Remote sensing of ice cap outlet glacier fluctuations on Nordaustlandet, Svalbard

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Landsat multispectral scanner images and 1:50,000 scale aerial photographs are used to measure marginal fluctuations in 22 outlet glaciers of the Nordaustlandet ice caps, Svalbard, for all or parts of the period 1969 to 1981. Little was previously known about the behaviour of these glacier termini. Digital analysis of Landsat computer compatible tapes yielded measurement errors of less than ±150 m, whereas data extracted from aerial photographs had an accuracy of ±25 m. Of the 22 glacier termini examined using aerial photographs, 15 were retreating, four were static and three were advancing. Retreat was usually in the order of hundreds of metres during the period of observation. For any outlet glacier, retreat was probably a result of either (1) glacier response to climatic warming since the early part of the 20th century, or (2) stagnation and thinning during the quiescent period between surges. Short term iceberg calving events may also be responsible for retreat in a few cases. All observed outlet glaciers of Austfonna were static or retreating between 1969 and 1981, but analysis of Landsat imagery and aerial photographs showed that five outlet glaciers from Vestfonna and one from Vegafonna were advancing for all or part of that period. Bodleybreen advanced by a mean of 440 and a maximum of 580 m a^{-1} between 1976 and 1981. Bodleybreen, Søre Rijpbreen, and Palanderbreen are identified as surging, based on increases or changes in the pattern of surface crevassing. The ice streams Aldousbreen, Frazerbreen, and Idunbreen also advanced between 1976 and 1981, but surface crevasse patterns remained largely unaltered and surging is not inferred.

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Glacier fluctuations and surface velocities have been measured using Landsat multispectral scanner (MSS) data in several parts of the Arctic and Antarctic (e.g. Krimmel & Meier 1975; Post et al. 1976; Colvill 1977). This study represents a systematic examination of marginal fluctuations in the outlet glaciers of the Nordaustlandet ice caps, Svalbard (Fig. 1), using digitally enhanced Landsat computer compatible tapes (CCTs) and aerial photographs. Its aim is to provide information on the marginal fluctuations of outlet glaciers in Nordaustlandet as part of a wider geophysical programme concerning the morphology and dynamics of the Nordaustlandet ice caps (Dowdeswell 1984; Dowdeswell et al. in press; Drewry & Liestøl 1985).

The accuracy associated with measurements of glacier fluctuations from Landsat CCTs and aerial photographs is assessed. Mean and maximum advance/retreat rates are presented for each outlet glacier, and the interpretation of these data in terms of climatic change and glacier surging is

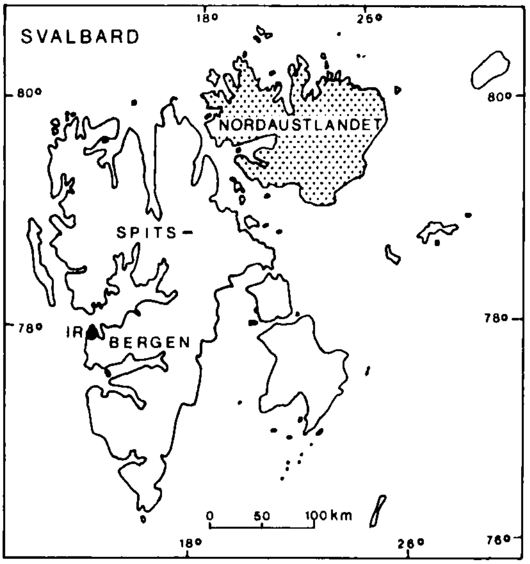

Fig. 1. The location of Nordaustlandet (shaded) within Svalbard. IR is Isfjord Radio.

discussed. Ice surface velocity measurements are not made from Landsat imagery of Nordaustlandet because few medial moraines or large chasms are present to act as markers.

