A surge of Perseibreen, Svalbard, examined using aerial photography and ASTER high resolution satellite imagery

Julian A. Dowdeswell & Toby J. Benham

The identification of surge activity is important in assessing the duration of the active and quiescent phases of the surge cycle of Svalbard glaciers. Satellite and aerial photographic images are used to identify and describe the form and flow of Perseibreen, a valley glacier of 59 km^2 on the east coast of Spitsbergen. Heavy surface crevassing and a steep ice front, indicative of surge activity, were first observed on Perseibreen in April 2002. Examination of high resolution (15 m) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery confirmed this surge activity. Perseibreen retreated by almost 750 m between 1961 and 1990. Between 1990 and the summer of 2000, Perseibreen switched from retreat and its front began to advance. Rapid advance was underway during the period June 2000 to May 2001, with terminus advance at over 400 m yr^{-1}. Between May and August 2001 the rate increased to over 750 m yr^{-1}. The observed crevasse orientation indicates that ice was in longitudinal tension, suggesting the down-glacier transfer of mass. Ice surface velocities, derived from image correlation between ASTER images, were 2 - 2.5 m d^{-1} between May and August 2001. The glacier was flowing at a relatively uniform speed with sharp velocity gradients located close to its lateral margins, a velocity structure typical of ice masses in the active phase of the surge cycle. The stress regime is extensional throughout and the surge appears to be initiated low on the glacier. This is similar to the active-phase dynamics of other Svalbard tidewater glaciers. Perseibreen has probably been inactive since at least 1870, a period of about 130 years to the present surge which defines a minimum length for the quiescent phase.

J. A. Dowdeswell & T. J. Benham, Centre for Polar Observation and Modelling, Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK, jd16@cam.ac.uk.

A number of the glaciers and ice cap drainage basins in Svalbard, Norwegian High Arctic, are inferred to be of surge-type (Liestøl 1969, 1993; Schytt 1969); that is, they experience decades to centuries of stagnation and marginal retreat punctuated by periods of a few years where ice velocity increases by several orders of magnitude, the ice-surface becomes heavily crevassed, and down-glacier transfer of mass and ice front advance take place (Meier & Post 1969). Estimates of the proportions of glaciers in the archipelago that surge range between about 13 and 36% (e.g. Dowdeswell et al. 1991; Hamilton & Dowdeswell 1996; Jiskoot et al. 1998), although Lefauconnier & Hagen (1991) propose that the figure may be as high as 90%. However, only about 100 Svalbard ice masses have been observed during the active phase of the surge cycle (Dowdeswell et al. 1991; Hagen et al. 1993; Jiskoot et al. 1998, 2000). The identification of surge activity is important

