SURFACE ELEVATION CHANGE AND HIGH RESOLUTION SURFACE VELOCITIES FOR ADVANCING OUTLETS OF JOSTEDALSBREEN

BY

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ABSTRACT. Velocity fields for the three outlet glaciers Nigardsbreen, Bergsetbreen and Baklibreen of Jostedalsbreen, southern Norway, have been obtained from successive orthophotos by digital image processing. The orthophotos were generated with standard digital photogrammetry. They are based on air photos acquired ten days apart in August 2001 and produced with a ground resolution of 0.5 m. Glacier displacements were calculated by matching homologous points in each orthophoto using a regular grid with 10 × 10 m resolution. Displacements, calculated using cross-correlation matching of orthophotos for Nigardsbreen, show daily movement of up to 1.34 m and agree well with GPS-measured velocities during the same period. The average velocities for the three glaciers ranged from 0.38 to 0.56 m per day. Surface elevation change have been calculated by differencing the 5 m resolution **digital elevation model (DEM)** obtained from the August 2001 air photos with two 25 m resolution DEMs from 1984 (Nigardsbreen) and 1993 (all three outlets). These calculations show an average increase in surface elevation of 22.1 m for Nigardsbreen between 1984 and 2001. Bergsetbreen and Baklibreen show increases of 3.2 m and 14.3 m between 1993 and 2001. In addition a DEM produced from air photos from 1997 was used for Nigardsbreen, making it possible to show how the surface elevation has changed between the years 1984, 1993, 1997 and 2001. The advance of the glacier snouts is also clearly visualized by the DEM differencing

Key words: digital photogrammetry, glacier velocities, orthophotos, volume change

Introduction

During the last few decades most glaciers in the world have been retreating (IAHS(ICSI) *et al.* 1998, 2001). As a widely recognized exception to this global trend, the glaciers in the western part of Norway have been advancing since the late 1980s until the start of this millennium. This advance was related to increased winter precipitation in the late 1980s and beginning of the 1990s (Kjøllmoen 2003b, 2004). In order to survey both velocity and surface elevation changes on the outlets of Jostedalsbreen, air photos covering ten outlets of this large glacier were acquired on 19 and 29 August 2001. The temporal resolution of ten days was considered feasible for mapping the expected glacial displacements, based on the precision of the method used.

The first objective of this study was to better understand the glacier-dynamic processes associated with the above-mentioned glacial advance. In addition, the study aimed to evaluate, for the first time, the applicability of high-resolution digital image matching techniques for deriving glacier surface velocities over short time intervals from repeated aerial photography. Therefore, the flow fields of two steep outlet glaciers, Bergsetbreen and Baklibreen, as well as one valley glacier, Nigardsbreen, were mapped using photogrammetric orthophoto generation and cross-correlation matching of orthophotos from different dates. Digital elevation models (DEMs) existed from 1984 and 1993, and two new ones were generated with aerial photographs of 1997 and 2001 for Nigardsbreen. The 1993 and 2001 DEMs are the only ones covering Bergsetbreen and Baklibreen. An assessment was made on the volume change of the glaciers by differencing these multi-temporal DEMs using a **geographical information system (GIS)**.

Several of the outlets of Jostedalsbreen and especially Nigardsbreen have been the subject of many glaciological studies in the past which has

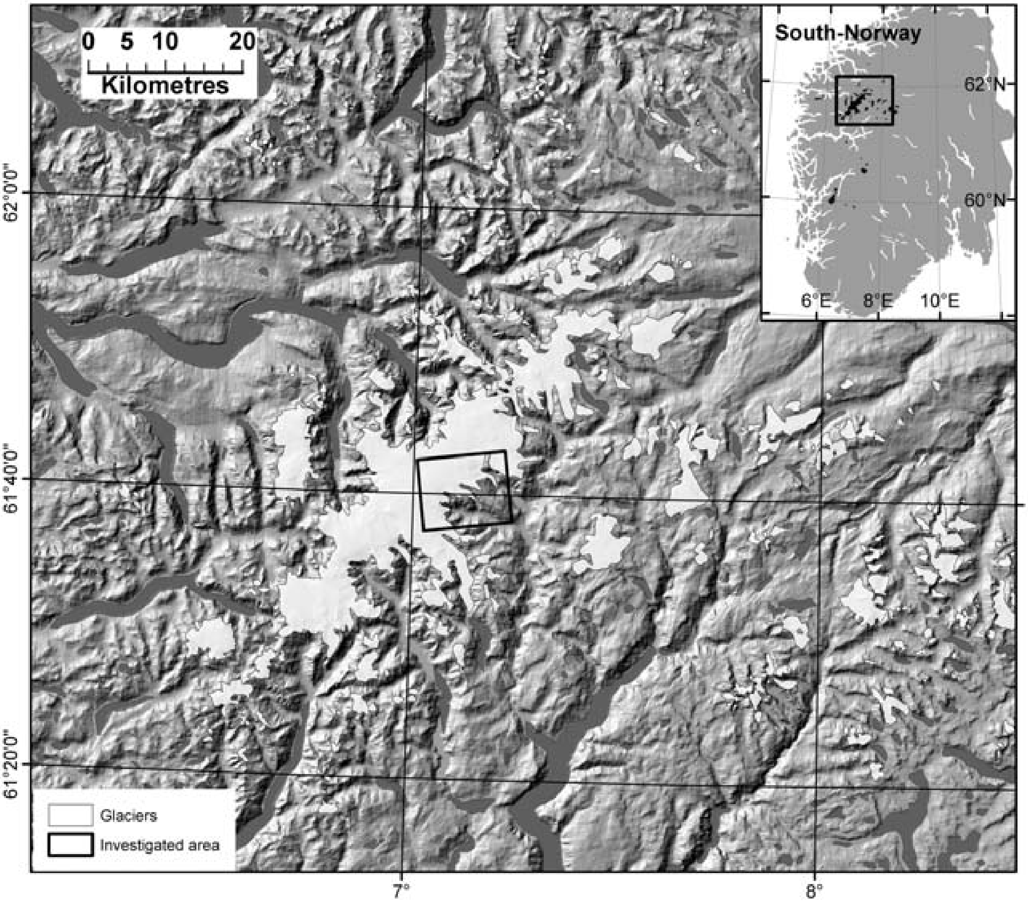

Fig.1. Location of Jostedalsbreen in southern Norway and location of the study area (rectangle).
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led to comprehensive sets of data: length change dating back to 1748, mass balance dating back to 1962, and velocity measurements from several of the decades since the 1930s are available (Østrem *et al*. 1976). A GPS measurement campaign for glacier velocity was undertaken in 2001 and 2002 (Tønsberg 2003), covering the period in late August 2001 when the air photos used in this study were acquired. These data serve as a solid base for comparison and validation of the results from this study together with the earlier work mentioned above.

Nigardsbreen, Baklibreen and Bergsetbreen

All three investigated glaciers, Nigardsbreen (61°41'N, 7°11'E), Baklibreen (61°40'N, 7°5'E) and Bergsetbreen (61°39'N, 7°4'E), are outlets of Jostedalsbreen (487 km^2), the largest glacier on mainland Europe (Østrem *et al*. 1988) situated in the western part of southern Norway (Fig. 1). All three outlets used in this study are located on the southeastern side of the ice cap. Jostedalsbreen is a maritime glacier exemplified by Nigardsbreen, with a mean specific winter balance of 2.4 m water equivalents, and a mean equilibrium line altitude of 1506 m a.s.l. in the period 1962–2003 (Kjøllmoen 2003b, 2004). During winters of high precipitation the winter balance has reached levels of 5.6 m water equivalents (1989) in the upper areas of Nigardsbreen (Østrem *et al*. 1991).

Nigardsbreen is a valley glacier, 9.6 km in length, which drains a large area of the ice cap and flows down into a deep U-shaped valley through three different tributary icefalls (Fig. 2). Baklibreen is a smaller and much steeper glacier (Fig. 2). The

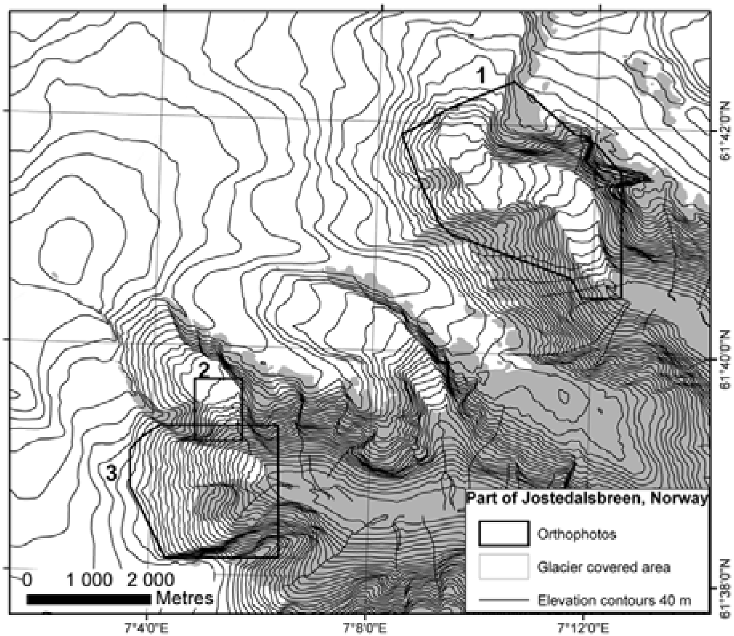

Fig. 2. Map of the three investigated outlets Nigardsbreen (1), Baklibreen (2) and Bergsetbreen (3). The coverage of the orthophotos used is shown
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lower part of Baklibreen is a hanging glacier with up to 33° inclination situated on the valley side of Krundalen, just above the snout of Bergsetbreen. Bergsetbreen drops steeply into the valley end of Krundalen having a slope angle of 27°, which continues over an area covering 1000 vertical metres (Fig. 2). The orthophoto coverage used in this study is shown in Fig. 2. Nigardsbreen extends from 355 to 1950 m a.s.l., Baklibreen from 950 to 1950 m a.s.l., and Bergsetbreen from 560 to 1960 m a.s.l. (Østrem *et al*. 1988).