Methods

Landsat CCTs from 25 March 1973 (ID. 124511580), 4 July 1976 (ID. 252911385) and 1 August 1981 (ID. 2234002133) were contrast stretched and enlarged on a GEMS digital image analyser until individual pixels (79 by 56 m) could be distinguished. The ability to manipulate Landsat digital data to exploit the full radiometric and spatial resolution of the MSS is particularly important when glacier fluctuations in the order of hundreds of metres are the object of investigation. Changes in the position of the terminus of Bodleybreen between 1976 and 1981 are shown in Fig. 2. Photographic slides of each outlet glacier were produced from the digital image analyser. The slides were projected through a photographic enlarger and the outlines of both rock outcrops and the outlet glacier margins were traced. This process was repeated for imagery from each date, and information from different times was compared by superimposing tracings of static features (i.e. rock outcrops). Any differences in the location of glacier margins should then represent real fluctuations in position plus an error term. Inaccuracies increase with distance from rock outcrops, and only ice margins closer than 5 km to terrestrial features were included. Errors in the procedure were measured through a series of operator error tests. First, the same operator recorded the marginal fluctuations of ten outlet glaciers twice, leaving six months between the analyses. The mean difference between the measurements was 102 m, with a standard deviation of 47 m. Second, five operators recorded fluctuations of the margins of a single outlet glacier, measuring a shift of 510 ± 80 m. From these tests, an error term of less than approximately ±150 m can be attached to outlet glacier fluctuations measured from digitally enhanced Landsat MSS data.

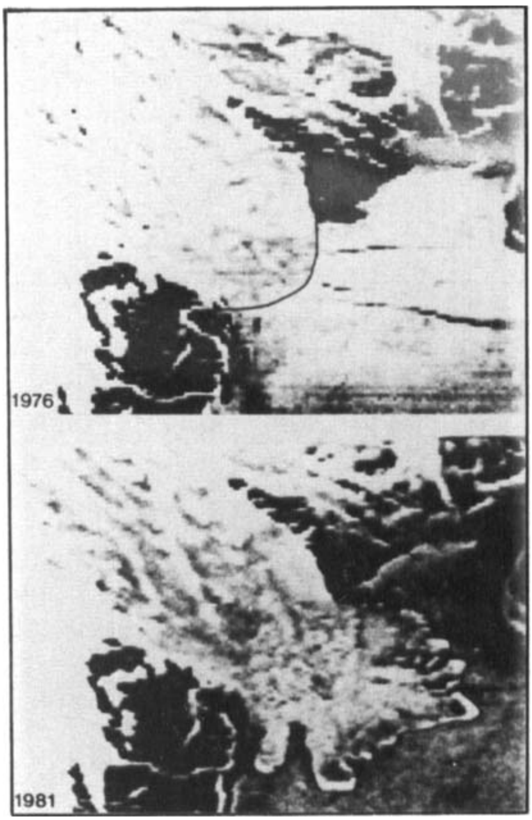

Fig. 2. Surge of Bodleybreen, Vestfonna, recorded from contrast stretched and enlarged digital Landsat MSS band 7 subscenes (approximately 7 by 7 km) for 4 July 1976 and 1 August 1981.

Tracings of 1:50,000 scale aerial photographs of outlet glaciers and surrounding rock outcrops at different dates were also compared. Operator error tests involving repeat measurements suggested maximum errors of ±25 m from this source. Data from aerial photographs are therefore of significantly greater accuracy than those from the analysis of Landsat CCTs. The latter, however, have the advantage of both wider spatial and greater temporal coverage.

Results of Landsat CCT and aerial photograph analysis

The mean and maximum distances and rates of outlet glacier fluctuations measured from enhanced Landsat CCTs are presented in Table 1. Mean distance data represent measurements of 0.5 km intervals across the terminus of each outlet glacier, while maximum distances record the largest shift in position of the ice front. The period between 1973 and 1976 imagery is approximately 3.3 years, and five years elapsed between the 1976 and the 1981 scenes. Rates of change were calculated from data on total movement between scenes in order to provide a comparable

Table 1. Outlet glacier fluctuations in Nordaustlandet from Landsat MSS data.

