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Glacial recession 2001–2006 and its landscape effects in the Lindströmfjellet-Håbergnuten mountain ridge, Nordenskiöld Land, Spitsbergen

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Abstract: The current climate warming results in a quick recession of glaciers on the northern slopes and valleys of the Lindströmfjellet-Håbergnuten mountain ridge in Nordenskiöld Land. The equilibrium line altitude has risen from *c.* 500–550 m in 1936 to ≥750 m in 2001 and *c.* 800 m in 2006. The slopes, almost completely glaciated during the Little Ice Age, and even in 1936, have mostly been abandoned by glaciers afterwards. The upper parts of the glaciers undergo a clear retreat diminishing their accumulative (firn) fields. The lower parts of the active glacial tongues have been transformed into marginal zones built of dead ice covered with morainic and glacifluvial deposits. The surfaces of the marginal zones are progressively lowered due to ablation of dead ice. The state of the described glaciers is not balanced under the current climatic conditions. Thus, the landscape transformation of the mountain ridge will most certainly continue.

Key words: Arctic, Spitsbergen, climate warming, glacial recession, landscape transformation.

Introduction

The Lindströmfjellet-Håbergnuten mountain ridge is situated in Nordenskiöld Land which is the warmest and least glaciated region of Svalbard after Hagen *et al.* (1993). Glaciers covered 18% of the area in the map (1:100,000) sheet *Adventdalen* (Sørbel *et al.* 2001). However, at present the glaciers take up less than 10% of the area between Adventfjorden and Colesdalen in the western part of the mentioned map sheet. Even during the Little Ice Age (LIA), the glaciers were situated only on the northern (including northeastern and northwestern) slopes of the mountain ridge, 10–15 km southwest of Longyearbyen. The surface glaciation of

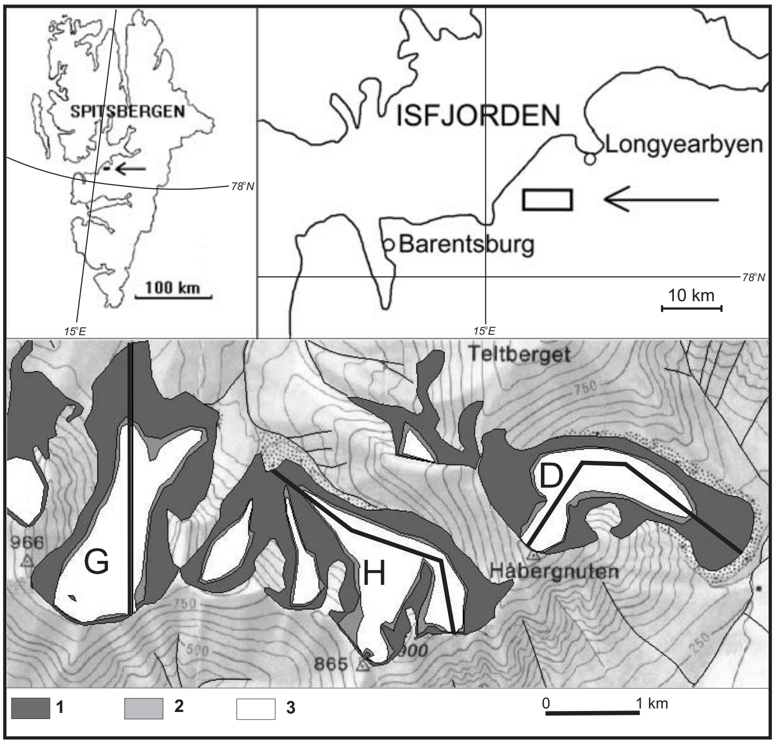

Fig. 1. Area of investigations – location, topography and glacial recession (apart from the westernmost outskirts): 1 – areas abandoned by glaciers from 1936 to 2001, 2 – areas abandoned by glaciers from 2001 to 2006, 3 – areas covered by glaciers in 2006. The glaciers: Dryadbreen (D), Grumantbreen (G), and Håbergbreen (H). Base map after Adventadalen (1981).

the ridge consists of three glaciers (Grumantbreen, Håbergbreen – at present split out in four parts, and Dryadbreen) and a few unnamed glacierets (Fig. 1).

During the LIA all the glaciers had filled out deep and well shadowed valleys. Now the glaciers cover mainly valley bottoms. The glacierets fill wide and shallow slope troughs.