Earlier investigations

Two of the glaciers have length change data: Nigardsbreen has a continuous record from 1899 and Bergsetbreen has records between 1899 and 1945, and from 1996 and onwards. For Nigardsbreen there are also historical data on glacier length dating back to 1748 (Østrem *et al*. 1976). In addition, Nigardsbreen has a mass balance data series, the longest for the Jostedalsbreen outlets and the second longest in Norway, dating back to 1962.

Nigardsbreen had a continuous positive mass balance in the majority of the years from 1964 to 2000 and gained 17 m water equivalents from 1962 to 2003; however, it still continued to retreat rapidly until the 1970s. From 1987 to 2003 Nigardsbreen advanced 270 m. This advance was explained by increased winter precipitation in the late 1980s and the beginning of the 1990s (Andreassen *et al*. 2006). The overall net retreat for Nigardsbreen from measurements started in 1899 is 2300 m, and the net retreat from the Little Ice Age maximum in 1748 until 1899 was calculated at 1995 m (Østrem *et al*. 1976). Since 1899 Bergsetbreen has shown a net retreat of 320 m; however, it is known to have advanced rapidly just before length change measurements started again in 1996 (Andreassen *et al*. 2006). Surface elevation and velocity of Baklibreen was monitored from 1987 to 1999 (Kjøllmoen 2000) and surface elevation again from 2001 to 2003 (Kjøllmoen 2004) due to an ice avalanche killing three hikers in 1986.

Concerning glacier velocities Nigardsbreen is by far the most investigated of the three outlets. Velocity measurements for Nigardsbreen were conducted and recorded as early as 1937 and 1938 by a German expedition (Pillewizer 1950) using the terrestrial photogrammetric method introduced by Finsterwalder (1931). Liestøl used a similar method in 1949, 1951, 1953 and 1961 (Østrem *et al*. 1976); and trigonometric stake measurements were made from 1966 to 1969 (Nielsen 1970). The previous investigations revealed velocities ranging from a few centimetres

Table 1. Data on the digital elevation models used

Photo date	Resolution (m)	Flying height (m.a.s.l)	Height accuracy (RMS m)	Coverage (glaciers)	Source†
10 Aug. 1984	25	6300	5	Nigardsbreen	NVE
8 Sep. 1993	25	6150	5 (4–6)	All	SK
14 Aug. 1997	5	6150	1.3*	Nigardsbreen	UoO
29 Aug. 2001	5	3950	0.8*	All	UoO

*Height accuracy for the 1997 and 2001 DEMs is calculated based on the flying height, an average terrain elevation of 850 m a.s.l. with a height accuracy of *c*. 0.025% of the flying height (above terrain) using error propagation
†NVE, Norwegian Water Resources and Energy Directorate; SK, Norwegian Mapping Authority; UoO, the Department of Geosciences, University of Oslo.

per day at the tongue up to 1.4 m per day (md^{-1}) in one of the icefalls.

Tønsberg (2003) reports on increased velocities on the tongue of Nigardsbreen in later years (2001–2002) compared to reports from 1950–1970 and attributes this change to the increased thickness and width of the tongue. Using differential GPS, he found velocities ranging from 0.22 to 0.80 m d^{-1} in different periods during 2001 and 2002 in the elevation range of 460 to 790 m a.s.l. He also found the velocity to be increasing with elevation and to be higher during the summer season, especially in the lower parts of the tongue.

Methods

Generation of DEM and orthophotos

Cross-correlation matching has been used for mapping glacier velocities in satellite imagery since the early 1990s (Bindschadler and Scambos 1991) and in aerial orthophotos since 1995 (Rolstad 1995). Aerial photogrammetry has been used as an effective tool for velocity and geometry change measurements of glaciers, landslides and creeping permafrost landforms such as rock glaciers for several decades (Finsterwalder 1931; Haeberli *et al*. 1979; Kääb *et al*. 1997; Kääb and Funk 1999), and since the advent of digital photogrammetry cross-correlation matching of orthophotos has also been widely used (Baltsavias 1996; Kääb and Vollmer 2000; Kaufmann and Ladstädter 2003; Delacourt *et al*. 2004)

In this study orthophotos were generated using a Z/I-Imaging **digital photogrammetric workstation (DPW)** with air photos acquired on 19 and 29 August, 2001 by Fotonor. The air photos have a 1: 20 000 scale (flying height of 3100 m above mean ground level) and are scanned with 14 μm resolution giving 0.3 m geometrical resolution. Orthophotos are air photos transformed to orthogonal projection (i.e. map projection) by the use of a digital elevation model (DEM) and a DPW (Kasser and Egels 2002). Having a stereo model it is possible to automatically generate a DEM using the digital image matching module in the DPW. An orthophoto is then generated for each date for each glacier by resampling of the scanned aerial photographs using the orientation parameters and the corresponding DEM. The orthophotos were generated with a 0.5 m resolution using DEMs of 5 m resolution.

Cross-correlation of orthophotos

For measurement of local horizontal displacements of the glaciers, cross-correlation matching of orthophotos was used using the CIAS-software (Kääb and Vollmer 2000). This software matches homologous (conjugate) points in two geo- and coreferenced orthophotos of the same area taken at different times. The points are selected as a regular grid with 10 m spacing in the orthophoto of time 1. A small reference window is extracted from the orthophoto of time 1 around each point and the homologous point to the centre point of this small window is searched for in a larger test area around the corresponding coordinate in the orthophoto of time 2. A cross-correlation factor is calculated for each possible location of the reference window within this test area. The location that yields the highest correlation factor is taken to be the position of the homologous point in the orthophoto of time 2. For a thorough description see Kääb and Vollmer (2000). If displacement has taken place during the time interval between the two acquisitions, then the displacement is measured as the horizontal coordinate distance between the positions of the two homologous points (this method does not measure the

Table 2. Maximum and average velocities measured by cross-correlation of the 19 and 29 August 2001 orthophotos

	Max (m d^{-1})	Average (m d^{-1})
Nigardsbreen	1.34	0.56
Baklibreen	2.09	0.38
Bergsetbreen	1.61	0.53

Table 3. Comparison of GPS measured stake displacements between 22nd June and 22nd August 2001 and between 22nd August and 19th September (Tønsberg 2003), and the average of velocities obtained by cross-correlation of orthophotos acquired 19th and 29th August 2001 in a 100 m radius circle around the stake positions. The positions of the GPS-measured stakes are shown in Fig. 7

GPS Point	Orthophoto velocity (m d^{-1})	GPS velocity 06–08–2001 (m d^{-1})	Difference ortho and GPS velocity (%)	GPS velocity 08–09–2001 (m d^{-1})	Difference ortho and GPS velocity (%)
1	0.31	0.35	–12.9	0.29	6.5
2	0.61	0.60	1.6		
3	0.57	0.59	–3.5	0.53	7.0
4	0.60	0.61	1.7	0.54	10.0
5	0.62	0.60	3.2	0.55	11.3
6	0.66	0.67	–1.5	0.60	9.1
7	0.70	0.70	0.0	0.65	7.1
8	0.77	0.80	–3.9	0.73	5.2
Average deviation			3.5		8.0

vertical displacement). A reference window size of 15 × 15 pixels was used for all glaciers. This size seemed to be sufficient to contain enough information for matching the 0.5 m resolution photos of glacier surfaces used in this study. The size of the test area was 100 × 100 pixels. The test area has to be large enough to detect a displacement of the expected magnitude. The size was determined by some initial trial testing. According to Kääb and Vollmer (2000) the accuracy of this method is in the order of one pixel and at least at the same level as results from analytical photogrammetry. Although originally developed for deformation mapping of rock glaciers using aerial orthophotos, this method has also been used to map glacier movement using ASTER satellite data (Kääb 2002, 2005; Kääb *et al.* 2006).

When a sufficient number of points have been matched by cross-correlation, it is possible to perform filtering on the resulting data. Displacement vectors with low cross-correlation factors or unnatural directions can be easily filtered out. A correlation coefficient threshold of 0.8 was used for all locations together with a directional filter, filtering any vector deviating greatly from the assumed flow direction. The filtered data were then imported into a GIS and some manual removal of points was undertaken. Using a correlation coefficient threshold of 0.8 and a directional filter adapted to the main flow direction of the different glaciers as well as manual editing, we excluded 37–50% of the original matched points.

DEM differencing

Having the 5 m resolution DEMs of 29 August, 2001 and 14 August, 1997, the 25 m resolution DEMs of 1984 from the **Norwegian Water Resources and Energy Directorate (NVE)** and of 1993 from the Norwegian Mapping Authority (Statens Kartverk), the vertical surface changes for the periods were calculated simply by subtracting the older model from the newer by the use of ESRI's Arc GIS software. The 1984 and 1993 DEMs have been interpolated from contour lines of 10 m and 20 m equidistance respectively. The 1984 and 1997 DEMs cover only Nigardsbreen. A resampling to 25 m was done for the 2001 and 1997 DEMs in order for them to be comparable with the others. The height accuracy of the 2001 and 1997 DEMs is assumed to be 0.8 m and 1.3 m (*c.* 0.025% of 3100 and 5300 m flying height), while both the 1984 and 1993 DEMs have an accuracy closer to 5 m (Table 1).