ID. and Glacier (Figs. 3 and 4)	1973–1976 Mean (m)	change ($m\ a^{-1}$)	Max. (m)	change ($m\ a^{-1}$)	1976–1981 Mean (m)	change ($m\ a^{-1}$)	Max. (m)	change ($m\ a^{-1}$)
1 Bodleybreen	+520	+156	+780	+235	+2200	+440	+2910	+582
2 Eltonbreen	0	0	0	0	0	0	0	0
3 Aldousbreen	—	—	—	—	+510	+102	+1200	+240
4 Frazerbreen	0	0	0	0	+720	+144	+930	+186
5 Idunbreen	−190	−57	−400	−120	+240	+48	+630	+126
6 N. Rijpbreen	—	—	—	—	0	0	0	0
7 S. Rijpbreen	—	—	—	—	+70	0	+180	+36
8 Etonbreen	−520	−156	−1210	−360	−450	−90	−780	−156
9 Botnvikabreen	0	0	0	0	0	0	0	0
10 Duvebreen	−80	0	−120	0	−280	−56	−340	−68
11 Schweigaardbreen	−280	−85	−430	−130	0	0	−160	−32
12 Nilsenbreen	−160	−47	−250	−75	−80	0	−180	−36
13 Leighbreen*	0	0	−300	−90	0	0	0	0
14 Worsleybreen**	—	—	—	—	−240	−37	−360	−55
15 Isispynten***	0	0	0	0	−170	−34	−480	−96
16 Palanderbreen	0	0	0	0	+170	+34	+250	+50
17 Ericabreen	0	0	0	0	0	0	0	0

*Western 1.5 km
**March 1973 to September 1979
***The 10 km north of the point

measure of fluctuations in the position of the ice margins. Where zero rather than a blank is reported in Table 1, it implies that a measurement was made but no discernible change in location was recorded. Given the errors of ±150 m involved in measurements from Landsat imagery, recorded fluctuations of less than this value provide no interpretable information on the direction of variations but imply that their magnitude is small. Data for Duvebreen (1973–76), Søre Rijpbreen (1976–81), and Nilsenbreen (1976–81) come within this category (Table 1).

Table 2. Outlet glacier fluctuations in Nordaustlandet from aerial photographs.

ID. and glacier (Fig. 5)	Period of Obs. (a)	Mean Change (m)	Mean Change ($m\ a^{-1}$)	Maximum change (m)	Maximum change ($m\ a^{-1}$)
1 Bodleybreen	1970–77	+1100	+160	+1450	+205
2 Eltonbreen	1970–77	0	0	0	0
3 Aldousbreen	1970–77	−50	−7	−185	−26
4 Frazerbreen	1970–77	−80	−11	−300	−43
5 Idunbreen	1970–77	−130	−19	−325	−46
6 Gimlebreen (E)	1969–77	−215	−27	−275	−34
7 Gimlebreen (W)	1969–77	−150	−19	−450	−56
8 S. Franklinbreen	1969–71	−50	−25	−110	−55
9 N. Franklinbreen	1969–71	0	0	0	0
10 Sabinebreen	1969–71	0	0	0	0
11 N. Rijpbreen	1969–70	−42	−42	−70	−70
12 S. Rijpbreen	1969–70	+55	+55	+100	+100
13 Etonbreen	1969–70	−260	−260	−485	−485
14 Botnvikabreen	1971–77	0	0	0	0
15 Duvebreen	1971–77	−120	−20	−210	−35
16 Schweigaardbreen	1971–77	−330	−55	−450	−75
17 Nilsenbreen	1971–77	−135	−22	−300	−50
18 Leighbreen*	1971–77	−145	−24	−250	−42
19 Worsleybreen	1970–77	−300	−43	−425	−61
20 Bråsvellbreen*	1969–77	−180	−22	−275	−34
21 Palanderbreen	1969–70	+30	+30	+95	+95
22 Ericabreen	1969–70	−45	−45	−80	−80