Glacial recession in Spitsbergen has persisted since the end of the LIA, *i.e.* since the beginning of the 20th century, due to a progressive temperature increase (*e.g.* Brázdil 1988; Førland *et al.* 1997; Kohler *et al.* 2004; Ziaja 2004a). The glaciers mentioned above, very voluminous after a few centuries' heaving, have been very quickly and directly affected by the warming. Since the beginning, the glaciers decreased in thickness melting from their surface downward, that did not affect their deeper ice layers. At that time the retreat of the glaciers was very small, as is visible in the Norwegian topographical map at 1:100,000 scale, based on aerial photos of 1936. There were only narrow front ice-cored moraines of the glaciers though the 1930s – the warmest decade of the 20th century. The area covered by the glaciers in 1936 was only slightly smaller than that at the end of the LIA. Since then, the glacial recession has greatly accelerated that caused many changes in the landscape (Sørbel *et al.* 2001; Ziaja 2001, 2002a, b, 2004b, 2005).

The main objectives of this paper are a summary of the glacial and landscape changes in a part of Nordenskiöld Land, supplemented with new data from 2001 to 2006.

Material and methods

The topographical map 1:100,000 (Adventdalen 1981), published by Norsk Polarinstitutt, based on oblique black-and-white aerial photographs, was the source of data on glaciers' extent in 1936. Field landscape mapping of the northern slopes of the Lindströmfjellet-Håbergnuten mountain ridge (surrounding the glaciers Grumantbreen, Håbergbreen and Dryadbreen) was carried out by Ziaja at 1:25,000 scale (using the enlarged topographic map 1:100,000) in summer 1995. Special attention was paid to areas abandoned by glaciers in the 20th century. Vertical infrared aerial photographs at 1:15,000 scale from 1990 made by Norsk Polarinstitutt were helpful in the mapping. The area was reinvestigated by Ziaja in summer 2001, and by both authors in summer 2006, with special attention to changes in glaciers and in their neighbourhood in the periods 1995–2001 and 2001–2006.

Measurements of the glaciers' altitudes, widths and lengths were made in 1995, 2001 and 2006, and new elevation contour lines were drawn for 1995 and 2001. This was useful for determining the equilibrium line altitude (ELA) by the Hess method based on the inflection of the elevation contour lines on the topographic maps in both these years (Leonard and Fountain 2003). The ELA was verified by determining snow line at the end of the melting periods in 1995, 2001 and 2006. Paulin altimeter was used for measurements of altitude. GPS (*12 Garmin*) was used for measurements of altitudes in 2001 and for all measurements (altitude and geographical coordinates, *i.e.* distance and area) in 2006. The measurements by the altimeter were exact to 5 m. A combination of the two methods of altitude measurements, by the altimeter and the GPS, working in autonomous mode (not differential GPS), gave the same level of accuracy. The measured altitudes were compared and calibrated against altitudes of precisely determined topographic points. The measurements along the profile lines (Figs 1, 2) were repeated 2–3 times in 1995 and 2001 (differences between them were small, from 0 to 2–3 m), but they were not repeated in 2006. The same survey was made in marginal zones of the glaciers.

The area of the glaciers' extent in 1936 was measured on the topographical map 1:100,000. Hagen *et al.* (1993) measured the area by planimetry. Ziaja repeated the computation manually using tracing (millimetre) graph paper, and obtained values about 9% higher. The area of glaciers' extent in 2006 was measured automatically

