debris from adjacent slopes) and, at present, it is not possible to evaluate the impact of each factor separately. However, some of them measurably affect variations among retreat rates in particular situations.

Climate is the main factor impacting the glacier mass balance and also, implicitly, the retreat rates. The studied glaciers are in close proximity; thus, the climate conditions are very similar for all of them. After the LIA, the mean annual temperature has risen by about 4° C, in consequence of which the glaciers have all been in retreat. However, as the highest retreat rates are seven times larger than the lowest differences must mainly relate to other factors such as glacier dynamics and their location.

The biggest fluctuations of the ice front position are observed in respect of the tidewater Nordenskiöldbreen. It is well known that tidewater glaciers are much more dynamic and react much faster to mass balance changes, fluctuations in ice flow velocity and water depth at grounding line (*e.g.* Syvitski *et al.* 1987; Jania 1988; Powell 1991; Ziaja 2001; Vieli *et al.* 2002, 2004; Koppes and Hallet 2006) than in the case of land-terminating glaciers. For Nordenskiöldbreen, a dramatic decrease in the aerial retreat rate is evident; whereas it was *c.* 153 000 m² a⁻¹ for the

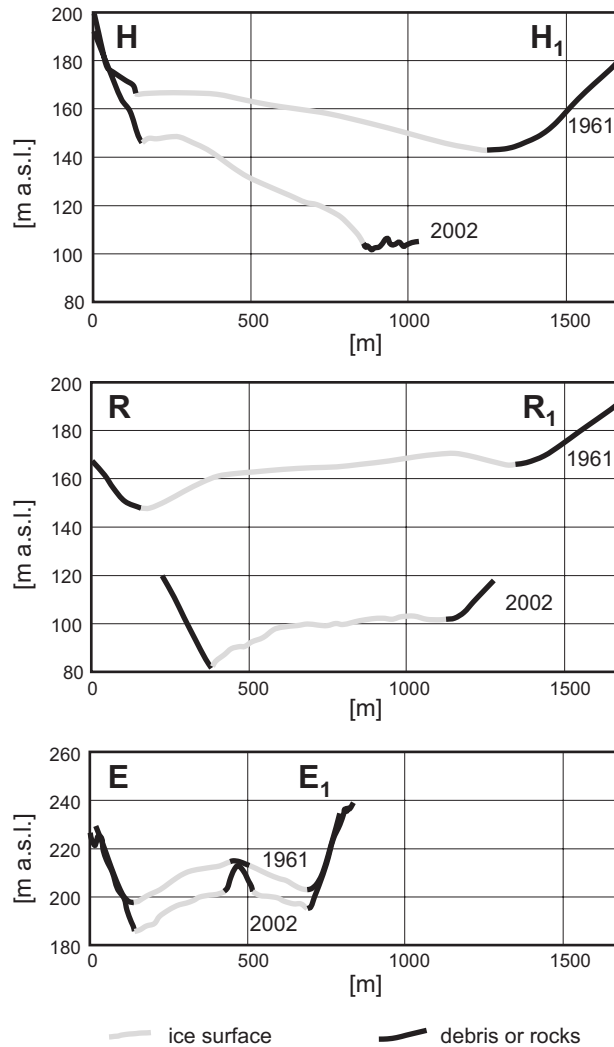


Fig. 10. Changes in ice thickness of Ebbabreen, Hørbreen and Ragnarbreen between 1961 and 2002. Locations of the transects are marked on Fig. 1.

period LIA to 1961 it has been only $19\,000\text{ m}^2\text{ a}^{-1}$ during the last decade (Table 3). This change may be explained mainly by the decrease in the sea-water depth at the ice front (from almost 100 m to < 40 m). In turn, this also directly and negatively affects the calving rate, the size of produced icebergs and finally the sedimentation rate from icebergs in Billefjorden (Szczeniński 2004). The stabilizing role of relatively shallow water in front of a tidewater ice cliff seems to be a common feature at many glaciers (*e.g.* Syvitski *et al.* 1987). Powell (1991) regarded water depth and processes at the grounding line as a “second-order” controls of tidewater glacier termini fluctuations. In particular cases, they may lead to feedback effects,

resulting in glacier responses which are significantly different from those expected only from climatic conditions.