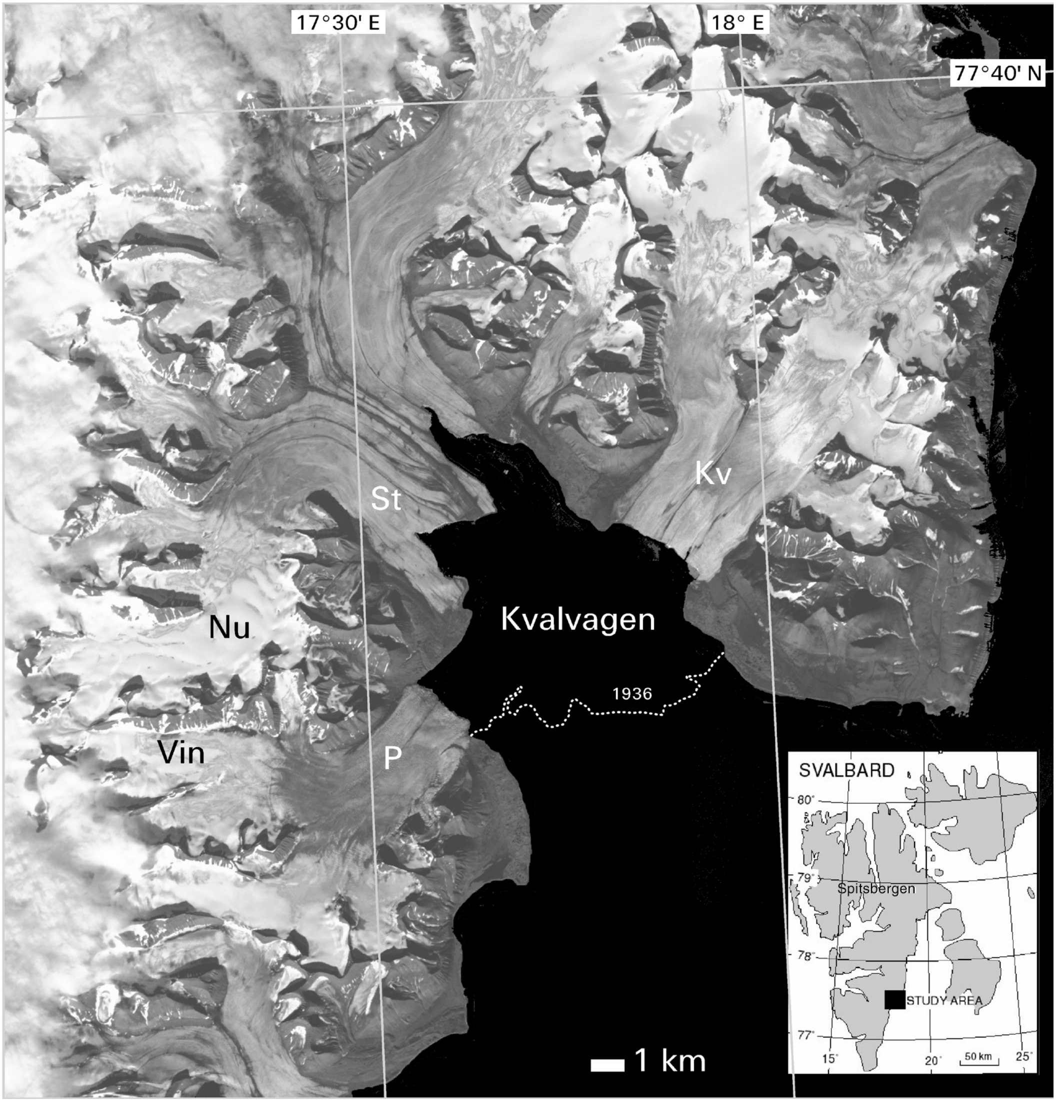


Fig. 1. An ASTER image of the coast and glaciers around Kvalvagen, including Perseibreen, acquired on 19 August 2001 (scenes 207/19/1 and 207/20/1, Orbit 8885). The approximate position of the 1936 ice front is shown. The location of the study area within Svalbard is inset. P is Perseibreen, St is Strongbreen, Kv is Kvalbreen, Nu is Nuddbreen and Vin is Vinbeggbreen.

in order both to assess the absolute duration of the active and quiescent phases of surge behaviour (Dowdeswell et al. 1991, 1995) and to provide observations to enhance our understanding of the processes relating to this form of non-steady ice flow (e.g. Nuttall et al. 1997; Rolstad et al. 1997; Melvold & Hagen 1998; Murray et al. 1998, 2003a, b; Luckman et al. 2002).

In this contribution, we use satellite and aerial photographic imagery to identify and describe the form and flow of a Svalbard glacier, Perseibreen (Fig. 1), during the active and stagnant phases of the surge cycle. Heavy surface crevassing and a steep ice front, which are often the initial indicators of surge activity in Svalbard glaciers (e.g. Liestøl 1969; Dowdeswell et al. 1991; Hagen et al. 1993), were first observed on Perseibreen in April 2002. We emphasize the utility of newly available high resolution (15 m) imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument on the recently launched Terra satellite in confirming this surge activity and enabling calculations of the ice surface velocity field.

Perseibreen is a valley glacier of about 59 km^2 in area, located on the east coast of Spitsbergen at 77° 25' N, 17° 30' E (Hagen et al. 1993) (Fig. 1). Its identification number in the Glacier Inventory of Svalbard is 115 03. The glacier drains into Kvalvagen, on the south-eastern side of Spitsbergen. The upper part of the glacier is divided into several sub-basins defined by intervening rock ridges. Ice in these upper basins joins to form a single trunk glacier with a maximum flowline length of 11.5 km (Fig. 1). The glacier has an elevation range between zero and about 650 m above sea level, and is predominantly east-facing.

Data sources and methods

Three sources of data are used to reconstruct the terminus position and surface characteristics of Perseibreen. First, historical maps of the east coast of Spitsbergen were used to establish the relative distribution of ice in the area of what is now the ice-free bay of Kvalvagen (Fig. 1). These early maps together with historical reports, discussed in some detail by Lefauconnier & Hagen (1991), provide information on the gross distribution of ice at several dates from 1870 onwards. Their relative accuracy can be established by comparing their coastal outlines with those in modern maps. Secondly, oblique and vertical aerial photographs in the collections of the Norwegian Polar Institute (NPI) were also acquired. The earliest photographs were oblique images from 1936, followed by a set of larger-scale vertical photographs from 1948 of part of the glacier and a series of smaller-scale (1:40 000 to 1:50 000) vertical photographs from 1961 onwards.

The third data set used in this study is a series of ASTER satellite images. The ASTER instrument, carried aboard the Earth Observing System AM-1 satellite known as Terra, is in a sun-synchronous polar orbit. Images are 60 by 60 km in coverage, and a stereo capability is provided in a single near-infrared band (3N) by a second rear-looking telescope. The instrument provides wide spectral coverage with bands in the visible and near-infrared (VNIR) (0.52 - 0.86 μm), and also in the short-wave infrared (1.6 - 2.4 μm) and thermal infrared (8 - 12 μm) bands. We use only VNIR digital imagery here, which has a spatial resolution of 15 m.

Image correlation methods were used to extract ice surface velocities from a pair of ASTER images (Scambos et al. 1992). The images were co-registered to a common coordinate system, but the surface character of the ASTER imagery for May and August 2001 differed considerably, with far greater snow cover in the earlier image. Therefore, use of image transformation techniques such as Principal Components Analysis (as suggested by Scambos et al. 1992) did not yield single-band images suitable for image correlation. Visual analysis and trial correlation indicated that the nadir (3N) and backward-looking (3B) near-infrared bands were closest in general greyscale character, while retaining 15 m resolution. Correlation was performed on this imagery using IMCORR software (Scambos et al. 1992), encapsulated within our own visual front-end software.

Errors in measurement of displacements by correlation may arise from co-location of images, and from inaccuracy in the correlation process. In the absence of detailed ground control-point information, we used the May 2001 ASTER image as the reference coordinate system. We made use of image correlation and visual inspection to identify suitable control points. It is difficult to assess the co-location errors involved, but we suggest that the error from this source is probably within a half to one ASTER pixel (7.5 m - 15 m).

The image correlation process returns an estimate of displacement error, which makes reference to strengths of other potential matching points within the neighbourhood. Only matches achieved within a conservative error threshold were accepted. We estimate that error from this source is sub-pixel, within a quarter to a half of a pixel (ca. 4 - 7.5 m).