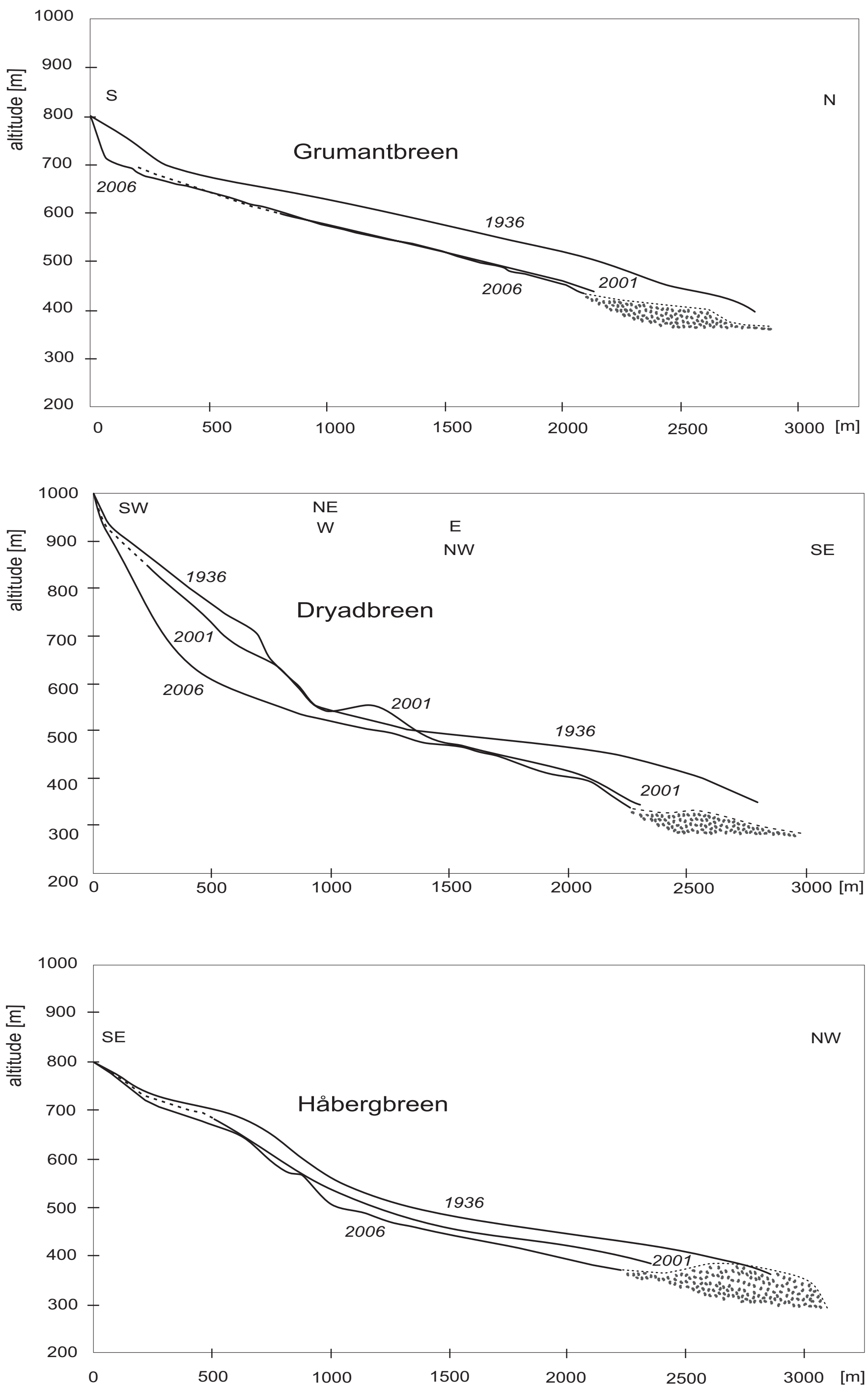

Fig. 2. Change of thickness and frontal extent of three glaciers in 1936, 2001 and 2006 (profile lines shown in Fig. 1).

by GIS (*Arc View GIS 3.3*). Because of that all the previous measurements were also remade automatically by GIS and used for the following analysis (Table 1). Their values are 3–9% higher than those obtained manually by Ziaja.

Table 1

Changes in area of the glaciers under study.

Area	Grumantbreen	Håbergbreen	Dryadbreen	Total
1936 [km^2]	3.29	3.73	2.59	9.61
2001 [km^2]	1.602	1.834	1.091	4.527
2006 [km^2]	1.358	1.554	0.914	3.826
Decrease 2001–2006 [km^2]	0.244	0.280	0.177	0.701
Decrease 2001–2006 [%]	15.2	15.3	16.2	15.5

Results

The glacial recession and the resultant landscape changes in the Lindströmfjellet-Håbergnuten mountain ridge from the beginning of the LIA to 2001 have already been reported by Ziaja (2001, 2002a, b, 2004b, 2005). An additional survey was made by both authors during summer 2006.

Fig. 3. Grumantbreen. Its ice-cored marginal zone and front in the foreground underwent only a slight lowering due to their ablation since 2001. The rocky slopes at the background were uncovered due to a significant thinning of its upper part which began between 1995 and 2001. Photo looking south (2006).

Fig. 4. The middle and upper part of Dryadbreen underwent a large decrease of thickness from 2001 to 2006. The highest (accumulative) field of the glacier is becoming smaller and smaller in connection with a progressive reduction of its lateral extent. The outstanding altitude of Håbergnuten (1031 m) is the main factor maintaining the glacier. Photo looking southwest (2006).

The area of three glaciers – Grumantbreen, Håbergbreen and Dryadbreen – decreased by 35% (or 0.6% per year on average) from 1936 to 1995, by 25% (or 4.2% per year) from 1995 to 2001 (Ziaja 2005), and by 15.5% (or 3.1% per year) from 2001 to 2006 (Table 1). Hence, the average annual rate of surface glacial recession from 1995 to 2001 was seven times higher than in the period 1936–1995 (Ziaja 2005). Afterwards, the recession somewhat slowed: the annual rate from 2001 to 2006 was only five times higher than in the period 1936–1995 (Table 1). A climate cooling could not be a reason for that because the beginning of the 21st century was not colder than the 1990s. Retreat of glaciers to more shadowed parts of slopes and valleys, could be the cause. However, their volume and thickness have been decreased as quickly as before.