*Western 5 km

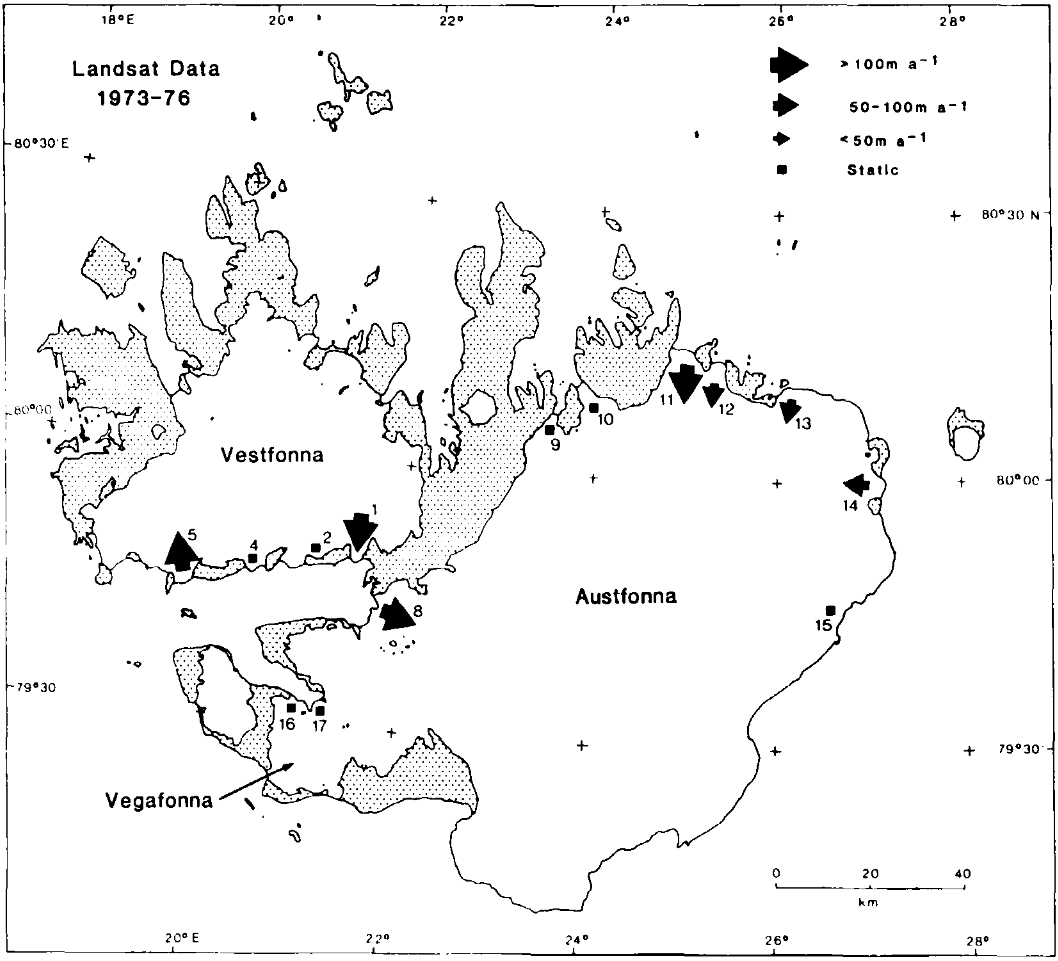

Fig. 3. Maximum rate of fluctuation of Nordaustlandet outlet glaciers between 1973 and 1976 from Landsat CCTs obtained on 25 March 1973 and 4 July 1976 (Table 1).

The most rapid outlet glacier advance between 1973 and 1981 was that of Bodleybreen (Fig. 2), where mean and maximum rates of 440 and 582 m a^{-1}, respectively, were measured over the period 1976-81 (Table 1). By contrast, Etonbreen retreated by a mean of 156 m a^{-1} and a maximum of 360 m a^{-1} between 1973 and 1976. Both these outlet glaciers are known to surge (Liestøl in press), with Bodleybreen in the active and Etonbreen in the quiescent period of the surge cycle. Marginal fluctuations of Worsleybreen are measured between 25 March 1973 and 16 August 1979 (Landsat scene ID. 2238001093) because 1981 imagery does not cover this area.