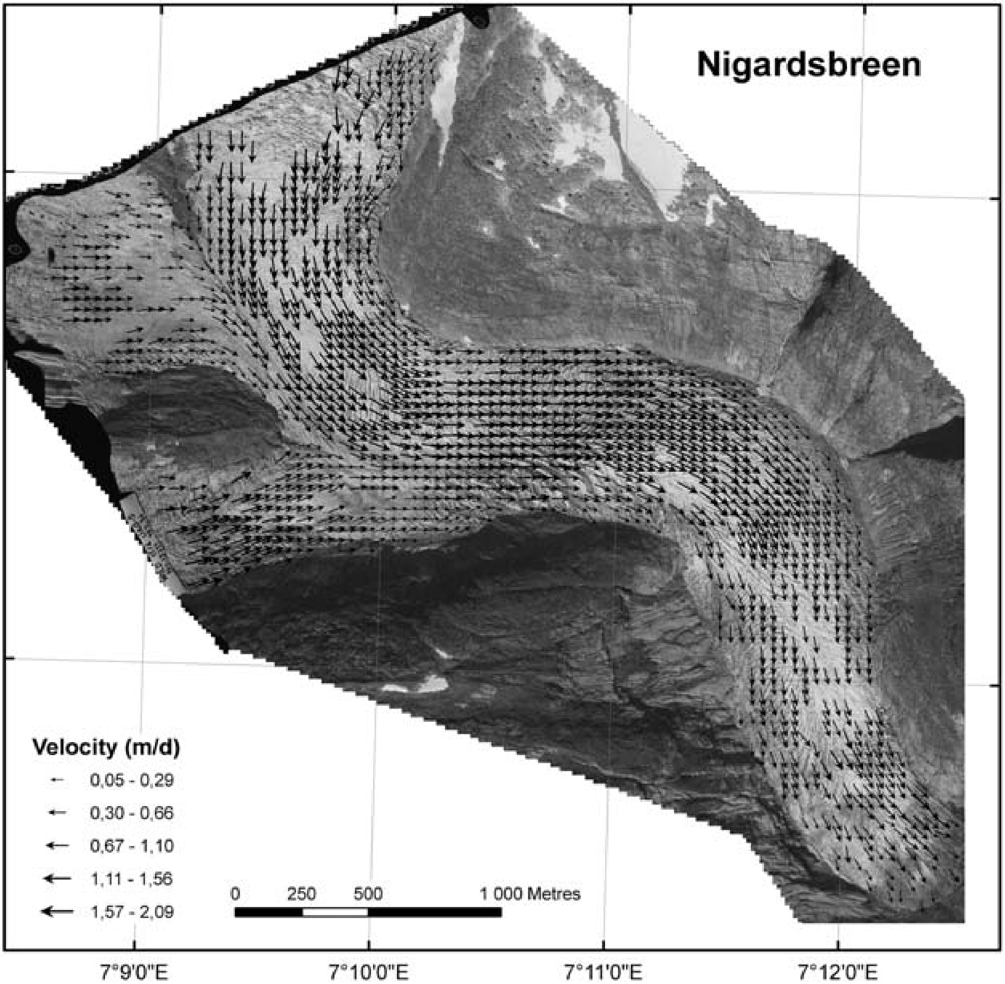

Fig. 3. Velocity vectors on Nigardsbreen from cross-correlation matching of the 19 and 29 August 2001 orthophotos. The 10 × 10 m spatial resolution of the original velocity results has been thinned to a 40 × 40 m resolution

Glacier velocities

Velocity estimation

The orthophoto resolution is 0.5 m. The calculated velocities from cross-correlation matching of orthophotos are shown in Tables 2 and 3. According to Kääb and Vollmer (2000) the accuracy of the cross-correlation matching is about the size of one pixel, giving an accuracy of 0.5 m for the whole measuring period of ten days (19 and 29 August 2001). This is equivalent to an accuracy of 0.05 m d^{-1} when presenting the results from the ten day period as metres per day. The resulting velocities are presented as vector plots showing the magnitude and direction of the displacements (Figs 3, 4, 5 and 6), and as interpolated velocity fields with velocity-isolines (Figs 7, 8 and 9). The interpolation used is a local second-degree polynomial interpolation. This method only interpolates the magnitude of the displacements, and is a smoothing and inexact interpolation method, used to improve visualization rather than give an exact presentation of the results.

Nigardsbreen

The highest velocities on Nigardsbreen, which reached 1.34 m d^{-1}, were found in the main icefall leading down to the valley glacier (Figs 3 and 7).

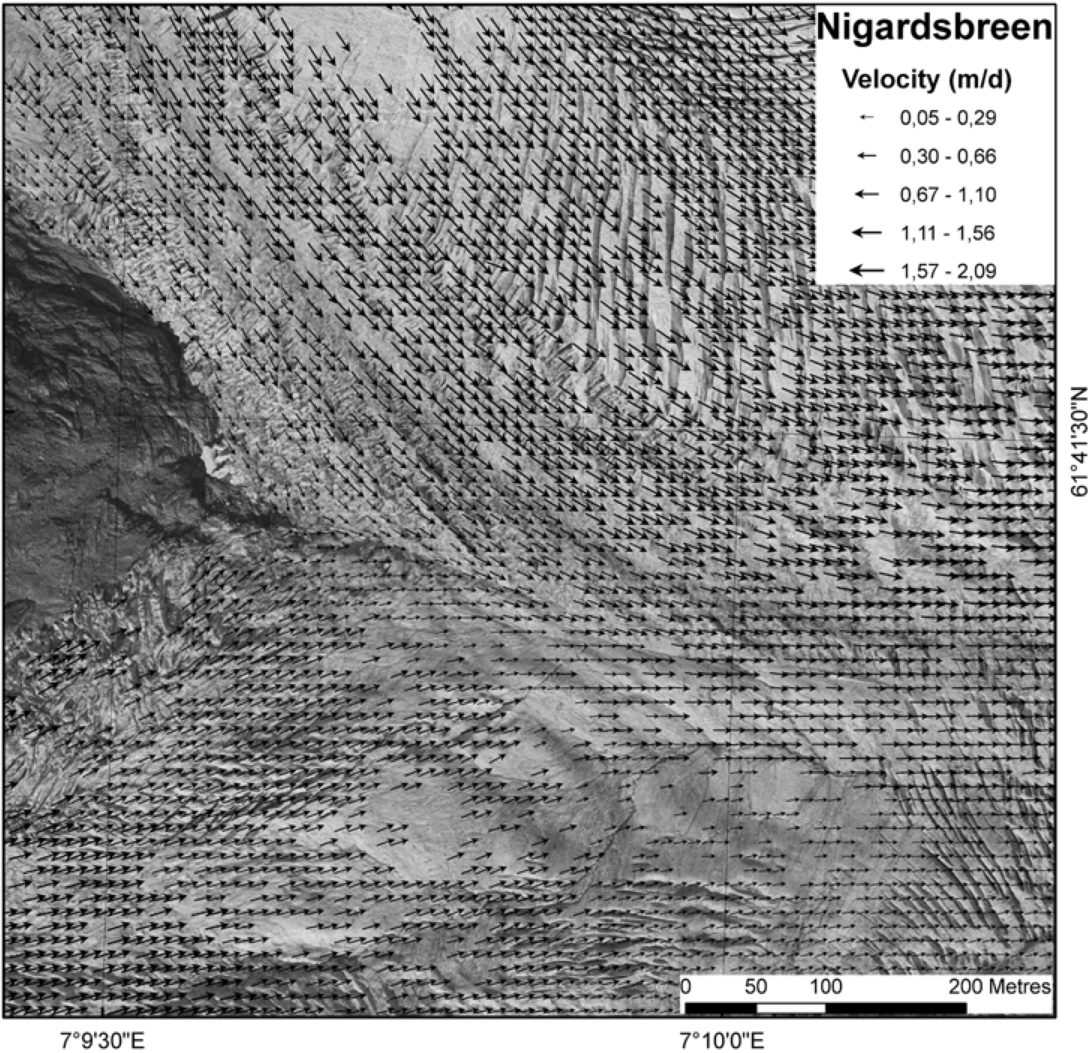

Fig. 4. An image showing a smaller area of the measured velocity vectors on Nigardsbreen with the velocity results in the original 10 × 10 m resolution

High velocities were also found in the upper part of the southernmost icefall, where velocities reach 1.19 m d^{-1}. This is in the area where Liestøl measured a displacement of 1.40 m d^{-1} using terrestrial photogrammetry in summer 1951 (Østrem *et al.* 1976) and Bergersen (1954) measured a displacement peak of 0.9 m d^{-1} in summer 1952. Below the icefalls velocities gradually decrease towards the glacier snout. The calculated velocities from cross-correlation matching of orthophotos are shown in Table 3. From Figs 3, 4 and 7 it can also be seen that the velocities of the two western tributaries decrease before they enter the main glacier stream.

A comparison of the glacier velocities from this study with the ones measured by GPS between 22 June and 22 August, 2001 and between 22 August and 19 September, 2001 by Tønsberg (2003), is shown in Table 3. An average deviation of 3.5% for the first measurement period and 8.0% for the second is found. The positions of the stakes used for measurement by Tønsberg (2003) were chosen in order to be as close as possible to earlier observations. A schematic view of the earlier and new velocity measurements is presented in Table 4. The average velocity along the centreline of Nigardsbreen from these results was 0.76 m d^{-1} (276.8 m