Image correlation using this method can be affected by deformation or rotation of ice surface features between image acquisitions. At Perseibreen, however, it appears that ice flow was relatively uniform across-glacier, with strong shear margins close to either side-wall. This is typical of many Svalbard surge-type glaciers (e.g. Hambrey & Dowdeswell 1997; Dowdeswell et al. 1999; Murray et al. 2003a, b). Such "plug flow" is also typical of active-phase surge-type glaciers in general (e.g. Meier & Post 1969; Kamb et al. 1985). Issues concerning deformation or rotation are therefore relatively insignificant in this case.

In the absence of a high resolution Digital Elevation Model for the area, we have recorded only horizontal displacements. However, a nominal ice surface slope estimate of 3° would result in a maximum difference of only 1 - 2 m between two- and three-dimensional displacement values. Any such error would be subsumed within other measurement errors for the displacements.

Historical changes in the glaciers around Kvalvagen

Examination of oblique aerial photographs shows that the substantial bay that now forms the inner part of Kvalvagen in eastern Spitsbergen, and into which Perseibreen, Strongbreen and Kvalbreen now flow (Fig. 1), was completely filled with glacier ice in 1936 (Lefauconnier & Hagen 1991). However, Hauglin's early map of 1870 indicates that the bay was free of glaciers at that time, and that Kvalbreen and Strongbreen had separate ice fronts, as they do today (Lefauconnier & Hagen 1991) (Fig. 1). In addition, Strongbreen is depicted with two lobes in the early map, which probably represent ice flowing from Nuddbreen and Morsjnevbreen, again similar to the situation today. This level of detail on the Hauglin map suggests that it provides some accuracy in terms of the relative positions of the glacier fronts and adjacent bedrock.

Lefauconnier & Hagen (1991) also report on a map by Vasiliev which showed that ice was close to the mouth of the bay by 1900. This view is supported by Rabot (1900), who records the observations of whalers that what had been a useful anchorage for them was filled with glacier ice in the years just prior to 1876. This suggests that an advance, possibly a surge, of Strongbreen may have taken place between 1870 and 1876

Since the first oblique photographs of 1936, a sequence of vertical aerial photographs acquired by the NPI shows that the ice fronts of Strongbreen and Kvalbreen have been consistently in retreat and have separated to form the two tidewater margins that we see today. Once its larger neighbours retreated past it, Perseibreen also gained a separate tidewater ice front. The locations of the glaciers draining into Kvalvagen in summer 2001 are shown on the image in Fig. 1. The area of open water resulting from retreat since 1936 is illustrated clearly.

Table 1. Fluctuations of the terminus of Perseibreen between 1961 and 2001 (Fig. 2), measured from a time series of vertical aerial photographs and ASTER satellite images. The standard deviations represent variability across the ice front.

Time interval	Mean & standard deviation advance/retreat (m yr^{-1})	Max. advance/ retreat (m yr^{-1})	No. of days
Aug 61 [a]–Aug 90 [a]	–26 ± 11	–47	10 589
Aug 90 [a]– June 00 [b]	24 ± 18	46	3609
June 00 [b]–May 01 [b]	434 ± 77	561	309
May 01 [b]–Aug 01 [b]	773 ± 192	1113	107

[a] NPI aerial photographs.

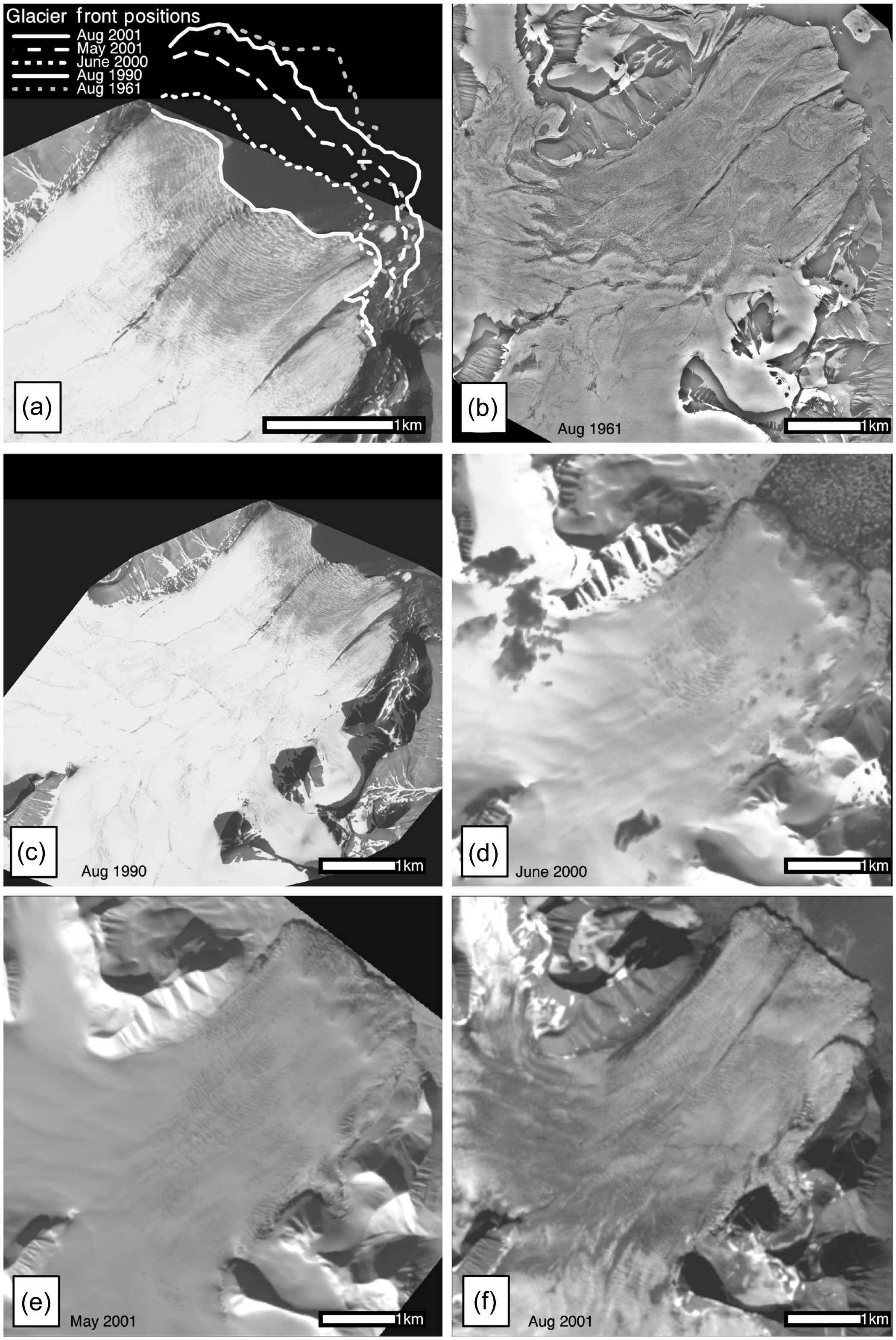
[b] ASTER satellite images.