The Landsat-derived data in Table 1 are summarized in Figs. 3 and 4, where the spatial distribution of maximum advance/retreat rates is mapped for the periods 1973–76 and 1976–81. During the former interval only one glacier was advancing, while six were retreating and seven were static (or fluctuating within the error limits of the study). However, between 1976 and 1981 six glaciers were advancing, six were retreating and five were static. Care must be taken not to assign too much significance to this apparently dramatic shift. Only a single outlet glacier, Idunbreen (glacier 5 in Figs. 3 and 4), changed from retreating to advancing mode over the two periods according to Landsat data (Table 1). Bodleybreen (glacier I) was advancing in both periods. Of the other four glaciers advancing between 1976 and 1981, no data were available for Søre Rijpbreen

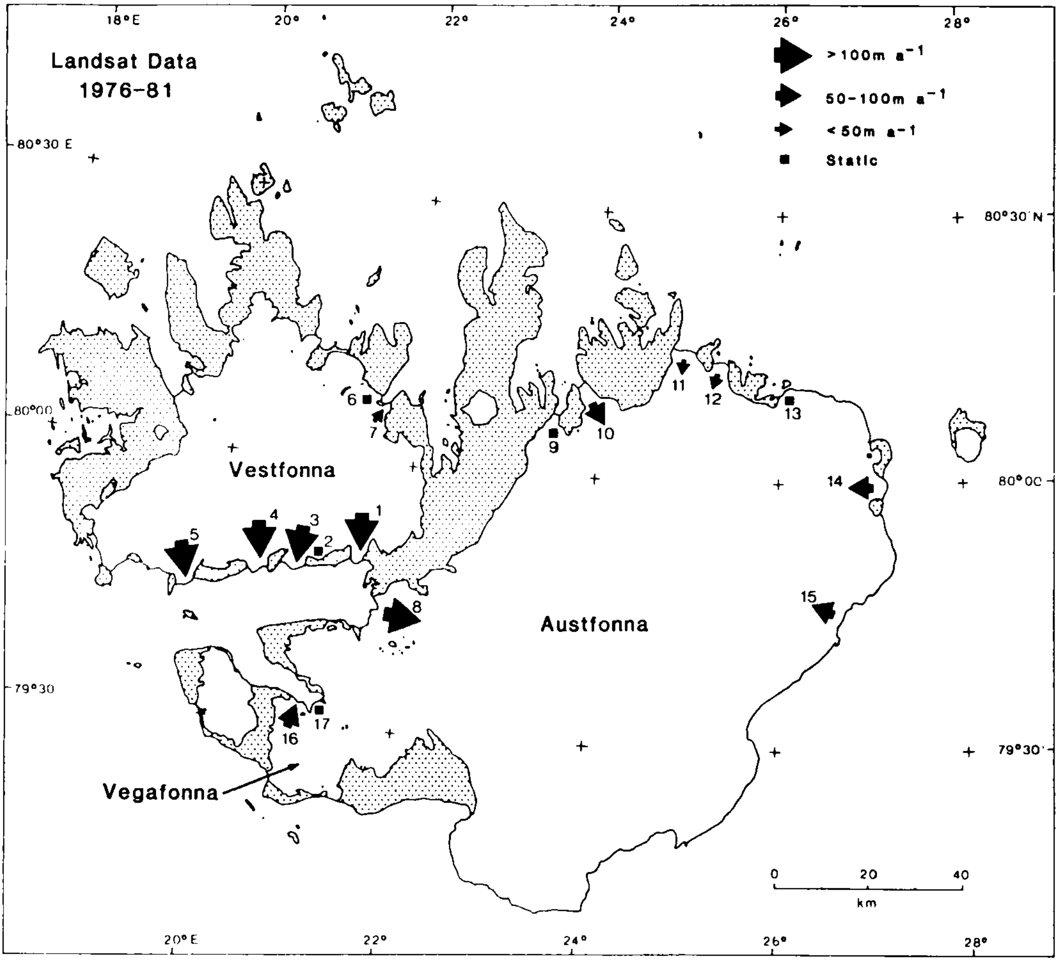

Fig. 4. Maximum rate of fluctuation of Nordaustlandet outlet glaciers between 1976 and 1981 from Landsat CCTs obtained on 4 July 1976 and 1 August 1981 (Table 1).

