Svalbard surge dynamics derived from geometric changes

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ABSTRACT. Geometric changes on a sample of Svalbard glaciers were studied using subtraction of repeat digital terrain models to determine early surge-stage dynamics. Changes in surface features were also analyzed. A number of new surges were found for glaciers not known to have surged previously. The surge development could be followed through three stages, of which the first two had not been previously described in Svalbard. The first two stages are mainly identified from glacier thickness changes and showed little visual evidence. In stage 1, initial surface lowering was found in the upper part of the glacier, followed by a thickening further down-glacier in stage 2. Stage 3 represents the period of well-developed surge dynamics that is usually reported. Some surges ceased at stage 2 as a partial surge and never developed into a fully active surge. These partial surges could be misinterpreted as rapid response to climate change. The results of this study further support previous findings that the majority of Svalbard glaciers are of surge type.

INTRODUCTION

Glacier surges are cyclical velocity fluctuations that reflect internal changes in the glacier system rather than changing climate (Meier and Post, 1969; Raymond, 1987). Climate changes, however, can influence the recurrence interval of the surge (e.g. Hagen and others, 1993; Harrison and Post, 2003) or potentially 'switch off' the surge behaviour (Dowdeswell and others, 1995). Surge-triggering mechanisms are still incompletely understood, and several processes have been proposed including changes in the thermal or hydrological properties of the glacier (e.g. Clarke and others, 1984; Kamb and others, 1985; Murray and others, 2003b). In Svalbard, many surging glaciers have been recognized (Liestøl, 1969), although there is disagreement over the overall number of surge-type glaciers in the archipelago. According to Lefauconnier and Hagen (1991), up to 90% of Svalbard glaciers are surge-type, whereas Jiskoot and others (1998) concluded that the number is only 13%. Svalbard surges are characterized by both a long quiescent phase and surge phase with relatively low surge velocities compared to other regions with surging glaciers (Dowdeswell and others, 1991). Typically the active phase of Svalbard surges lasts for several years, with the quiescent phase lasting from 30 to more than 150 years (Hagen 1987; Dowdeswell and others, 1991; Hagen and others, 1993; Murray and others, 2003a,b; Sund and Eiken, 2004). Sometimes the quiescent phase may last as long as 500 years (Solheim, 1991). One of the common criteria for defining a surge is a cyclic occurrence. In Svalbard, however, most surge events are observed only once (Hagen and others, 1993), which can be attributed to a long recurrence interval that exceeds the historical observation period. Although some Svalbard glaciers have been studied during a developed surge stage (Hagen, 1987; Murray and others, 1998, 2003a,b; Dowdeswell and Benham, 2003; Sund, 2006), the initiation phase of surges is poorly studied due to the difficulty of recognizing a surge at an early stage. Surface crevassing in areas where no crevasses have been observed earlier can be the first indication of a surge initiation (Hagen and others, 1993). Once a surge has developed, routine spaceborne imaging and the related large data archives have greatly facilitated the search for signs of surges and the recapturing of the course of events.

In this paper, we present a number of new observations of Svalbard surge-type behaviour, based on evidence from geometric changes and complemented by observations of newly developed crevasse fields. Two criteria are used to identify a surge, either individually or in combination: (1) mass displacement from the upper to the lower glacier part; and (2) presence of new crevasse fields, which indicate rapid or strong changes in stresses. The aims of our study are to contribute to a more complementary picture and better understanding of the transition from build-up stage via initial surge dynamics to the previously described mature stage where the changes are more pronounced. We also investigate whether all surges develop fully, the implications of partial surges for interpretation of surface lowering related to varying climate conditions and finally the large spread in estimates for the number of surge-type glaciers in Svalbard.

METHODS

We have studied 50 glaciers for surge evidence in the island Spitsbergen, Svalbard (Table 1; Fig. 1). We refer to the glacier inventory by Hagen and others (1993) for more detailed information on the glaciers. Small glaciers not specifically mentioned in the inventory are listed, with information on their length and area according to the most recent maps, in Table 1.

Different sources of data were used to examine the evolution of selected glaciers during this and the last century. We examined satellite images and aerial photographs to identify the development of new crevasse fields, and visible geometric changes. The Norwegian Polar Institute's (NPI) air-photo archive, used here, consists of a collection of aerial photos since 1936. We refer to the photographs from this archive as Syy, where yy denotes the acquisition year in the last century. Maps and written sources were also examined. The geometric changes are mainly derived from comparison of digital terrain models (DTMs) from different times.

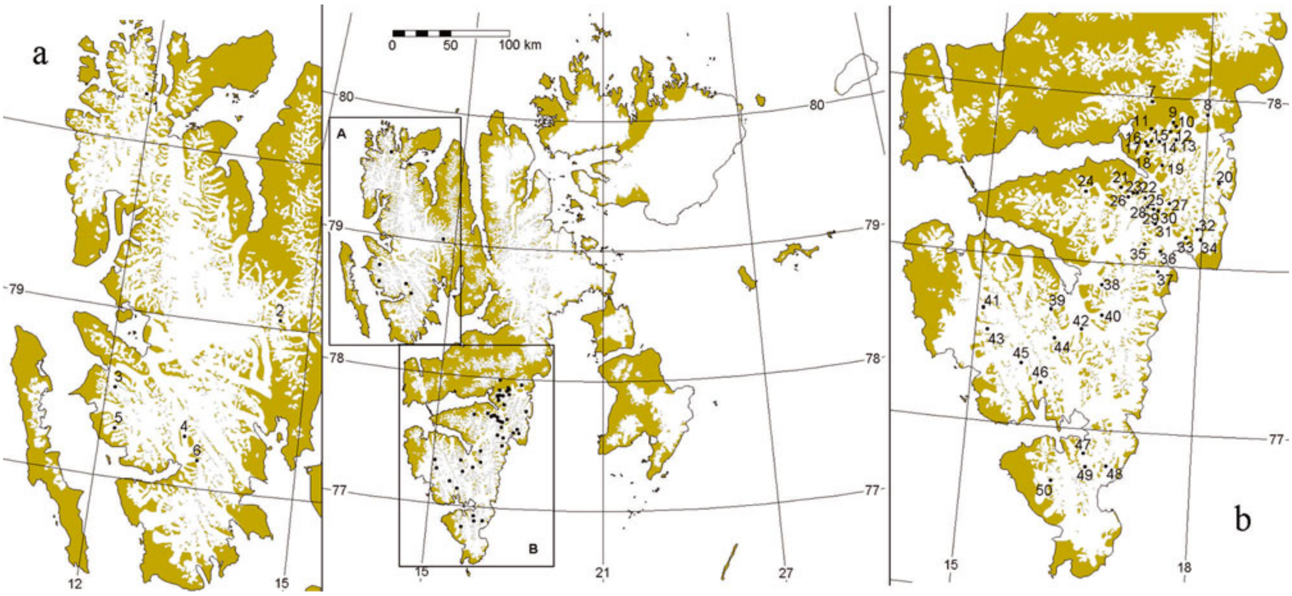

Fig 1. Locations of the glaciers: (a) the Svalbard archipelago; (b) northwest Spitsbergen; (c) south Spitsbergen. The numbers indicate the location of glaciers and glacier systems listed in Table 1.