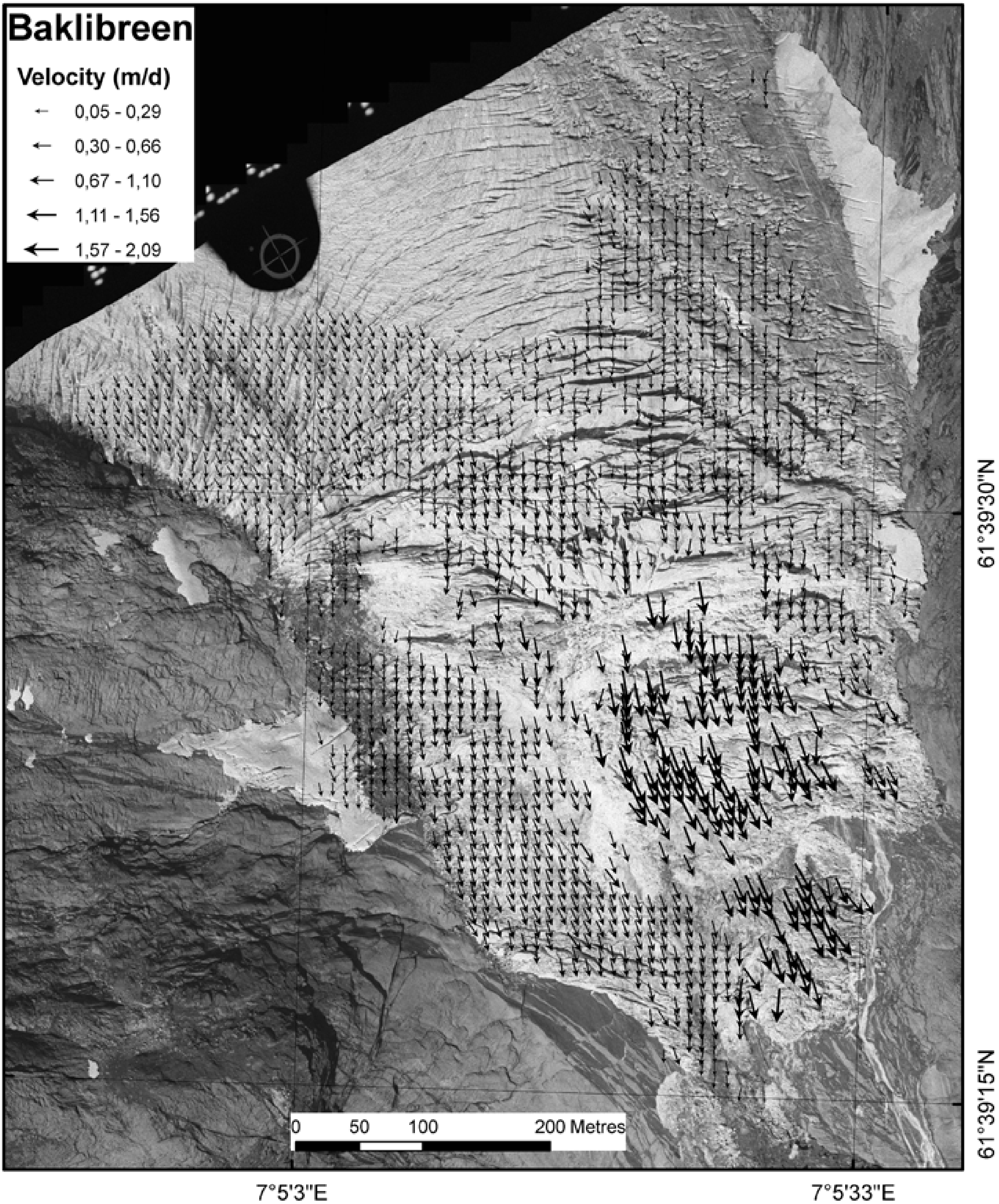

Fig. 5. Velocity vectors on Baklibreen from cross-correlation matching of the 19 and 29 August 2001 orthophotos pictured in the original 10 × 10 m resolution

a^{-1}). Given the 4.2 km distance from the upper areas covered by velocity measurements to the front, and the 2.5 km distance further up to the **equilibrium line altitude** (**ELA**), a surface travel time of 24.2 years can be calculated from the ELA to the snout for an object (e.g. a stone) travelling on the glacier surface. We assumed that the average velocity found between the snout and 1100 m a.s.l. is also applicable for areas all the way up to the ELA.

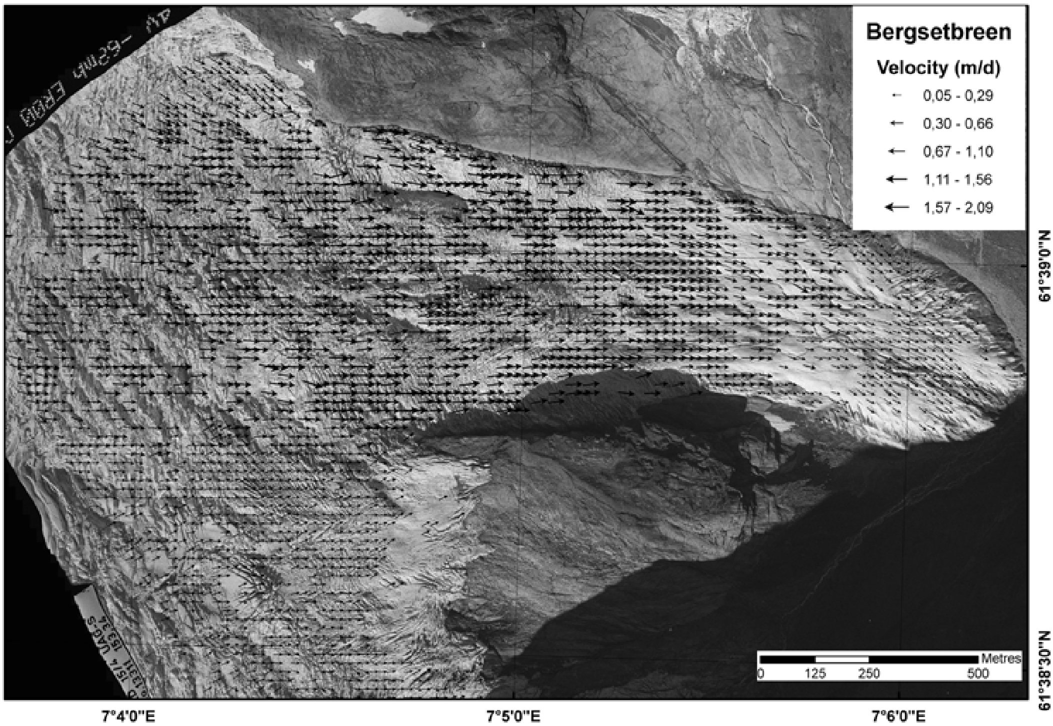

Fig. 6. Velocity vectors on Bergsetbreen from cross-correlation matching of the 19 and 29 August 2001 orthophotos. The 10 × 10 m spatial resolution from the original results has been thinned to a 40 × 40 m resolution

Baklibreen

The highest velocities at Baklibreen were found in the area of the greatest slope, in the lower and thin part of the glacier, reaching a maximum of 2.09 m d^{-1} (Figs 5 and 8, and Table 2). The average velocity for Baklibreen is 0.38 m d^{-1}. The velocities show the same pattern of increasing towards the front as found during the investigations in 1988–1996 (Kjøllmoen 2000). No travel time has been calculated for Baklibreen because the velocity field is too inhomogeneous and the glacier section covered by measurements is too small.

Bergsetbreen

Bergsetbreen show velocities averaging 0.53 m d^{-1} and reaching a maximum of 1.61 m d^{-1} in the steep mid-section (Figs 6 and 9, Table 2). On the upper southern flank and at the flat lower part of the tongue, the lowest velocities averaged around 0.11 m d^{-1}. No published velocity measurements exist from Bergsetbreen for comparison. The following discussion section outlines possible reasons for the patchy appearance of velocity patterns. The southern outlet is hidden in shadows in both orthophotos and it was not possible to calculate velocities for this part of the glacier. If we assume that Bergsetbreen has an ELA at the same level as Nigardsbreen, the velocity field covers the complete area from the glacier snout to the ELA at 1500 m a.s.l. The average velocity along the centreline in these areas is 256.45 m a^{-1} and gives an 8.6-year travel time for the 2.2 km distance.

Surface elevation changes

DEM subtraction

Surface elevation changes were found by subtracting the multi-temporal DEMs (see Table 1 on DEM data). The total height accuracy of the DEM subtraction and hence the accuracy of the measured surface elevation changes depend on the accuracy of each model used and is the Pythagorean sum of

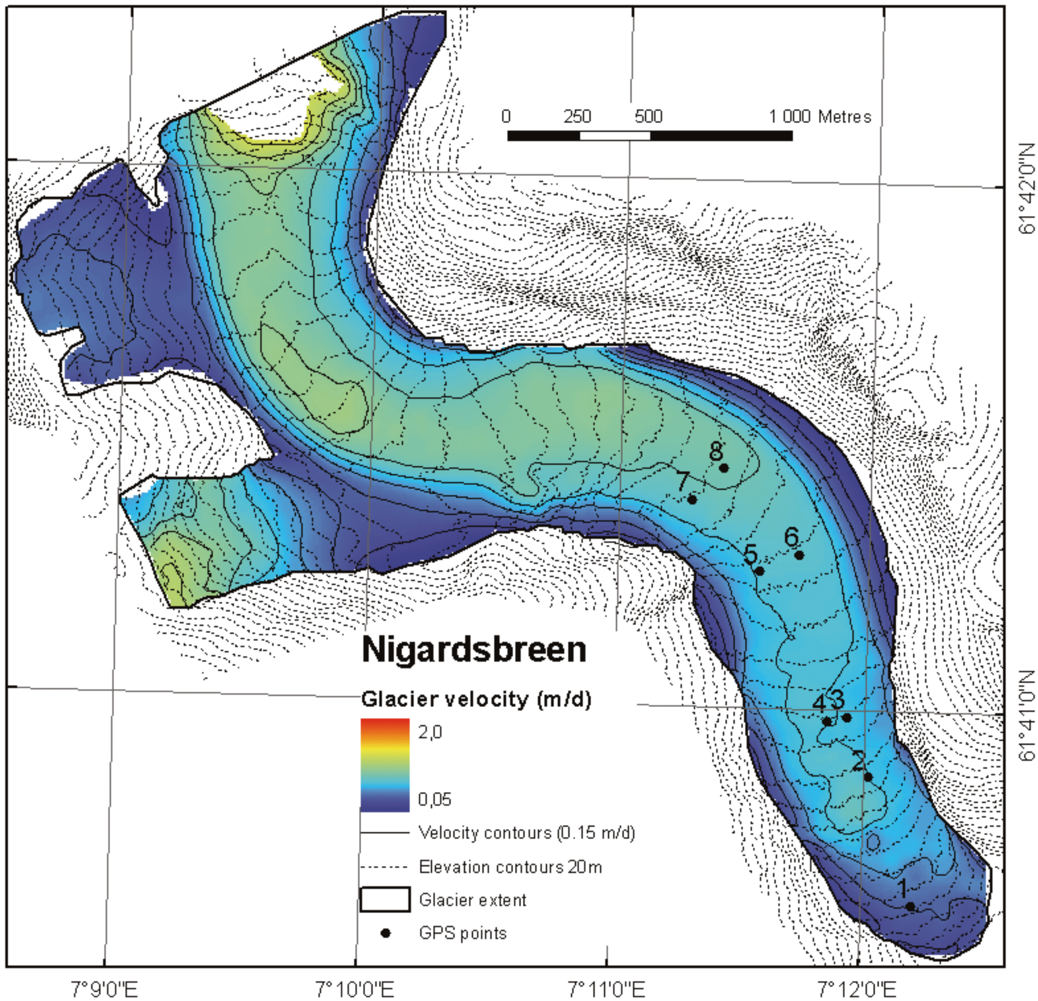

Fig. 7. Velocity field of Nigardsbreen interpolated from the velocity vectors. The location of the GPS points used for velocity measurements by (Tønsberg 2003) is shown

the two DEM accuracies since no correlation is present. Given the DEM height accuracies in Table 1, the accuracy of each subtraction can be estimated and is shown in Table 5. These accuracies will have implications for the interpretation and validity of the surface elevation change results.