(glacier 7) and Aldousbreen (glacier 3) in the earlier period, and both Frazerbreen (glazier 4) and Palanderbreen (glacier 16) recorded no discernible movement from Landsat imagery. According to evidence from the analysis of aerial photographs (Table 2), Søre Rijpbreen and Palanderbreen were advancing between 1973 and 1976, but Aldousbreen and Frazerbreen were retreating. Thus, combining satellite and aerial photographic data, it appears that three of the major outlet glaciers on the south side of Vestfonna have shifted from a period of retreat to one of advance during the late 1970s.

A summary of outlet glacier fluctuations measured from aerial photographs is found in Table 2. Values of zero imply that fluctuations were within the error limits of the method (±25 m). Note that the dates and intervals over which observations were made are variable, and dependent on the availability of aerial photographs. Rates of change are greatest for Bodleybreen and Etonbreen (Table 2), a result similar to that of Landsat image analysis (Table 1). The distribution and magnitude of fluctuations is mapped in Fig. 5, where three glaciers are advancing, 15 are retreating and four are static.

Glaciological interpretation of outlet glacier fluctuations

The advance and retreat of glaciers is often associ-

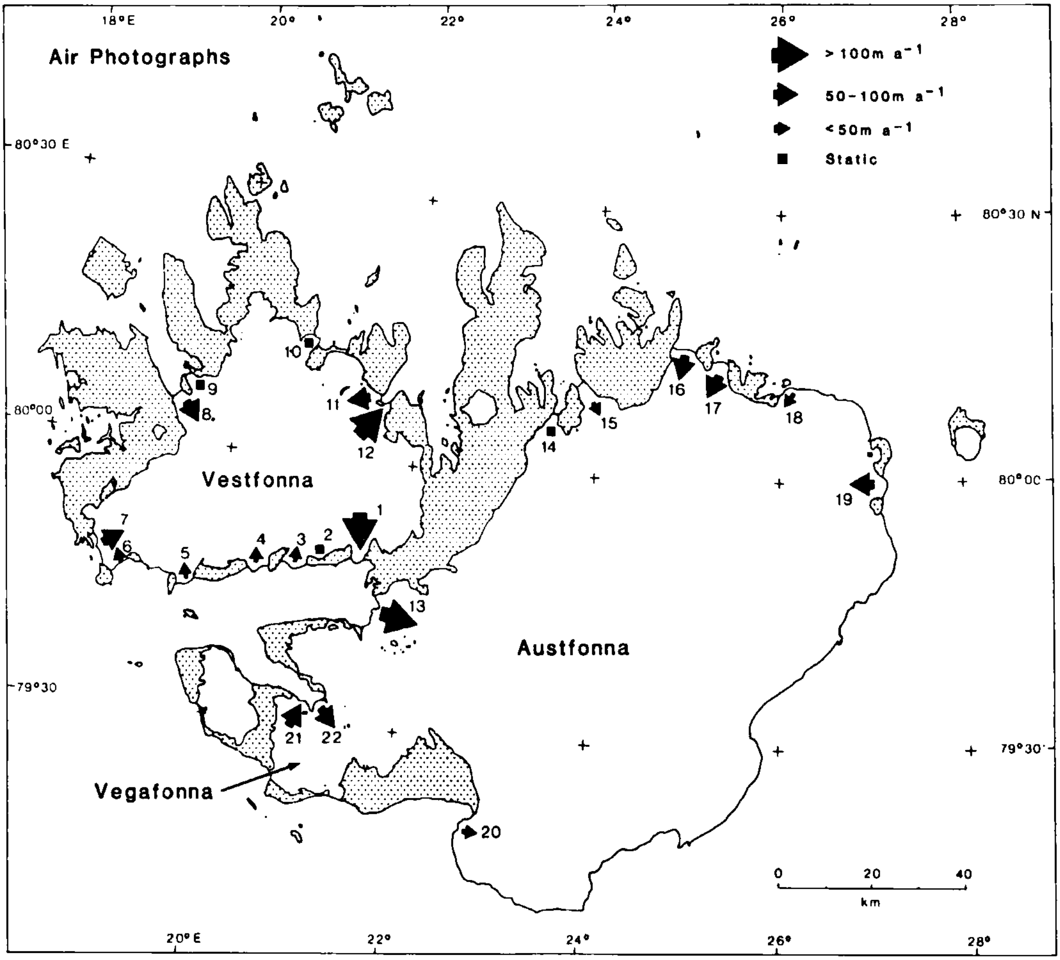

Fig. 5. Maximum rate of fluctuation of Nordaustlandet outlet glaciers from aerial photographs taken between 1969 and 1977. The time periods over which data were collected are listed in Table 2.