Geometric changes

New and old maps (Kjellström, 1901; De Geer, 1919; Cöster, 1925; NPI main map series of Svalbard, 1 : 100 000) were studied to reconstruct the extent of glaciers at different times. DTM subtraction was used to derive vertical changes and infer information on glacier dynamics related to the surges. The 1936 DTM, with 100 m grid size, was generated from map contour lines based on oblique aerial photos. In the case of Kroppbreen, Perseibreen and Vindeggbreen, the 1936 photos were taken in the up-glacier direction, which makes the elevation accuracy lowest in the upper part, where it is estimated to be ~±15 m root mean square (rms). The 1990 DTM, with a grid size of 20 m, was photogrammetrically compiled by the NPI, from vertical aerial photos. The estimated vertical accuracy of the 1990 DTM is ~±2 m rms in flat areas, decreasing to ~±6 m rms on steep slopes. On Scheelebreen, there are no 1990 photos from the upper part of the glacier, and the (NPI) 1990 DTM is here based on photos from 1961. The boundary between the 1961 and 1990 elevation data is approximately in the upper third of the accumulation area. This is also the case for Ljosfonn and the upper part of Liestølbreen. The accuracy of the DTM is the same throughout, but the use of the 1961 DTM could add differences on a scale of several tens of metres, mainly towards more positive values in the case of normal accumulation in the period up to 1990.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) launched in December 1999, with scenes covering 60 km × 60 km provides new opportunities to detect surface elevation changes. With a spatial resolution of 15 m for the stereo channels, ASTER-derived elevations are not sufficient to detect fine changes in topographic details, but have been shown to clearly depict large-scale patterns of elevation changes (Kääb, 2008). A successful photogrammetric DTM extraction from optical stereo data requires sufficient optical surface contrast for matching of stereo parallaxes. ASTER data from 2000, 2001 and 2005 were not used for DTM generation due to the lack of optical contrast but were used for visual inspection. ASTER data for late summer 2003 could be used for DTM production because of particularly strong snowmelt that season. The 2003 DTM was compiled using photogrammetric methods within the PCI Geomatica Orthoengine software. The near-infrared nadir and back-looking bands 3N and 3B were used for DTM generation, and colour composites of the visible and near-infrared bands 1, 2 and 3N were used for visual interpretations. Generation and accuracy assessment of ASTER-derived DTMs are discussed in more detail by, for example, Kääb (2002) and Toutin (2002). For our ASTER-derived DTMs we estimate the vertical accuracy for an individual elevation point to be better than ±15 m rms for conditions of sufficient optical contrast in the image used, as supported by an extensive test study in eastern Svalbard (Kääb, 2008). The 2006 DTM from Store Norske used for Kroppbreen is based on airborne laser scanning except for a small area near the front, which we compiled using digital aerophotogrammetry. The accuracy of the laser-scanning DTM is better than ±1 m rms. Vertical changes between the DTMs were obtained by subtraction using Golden Software Surfer. At Kroppbreen, repeated Global Navigation Satellite Systems (GNSS) measurements were made of stakes on the glacier, using static relative measurements to a fixed point on the terminal moraine. A network of vectors has been measured and position accuracies of stakes of ~±2 cm rms have been achieved.

Crevasse identification

In order to identify visible glacier changes, several amateur photos taken from scheduled flights to and from Svalbard were examined and compared with the NPI aerial photos. Not all glaciers are covered in all years by the NPI photographs, but most are covered both by the 1936/38 and 1990 flights. For Kroppbreen, Store Norske provided aerial photos from 2006. In order to investigate possible dynamic changes as a cause of pronounced and new crevassing, elevation changes were used to confirm such

Table 1. Overview of the studied glaciers. L/T column shows whether the glacier is land- (L) and/or tidewater-terminating (T) or both. Glacier numbers (Gl. No.) refer to Figure 1, numbered from north to south and west to east. In the Evidence column, evidence from crevasses (~), elevation change (#) and moraines (M) is shown. In the Source column, A indicates ASTER images, S indicates NPI aerial photos and SN indicates Store Norske aerial photos