Nigardsbreen

Nigardsbreen showed only minor surface elevation changes from 1984 to 1993 with a thickening of 5–6 m in the lower parts and surface lowering of up to 10 m in the highest areas (Figs 10 and 11). The average change for this period was a lowering of 3.3 m within the 1993 glacier outline (Table 5). From 1993 to 1997 there was a thickening for the whole investigated section with an average of 19.3 m within the 1997 glacier outline. (An area in the middle part had to be masked out due to errors in the generation of the 1997 DEM; Fig. 10). Due to an advance of approximately 200 m in this period the glacier experienced its greatest surface elevation change in the lower areas, with the maximum value being over 40 m. Above the advancing

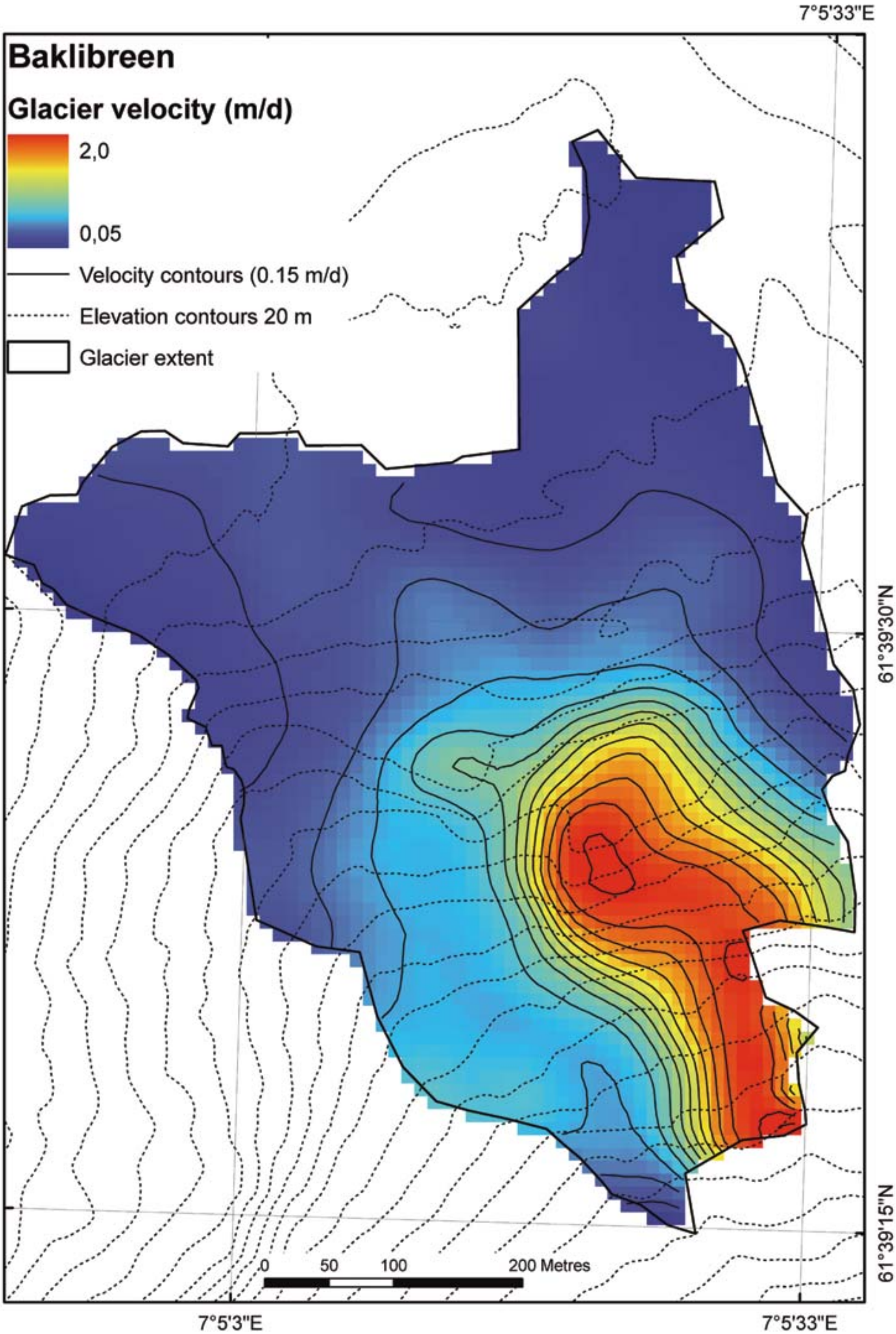

Fig. 8. Velocity field of Baklibreen interpolated from the velocity vectors

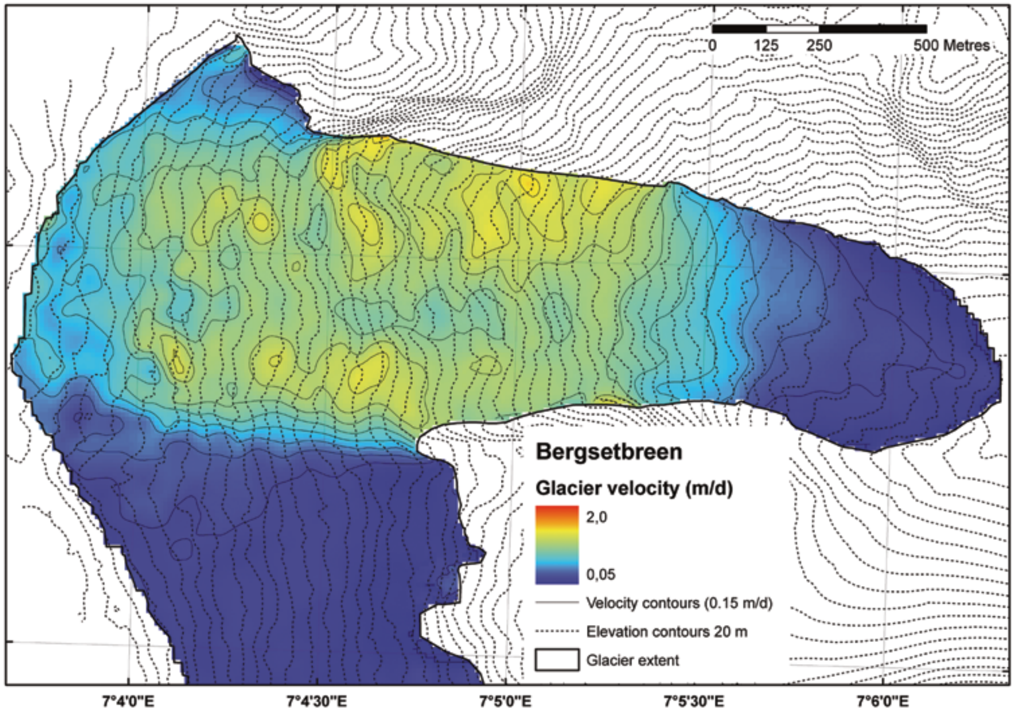

Fig. 9. Velocity field of Bergsetbreen interpolated from the velocity vectors

snout, thickening was approximately 20 m (Fig. 11). It is also worth noticing the thickening in the lower part of the northwestern icefall. For the last period, from 1997 to 2001, the change was somewhat smaller than for the preceding period but still positive in all the investigated elevation intervals, showing a rise in the lower advancing areas with approximately 33 m decreasing to approximately 5 m for the areas above 550 m a.s.l. (Fig. 11). The average thickening within the 2001 outline was 5.2 m (Table 5). For comparison with Baklibreen and Bergsetbreen, surface elevation changes were also calculated for the periods 1984 to 2001 and 1993 to 2001 (Table 5) (The small differences are due to different outlines being used for different periods).

Baklibreen

The surface elevation change at Baklibreen from 1993 to 2001 did not show the elevational trend indicated by Nigardsbreen, but showed an average thickening of 14.3 m with a surface change between –5.6 and +34.8 m (Fig. 12, Table 5).

Table 4. Comparison of glacier velocities (m d^{-1}) conducted by terrestrial photogrammetry in 1937 (Pillewizer 1950), by Liestøl in 1949, 1951, 1953 and 1961 (Østrem et al. 1976), trigonometric stake measurements in 1968/69 (Nielsen 1970), and the GPS and orthophoto measured ones from 2001 presented here (Tønsberg 2003)

GPS points	1937	1949	1951	1953	1961	1968/ 1969	2001 GPS	2001 ortho
2 and 3	0.32	0.32	0.26	0.80	–	0.11	0.60	0.59
5 and 6	0.63	–	–	–		0.37	0.64	0.64
7 and 8	0.51	0.73	0.76	0.62	0.43	0.56	0.75	0.74

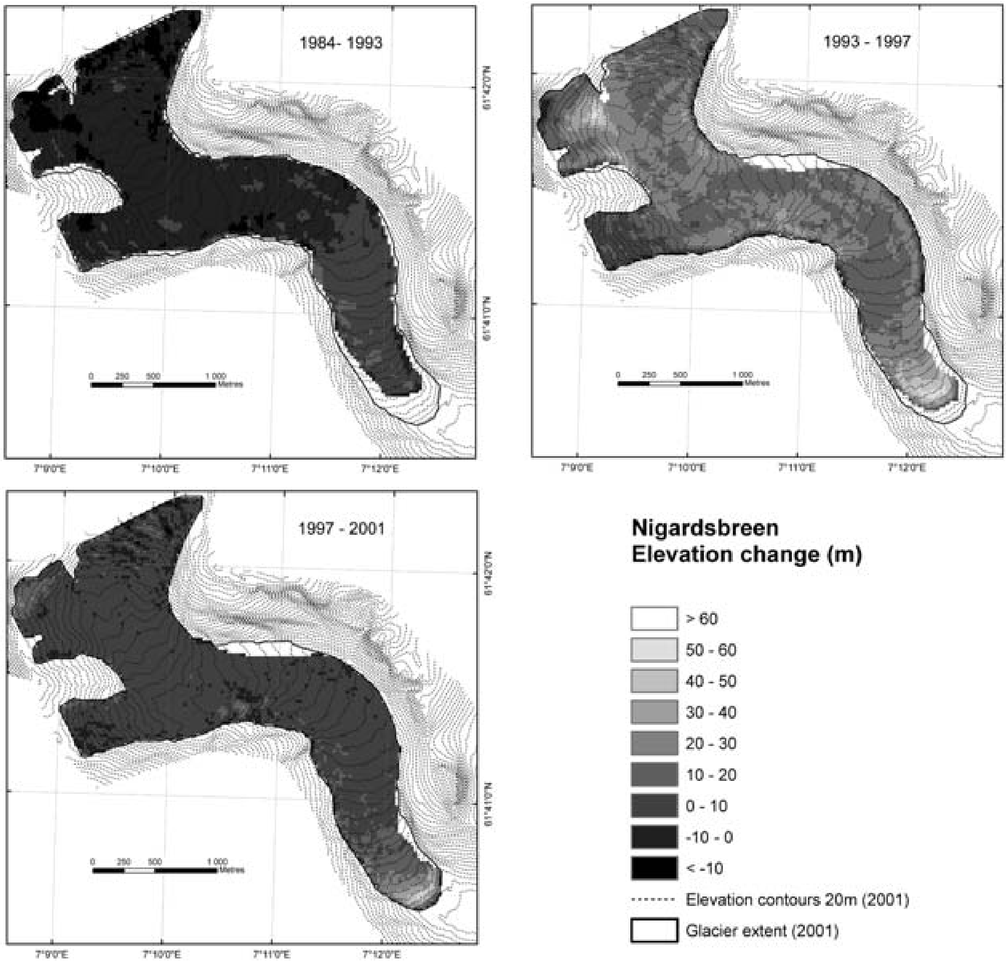

Fig. 10. Surface elevation change of Nigardsbreen calculated from differencing the DEMs for 1984–1993, 1993–1997 and 1997–2001