ated with changes in mass balance, which is itself related to climatic changes in complex fashion (e.g. Meier 1965; Paterson 1981). Relatively short periods of rapid advance, followed by longer intervals during which retreat occurs, may also be a result of glacier surging (Meier & Post 1969). We now discuss the observed outlet glacier fluctuations in Nordaustlandet (Tables 1 and 2) in terms of their links with climatic change and glacier surging.

Glacier retreat

The data presented above suggest that, aside from several exceptions, a significant majority of the observed outlet glaciers of the Nordaustlandet ice caps have retreated by several hundreds of metres between 1969 and 1981 (Tables 1 and 2). The information from analysis of aerial photographs indicates that most glaciers recorded as static from Landsat imagery were probably retreating at a rate beyond the resolution of the MSS. The most straightforward interpretation of this pattern is that it represents continuing glacier response to the end of the Little Ice Age in Svalbard, which was recorded as a mean annual temperature rise of 4°C at Isfjord Radio (Fig. 1) during the early part of the 20th century (Steffensen 1982). Unfortunately, very few mass balance data are available for the Nordaustlandet ice caps to test this suggestion (cf. Schytt 1964; Dowdeswell 1984). Little previous work exists on recent glacier fluctuations in Nordaustlandet, although Blake (1962:343) reported on the basis of field observations that 'many of the outlet glaciers in Nordaustlandet were in maximum positions since general deglaciation during the latter half of the 19th century'.

Where outlet glaciers or ice walls terminate in the marine environment the pattern of marginal advance and retreat is affected by the rate at which icebergs are calved. Over relatively long periods (decades) this is influenced by changes in mass balance (e.g. Bindschadler & Rasmussen 1983) but, over shorter periods such as those in this study, single large calving events can also result in retreat of several hundreds of metres. Over the time period of the work presented above it is, therefore, difficult to distinguish between retreat due to the effects of short term calving and longer term climatic changes for individual outlet glaciers, although the observed pattern of general outlet glacier retreat on Nordaustlandet suggests that the more random effects of short term calving events are probably limited.

In addition to climatic change, ice marginal retreat can also result from stagnation and thinning during the relatively long quiescent period betweeen rapid advances which together make up the surge cycle (cf. Liestøl 1969). This is the case for Søre Franklinbreen and the rapidly retreating Etonbreen, both of which have been observed to surge. A total of seven surging glaciers have so far been identified in Nordaustlandet (Liestøl in press), and evidence from ice surface profiles and surface roughness measurements indicates similarities between these drainage basins and several other outlet glaciers on the island (Dowdeswell 1984). Further, submarine morphology offshore of a known surging glacier, Bråsvellbreen, is also similar to that beyond a neighbouring outlet glacier that has not been observed to surge (Solheim & Pfirman 1985; Solheim pers. comm.). Thus, it is possible that a relatively large number of Nordaustlandet outlet glaciers surge, implying that the general pattern of glacier retreat recorded in Tables 1 and 2 could be explained as a response to stagnation during the relatively long quiescent period. The continued study of Landsat imagery will help to establish how many other outlet glaciers in Nordaustlandet are subject to surges. It is, however, important to stress that climate- and surge-related explanations of the observed trend of glacier retreat in Nordaustlandet are not mutually exclusive: outlet glaciers which do not surge may be responding directly to climatic change while surging glaciers are retreating due to periods of stagnation between rapid advances.