Glacier	L/T	Gl. No.	Location		Small glaciers		First year surge obs.	Evidence	Years of documentation	Source
			N	E	Length km	Area km^2				
Stage 1										
Liestølbreen	T	38	77°26.0′	16°40.0′			2003	~ #	1990, 2003, 2006	DTM, A, S
Scheelebreen	L/T	26	77°42.0′	16°57.0′			2003	~ #	1956, 1961, 1971, 1990, 2003–08	DTM, A, S
Vallåkrabreen*	L	16	77°52.0′	17°8.5′			2006	~ #	1977, 1990, 2003, 2006	DTM, A, S, SN
Stage 2 – ongoing										
Austjøkulen*	T	49	76°53.4′	16°37.2′			2004	~	1990, 2004	A, S
Bungebreen*	L	50	76°50.5′	16°11.0′			2004	~	1990, 2004, 2008	Photos, A, S
Elisebreen*	L	5	78°38.7′	12°13.2′			2006	~ #	1936, 1990, 2006, 2008	Photos, A, S,
Kroppbreen*	L	12	77°54.2′	17°29.0′			2000	~ #	1936, 1961, 1970, 1977, 1990, 2000–08	DTM, Photos, A, S, SN
Polakkbreen*	L/T	44	77°16.0′	16°5.0′			2003	~ #	1961, 1990, 1996, 2003, 2007–08	DTM, A, S
Ragna-Mariebreen*	L	19	77°48.0′	17°23.6′			2003	~ #	1990, 2003, 2004	DTM, Photos, A, S
Stage 2 partial surges										
Bjuvbreen	L	11	77°54.5′	17°12.5′				~	1936, 1980–2000	S, Hamilton (1992), Åsberg (2001)
Firmbreen*	L	15	77°52.2′	17°13.3′			2006	~ #	1990, 2003, 2006	Photos, A, S
Kjølhøbreen*	L	29	77°40.1′	17°18.5′			1970	~ #	1970, 1990, 2003	DTM, A, S
Knoppbreen*	L	28	77°40.4′	17°13.3′			1970	~ #	1970, 1990, 2003	DTM, A, S
Naglebreen*	L	35	77°33.8′	17°13.0′			1970	~ #	1970, 1990, 2003	DTM, A, S
Nataschabreen*	L	27	77°41.3′	17°31.8′			1970	~ #	1936, 1990, 2003	DTM, A, S
Snøkuvbreen*	L	24	77°42.5′	16°21.0′				#	1936, 1990	DTM, S
Søkkbreen*	L	31	77°37.5′	17°20.7′			1990	~	1970, 1990, 2003	A, S
Vintervegen*	L	6	78°35.0′	13°31.0′			1990	~	1990, 1995	S, Photos
Stage 3										
Comfortlessbreen	T	3	78°46.0′	12°8.0′			2006	~	1936, 1990, 2006, 2008	Photos, A, S,
Dobrowolskibreen*	L/T	40	77°20.7′	16°41.8′			2003	~	1990–95, 2003–04, 2006–07, 2008	Photos, A, S,
Ingerbreen*	L/T	20	77°45.3′	18°12.2′			2001	~ #	1990, 2000, 2001, 2003, 2005	DTM, A, S
Mendelejevbreen–Fredfonna	T	47	76°55.8′	16°35.1′			2000	~	1995, 2001–08	Photos, A, S, Polish station, Hornsund
Nathorstbreen–Ljosfonn	T	42	77°18.0′	16°26.0′			2003	~ #	1990, 2003–09	DTM, Photos, A, S
Perseibreen–Vindeggbreen	T	37	77°29.0′	17°25.0′			2000	~	1936, 1990, 2003	DTM, A, S, Dowdeswell and Benham (2003)
Polakkbreen*	T	44	77°16.0′	16°5.0′			2003	~ #	1961, 1990, 1996, 2003, 2007–09	DTM, Photos, A, S
Skilfonna*	T	48	76°53.8′	16°53.8′			2004	~	1990, 2004, 2007	Photos, A, S
Skobreen	L	25	77°42.0′	17°11.2′			2000/1990	~ #	1990, 2000, 2001, 2003, 2005–08	DTM, A, S, Sund (2006)
Zawadzkibreen	T	39	77°21.0′	16°0.0′			2003	~ #	1990, 1996, 2003, 2006–08	DTM, Photos, A, S
Small glaciers										
Brodtkorbfjellet*	L	18	77°50.0′	17°10.5′	2.5	1.6	1990	~	1990	S
Kjølhø south*	L	30	77°39.8′	17°22.7′	1.2	0.5	1990	~	1990	S
Kleivbreen*	L	14	77°52.2′	17°19.9′	1.2	1.9	2003	~	1990, 2003	A, S
Klubbebreen*	L	22	77°42.8′	17°4.1′	2.6	0.9	1990	~	1990	S
Klubbebreen S.*	L	23	77°42.8′	17°0.9′	1.1	0.9	1990	~	1990	S
Kroppbreen small glacier S.*	L	9	77°55.1′	17°33.3′	1.1	0.5	1990	~	1961, 1990	S
Kroppbreen small glacier N.*	L	10	77°55.8′	17°30.6′	1.1	0.5	1990	~	1961, 1990	S
Sergievskifjellet*	L	36	77°32.6′	17°26.4′	2.3	1.8	1990	~	1990	S
St. Olgafjellet*	L	33	77°35.3′	17°46.9′	2.1	2.2	1990	~	1990	S
Tinkarpbreen*	L	7	77°59.3′	17°11.9′	2.3	2	2000	~	1990, 2000, 2001, 2005	Photos, A, S
Vallåkrabreen (Bringen)*	L	17	77°51.4′	17°9.8′	1.1	0.9	1990	~	1990	S

Table 1. Continued

Glacier	L/T	Gl. No.	Location		Small glaciers		First year surge obs.	Evidence	Years of documentation	Source
			N	E	Length km	Area km^2				
Examples of other surges										
Andrinebreen*	L	8	77°57.5′	18°0.0′				M	1936/38, 1990	Map, S
Chaveauxbreen*	T	1	79°38.5′	11°55.0′			1990	~	1990, 2006	A, S
Edvardbreen – part of*	L	13	77°52.7′	17°34.0′				M	1956	S, evidence of 6 surges
Høgstebreen – a. Torellbreen	L	41	77°20.2′	15°5.0′			1990	~ #	1990, 2007	Photos, Jania and others (2006)
Indrebøbreen*	T	32	77°36.9′	17°55.7′				M	1936, 1990	Map
Kvalbreen*	T	34	77°35.0′	17°59.0′				M	1936, 1990	Map
Luntebreen	L	21	77°43.6′	16°50.0′			1961	~	1956, 1961, 1990, 2003	Photos, A, S
Mühlbacherbreen*	T	46	77°7.8′	15°56.5′			1961	~	1961, 1990, 2006, 2007	Photos, A, S
Nornebreen–Paierlbreen	T	45	77°11.0′	15°40.0′			1990	~	1990, 1996–2002	S, Jania and others (2006)
Profilbreen–a. Torellbreen*	L/T	43	77°16.5′	15°10.0′			2007	~	1990, 2007	Photos, S
S. Osbornebreen*	T	4	78°39.0′	13°17.0′			1990	~	1990, 1995, 2007–08	Photos, S
Størmerbreen*	L	2	79°1.6′	14°31.8′			1990	~ M	1990, 2000	A, S

*Glacier not previously explicitly mentioned in surge context.

behaviour. Even medium-resolution spaceborne images such as from ASTER can be used to identify crevasse fields from the early stage of a surge, in particular when pronounced snowmelt makes crevasses better visible at the surface. The medium spatial resolution of ASTER, up to 15 m, limits the identification of small crevasses. On snow cover, only wide crevasses could be distinguished due to poor optical contrast. Narrower crevasses could, nevertheless, be identified as linear features when they were much longer than the spatial image resolution. On several of the glaciers, the first observed occurrence of new crevasses was in 2003, probably reflecting very low snow cover in that year. However, the fact that many newly observed crevasses also appear in areas that were below the snowline on the 1990 aerial photos suggests that snow cover alone was not the only reason behind observation of new crevasses.

RESULTS

We concentrate mainly on the more recent surges, although other surges are also mentioned to describe both the dynamic and spatial range of the surge behaviour in Svalbard. Based on our observations, we have defined three stages of surge development, described in turn below. The transition between the stages is not abrupt, however, and the magnitude of the elevation changes and crevassing during the different stages will vary substantially between individual glaciers, and will depend on, for example, bed and surface topography and ice thickness. Crevassing can start as early as stage 1 but may not form extensively until stage 3. In addition, the measurement techniques used influence the degree of elevation changes to be detected, and thus the separation between stages 1 and 2. Note that stages 1 and 2 *do not* correspond to previously defined surge phases (e.g. Dolgushin and Osipova, 1975; Murray and others, 2003b), which describe different phases within the later surge stage (our stage 3).

Stage 1

Stage 1 is the earliest phase where a surge development could be detected when the glacier changes from build-up to surge. It is characterized by an initial surface lowering in a section of the reservoir area and increased ice velocities in this area. This stage was also often found to be associated with the first signs of transversal and marginal crevassing. One example of this stage was found on Zawadzkibreen (Fig. 2). When analyzing the elevation change between 1990 and 2003, a lowering of up to 40 m in the upper accumulation area basins was found. Yet, a corresponding increase in ice thickness at lower glacier parts was not found at this stage. This is presumably because the displaced mass has been dispersed over a larger area as the ice flows out of the smaller basin so that elevation changes could not be detected within the resolution and accuracy of the ASTER DTM. On the 2003 ASTER images, the first development of increased crevassing in the upper accumulation zone was found to extend down-glacier to the confluence with the tributary glaciers. By June 2007 the glacier had reached stage 2. Marginal crevasses extending past the tributary basins and further down-glacier were observed and a slight bulge appeared at the border between activated and non-activated glacier sections at the terminus. Other examples for stage 1 are Liestølbreen, Ljosfonn (Fig. 2), Scheelebreen (Fig. 3) and Vallåkrabreen (Fig. 4b).