Among the land-terminating glaciers, Hørbyebreen has retreated from an area several times bigger than that pertaining to the other glaciers. Several factors are likely to have been responsible for the exceptional behavior of this glacier: the southern aspect of the lower portion; a large part of the glacier tongue lies at a very low altitude; the ice is relatively thin at its margins and it has a relatively thin cover of supraglacial debris. However, we consider that the primary reason for the exaggerated retreat is a glacier surge, which is considered to have taken place at the beginning of the 20th century (Croot 1988; Karczewski 1989) concurrently with an advance of one of the main tributary glaciers (Rachlewicz 2003a). This formed moraines without ice cores (Gibas *et al.* 2005) and looped medial moraines. During this event glacier equilibrium was disestablished in respect that a large mass of ice was transferred to the lower altitudes of the ablation zone. After the surge, the mass flow from the accumulation zone has been much slower and probably insufficient to supplement the extensive mass of ice in the low-altitude ablation zone.

Elevation is considered to be one of the possible factors causing the fast retreat of Hørbyebreen. An analysis of the correlation between the altitude of the ice margin and its average retreat rate in the last decade (Fig. 11) appears to show a relationship between the two. However, it is obvious that other factors must be involved. For example, Bertilbreen has a high average retreat rate, although its margin is relatively elevated (240 m). Such a situation may partly be explained by the southern aspect of the glacier tongue. The lowest retreat rates are shown by the high-altitude small, probably cold-based, glaciers (Bertrambreen, Pollockbreen, the No name glacier). If the area which has been deglaciated is also taken into consideration, it is made clear that those glaciers which have wide marginal zones (Hørbyebreen, Mc Whaebreen) have been reduced faster than those with narrow zones.

A possible reason for the variations in retreat rates relative to changes in annual air temperature may be due to different, from other authors, time intervals taken for consideration in the study. For instance, in the case of Hornbreen in the Hornsund Fjord, the fastest retreat was noted in respect of years 1918–1936 (an abrupt warming occurred at that time); both before and after the retreat rates were appreciably lower (Ziaja 2001). It must be remembered that the data presented in this paper, for the whole period from the LIA till 1960 have been averaged. It is not possible therefore to identify such fluctuations. When data as are available on the temporal changes of the retreat rates are considered (Fig. 6), it is clear that the recent retreat rates have increased for most of the glaciers. This is related to current climatic warming. Where glaciers show a different trend, it is clearly because they are high elevated small glaciers as discussed above, or are controlled by other factors *e.g.*: Nordenskiöldbreen, Svenbreen and Ferdinandbreen. In the case of the last two of these, this may partly be due to their bedrock relief. Both glaciers now

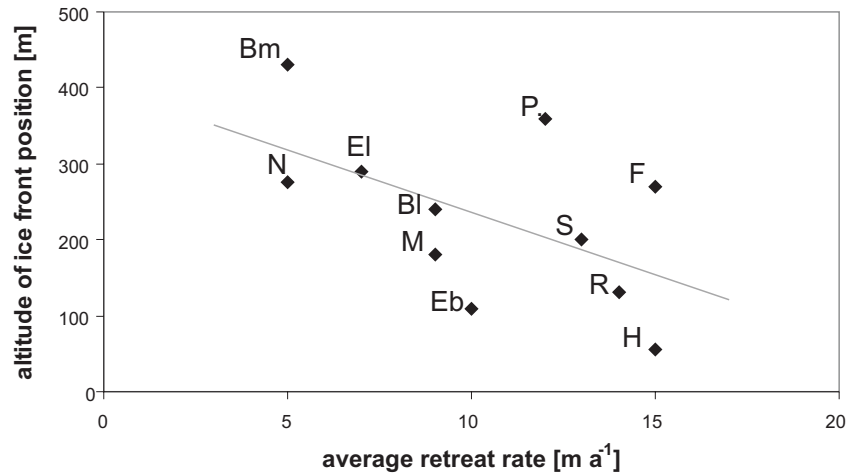


Fig. 11. Relation of average retreat rate (for the last decade) and elevation of the ice front positions (Bl – Bertil; Bm – Bertram; Eb – Ebba; El – Elsa; F – Ferdinand; H – Hørbye; M – McWhae; N – No name; P – Pollock; R – Ragnar; S – Sven; Nordenskiöldbreen not included).

terminate immediately behind rock sills, which appear to have acted as blockage to the flow. It is concluded that their recent ice mass loss is mostly related to a diminishing ice thickness. Earlier, when the ice had covered the sills and flowed past them, as documented, for example, on photography by Slater (1925), their thickness was much smaller thereby, resulting in a relatively faster retreat.