Glacier advance and surging

Surging glaciers have been identified by Schytt (1969) and Liestøl (in press) from aerial photographs of Nordaustlandet. Although aerial photographs provide a data set of relatively high resolution, Landsat imagery has the advantage of monitoring the whole of Nordaustlandet every 18 days (16 days for Landsats 4 and 5), assuming that cloud cover is not present. The changing configuration of the terminus of the surging glacier Bodleybreen in enhanced Landsat imagery from 1976 and 1981 is shown in Fig. 2, while its rate of advance is recorded in Table 1. Therefore, as shown previously by Post et al. (1976), Landsat MSS data are clearly capable of identifying glaciers which have advanced relatively rapidly.

There is, however, a problem in distinguishing between an advancing glacier per se and an advancing glacier that is also surging using Landsat imagery alone, if surging is defined as a state in which bed decoupling and lubrication lead to velocity increases of several orders of magnitude (Meier & Post 1969). Whereas aerial photographs reveal heavy surface crevassing and sometimes deformed ice structures on surging glaciers, it is often difficult to resolve such features on MSS imagery. The pattern of medial moraines can provide a useful guide (e.g. Post et al. 1976), but few are present on the Nordauslandet ice caps. Thus, although six glaciers were advancing between 1976 and 1981 according to Landsat data (Table 1), it is less clear which of these were also surging. Aerial photographs of Søre Rijpbreen and Palanderbreen show heavily fractured surfaces which were not present on previous photographs, indicating a relatively sudden increase in velocity, and these glaciers are therefore classified as surging (Liestøl in press). Bodleybreen was relatively heavily crevassed on both 1970 and 1977 aerial photographs. However, analysis of the pattern of this crevassing indicates a considerable change in both the number and orientation of crevasses during this period, which is interpreted to be associated with a surge of this glacier.

Dowdeswell (1984) suggested that Aldousbreen, Frazerbreen, and Idunbreen may represent features similar to ice streams in the large ice sheets. Each exhibited rough surface topography (undulations of wavelength 3–4.5 km and amplitude 15–25 m) throughout the period of Landsat data availability, and is also heavily crevassed on both 1970 and 1977 aerial photographs.

The pattern of crevassing did not change significantly, however, during this seven-year period. These outlet glaciers are interpreted as zones of *consistently* higher ice velocity than the surrounding ice ridges. The recorded advances of these glaciers are not as large or, as yet, so prolonged as that of Bodleybreen (Table 1), which drains a basin of approximately comparable size on the south side of Vestfonna. Remotely sensed data acquired over the next few years should aid in establishing whether or not these three glaciers represent ice streams which also undergo periodic surges.

Conclusions

Remote sensing methods have been used to measure marginal fluctuations of 22 outlet glaciers of the Nordaustlandet ice caps for all or parts of the period 1969 to 1981. Little was previously known about the behaviour of these glacier termini. Digital analysis of Landsat MSS data yielded measurement errors of less than ± 150 m, whereas data extracted from 1:50,000 scale aerial photographs had an accuracy of ± 25 m. The future availability of Thematic Mapper imagery, with a nominal resolution of 30 m, will significantly reduce errors associated with the measurement of glacier fluctuations using Landsat data.

The majority of outlet glaciers studied underwent retreat of some hundreds of metres during the period of observation. For any outlet glacier this was probably a result of either (1) glacier response to climatic warming since the early part of the 20th century or (2) stagnation and thinning during the quiescent period between surges. Short term iceberg calving events may also be responsible for retreat in a few cases. All observed outlet glaciers of Austfonna (sensu Dowdeswell & Drewry 1985) were static or retreating between 1969 and 1981, but five Vestfonna and one Vegafonna outlet were advancing for all or part of that period. Bodleybreen, Søre Rijpbreen, and Palanderbreen exhibited considerable or changing surface crevassing in association with rapid terminal advance and are therefore interpreted to be surging. It is not clear, however, whether the ice streams Aldousbreen Frazerbreen and Idunbreen may also undergo periodic surging or are advancing for other (possibly climatic) reasons. Continued monitoring of remotely sensed data is necessary to answer this question and that of which other drainage basins on the Nordaustlandet ice caps undergo surge type behaviour.

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