Table 5. Mean surface elevation change (m) from DEM differencing with the mean absolute value in parentheses. For each calculation the glacier border of the last date has been used. The accuracy (m) for each surface change calculation is also shown

	1984–2001	1993–2001	1984–1993	1993–1997	1997–2001
Nigardsbreen	22.1 (22.2)	24.6 (24.6)	–3.3 (5.7)	19.3 (19.9)	5.2 (5.6)
Baklibreen	–	14.3 (14.3)	–	–	–
Bergsetbreen	–	3.2 (6.6)	–	–	–
Accuracy	5.1	5.1	7.1	5.1	1.5
Years	17	8	9	4	4

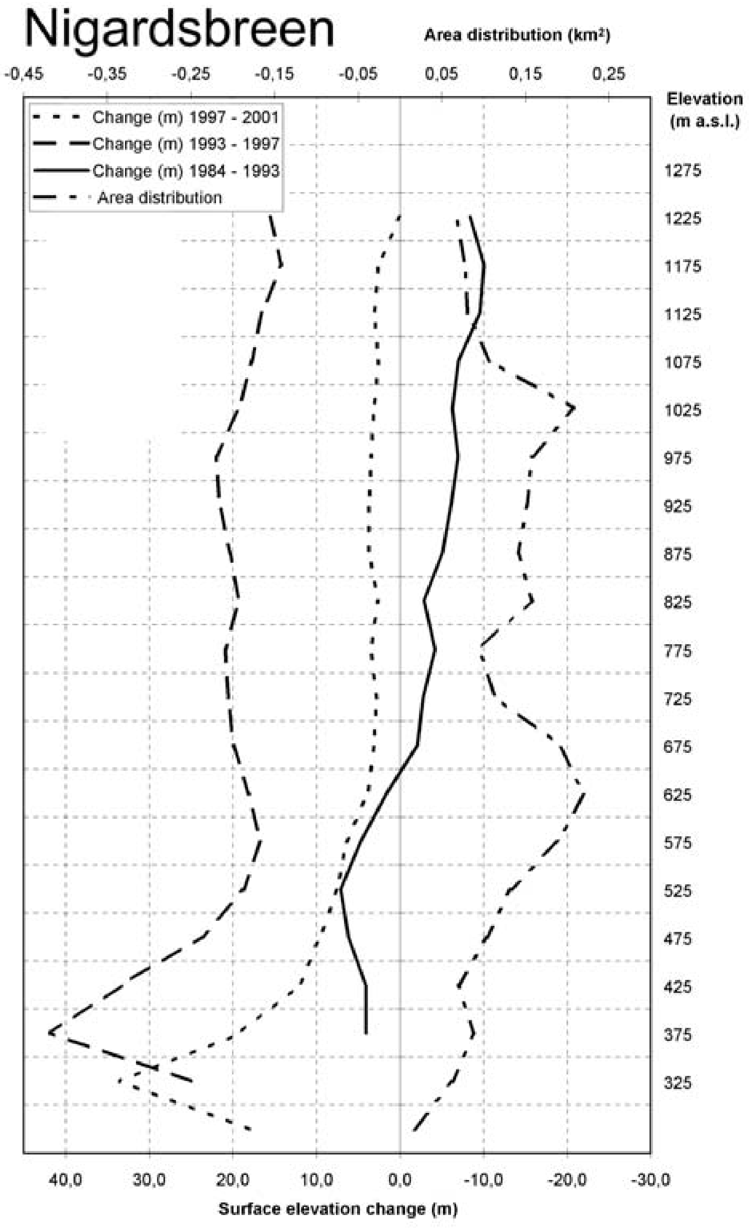

Fig. 11. Surface elevation changes from differencing the DEMs. Also shown is the area distribution plotted as a function of elevation for the investigated area on Nigardsbreen. The points making the curve are average values for zones covering every 50 m of elevation (the curve to the far right is the area distribution)

Bergsetbreen

Bergsetbreen advanced during the 1993–2001 period and thickened by almost 70 m in its lower parts but there was only a slight lowering for the rest of the glacier (Fig. 13). The average surface elevation change was positive, with a value of 3.2 m (Table 5), although with an accuracy of ±5.1m.

Discussion

Glacier velocities

As noted earlier, the accuracy of the cross-correlation matching method is about 0.5 m using orthophotos of 0.5 m resolution, giving accuracy for the daily velocities of 0.05 m d^{-1}. This means that all the presented velocities in Table 3 are significant.

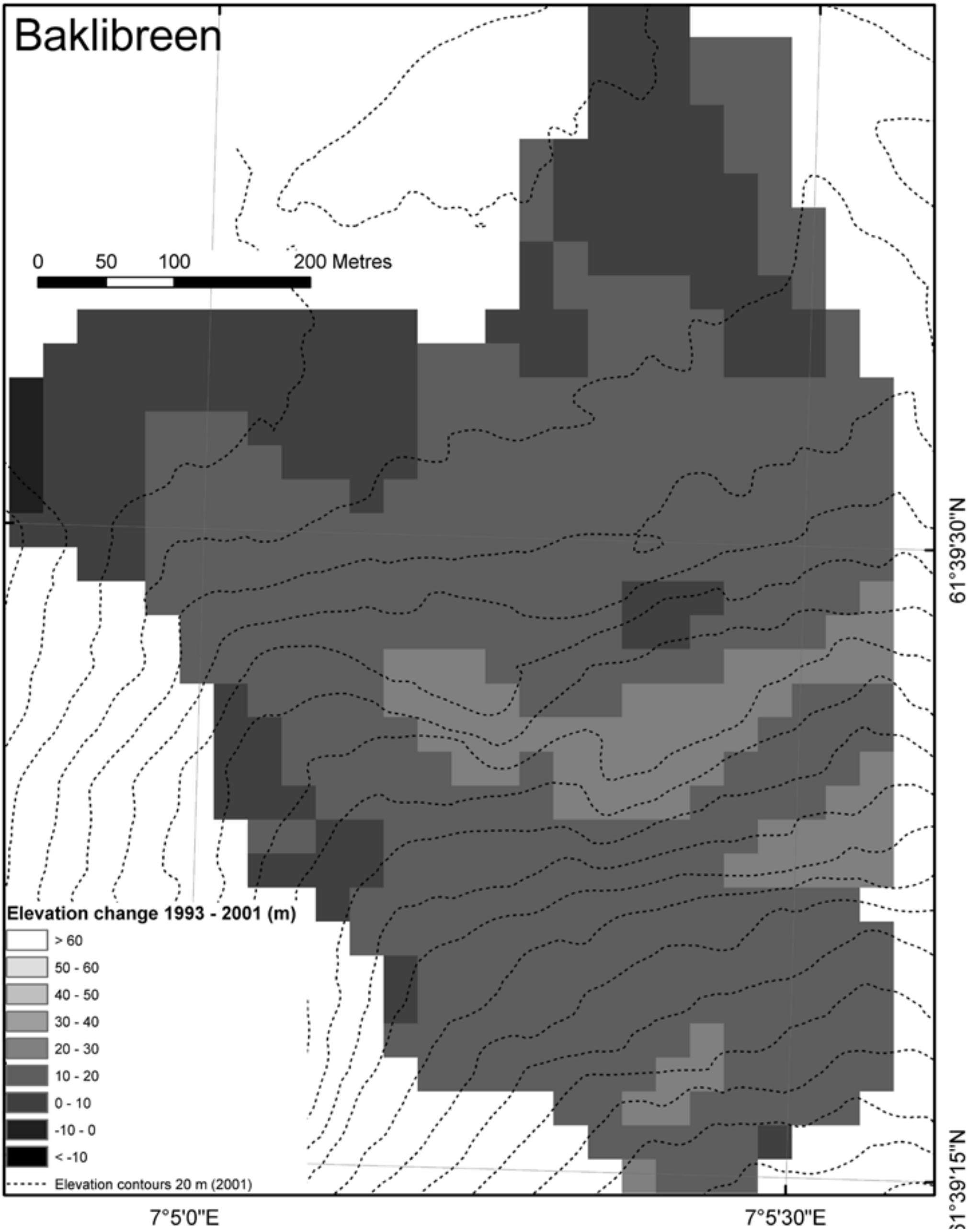

Fig. 12. Surface elevation change from 1993 to 2001 on Baklibreen from differencing of DEMs

The good agreement between the orthophoto captured velocities at Nigardsbreen and the GPS measured ones from the same period also confirms that the method of cross-correlation matching is working (Table 3). As seen from Table 3, the similarity between GPS-measured velocities is greater in the June to August period than for the August to September period. This may be explained by a decrease in surface melting, leading to a drop in subglacial water pressure and finally resulting in a decrease in