Another climatic factor for the increased retreat rate is the duration of the ablation season. As shown by annual and seasonal changes the process of ablation occur mostly in short summer season (Table 5, Fig. 9) and an extension of that period may accelerate the retreat rate. As reported by Ziaja (2004), the length of the summer season has increased since the 1950s by about 2 to 3 weeks.

There are also several other factors to be considered including:

- response time to climatic changes,
- fluctuations of equilibrium line altitude,
- changes in glacier thickness,
- proportion of winter and summer precipitation.

However, for the presented glaciers we consider that the most important factors influencing the retreat rates are:

- climate (the primary factor),
- glacier type (tidewater / land-terminating, surging / non surging),
- water depth at the grounding line of tidewater glaciers,
- the altitude of the glacier margin (a function of glacier dynamic, equilibrium line altitude, its size and others),
- shape of glacier margin,
- aspect and bedrock relief.

Comparison of retreat rates with other glaciers on Spitsbergen. — The sequence of terrestrial and aerial photographs shows that most Spitsbergen glaciers have been retreating and thinning since around 1900 (Liestøl 1988). Subsequently the retreat has been almost continuous, interrupted only by isolated surge advances. Table 6 lists some examples of the retreat rates observed for different glacier types. In general four major groups are distinguished: those large and very dynamic tidewater glaciers which enter deep waters; tidewater glaciers having slower ice velocities and ending in relatively shallow water, medium-size valley glaciers and small, usually cold-based valley or cirque glaciers.

The fastest retreat is represented by the large tidewater glacier systems (*e.g.* Kronebreen, Hambergbreen, Hornbreen), which have ice flow velocities of several meters per day; they are regarded as the most dynamic glaciers on Spitsbergen (Svendsen *et al.* 2002; Vieli *et al.* 2004). Their average post-LIA retreat rate is over 100–150 m a⁻¹, although, rates are even higher than this in shorter time spans. For example rates up to 220 m a⁻¹ were reported by Ziaja (2001) for Hornbreen in the years 1918–1936. Significantly, however, even the maximum rates are only half of those for certain Alaskan glaciers – which are apparently the most dynamic glaciers worldwide (Koppes and Hallet 2006). These glaciers belong to surge type.

Also there are tidewater glaciers with a significantly slower retreat rate – within a range 15 to 66 m a⁻¹. To this group belongs Nordenskiöldbreen, which is one of the subjects of the present study. There are several reasons for the discrepancy in the retreat rate; these include overall mass balance, ice flow velocity and water depth at ice cliff line. The latter is certainly the case in respect of Hansbreen (Hornsund, southern Spitsbergen), where the rapid glacier retreat in 1990 is attributed to the effect of the basal topography (depression) rather than a change in mass balance (Viel *et al.* 2002). In the case of certain Alaskan temperate glaciers it is known that the decreasing water depth at a grounding line of the tidewater glaciers may actually lead to stabilization of their ice fronts or even to an advance, regardless of glacier mass balance change (Powell 1991).

The next class groups the majority of the medium size land-terminating glaciers. These are polythermal and their maximum LIA position is usually marked by ice-cored moraines. Their retreat rates are between about 10 and 20 m a⁻¹, which is much slower when compared with the tidewater glaciers. The group comprises most of the glaciers detailed in this paper (Ebbabreen, Hørbye breen, Ragnar breen, Pollock breen, Mc Whaebreen, Ferdinand breen, Sven breen, Bertil breen).

These glaciers, which are located typically in the upper parts of valleys and are mostly cold-based types, have the lowest retreat rate (<10 m a⁻¹). Bertram breen, the No name glacier and Elsa breen represent this type.