Acceleration of the glaciers' retreat that began at the end of the 20th century is still going on. All three glaciers discussed are thinning out, their surface is being continuously lowered (Figs 1, 2).

Grumantbreen (Fig. 3) underwent relatively small changes from 2001 to 2006. Its thickness slightly decreased, of the order of a few m only, on most of the glacier's length, except for its highest and lowest parts. A significant thinning (down to a few dozen m) resulted in the exposure of bedrock on the slope near the eastern edge of its highest part. The lowest part of the glacier thinned by 5–10 m in 2001–2006, which resulted in reduction of the glacier's length by *c*. 40 m. The

Fig. 5. The Håbergbreen glacier's front built of clean dead ice and, in the foreground, the new intramarginal sandur in initial stage formed in the place of the intramarginal small lake which had appeared at the front a few years before 2001 and perished afterwards. Photo looking east (2006).

southwestern part of the glacier (west of the profile shown in Fig. 2, situated above the ELA at 750–800 m) is still accumulative, probably due to the largest shadowing by the Lindströmfjellet top. This shadow is much smaller on the southeastern edge of the glacier (reaching 800 m a.s.l.), which underwent a significant retreat.

Dryadbreen underwent a considerable decrease of thickness: up to 100 m in its middle and upper parts, *i.e.* above 500 m a.s.l., from 2001 to 2006 (Fig. 4). This thinning was much smaller (down to 20 m) below 500 m a.s.l. As a result, the glacier's front retreated by *c.* 40 m. The firn field of the glacier, above the ELA, became the smallest since the LIA but survived due to its position on the northern slope of the Håbergnuten top (1031 m), at an altitude above 800 m a.s.l.

Håbergbreen was transformed most intensively since 2001. The glacier, formerly split into four small parts, currently is at the advanced stage of decline. The glacier's front formed of clean dead ice retreated by 150 m from 2001 to 2006 (Fig. 5). Three of its four parts have already transformed into dead ice undergoing a continuous thawing without any evidence of down-slope movement (*e.g.* some characteristic big stones on the glacier's surface were not removed horizontally since 2001). Only the fourth and easternmost part of Håbergbreen (Fig. 6) was flowing slowly down in its highest part (above 600 m a.s.l.) from 2001 to 2006. This is evidenced by disappearance of the lower of two holes which formed in the glacier as a result of subglacial channels collapse between 1995 and 2001 (a small new hole ap-

Fig. 6. The highest easternmost part of Håbergbreen undergoes a progressive thinning and reduction of its lateral extent. There are visible the holes formed after 1995 due to a collapse of subglacial channels in the middle of the glacier and the tear which occurred after 2001 in its steepest and most narrow sequence below. Photo looking south (2006).

peared after 2001). A very small section of the easternmost part of glacier shadowed by the Håberget top from the west, and by the Håbergnuten massif from the east, could be the last part which was situated above the ELA at *c*. 770 m after 2001.

Two main types of landscape transformation predominate in areas abandoned by the discussed glaciers: (1) into mountain slopes devoid of moraine cover, in the upper parts of glacial basins, and (2) into extensive marginal zones covered mainly by dead glacial ice, up to *c*. 50 m thick, with a thin (up to *c*. 2 m) layer of moraine material, in the lower parts of glacial valleys.

Steep rock and talus slopes prevail in the areas uncovered from ice in the upper parts of all the glaciers discussed in the period 2001–2006. This type of landscape transformation predominates also in the areas uncovered from ice around the unnamed glacierets.

Marginal zones around the lower parts of glaciers are becoming more and more extensive due to the diminution of the glaciers' tongues (Fig. 7). Landscape transformation of particular parts of the marginal zones depends mainly on time duration since their releasing from glacier. Voluminous masses of dead ice continuously undergo melting. The older ice-cored moraines (formed more than 30 years ago) and all three intramarginal sandurs (formed in 1990s and afterwards) significantly lowered their surface, by 5–20 m, from 2001 to 2006, due to