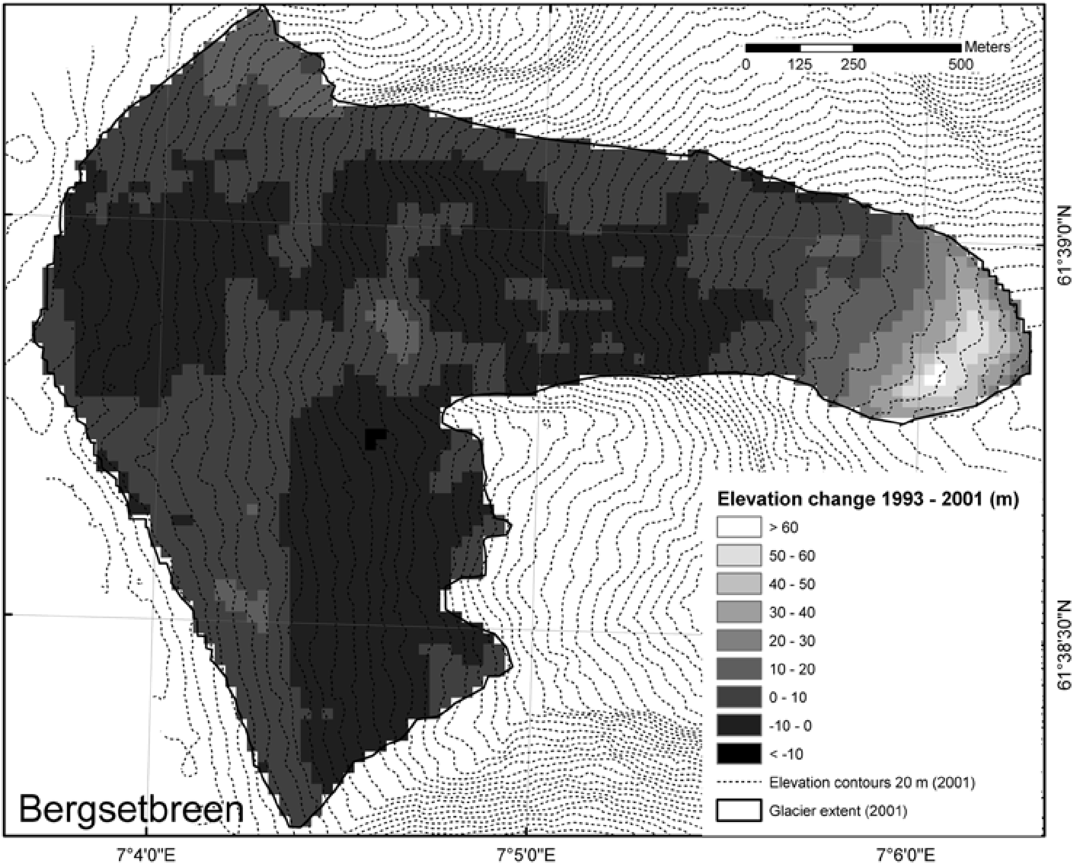

Fig. 13. Surface elevation change from 1993 to 2001 on Bergsetbreen from differencing of DEMs

sliding velocity in the late summer. The relation between subglacial water pressure and surface velocity is well known (Iken and Bindschadler 1986).

From Table 3 it can also be seen that the greatest deviation for the orthophoto velocities compared to the GPS measured ones from June to August was at point 1. This can be explained partly by the fact that the accuracy is a constant term having stronger relative effect on the smaller velocities.

Looking at how velocity on the tongue of Nigardsbreen has changed from 1938 to 2001, it is evident that the velocity is heavily affected by changes in glacier thickness, slope and width. The glacier retreated rapidly until the 1970s and advanced in the same manner from 1987 until 2003. The glacier thicknesses of all the earlier measurement periods in Table 4, except for 1968/69, were greater than the one in 2001 (Østrem *et al*. 1976). But given the surface development in Fig. 19 in Østrem *et al*. (1976), the surfaces of those periods were also less steep than the 2001 surface.

Since no detailed information on glacier surfaces from earlier times is available for direct comparison, it is difficult to model the impact these differences have in a detailed manner. However, from Table 4 it can be seen that the gentle surface slope of the retreating glacier in the late 1960s produced a much lower velocity at the tongue than the one measured for the steep front in 2001. The combination of glacier thickness, slope and width is probably also the explanation for the velocities of points 5 and 6 being so similar in 1937 and 2001, and the similarity in velocities of points 7 and 8 in 1949, 1951 and 2001. This means that the greater slope counteracted the effect of a thinner glacier in 2001, leaving the velocity more or less the same as in 1937 and 1949/50.

The reasons for the lower velocities at the lower part of two western icefalls can also be attributed to glacier slope and thickness. The glaciers are probably rather thin in both of these icefalls, and when the slopes become gentler just before they enter the main stream, the velocities decrease. This is best seen in Fig. 4 where there is a huge contrast in the velocities between the main stream and the tributary. This will also have implications for how the glacier geometry responds to a mass balance change.

There are no contemporary ground measurements of velocity at Baklibreen or Bergsetbreen. For Baklibreen there has been an increase in velocity since the monitoring project between 1987 and 1999 (Kjøllmoen 2000). This increase can also be attributed to a change in glacier thickness as shown in Fig. 12. Judging from the orthophotos Baklibreen is very thin and partly disintegrating in its steep lower parts, this indicates sliding rather than deformation as the main velocity component. It is in this hanging part of the glacier that ice avalanches usually originate. It is also in this very steep area, with slopes of 30° inclination, that we find the greatest velocities for Baklibreen and for all the three glaciers investigated.

As stated before, the velocity field of Bergsetbreen (Fig. 9) has a patchy appearance with the velocity changing rapidly within relatively small areas. Bergsetbreen is probably a rather thin glacier in its steep icefall, meaning that small changes in bottom topography will have an effect on the velocities seen on the surface. From the velocity field it can also be seen that there is a major difference in the velocity of the main drainage channel compared to the southern flank. The decreasing velocity towards the tongue is also due to changes in surface slope. The velocity pattern of the tributary icefalls on Nigardsbreen is also a property that would affect how glacier geometry responds to mass balance change.

Surface elevation changes

If one compares the mean surface changes for each glacier and period with the accuracy of the different surface change calculations (Table 5), it is clear that the overall change at Bergsetbreen from 1993 to 2001 and at Nigardsbreen from 1984 to 1993 is not significant; the same is found; when considering the mean of the absolute value of the changes (Table 5). Nevertheless, there seems to be an altitudinal trend with a thickening in the lower parts and a thinning in the upper parts for Nigardsbreen from 1984 to 1993 (Fig. 11), but due to the accuracy this interpretation should be treated with great care. Looking at Fig. 13 it is clear that even though the overall surface elevation change at Bergsetbreen was not significant, there is a significant thickening at the advancing front, with vertical growth reaching almost 70 m. Based on these data this means that Bergsetbreen's surface has been stable from 1993 to 2001 for all areas except for the advancing front, where there is a significant thickening. The reason for a stable surface elevation in the icefall is probably due to the steepness of Bergsetbreen. This steepness made it possible for the mass balance surplus from the late 1980s and early 1990s to be rapidly transported down the steep and thin icefall, giving a short reaction time for frontal changes below the icefall.

Baklibreen showed a thickening of 12.9 m from 1993 to 2001, and also a great spatial variability in the surface elevation increase, varying between –5.6 and 34.8 m. The great variance at Baklibreen can be explained by its rugged and partly disintegrated surface. The thin ice cover will also show huge differences due to small horizontal displacements in the disintegrated areas that cannot be attributed to changes in the total volume of the glacier. For comparison, the surface change data from the earlier works (Kjøllmoen 2000) showed an increase in ice thickness of 10 to 20 m from 1989 to 1994, a slight increase from 1994 to 1996 and no visible changes from 1996 to 1999. Measurements in 2001 showed a lowering of 0 to 3 m from 1999 (Kjøllmoen 2003a). Nevertheless, it seems that the increase revealed in this study from 1993 to 2001 is mainly explained by a thickening in the first few years of the period. One should also bear in mind that the investigations are not done for exactly the same area.

Having four available DEMs for Nigardsbreen made it possible to study the surface elevation changes in a more detailed manner. In general, Nigardsbreen was stable from 1984 to 1993 (there was a non-significant average surface lowering of 3.3 m), but experienced an average thickening of 19.3 m from 1993 to 1997, and an average thickening of 5.2 m from 1997 to 2001. From Fig. 11 it can also be seen that there were altitudinal differences for all three periods. The most striking feature is the great thickening near the snout in the two latter periods caused by the advancing front. There are also small signs of an advance in the 1984–1993 data with an average thickening of 7.1 m in the areas around 525 m a.s.l. Since it is the ablation area that is investigated, the surface elevation change must be due to increasing mass transport from higher elevations.

At the lower part of the northwestern icefall a thickening of up to 58 m for the 1993 to 1997 period can be seen (Fig. 10). Looking at the velocity pattern in this area, it can be seen that velocity decreases with decreasing altitude (Fig. 7). Mass surplus transported down this icefall would, as has been discussed for Bergsetbreen, lead to a mass build-up where the velocity decreases at the bottom of the icefall, because the high velocity of the main glacier stream would obstruct the tributary from rapidly deploying its mass further down.

Calculated transport times from the equilibrium line to the terminus for Nigardsbreen and Bergsetbreen were 24.2 and 8.6 years, respectively. According to Nye (1960), a kinematic wave travels three to five times faster than the surface velocity. According to van de Wal and Oerlemans (1995) one would usually not detect terminus changes when a kinematic wave arrives because of diffusion. But for steep glaciers like Nigardsbreen (10–20°) and Bergsetbreen (27°) the diffusion term would be very small because of its inverse dependence of slope, and the travel times for kinematic waves described by Nye (1960) valid.

The steepness of the two glaciers would also lead to basal sliding being a substantial part of the total surface velocity. Estimating deformation profiles (Paterson 1994) based on DEM slope and the few thickness data sets that exist reveals that basal sliding probably accounts for at least 40–60% of the total surface velocity on Nigardsbreen. Kinematic wave velocity is a weighted sum of glacier deformation (weight 5) and sliding (weight 3). The proportion of basal sliding on Nigardsbreen implies that the kinematic wave should not travel more than four times faster than the surface velocity. For Nigardsbreen and Bergsetbreen this means that it would take around six and two years, respectively, for a kinematic wave to travel from the ELA down to the front of the glacier.