Recent terminus fluctuations of Perseibreen

Changes in the position of the terminus of Perseibreen are plotted from geo-rectified vertical aerial photographs and ASTER imagery at five intervals over the period 1961 to 2001 (Fig. 2a). The individual aerial photographs and satellite images of the ice front are shown in Fig. 2b - f. The rates of ice front advance or retreat are given in Table 1. The terminus of Perseibreen retreated by almost 750 m (averaged across its 2.6 - 2.7 km-wide margin) between 1961 and 1990, at a mean rate of 26 m yr^{-1}. Some time between 1990 and the summer of 2000, the retreat of Perseibreen ended. Its front began to move forward, advancing by almost 250 m at a mean rate of 24 m yr^{-1}, to cover an area of 0.65 km^2.

While it is not clear exactly when the readvance began, the data in Table 1 show that rapid advance was certainly underway during the period from June 2000 to May 2001. The terminus of Perseibreen advanced by 368 m (averaged across its width) over this interval at a rate of over 400 m yr^{-1}. Between May 2001 and our last satellite image from August 2001, the rate of advance

Fig. 2 (opposite page). Time series of images of the terminus region of Perseibreen from vertical aerial photographs and ASTER satellite images. Note the changing nature of the crevasse patterns. (a) Ice front positions superimposed on 1990 aerial photograph. The ice front in: (b) 15 August 1961 (NPI no. S61-3223); (c) 12 August 1990 (NPI no. S90-4038); (d) 29 June 2000 (ASTER scene 207/20/2, orbit 2827); (e) 4 May 2001 (ASTER scene 210/19/3, orbit 7327); (f) 19 August 2001 (ASTER scene 207/20/1, Orbit 8885).


Glacier front positions
Aug 2001
May 2001
June 2000
Aug 1990
Aug 1961
(a)
1km
(b)
Aug 1961
1km
(c)
Aug 1990
1km
(d)
June 2000
1km
(e)
May 2001
1km
(f)
Aug 2001
1km

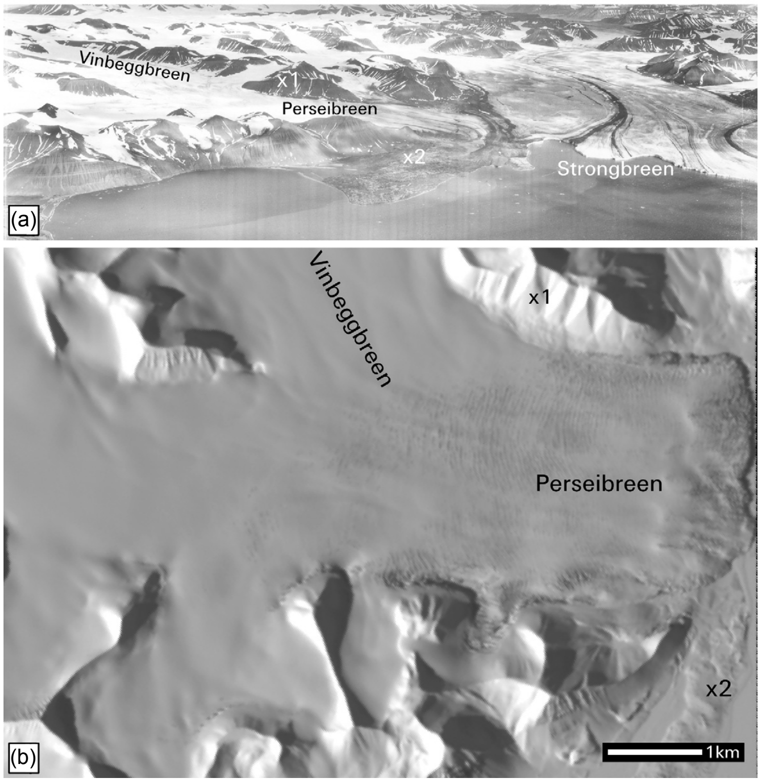


Fig. 3. Imagery of Perseibreen in August 1936 and May 2001. (a) Oblique aerial photography of the glacier acquired in summer 1936 (NPI no. S36 1724). (b) ASTER satellite image, acquired during a surge showing heavy surface crevassing and a steep ice front on 4 May 2001 (scene 210/19/3, orbit 7327). Points labelled x1 and x2 are located on both the oblique and vertical aerial photographs to aid comparison.

had increased still further to over 750 m yr^{-1} (Table 1). It should be remembered, however, that the value of 750 m yr^{-1} was measured over the late spring and summer months only, when meltwater inputs and thus velocity might be expected to be at their highest (e.g. Nuttall et al. 1997).