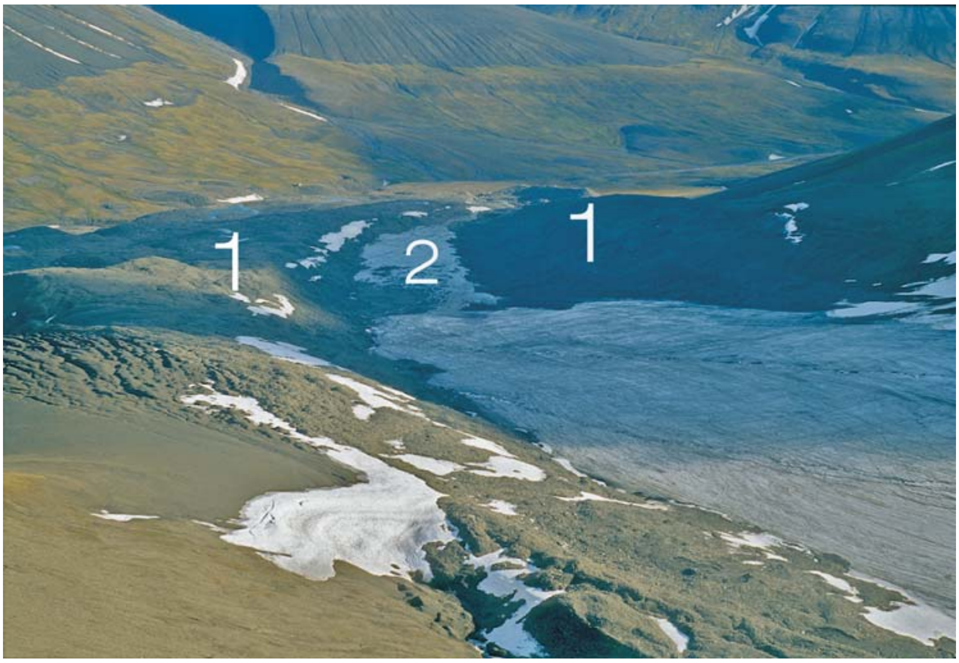

Fig. 7. The marginal zone around the lowest part of the Dryadbreen glacier undergoes progressive widening and consists of the ice-cored moraines (1) and the intramarginal sandur at the glacier's front (2). The sandur separates the glacier from its older ice-cored moraines. Photo looking southeast (2006).

the intensive melting of dead ice, especially above subglacial and inglacial channels, and in fissures. The smallest changes occurred in the Grumantbreen's marginal zone (Fig. 3), from 2001 to 2006 lowered by 5–10 m. The intramarginal sandur at the Dryadbreen's front (Fig. 7) increased in length by 40 m due to the glacier's frontal retreat. Its surface was lowered from 345 m a.s.l. in 2001 to 331 m a.s.l. in 2006. A small intramarginal lake (with water table at 390 m a.s.l., with a basin formed of dead ice) which existed at the Håbergbreen's front between 1995 and 2001, perished since then. A new intramarginal sandur began to form there (at *c*. 375 m a.s.l.).

Discussion and conclusions

The retreat of glaciers in the Lindströmfjellet-Håbergnuten mountain ridge is progressing quickly. All the glaciers undergo significant areal and voluminal reduction. This process is well known from Spitsbergen, and from the Isfjorden coasts in the warmest part of the island – in particular (Tolgensbakk *et al.* 2000; Lønne and Lyså 2005; Rachlewicz *et al.* 2007). The current climate warming, since the beginning of the 20th century, with a considerably warm period in the 1990s and

2000s, is the main factor determining the progressive rise of the ELA on all glaciers. The ELA rose from *c*. 500–550 m a.s.l. in 1936 to at least 650–700 m a.s.l. in 1995 (Ziaja 2001), to ≥750 m a.s.l. in 2001 (Ziaja 2005) and *c*. 800 m a.s.l. in 2006.

The retreat of glaciers left upper or steeper mountain slopes devoid of morainic cover, while the glacier tongues were transformed into ice-cored moraines (Ziaja 2001, 2005). Continuation of this type of glacial retreat, without transformation of not debris covered glaciers into rock glaciers, is evident in Nordenskiöld Land, southwest of Longyearbyen. This is in contrast to the opinion of Humlum (2002, 2007) that many glaciers in Nordenskiöld Land undergo, at least partial, transformation into rock glaciers or debris-covered glaciers and not into ice-cored moraines.

Marginal zones of the three valley glaciers studied consist mainly of ice-cored moraines, with a lot of kettle holes. They are detached from the glaciers by intramarginal sandurs developed on dead ice. Surfaces of these zones are being lowered by a few meters per year due to ablation of dead ice.

The state of the described glaciers is not balanced with the current climatic conditions. Thus, the landscape transformation on the northern slopes of the Lindströmfjellet-Håbergnuten mountain ridge will most certainly continue during at least the next few decades.

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