Stage 2

In contrast to stage 1, stage 2 is defined here as a larger mass displacement with surface lowering in major parts of the reservoir area and a measurable mass displacement down-glacier towards the receiving area. The separation is arbitrary in that it depends on the measurement accuracy available, but is meant to describe and classify measurements. However, our separation would not drastically change with, for instance, much more precise methods such as laser scanning, because the vertical accuracy of ASTER-derived DTMs of in the order of 15 m might also

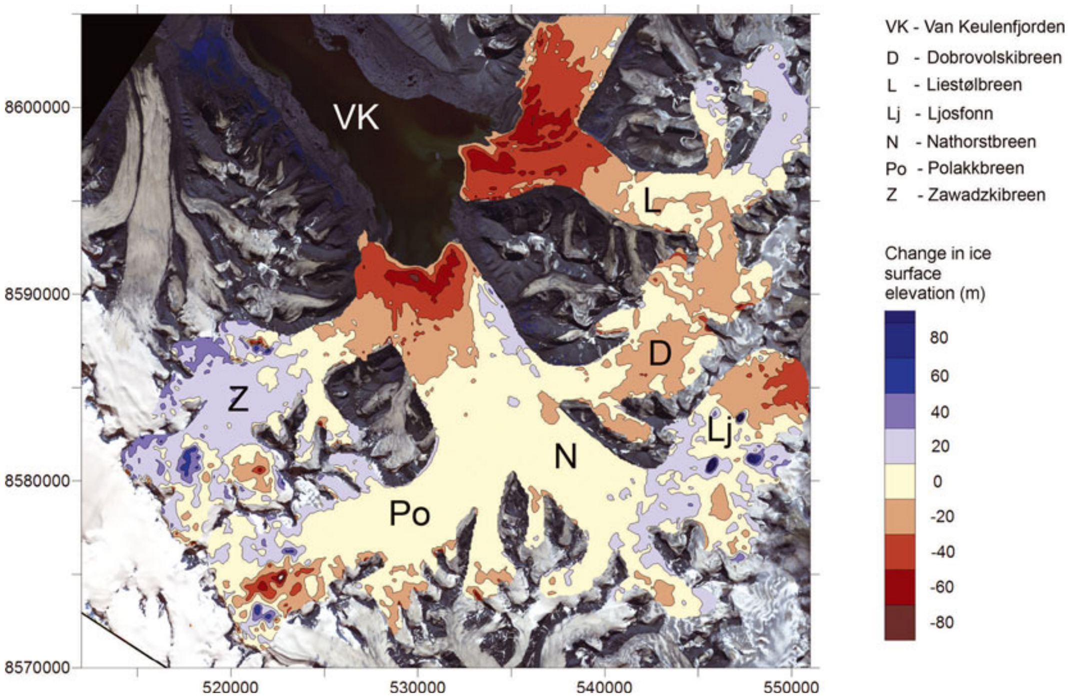

Fig. 2. Van Keulenfjorden. Elevation changes from 1990–2003 DTMs, based on a grid of 30 m, superimposed on an ASTER scene of 2003. For the upper part of Liestølbreen, Nathorstbreen–Ljosfonn (in surge stage 1), the 1990 DTM is partly combined with a 1961 DTM. Zawadzkibreen is in stage 1 and Dobrowolskibreen and Polakkbreen are in stage 2.

roughly be seen as a possible threshold between glacier thickness changes due to surge-type activity and those not related to surge-type activities. More pronounced crevasse fields, often marginal, may also occur in addition to an unusually undulating surface. However, the velocity or stresses have not increased enough to disintegrate the majority of the glacier surfaces. Generally, for both stages 1 and 2, it is noteworthy that large mass displacements can take place and still result in limited fracturing of the surface, indicating that the process is still relatively slow.

There are individual differences from glacier to glacier, possibly caused by the various geometries of the glaciers.

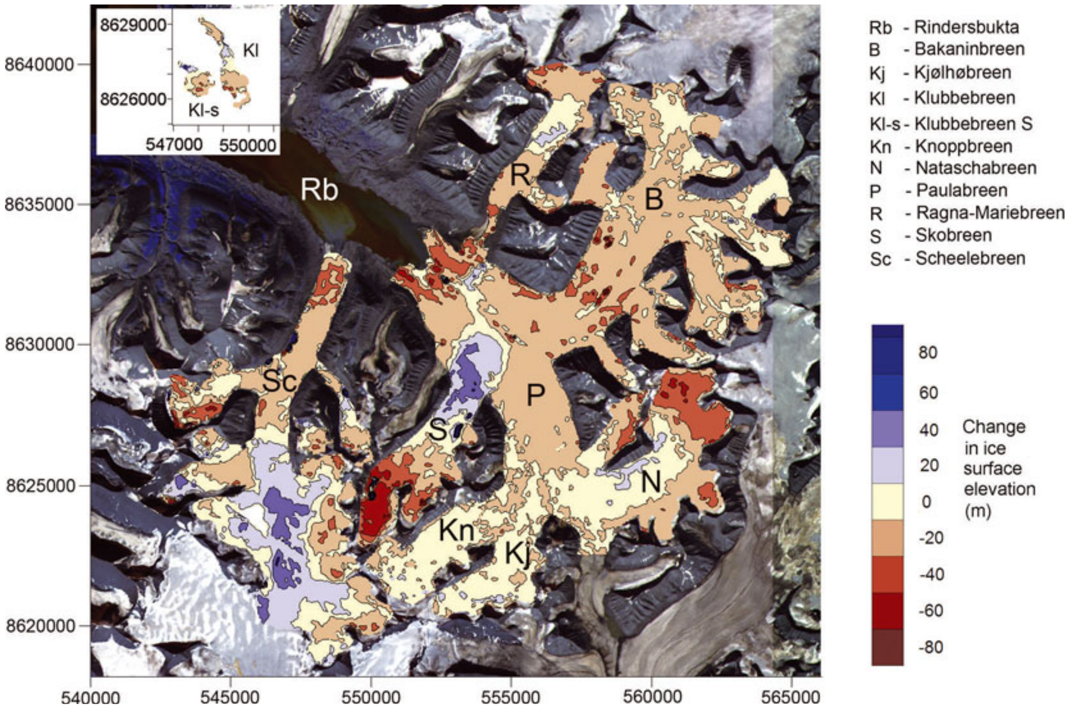

Fig. 3. Rindersbukta. Elevation changes from 1990–2003 DTMs, based on grid of 30 m, superimposed on ASTER 2003 scene. The 1990 DTM is partly combined with a 1961 DTM in the upper part of Scheelebreen, which is in stage 1 (Luntebreen is the lowered northwestern basin). Ragna-Mariebreen and Nataschabreen are in stage 2, Skobreen is in stage 3 and Bakaninbreen, Knoppbreen and Kjølhøbreen are post-surge. Insets show two small glaciers (Nos 30 and 31 in Table 1) which surged recently.