Form and flow of Perseibreen

Surface crevassing

The surface of Perseibreen was heavily crevassed when observed during a commercial flight into Svalbard on 6 April 2002. The ice front also appeared to be steep, and advancing into the disturbed winter sea ice cover beyond its tidewater margin. Importantly, the crevassing appeared to extend into the upper basins feeding the trunk glacier, although parts of the ice surface were obscured by snow cover. The combination of terminus advance together with crevassing not only close to the ice front, but extending into the glacier accumulation area, suggested that a surge was in progress.

The subsequent inspection of ASTER satellite images from May and August 2001 confirmed that crevasses, oriented generally perpendicular to ice flow direction (Fig. 3), were present over much of the glacier. Digital image enhancement by thin-edge detection of ice surface features allows the pattern of crevassing to be illustrated clearly for the August 2001 image, which has less snow cover than imagery obtained earlier in the year (Fig. 4). The sensor and scene geometry of the backward-looking ASTER 3B band data provided the clearest view of surface crevassing.

The development of crevassing on the surface of Perseibreen can also provide information on the timing of surge activity and the nature of the stress regime. Almost no crevasses were observed on 1961 aerial photographs of the glacier. A series of crevasses, perpendicular to flow and distributed in a roughly semi-circular pattern within ca. 1.6 km of the glacier terminus was visible in 1990 photographs (Fig. 2a, c). However, no crevasses were observed higher on the glacier or in any of its tributary basins. The crevasses are

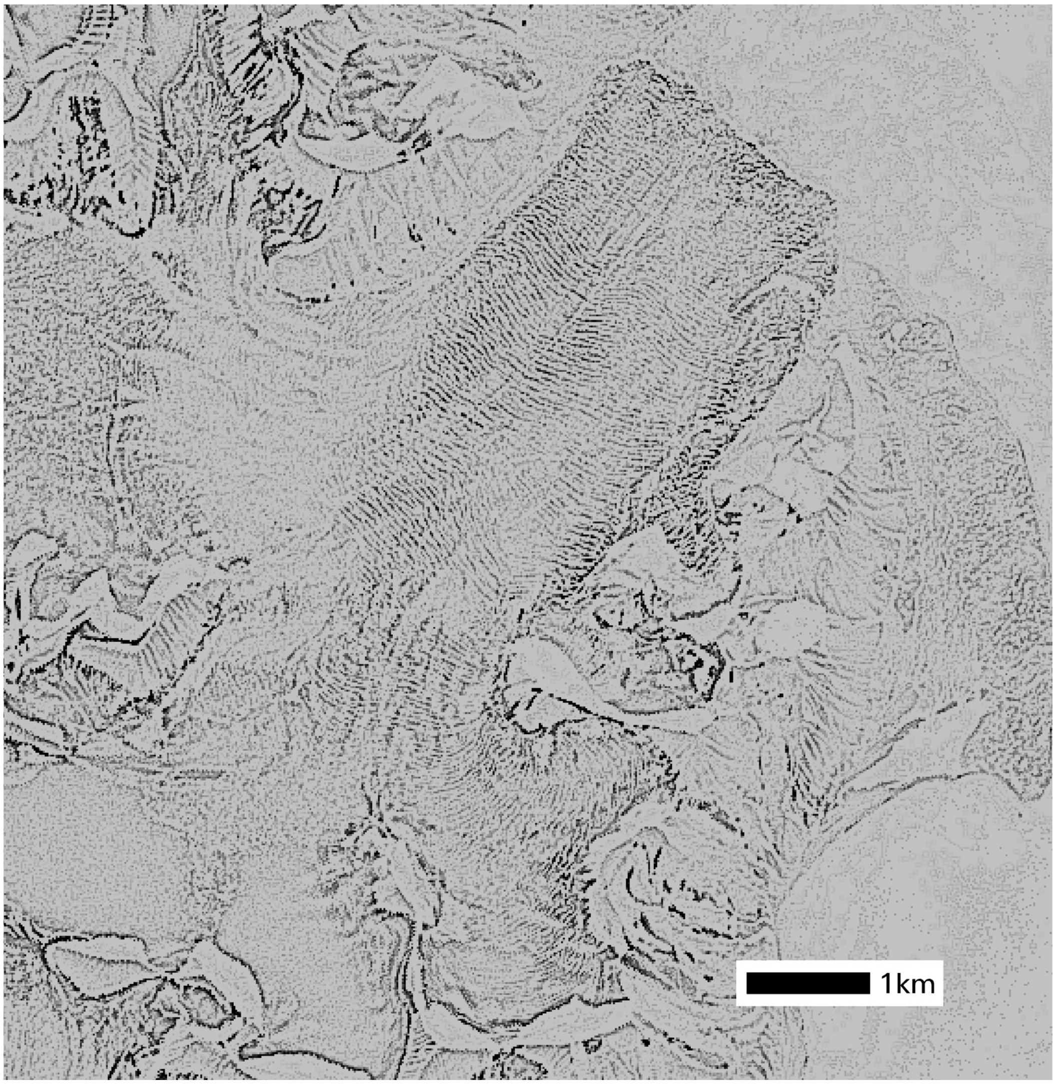


Fig. 4. Thin-edge detection of ASTER imagery (band 3B), emphasizing the distribution of crevasses on Perseibreen in August 2001.

distributed around what appears to be a concave calving bay within the ice front, and may have formed as the glacier margin retreated into slightly deeper water and came into a regime of longitudinal tension. Whilst the snow cover present on the glacier in these photographs might possibly conceal crevassing, we note that in the coarser resolution ASTER images of June 2000 and May 2001, where snow cover appears similar or even more widespread, evidence of crevassing higher on the glacier is visible.