Central Spitsbergen is, as postulated by Ziaja (2001), evidently more sensitive to climatic changes than other parts of the island. The region is characterised by the lowest precipitation in the region (Hagen *et al.* 1993), which results in this part of Svalbard having one of the lowest proportions of glaciated terrains, about 40%,

Table 6
Examples of glacier retreat rates for different glacier types from Spitsbergen

Glaciers	Region	Glacier type	Retreat rate [m a ⁻¹]	Period	Reference
Hambergbreen	SE Spitsbergen	tidewater glacier	160	1900–2000	Pälli <i>et al.</i> (2003)
Kronebreen	Kongsfjorden NW Spitsbergen	tidewater glacier	150	1950–2000	Svendsen <i>et al.</i> (2002)
Hornbreen	Hornsund S Spitsbergen	tidewater glacier	135 122	1900 – 2000 1900–1990	Pälli <i>et al.</i> (2003) Ziaja (2001)
Vasilievbreen	SE Spitsbergen	tidewater glacier	55	1936–1990	Ziaja (2001)
Nordenskiöldbreen	Billefjorden Central Spitsbergen	tidewater glacier	12–35	1900–2005	this paper
Blomstrandbreen	Kongsfjorden NW Spitsbergen	tidewater glacier	35	1960–2000	Svendsen <i>et al.</i> (2002)
Glaciers ending on land	Kongsfjorden NW Spitsbergen	valley glaciers	10–20	1900–2000	Svendsen <i>et al.</i> (2002)
Ebbabreen, Hørbye breen, Ragnarbreen, Pollockbreen, Mc Whaabreen, Ferdinandbreen, Svenbreen, Bertilbreen	Billefjorden Central Spitsbergen	polythermal valley and outlet glaciers	9–15	1900–2005	this paper
Aldegondabreen	Grønfjorden Central Spitsbergen	valley glacier	17	1936–1990	Navarro <i>et al.</i> (2005)
Scottbreen	Bellsund SE Spitsbergen	valley glacier	16	1936–2002	Zagórski and Bartoszewski (2004)
Waldemarbreen	NW Spitsbergen	valley glacier	10	2000–2003	Bartkowiak <i>et al.</i> (2004)
Bertrambreen, Elsabreen, No name glacier	Billefjorden Central Spitsbergen	small high altitude cold valley glaciers	5–7	1900–2002	this paper
Habergbreen	Central Spitsbergen	small high altitude valley glacier	4	1936–2001	Ziaja (2005)

compared with the average of 60% for the Svalbard Archipelago (Hagen *et al.* 1993, 2003a). Nevertheless our data shows no significant regional changes in glacier retreat rates.

Conclusions

In the case of Ebbabreen – a glacier with both not covered with debris and “clean ice border” (where real ice front is buried under thick debris mantle) types of margins the measurements of the retreat rates revealed very similar values.

Also, several similar land-terminating glaciers were observed to have very similar average rates. Thus, the sensitivity of a clean ice border seems to be of no lesser importance than in the case of the true debris-free ice front. Moreover, for many studies (landform evolution, plant succession, albedo balance, *etc.*) a clean ice border is more important than a semi-permanent debris-covered “real” ice front.

All of the glaciers studied in the vicinity of the northern reaches of Billefjorden (Bertilbreen, Bertrambreen, Ebbabreen, Elsabreen, Ferdinandbreen, Hørbyebreen, Mc Whaebreen, Nordenskiöldbreen, Pollockbreen, Ragnarbreen, Svenbreen and the No name glacier) have been retreating since the termination of the Little Ice Age at the end of 19th century. The fastest retreat rate has been observed in the case of the tidewater Nordenskiöldbreen (mean average linear retreat rate 35 m a^{-1}). With respect to the land-terminating glaciers, the rates range from 5 to 15 m a^{-1} . The total area deglaciated since the end of Little Ice Age is about 25 km^2 (both land and fjord) and the decrease in clean ice glacier area over the same period is between 5 and 53.5% for particular glaciers. Most of the glaciers are retreating at an increasing rate (up to several times in some cases) in recent decades. This presumably is due to climate warming – the primary control of the recession rate. Most of the retreat occurs during short summer season. However, several secondary factors are important for the studied cases. Tidewater glaciers retreat faster than those terminating on land. The water depth at a grounding line is an important factor for the retreat rate of the former. Deglaciation is more intensive in the case of glaciers after surge than for non-surgings glaciers. The altitude of glacier margin (a function of glacier dynamic, equilibrium line altitude and its size), the shape of glacier margin, aspect and bed-rock relief are further factors of some importance.

A comparison with the retreat rates observed in other parts of Spitsbergen reveals that the retreat rates are in ranges typical for certain glacier types and sizes, except for large fast flowing tidewater glaciers, which may retreat as much as 200 m a^{-1} , however, such type is not represented in Billefjorden region.

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