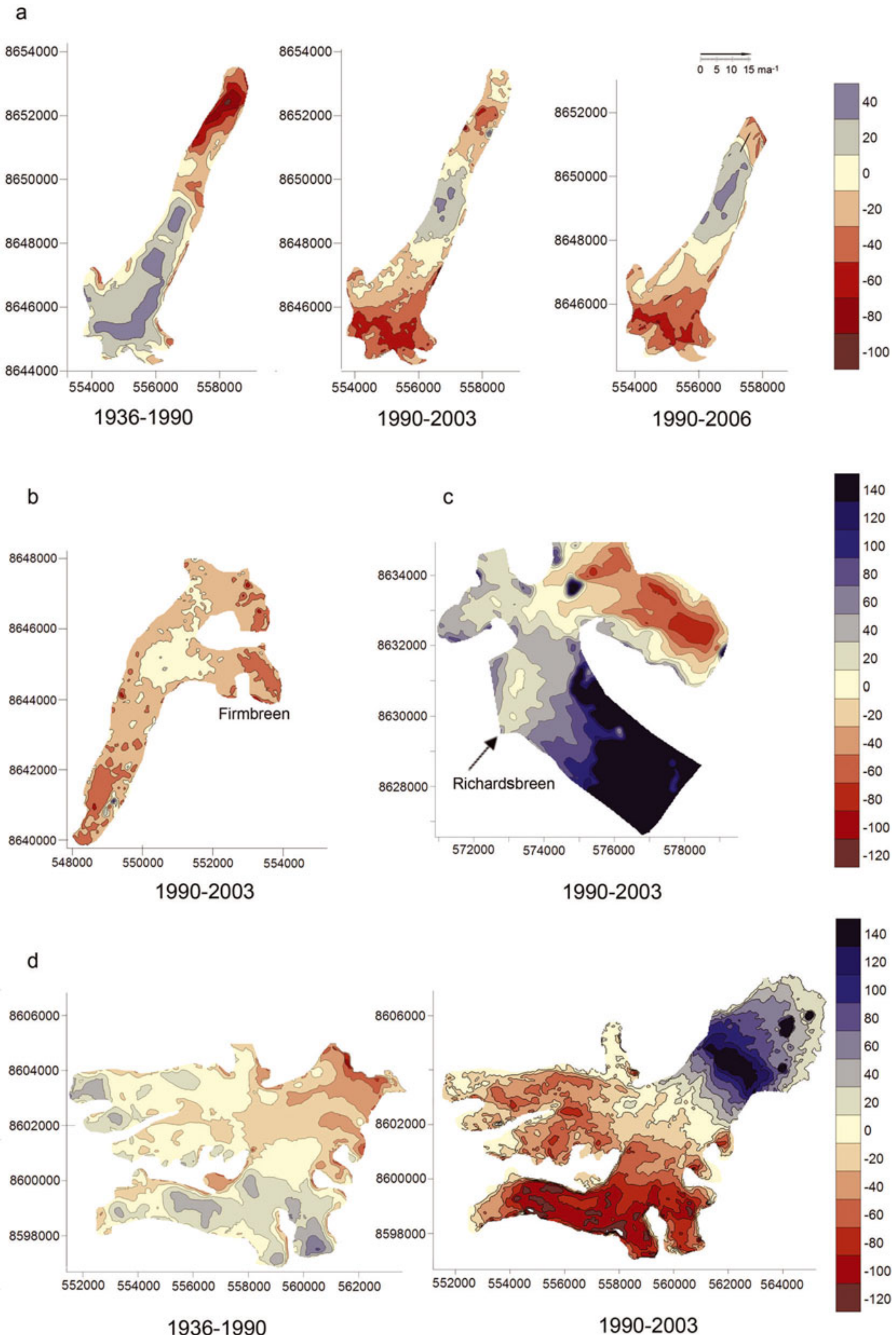

Fig. 4. (a) Kroppbreen, flowing northeastwards. DTM subtractions, based on grid of 30 m; during build-up (1936–90), stage 2 surge (1990–2003) and progress of stage 2 surge (1990–2006). (b) Vallåkrabreen and Firmbreen flowing southwestwards. Subtracted 1990–2003 DTMs, based on grid of 30 m. Vallåkrabreen, with a slight decrease in the upper part (stage 1) and a stage 2 surge of Firmbreen. (c) Ingerbreen, flow turning 180° from northwest to southeast. Subtracted 1990–2003 DTMs, based on grid of 30 m. The lower part of the glaciers is covered by clouds on the 2003 DTM, and the elevation changes here are not reliable (black colour). (d) Perseibreen and Vindeggbreen flowing northeastwards. DTM subtractions, based on grid of 30 m; during build-up and possible partial surge (1936–90) of the northern basin and surge stage 3 (1990–2003).

On Kroppbreen a comparison of the surface profile calculated from the 1936 and 1990 maps (Fig. 4a) showed a build-up of up to 40 m in the upper part while the lower half of the glacier experienced thinning, resulting in a steeper profile. The lower area of the glacier has also become narrower due to melting during this time. The first changes were observed on a 2000 ASTER scene together with wide crevasses and some sort of surface collapse in the upper part. This crevassing is the most spectacular we have found at this stage. The other glaciers at this stage displayed crevasses of a smaller magnitude, if any. The 2001 ASTER scene over Kroppbreen showed smaller lateral crevasses along the eastern margin constrained to the upper basin. The first indication of surge behaviour from elevation changes we observed for this glacier was for the period 1990–2003 (Fig. 4a). The glacier experienced a surface lowering of up to 60 m in the accumulation area, while the elevation increased by up to 40 m in the centre. In the 2005 ASTER scene, the crevasses were found further down-glacier. Fresh cracks that penetrated through the snow layer and snow-covered crevasses superimposed on the older large ones were seen on the high-resolution aerial photos from late August 2006. During this period, three generations of crevasses with different directions were found. A section of the lower part has also thickened as a result of mass displacement. The formation of marginal ice ridges points to flow resistance due to less developed sliding conditions and lateral friction compared to the lowered centre zone. The elevation changes between 1990 and 2006 (Fig. 4a) displayed a progression of stage 2 where the changes since 2003 were small in the wider upper part while the area of ice thickening enlarged and propagated further down-glacier with a slight increase in ice thickness and a more pronounced bulge as a frontal steepening of the thickening zone. Velocity measurements in 2007 showed that at this stage the velocities were highest (13.8 m a^{-1}) at ~290 m a.s.l. close to the top of the bulge which was now below the previously estimated equilibrium-line altitude (ELA) of 360 m a.s.l. (Hagen and others, 1993), while velocities in the upper, vertically lowering part of the glacier at ~490 m a.s.l. were less than half of this (5.4 m a^{-1}) (Fig. 4a). At this stage, the glacier still did not appear as surging in terms of previous descriptions (i.e. intense crevassing, moraine loops, advance). Other examples of glaciers in stage 2 of a surge are listed in Table 1.