The pattern of ice surface crevassing on ASTER satellite images of Perseibreen acquired in 2000 and 2001 is that of increasing surface crevassing, which appears to spread up-glacier through this period. By May 2001, crevasses were present to at least 5 km from the ice front, and had also developed in one of the small upper basins to the south of the trunk glacier. Thus, the surge was already underway by the date of this image. The presence of spring snow-cover makes this observation a minimum value for the area of crevassing. By August 2001, crevasses oriented perpendicular to ice flow were present not only over the

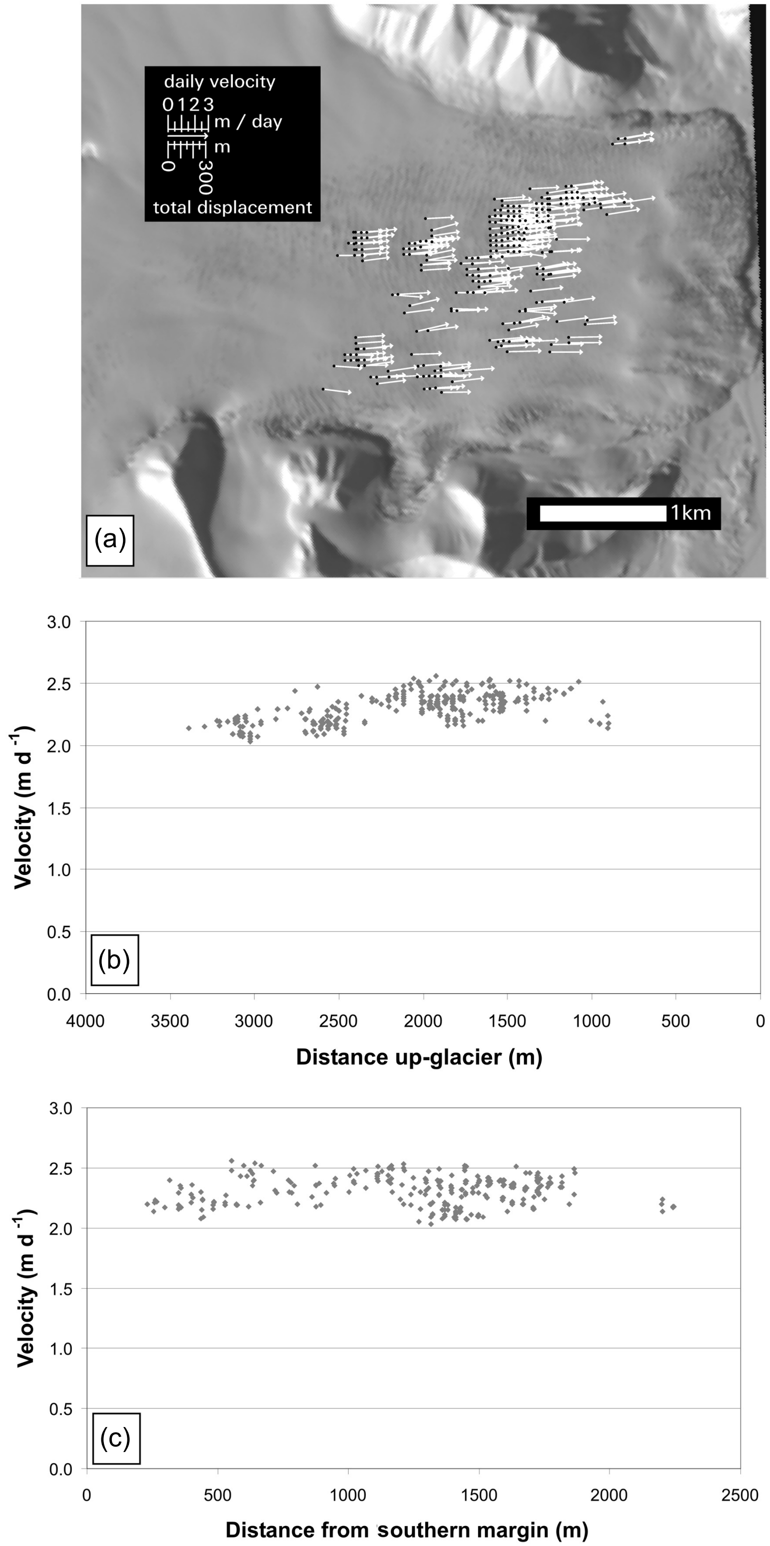


Fig. 5. Ice surface velocity field derived by feature tracking from ASTER images of 4 May and 19 August 2001. The velocities are averaged over this 107 day period. (a) Ice-flow vectors superimposed on May ASTER image. (b) Scatter plot of velocities with distance from ice front. (c) Scatter plot of velocities across the glacier.

trunk glacier, but also in a number of the upper basins (Fig. 4).

Velocity structure

The velocity structure in the lower part of Perseibreen (between about 900 m and 3.5 km up-glacier), derived from surface feature tracking, also indicated relatively rapid motion (Fig. 5). Ice surface velocities ranged from about 2 to about 2.5 m d^{-1} (730 - 912 m yr^{-1}), averaged over the period 4 May to 19 August 2001 (Fig. 5). These velocities match well with measured glacier terminus advance over the same period, which averaged 773 m yr^{-1} with a maximum of 1113 m yr^{-1} (Table 1). This also suggests that little mass is being lost by iceberg calving as the ice front advances into marine waters.