Comparing mass balance data (Kjøllmoen 2003b) with length change data (Kjøllmoen 2001) for Nigardsbreen, one sees that the great mass balance surplus which started in 1987 (1.48 m **water equivalents (w.e.)**) and continued in 1989 and 1990 (3.2 and 1.77 m w.e.) gave the greatest front changes in the years 1994 to 1996 (36, 50 and 40 m change). There were also advances of 10, 21 and 14 m in the years 1991, 1992 and 1993 (Kjøllmoen 2001). This implies that there was a five to seven year lag from the abrupt changes in mass balance until the glacier advanced.

If one regards the abrupt change in mass balance in the late 1980s as a perturbation that could initiate a kinematic wave, the time lag for changes at the front agree quite well with Nye's theory for kinematic waves. It should be noted, however, that several assumptions have been made on basal sliding and lack of diffusion etc. Nevertheless, it shows that both Nigardsbreen and Bergsetbreen are glaciers that react fast to climatic changes due to their high velocity and steep gradient. For Nigardsbreen this is amplified by having a large accumulation area draining into a narrow tongue (Oerlemans 1992).

Assuming that Nigardsbreen and Bergsetbreen experienced the same changes in mass balance during the late 1980s and early 1990s, it appears that they reacted in somewhat different geometrical ways. From 1993 to 2001 Bergsetbreen only showed significant changes in its lower parts (Fig. 13) while Nigardsbreen showed a general thickening in the whole ablation area (Fig. 11). Both showed thickening at the front and were advancing. Even though travel times of kinematic waves cannot be taken as expressions of the time it takes to transport the mass surplus itself, they may reflect differences in this capability. The steep icefall of Bergsetbreen would be able to transport a mass balance surplus more rapidly down to the terminus than Nigardsbreen. This explains why we only see a frontal change for Bergsetbreen whereas we see a change for the whole investigated area at Nigardsbreen.

Conclusion

The results from this work show how high-resolution measurements from cross-correlation matching of orthophotos can be used to assess the velocity field of a glacier over a few days. The measured velocities for three different outlets of Jostedalsbreen are in good agreement with GPS-measured velocities for Nigardsbreen during the same time period. The average velocities ranged from 0.38 to 0.56 m d^{-1} for the three glaciers Baklibreen, Bergsetbreen and Nigardsbreen. Based on the differences between DEMs from 2001 and 1993 on all glaciers, in addition to DEMs from 1997 and 1984 at Nigardsbreen, an average increase in surface elevation of 22.1 m from 1984 to 2001 was found for Nigardsbreen and an increase of 3.2 and 14.3 m for Bergsetbreen and Baklibreen for the period of 1993 to 2001. From the surface elevation change it can be seen how the three different glaciers reacted to the highly positive winter balance of the late 1980s and early 1990s. These differences can be explained by differences in slope, glacier thickness, hypsometry and velocity.

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References

Andreassen, L.M., Elvehøy, H., Kjøllmoen, B., Engeset, R.V. and Haakensen, N., 2006: Glacier mass balance and length variation in Norway. *Annals of Glaciology,* (in press).

Baltsavias, E.P., 1996: Digital ortho-images – a powerful tool for the extraction of spatial- and geo-information. *ISPRS Journal of Photogrammetry and Remote Sensing,* 51**:** 63–77.

Bergersen, A., 1954: En undersøkelse av Svartisen ved Holandsfjorden 1950–51, med tillegg: Hastighetsmålinger ved Nigardsbreen, Jostedalen 1952 (in Norwegian). MSc thesis. Department of Physical Geography, University of Oslo, Norway.

Bindschadler, R.A. and Scambos, T.A., 1991: Satellite-image-derived velocity field of an Antarctic ice stream. *Science,* 252(5003)**:** 357–364.

Delacourt, C., Allemand, P., Casson, B. and Vadon, H., 2004: Velocity field of 'La Clapière' landslide measured by the correlation of aerial and QuickBird satellite images. *Geophysical Research Letters,* 31(15).

Finsterwalder, R., 1931: Geschwindigkeitsmessungen an Gletschern mittels Photogrammetrie. *Zeitschrift für Gletscherkunde für Eiszeitforschung und Geschichte des Klimas,* 19**:** 251–262.

Haeberli, W., King, L. and Flotron, A., 1979: Surface movement and lichen cover studies at the active rock glacier near the Grubengletcher, Wallis, Swiss Alps. *Arctic and Alpine Research,* 11(4)**:** 421–441.

IAHS(ICSI), UNEP and UNESCO, 1998: Fluctuations of glaciers 1990–1995. *In:* Haeberli, W., Hoelzle, M., Suter, S. and Frauenfelder, R. (eds): Vol. 7. International Association of Hydrologic Sciences. Paris. 296 p.

IAHS(ICSI), UNEP, UNESCO and WMO, 2001: Glacier Mass Balance Bulletin No. 6. *In*: Haeberli, W., Frauenfelder, R. and Hoelzle, M. (eds): World Glacier Monitoring Service. Zürich. 93 p.

Iken, A. and Bindschadler, R.A., 1986: Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: Conclusions about drainage system av sliding mechanism. *Journal of Glaciology,* 32(110)**:** 101–117.

Kasser, M. and Egels, Y., 2002: Digital Photogrammetry. Taylor and Francis. London, 351 p.

Kaufmann, V. and Ladstädter, R., 2003: Quantitative analysis of rock glacier creep by means of digital photogrammetry using multi-temporal aerial photographs: Two case studies in the Austrian Alps. *In:* Phillips, M., Springman, S.M. and Arenson, L.U. (eds): Permafrost: Proceedings of the Eighth International Conference on Permafrost, Zurich, Switzerland, 21–25 July 2003. 1**:** 525–530.

Kjøllmoen, B. (ed.) 2000: Glasiologiske undersøkelser i Norge – Glaciological investigations Norway 1999. Rapport nr 2. Norges Vassdrags- og Energidirektorat (NVE). Oslo. Norway. 140 p.

Kjøllmoen, B. (ed.) 2001: Glaciological investigations in Norway in 2000. Report no 2. Norwegian Water Resources and Energy Directorate (NVE). Oslo. Norway. 122 p.

Kjøllmoen, B. (ed.) 2003a: Glaciological investigations in Norway in 2001, Report no 1. Norwegian Water Resources and Energy Directorate (NVE). Oslo. Norway. 102 p.

Kjøllmoen, B. (ed.) 2003b: Glaciological investigations in Norway in 2002. Report no 3. Norwegian Water Resources and Energy Directorate (NVE). Oslo. Norway. 92 p.

Kjøllmoen, B. (ed.) 2004: Glaciological investigations in Norway in 2003, Report no 4, Norwegian Water Resources and Energy Directorate (NVE). Oslo. Norway. 98 p.

Kääb, A., 2002: Monitoring high-mountain terrain deformation from repeated air- and spaceborne optical data: examples using digital aerial imagery and ASTER data. *ISPRS Journal of Photogrammetry and Remote Sensing,* 57(1–2)**:** 39–52.

Kääb, A., 2005: Combination of SRTM3 and repeat ASTER data for deriving alpine glacier flow velocities in the Bhutan Himalaya. *Remote Sensing of Environment,* 94(4)**:** 463–474.

Kääb, A. and Funk, M., 1999: Modelling mass balance using photogrammetric and geophysical data: a pilot study at Griesgletcher, Swiss Alps. *Journal of Glaciology,* 45(151)**:** 575–583.

Kääb, A. and Vollmer, M., 2000: Surface geometry, thickness changes and flow fields on creeping mountain permafrost: automatic extraction by digital image analysis. *Permafrost and Periglacial Processes,* 11**:** 315–326.

Kääb, A., Haeberli, W. and Gudmundsson, G.H., 1997: Analysing the creep of mountain permafrost using high precision aerial photogrammetry; 25 years of monitoring Gruben rock glacier, Swiss Alps. *Permafrost and Periglacial Processes,* 8(4)**:** 409–426.

Kääb, A., Lefauconnier, B. and Melvold, K., 2006: Flow field of Kronebreen, Svalbard, using repeated Landsat7 and ASTER data. *Annals of Glaciology,* (in press).

Nielsen, C., 1970: Triangulering av bevegelsesretninger i 1969. *In*: Pytte, R. (ed.): *Glasiologiske undersøkelser i Norge 1969*. Hydrologisk avdeling. Norges Vassdrags og elektrisitetsvesen. 96 p.

Nye, J.F., 1960: The response of glaciers and ice sheets to seasonal and climatic changes. *Proceedings of the Royal Society of London, Series A,* 257(1216)**:** 589–584.

Oerlemans, J., 1992: Climate sensitivity of glaciers in southern Norway: application of an energy-balance model to Nigardbreen, Hellstugubreen and Ålfotbreen. *Journal of Glaciology,* 38(129)**:** 223–232.

Paterson, W.S.B., 1994: The Physics of Glaciers. Pergamon/Elsevier Science. Oxford. 480 p.

Pillewizer, W., 1950: Bewegungsstudien an Gletschern des Jostedalsbre in Süd-Norwegen. *Erdkunde,* 4**:** 201–206.

Rolstad, C., 1995: Satellitt- og flybilder til bestemmelse av bredynamikk (in Norwegian). MSc thesis. Departement of Physical Geography, University of Oslo. Norway. 129 p.

Tønsberg, O.M., 2003: Kartlegging av bredynamikken på en fremrykkende bre -Nigardsbreen, Sør-Norge – vha GPS og fotogrammetri (in Norwegian). MSc thesis. Departement of Physical Geography, University of Oslo. 65 p.

van de Wal, R.S.W. and Oerlemans, J., 1995: Response of valley glaciers to climate change and kinematic waves: as study with numerical ice-flow model. *Journal of Glaciology,* 41(137)**:** 142–152.

Østrem, G., Liestøl, O. and Wold, B., 1976: Glaciological investigations at Nigardsbreen, Norway. *Norsk Geografisk Tidskrift – Norwegian Journal of Geography,* 30(1)**:** 187–209.

Østrem, G., Dale Selvig, K. and Tandberg, K., 1988: Atlas over breer i Sør-Norge – Atlas of Glaciers in South Norway. Meddelelse nr. 61 fra Hydrologisk Avdeling. Norges Vassdrags- og Energiverk. 248 p.

Østrem, G., Haakensen, N., Kjøllmoen, B., Laumann, T. and Wold, B., 1991: Massebalansemålinger på norske breer 1988 og 1989. NVE-Publikasjon nr 11. Hydrologisk avdeling, Norges vassdrags- og energiverk. 78 p.

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