Stage 3

At stage 3 almost the entire glacier experiences a pronounced acceleration. At the beginning of this stage, transversal crevasses may be limited in extent, but later widespread crevassing and large chasms often can be seen together with an advance of the terminus. However, not all glaciers in this stage advance. The appearance of this stage is well known from previous surge studies in Svalbard (e.g. Liestøl, 1969; Hagen, 1987; Murray and others, 1998; Dowdeswell and Benham, 2003; Sund, 2006). Ingerbreen, for example, has a terminal confluence with Richardsbreen (Fig. 4c). On the 2001 ASTER scene, there were slight changes on the glacier surface compared to the S90 photographs, indicating that the surge had already reached the front. Two larger depressions were found diagonally from southwest to northeast in the upper part and also some crevassed bumps at the terminus, indicating some degree of mass displacement and activation. These are similar to the features we have interpreted from Perseibreen in 2000 (Dowdeswell and Benham, 2003) and on the 2001 ASTER image. In 2003 the surface of Ingerbreen had totally changed its appearance and was heavily crevassed all over. Figure 4c shows the DTM subtraction between 1990 and 2003. Figure 4d shows the changes of Perseibreen and Vindeggbreen during build-up (1936–90), with a lowering of about 20 m in the upper part indicating an initial stage 1, and during full surge (1990–2003). On Skobreen, which is known to have developed to a stage 3 surge (Sund, 2006; Benn and others, 2009), extensive marginal and increased transverse crevassing was seen from 2000 on. The 1990–2003 DTM comparison (Fig. 3) shows a lowering of about 60 m at the head of the glacier and a thickening of about 40 m in the lower part of Skobreen, which by 2003 had reached stage 3. The surface rise had by then propagated beyond the moraine separating Skobreen from Paulabreen and started to affect the lower part of the latter. Note that the surge was still not detected by ground observations until 2 years later. The upper part of Paulabreen was not affected (Sund, 2006). Other examples of this stage are listed in Table 1. It is also interesting to note that the bulge from the Bakaninbreen surge (Dowdeswell and others, 1991; Murray and others, 1998) proceeded ~200 m down-glacier (Fig. 3) during the period 1990–2003, which is consistent with other evidence for slow termination of Svalbard surges (Murray and others, 2003b). Some other glaciers have recently attained stage 3: Comfortlessbreen is currently advancing into tidewater at Engelskbukta (Table 1). On Zawadzkibreen, all but a small part of the terminus was surging by September 2008. By February 2009 the terminus had advanced 2–3 km together with the termini of Nathorstbreen–Ljosfonn and Polakkbreen (Table 1).

Partial and ‘invisible’ surges

We term surges that do not develop beyond stage 2 ‘partial surges’ and discriminate them from surges in stage 3 as described above. A partial surge must not be confused with a mini-surge (Kamb and Engelhardt, 1987), which occurs at a much shorter timescale. A closer examination of aerial photos, maps and DTMs revealed dynamic changes in many glaciers that have not previously become apparent, as stage 2 can show limited changes in surface structures. The related elevation changes are not necessarily observed other than through DTM subtractions. Figure 3 shows very little change over the entire Knoppbreen and Kjølhøbreen basins. The NPI aerial photo archive revealed that in 1970 these basins were heavily crevassed and had marginal shear zones, indicating that a substantial mass displacement occurred, as the glaciers were not crevassed prior to this year and are uncrevassed at present. On the basis of the observed crevassing, we classify the 1970 dynamics in these basins as close to a stage 3 surge. The surge did not propagate more than halfway down Paulabreen. Figure 3 also shows a ~20 m high aggregation of ice along the northwestern margin of Nataschabreen. Lowering of about 40 m was found in the reservoir area. The curved medial moraine between this glacier and Kjølhøbreen also indicates that a larger mass displacement took place at Nataschabreen prior to the surges of Knoppbreen and Kjølhøbreen in 1970 (all are upper basins of Paulabreen; Fig. 3). A partial surge was also found on Firmbreen (Fig. 4b; Table 1).

Some apparent partial surges can occur in connection with other surges in the catchment. For example, around 1985 Osbornebreen surged (Rolstad and others, 1997). The next basin is unnamed and here is called S. Osbornebreen. This basin was not immediately affected, but the S90 photographs of the area shows that the lower part of S. Osbornebreen was also activated at the confluence with Osbornebreen and Vintervegen. However, very few crevasses were seen in the upper part of the glacier at this stage.

On the S95 photographs, the whole of S. Osbornebreen was covered by transverse crevasses, indicating increased velocities or stresses, although they are far lower in magnitude than found on Osbornebreen.

The almost synchronized surge of the Perseibreen–Vindeggbreen system shows how a slight delay in one basin may obscure the historical evidence of a surge. DTM comparison between 1936 and 1990 suggested that the Vindeggbreen basin probably underwent a partial surge prior to the recent surge, while there was a considerable build-up in the upper half of Perseibreen. Nevertheless, the medial moraine was folded into Perseibreen after the surge, indicating that Vindeggbreen was the last active basin during the major surge stage. This suggests that there was a reciprocal action between the basins in the initiation phase, where possibly Vindeggbreen started to flow more rapidly, causing a lowering of the basin, then Perseibreen followed and Vindeggbreen then had a final speed-up at stage 3. The last phase was described by Dowdeswell and Benham (2003). When the crevasse healing is finished, apparently only a surge of Vindeggbreen will be apparent from the looped moraine. Another example was found from the NPI 1936 map Kvalvågen C11, where it appears from the moraine morphology that first Indrebøbreen and then Kvalbreen surged into Strongbreen. Today the tidewater front has melted far back into the bay and no looped moraines are visible on the surface. The medial moraine between the two glaciers appears straight, giving no visual indication of a surge. This implies the possibility that several tidewater glacier complexes have experienced unrecorded surges.