There was also little discernible variation in velocity either with distance from the terminus (Fig. 5b) or across the glacier (Fig. 5c) over the area where feature tracking was possible (Fig. 5a). This suggests that the glacier was flowing at a relatively uniform speed with a sharp velocity gradient probably located close to its lateral margins. This is a velocity structure that is typical of ice masses in the active phase of the surge cycle (e.g. Meier & Post 1969; Kamb et al. 1985; Hambrey & Dowdeswell 1997; Nuttall et al. 1997; Rolstad et al. 1997; Murray et al. 1998, 2003a, b; Dowdeswell et al. 1999; Luckman et al. 2002).

Discussion: a surge of Perseibreen

The glaciers on the east coast of Spitsbergen were discussed in some detail by Lefauconnier & Hagen (1991) in the context of their surge history. These authors noted that there was no observational evidence of surge activity on aerial photographs of Perseibreen acquired at several intervals since 1936. In addition, they suggested that an examination of the medial and marginal moraines did not show any of the looped structures that are considered indicative of past surges (Meier & Post 1969; Dowdeswell et al. 1991). However, Lefauconnier & Hagen (1991) did comment that there appeared to be a build-up of ice in the accumulation area of the glacier shown on 1970 aerial photographs, and that this could be an indication that Perseibreen "may surge in the near future" (p. 35). The observations of the ice-surface crevassing and terminus advance documented here confirm this prediction, and indicate that Perseibreen is a surge-type glacier in the active phase of the surge cycle (Figs. 2 - 5, Table 1). At the time of reporting, the surge of Perseibreen has been going on for over one year, with May 2001 as a conservatively estimated start date. The surge may continue for several years given that Svalbard surges usually have a relatively long duration (Dowdeswell et al. 1991). However, an assessment of the length of the active phase is, as yet, premature.

There is, unfortunately, little evidence to indicate the duration of the interval between surges of Persiebreen; the time series of aerial photographs and historical maps suggests that no previous surge has occurred since at least the 1930s. There was an advance of part of the system of glaciers flowing into Kvalvagen between 1870 and 1876, but it is more probable that this involved Strongbreen and its associated drainage basin, and not Perseibreen. This is because the pattern of medial moraines on NPI maps and aerial photographs from 1936 suggests that Strongbreen extended beyond Perseibreen and further into Kvalvagen, and that the terminal moraines marking the extent of Perseibreen did not extend significantly beyond the side valley it still occupies (Fig. 1). Thus, Perseibreen has probably been quiescent since at least 1870, a period of about 130 years to the present surge.

Murray et al. (2003b) have noted that the nature of surge initiation and surge front propagation varies between Svalbard tidewater and land-terminating glaciers. At tidewater glaciers, such as Monacobreen, Osbornebreen and Fridtjovbreen (Rolstad et al. 1997; Luckman et al. 2002; Murray et al. 2003a), the changing nature of crevassing and velocity structure indicates that the surge starts over the whole lower region of the glacier and then propagates up-glacier. By contrast, several Svalbard glaciers with their termini on land, for example Usherbreen and Bakaninbreen (Hagen 1987, Murray et al. 1998), exhibit surge fronts formed in the upper glacier that propagate downward. The changing pattern of crevassing at Perseibreen, with the up-glacier spread of crevasses (Figs. 2, 4), suggests that the glacier behaves in a similar way to the tidewater glaciers described above. In addition, the crevasses on Perseibreen are orientated perpendicular to flow throughout the period of observation, implying longitudinal extension and the absence of a compressional wave associated with the down-glacier propagation of a surge front (Hodgkins & Dowdeswell 1994; Lawson et al. 1994).

Conclusions

Perseibreen is a Svalbard surge-type glacier in the active phase of the surge cycle (Figs. 1 - 2). A steep and advancing ice front, combined with heavy ice surface crevassing which extends over both the trunk glacier and the upper basins, supports this view. The surge was definitely underway in June 2000, but probably began before this. It was still underway in April 2002, and may continue for several years given that Svalbard surges usually have a relatively long duration (Dowdeswell et al. 1991).

During the surge, velocities reached 2 - 2.5 m d^{-1}, with strong lateral shear margins (Fig. 5). Ice terminus advance was up to 750 m yr^{-1} (Fig. 2, Table 1).

The up-glacier spread of crevasses orientated perpendicular to ice flow direction, and the lack of crevassing parallel to flow at any point during the surge, suggests that the stress regime is extensional throughout and the surge is initiated low on the glacier. This is similar to the active-phase dynamics of other Svalbard tidewater glaciers that are of surge-type (Murray et al. 2003b).

The examination of historical maps and NPI aerial photographs showed that Persiebreen has been retreating and stagnant since at least 1870 (Fig. 3a), indicating a minimum quiescent-phase length of 130 years.

High resolution (15 m) ASTER digital satellite imagery was useful in identifying surface features such as crevasses (Fig. 4), and in quantitative analyses such as image correlation using IMCORR software (Scambos et al. 1992) to derive ice surface velocity fields (Fig. 5a).

Acknowledgements.—The crevassed surface of Perseibreen was initially observed by Julian and Adam Dowdeswell while flying into Svalbard on a visit to the University Courses on Svalbard at the invitation of Dr Tine Rasmussen. The work was partly supported by a grant to the Centre for Polar Observation and Modelling from the Natural Environment Research Council. ASTER data were provided by the Distributed Active Archive Center, at the U.S. Geological Survey EROS Data Center in Sioux Falls, South Dakota. IMCORR source code was obtained from the National Snow and Ice Data Centre at http://nsidc.org/data/velmap/imcorr.html. We thank Luke Copland, University of Alberta, for helpful discussion regarding this software and its use for velocity tracking. We also thank the Norwegian Polar Institute for permission to reproduce aerial photographs from their collection.