DISCUSSION

Surge stages

Our results show that the initiation of surges can develop with little surface evidence until the surge has reached stage 3 and its peak acceleration as described by Murray and others (2003b). Substantial changes are found in the upper part of the studied glaciers before the stage 3 surge characteristics become clearly visible, as exemplified for Zawadzkibreen. Stages 1 and 2 have not previously been reported on Svalbard glaciers, probably because initial surge-related crevasses are covered by snow and are thus not visible when assessing the glacier in situ during winter or on coarse-resolution satellite images such as from the 30 m resolution Landsat Thematic Mapper. The stage 1 and 2 surge velocities and stresses have usually not yet reached values large enough to cause widespread crevassing. Stages 1 and 2 are characterized by elevation changes and possibly a corresponding initial onset of limited acceleration in parts of the glacier. On Kroppbreen, however, large crevasses found in the upper part indicate that substantial acceleration had already occurred during stage 1 or 2 and then slowed down to a more moderate development. Currently the velocities are higher in the lower, thickening part. The measured velocities of Kroppbreen show that velocity measurements at stages 1 and 2 are more useful for determining longitudinal comparison within the studied glacier than for comparison with other glaciers, as the velocities are not yet extraordinarily high. Thus, when long-term time series are not available, a short-term measurement alone will not be sufficient to detect dynamic changes unless the elevation change is also addressed. The longitudinal measurement of surge velocities showed an irregular velocity distribution, with higher velocities below the ELA. By investigating the surges at an earlier stage, it may be possible to find out more about the triggering mechanisms. This also implies that the initiation and acceleration towards a fully developed surge (stage 3) may be even longer-lasting than previously found (e.g. Hagen, 1987; Dowdeswell and others, 1991; Murray and others, 2003b).

In the first two stages, surge activity is implied by the observed elevation change, but down-glacier-propagating bulges may not be detected. Stage 3, the stage with the highest velocities, starts once the surge activity affects the entire glacier or large parts of it. The first two stages characterized here also have implications for the conclusions drawn by some previous studies that interpreted the surges of Svalbard tidewater glaciers as being initiated in the lower part (e.g. Rolstad and others, 1997; Dowdeswell and Benham, 2003; Murray and others, 2003a,b). In Svalbard all tidewater glaciers are grounded (Hagen and others, 2003). In view of our results, we argue that the glaciers in the previous studies had, by the time investigated, already reached their late surge stage 2 or early stage 3, so that the surges appeared to be initiated in the lower part. This is supported by the results of Dowdeswell and Benham (2003) who stated that rapid advance was present between June 2000 and May 2001, but that the glaciers started to advance between 1990 and 2000. The importance of timing of a study was also demonstrated by Sund and Eiken (2004) who showed that the Hessbreen surge was initiated in the upper-central part, while Liestøl (1976), due to a late observation, suggested a triggering in the lower part and also a subsequent initiation. Furthermore, if the assumption of different initiation areas for tidewater and land-based glaciers (Murray and others, 2003b) is correct, it must imply that glaciers that used to be tidewater glaciers (e.g. Scheelebreen) will now change initiation area, as the glacier now terminates on land.

Partial surges

Several examples of partial surges are introduced here. Small-scale surges are not totally unknown and have been observed previously, for example in a small glacier next to Steele Glacier, Alaska, USA (Meier and Post, 1969). On Bjuvbreen (Table 1), located in the same area as Kroppbreen, a boundary between stagnant ice and more active ice appeared in 1970. On the basis of the developing bulge, Hamilton (1992) classified the glacier as surge-type. The bulge built up in 1977 and propagated slowly down-glacier during the following years (Åsberg, 2001). However, these authors did not interpret the behaviour as a surge. Yet, we found similarities to the mass displacement occurring on Kroppbreen and interpreted the behaviour of Bjuvbreen as a partial surge. Visual evidence from a concave down-glacier front and crevasses on S36 photographs points to a surge of Bjuvbreen ~20 years prior to 1936. Hamilton (1992) estimated that the glacier was in a late surge or early quiescent phase by this time. We do not know if the ~1915 surge formed a bulge. On Trapridge Glacier, Yukon, Canada, Frappé and Clarke (2007) found that the two last surges observed differ in appearance. The last surge of Trapridge Glacier lasted for more than 20 years, with a lower velocity than previously. A distinctive bulge also propagated down the glacier. This also implies that for some glaciers the ratio between the durations of the surge and the quiescent phase could vary according to the development of the surge. However, the fast and quiescent periods can still be distinguished on the basis of visible geometric changes indicative of locally high strain rates

We have also identified partial surges of Luntebreen, which borders Scheelebreen with a semicircular moraine, and in a second basin further south (Fig. 3). Both surges are seen as a lowering in the upper part. Luntebreen is registered with another surge at ~1930 (Croot, 1988). It has been proposed that surges generally weaken with diminishing mass (Dowdeswell and others, 1995). In spite of increased temperatures since the 1920s (Hanssen-Bauer and others, 1990) and decreasing ice mass on many glaciers (e.g. Dowdeswell and others, 1997; Kohler and others, 2007), recently relatively large surges have occurred on, for example, Skobreen, Ingerbreen and Dobrowolskibreen. On Skobreen, the semicircular moraine that bordered the terminus prior to the last surge could indicate a smaller or partial surge in the past similar to that seen on Luntebreen. A bulge-like feature was also found in the 1936 profile of Skobreen (Sund, 2006). Thus, fluctuations between weaker or partial surges and stronger developed surges seem possible. The shape of the Luntebreen moraine after the last surge also supports this view. There are indications that such behaviour is also occurring on Hessbreen, where smaller bulges were found to accumulate down-glacier (Sund and Eiken, 2004). In addition, a noticeable mass redistribution from the upper to the middle part of the glacier was measured between 1952 and 1970 prior to the last surge (Liestøl, 1976). This could point to the occurrence of smaller mass displacements during the build-up period towards a larger surge. Such partial surges may explain why some glaciers have a very long build-up phase, as this partial adjustment could, on the one hand, delay a surge by partially emptying the surge reservoir, but could, on the other hand, favour a larger surge, as the small and partial releases of ice from the surge reservoir allow for a slower, more stable and possibly enhanced build-up of ice mass.

Number and frequency of surges

As mentioned before, the estimated fraction of surge-type glaciers in Svalbard has varied from 13% to 90%. This is possibly related to the different approaches in the various studies. As a result, for example, the currently surging glacier Comfortlessbreen was classified as a surge-type glacier on the basis of moraine structures by Croot (1988), but was removed from the surge-type glacier list in Jiskoot and others (1998, 2000).

The size of the observed surge-type glaciers in Svalbard can vary from approximately 0.5 km^2 as found here, to approximately 1100 km^2 for Bråsvellbreen (Liestøl, 1969). It has been suggested that long glaciers in Svalbard were more likely to be of surge type (Hamilton and Dowdeswell, 1996; Jiskoot and others, 2000). Like the other small glaciers studied here, the 0.5 km^2 Klubbebreen S. (Table 1) is more of a cirque glacier. It surged recently and went through a major mass displacement. The smallest glaciers have been ignored in the glacier population used in previous studies. Favourable conditions for accumulation through snowdrift and avalanches can be of greater importance for small glaciers than for larger or wider glaciers. Deep cirques might create favourable conditions for both build-up and surges in small glaciers that are located high enough to maintain sufficient accumulation in times of less favourable climatic conditions. Surges on such small glaciers are more difficult to discover and might have influenced the number of glaciers that are interpreted as surge-type. The surge of Klubbebreen S. demonstrates that even relatively large surges in small glaciers could be overlooked if not studied explicitly. This fact may also partly explain the very different estimates for the number of surge-type glaciers in Svalbard. Even if the surges themselves are not assumed to be connected to climate (Meier and Post, 1969), long surge cycles such as in Svalbard will undoubtedly be influenced indirectly through the mass balance and through changes in the thermal regime of the glaciers (Baranowski, 1978; Dowdeswell and others, 1995), which is why the appearance of the surges may also vary both between the individual glaciers and within the same glacier over time, as suggested for Bjuvbreen here and for Trapridge Glacier by Frappé and Clarke (2007).

The many new surges found in this study imply either that many glaciers have a longer quiescent phase than covered by human scientific activity or that surface evidence (e.g. looped moraines) of some surges has disappeared. Investigations in Svalbard during the last 100–150 years have predominantly been carried out along the coast. There is also little information about the inland glaciers prior to the first systematic aerial photo coverage of the Svalbard archipelago in 1936/38. Evidence of surges could be found from surface structures (Lefauconnier and Hagen, 1991) and also in historical documents.

Cöster (1925) describes the difference between the glaciers Höganäsbreen, which is in ‘a state of rest’, and Helsingborgbreen where ‘the lateral margin is nearly perpendicular, with pinnacles of ice’, indicating a sudden advance. The adjacent glaciers are located inland in Kjellströmdalen and have relatively equal orientation, area and elevation distribution. Thus if the advance of Helsinborgbreen was due to positive mass balance, some indications of the same on Höganäsbreen should be expected. Gripp (2004 [1927]) reported that folded moraines are found close to the terminus of Nathorstbreen, indicating surges of the different tributaries in the system that also includes Zawadzkibreen. However, the present medial moraines were until recently flow-parallel. The same appeared at the interaction between Kvalbreen and Indrebøbreen, where visual evidence of surges is currently difficult to find. On Negribreen also, which is known to have surged around 1935–36 (Liestøl, 1969), currently only parallel medial moraines can be seen.

Imaging from satellites has brought new possibilities of monitoring glacier changes more frequently than is possible using aerial photographs. Another approach to surge evidence was pursued by Mavlyudov (2006), who studied surge-type glaciers from unusual surface structures originating from old, inactive crevasses. He found additional surge-type glaciers to those mapped by Dowdeswell and others (1991). Finally the glaciers in Svalbard consist of complex systems of tributary and trunk glaciers, the so-called Spitsbergen type (Ahlmann, 1933). This sometimes makes it complicated to delimit the dynamic activity. The naming of the glaciers could also make it difficult to assess data from old sources, as the trunk glacier might have one name while the upper basins have another. This makes it difficult to date surges, particularly historical surges, as the outlet glacier may have one name but be fed by various inland basins or tributaries that may surge independently. Thus it can be challenging to extract the origin of an advance of such an outlet. It may also appear that these outlets surge often, because surges might originate from different basins. Hambergbreen is an example of such a glacier (Lefauconnier and Hagen, 1991), and the previously discussed Paulabreen is another. If we include all larger mass displacements as well as partial surges, surges in small glaciers and vanished evidence from moraines, it suggests that the fraction of surge-type glaciers in Svalbard is closer to former maximum estimates of 90% than to former minimum estimates of 13%. However, due to long quiescent phases and varying climate conditions, the exact number is difficult to determine.

Elevation changes as indications of surges or climate change?

The examples from Kjølhøbreen, Knoppbreen, Nataschabreen (Fig. 3) and Firmbreen–Vallåkrabreen (Fig. 4b) where partial surges resulted in a general lowering of the entire glacier surface, demonstrate the importance of addressing the dynamics of the glaciers in Svalbard prior to conclusions on large mass losses resulting solely from climate change. This is also valid for surges in stage 2 and partial surges.

Kohler and others (2007) found that accelerated glacier thinning in a surface profile across Wedel Jarlsberg Land (WJL) was consistent with climate trends found on other Svalbard glaciers. However, Hagen and others (2005) and Jania and others (2006) found surge behaviour in two systems draining from Amundsenisen: Høgstebreen (1990–96) and Nornebree–Paierlbreen (1996–2002) which are within the WJL profile. The surge in the Høgstebreen system seems to occur slowly and is still going on. We have found that at the same time the adjacent basin Profilbreen (Table 1) is also moving faster, as new crevasse fields were observed at the confluence with vestre Torellbreen (Table 1). For Nornebreen–Paierlbreen we interpret a surge initiation already started prior to 1990, as crevasses already covered the entire basin by this year, with indications for the Paierlbreen basin being the main surging basin and with Nornebreen only responding to the increased flux.

Hagen and others (2005) concluded that in Svalbard surface-elevation changes alone cannot be used to assess mass balance but that the dynamics must also be evaluated. They suggested a survey interval of 10 years or more for short-term variations. However, the slow development of some surges such as those we have reported in this paper indicates that a development towards a full surge could last more than 10 years. Evaluation of the surge status is important to avoid misinterpretation of rapid surface elevation changes that are caused by surge activity. Under changing climate conditions, a surge may also accelerate the climate-induced thinning of a glacier as large parts of the glacier mass are brought to lower elevations that are more exposed to ablation. Thus, long, thin valley glaciers at low elevations might be more sensitive to climate change than small cirque glaciers when surges are considered. By contrast, a general surface lowering does not necessarily signify an initial surge. Under atmospheric warming, warmer summers may lead to more widespread melting and formation of superimposed ice at higher elevations (Wadham and Nuttall, 2002), which may appear as surface lowering due to the higher density of superimposed ice compared to snow and firn. Therefore the pattern and rate of the surface lowering should also be carefully considered when assessing early stages of surges.

CONCLUSION

A number of new surges in glaciers in Svalbard that were not previously known to have surged have been identified in this study. The development of a surge was divided into three stages, where the new results in this study cover stages 1 and 2 while stage 3 corresponds to the main surge phase identified by previous workers. Subtraction of DTMs revealed lowering of restricted areas in the accumulation area of the glaciers in stage 1 in connection with the transition from build-up to the initial surge stage. In some glaciers these changes were accompanied by new yet moderate crevassing. In stage 2 the mass displacement was approaching the receiving area and a thickening was observed in addition to a more pronounced lowering in the now more defined reservoir area. The crevassing was still limited in stage 2. None of our results indicate surge initiation in the terminus zone of tidewater glaciers. For all tidewater glaciers studied here, the initial signs of surge were found in the upper glacier parts, similar to the land-based glaciers studied. Our results showing signs of surge initiation earlier than in previous studies point to even longer surge durations in Svalbard than assumed so far. Our study pinpoints the areas of surge initiation, which could help to focus the future surge initiation studies. We have found that some surges cease at stage 2 and do not develop to a full surge. We term these 'partial surges'. Some of these rarely leave morphological evidence into the quiescent phases. Partial and stage 2 surges may be misinterpreted as rapid response to climate change, due to the thinning in the upper glacier parts as a consequence of mass displacement, and due to thinning in the lower glacier parts as result of ablation. Finally our results suggest that a majority of current Svalbard glaciers are of surge type, as already proposed by Liestøl (1969).

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