References

Dowdeswell, J. A., Hamilton, G. S. & Hagen, J. O. 1991: The duration of the active phase on surge-type glaciers: contrasts between Svalbard and other regions. *J. Glaciol. 37*, 388–400.

Dowdeswell, J. A., Hodgkins, R., Nuttall, A.-M., Hagen, J. O. & Hamilton, G. S. 1995: Mass balance change as a control on the frequency and occurrence of glacier surges in Svalbard, Norwegian High Arctic. *Geophys. Res. Lett. 22*, 2909–2912.

Dowdeswell, J. A., Unwin, B., Nuttall, A.-M. & Wingham, D. J. 1999: Velocity structure, flow instability and mass flux on a large Arctic ice cap from satellite radar interferometry. *Earth Planet. Sci. Lett. 167*, 131–140.

Hagen, J. O. 1987: Glacier surge at Usherbreen, Svalbard. *Polar Res. 5*, 239–252.

Hagen, J. O., Liestøl, O., Roland, E. & Jørgensen, T. 1993: *Glacier atlas of Svalbard and Jan Mayen. Nor. Polarinst. Medd. 129.*

Hambrey, M. J. & Dowdeswell, J. A. 1997: Structural evolution of a surge-type polythermal glacier: Hessbreen, Svalbard. *Ann. Glaciol. 24*, 375–381.

Hamilton, G. S. & Dowdeswell, J. A. 1996: Controls on glacier surging in Svalbard. *J. Glaciol. 42*, 157–168.

Hodgkins, R. & Dowdeswell, J. A. 1994: Tectonic processes in Svalbard tidewater glacier surges: evidence from structural glaciology. *J. Glaciol. 40*, 553–560.

Jiskoot, H., Boyle, P. & Murray, T. 1998: The incidence of glacier surging in Svalbard: evidence from multivariate statistics. *Comput. Geosci. 24*, 387–399.

Jiskoot, H., Murray, T. & Boyle, P. 2000: Controls on the distribution of surge-type glaciers in Svalbard. *J. Glaciol. 46*, 412–422.

Kamb, B., Raymond, C. F., Harrison, W. D., Engelhardt, H. F., Echelmeyer, K., Humphrey, N., Brugman, M. & Pfeffer, T. 1985: Glacier surge mechanism: the 1982–1983 surge of Variegated Glacier, Alaska. *Science 227*, 469–479.

Lawson, W., Sharp, M. J. & Hambrey, M. J. 1994: The structural geology of a surge-type glacier. *J. Struct. Geol. 16*, 1447–1462.

Lefauconnier, B. & Hagen, J. O. 1991: *Surging and calving glaciers in eastern Svalbard. Nor. Polarinst. Medd. 116.*

Liestøl, O. 1969: Glacier surges in west Spitsbergen. *Can. J. Earth Sci. 6*, 895–897.

Liestøl, O. 1993: Glaciers of Svalbard, Norway. *US Geological Surv. Prof. Pap. 1386*, E127–E151.

Luckman, A., Murray, T. & Strozzi, T. 2002: Surface flow evolution throughout a glacier surge measured by satellite radar interferometry. *Geophys. Res. Lett. 29*, 2095, 10.1029/2001GL014570.

Meier, M. F. & Post, A. S. 1969: What are glacier surges? *Can. J. Earth Sci. 6*, 807–817.

Melvold, K. & Hagen, J. O. 1998: Evolution of a surge-type glacier in its quiescent phase: Kongsvegen, Spitsbergen, 1964–1995. *J. Glaciol. 44*, 394–404.

Murray, T., Dowdeswell, J. A., Drewry, D. J. & Frearson, I. 1998: Geometric evolution and ice dynamics during a surge of Bakaninbreen, Svalbard. *J. Glaciol. 44*, 263–272.

Murray, T., Luckman, A., Strozzi, T. & Nuttall, A.-M. 2003a: The initiation of glacier surging at Fridtjovbreen, Svalbard. *Ann. Glaciol. 36*, 110–116.

Murray, T., Strozzi, T., Luckman, A., Jiskoot, H. & Christakos, P. 2003b: Is there a single surge mechanism? Contrasts in dynamics between glacier surges in Svalbard and other regions. *J. Geophys. Res. 108(B5)*, 2237, 10.1029/2002JB001906.

Nuttall, A.-M., Hagen, J. O. & Dowdeswell, J. A. 1997: Quiescent-phase changes in velocity and geometry of Finsterwalderbreen, a surge-type glacier in Svalbard. *Ann. Glaciol. 24*, 249–254.

Rabot, C. 1900: *Les variations de longueur des glaciers dans le régions arctiques et boréales. Extrait des Archives des sciences physiques et naturelles, Années 1899 et 1900.* Geneva: Georg and Co. Editeurs.

Rolstad, C., Amlien, J., Hagen, J. O. & Lundén, B. 1997: Visible and near-infrared digital images for determination of ice velocities and surface elevation during a surge on Osbornebreen, a tidewater glacier in Svalbard. *Ann. Glaciol. 24*, 255–261.

Scambos, T. A., Dutkiewicz, M. J., Wilson, J. C. & Bindschadler, R. A. 1992: Application of image cross-correlation to the measurement of glacier velocity using satellite image data. *Remote Sens. Environ. 42*, 177–186.

Schytt, V. 1969: Some comments on glacier surges in eastern Svalbard. *Can. J. Earth Sci. 6*, 867–873.