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Fluctuations of the Terminuses of White and Thompson Glaciers, Axel Heiberg Island, N.W.T., Canada

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ABSTRACT

Using imagery from airborne cameras and synthetic aperture radars, maps at a scale of 1:5000, and information from ground surveys, we document and seek to interpret the changes in position of the contiguous terminuses of White and Thompson Glaciers, Axel Heiberg Island. The period spanned by the imagery is 1948 to 1995, although our detailed analysis only covers images from 1960, 1972, 1977, 1988 and 1995. Rates of terminus advance fluctuate both at year-to-year and decadal scales, the magnitude of fluctuations exceeding the uncertainty of positioning from photogrammetric analysis. The advance of Thompson Glacier has decelerated noticeably while the retreat of White Glacier has accelerated moderately. However interpretation is complicated by interactions between the two terminuses. A wedge of ice more than 1 km long has been transferred from White Glacier to Thompson Glacier, and if the glaciers continue to evolve as they have done in recent years White Glacier will soon cease to have a recognizable terminus; it will be a tributary of Thompson Glacier. The time series of the advance rates are coherent both with each other and with the mass-balance time series of White Glacier, but these correlations are presumed to be fortuitous.

Key Words: imagery, glaciers, terminus fluctuations

INTRODUCTION

White and Thompson Glaciers on Axel Heiberg Island, N.W.T., Canada (Figure 1) are among the most studied glaciers at high northern latitudes. Investigations date back to 1959 (B.S. Müller 1961) and cover a wide range of quantities of glaciological interest. Continuing mass-balance and related measurements have recently been reassessed by Cogley *et al.* (1995). The time series of annual mass balance now extends from 1959-60 to 1994-95 for White Glacier. It has not been possible, however, to sustain the early series of repeated surveys of the glacier margins (Müller 1963; Kälin 1971). Here, using available imagery from a number of dates, we reconstruct the evolving terminus positions of the two glaciers. The photographic record extends back to 1948, and we have selected several images for detailed photogrammetric analysis. Our work complements and extends that of Moisan and Pollard (1992).

White Glacier is a valley glacier with an area of 38.7 km^2. Its accumulation area, and the lower 1—2 km of its tongue, are in physical contact with ice of the much larger Thompson Glacier, an outlet glacier of Müller Ice Cap. The area of Thompson Glacier including tributaries is about 265 km^2. It is advancing, while White Glacier is retreating.

The advent of Global Positioning System (GPS) technology, and the launch of Radarsat in 1995, have opened a new era in the remote sensing of glaciers. Earlier satellite imagery, for example from the Landsat series, was of limited value for the monitoring of high-latitude glaciers (Jung-Rothenhäusler 1993), partly because of inadequate resolution but mainly because of the very limited viewing opportunities afforded by the persistent high-latitude cloud cover. Satellite radar promises to eliminate this constraint. GPS receivers offer a versatile and highly accurate means of detecting short-term, metre-scale change in such mobile elements of the landscape as glacier terminuses. We hope to conduct the first GPS resurvey of the White and Thompson terminuses in May 1996, and if possible to extend annual GPS monitoring into the future. Our purpose in this paper is to lay a retrospective foundation for future satellite-based monitoring (Kargel and Kieffer 1995) and GPS resurveys of these two well-studied high-latitude glaciers.

IMAGERY OF WHITE GLACIER AND THOMPSON GLACIER

The early history of mapping and aerial photography in the Arctic Islands of Canada is outlined in Dunbar and Greenaway (1956). Ommanney (1969) updates that account with

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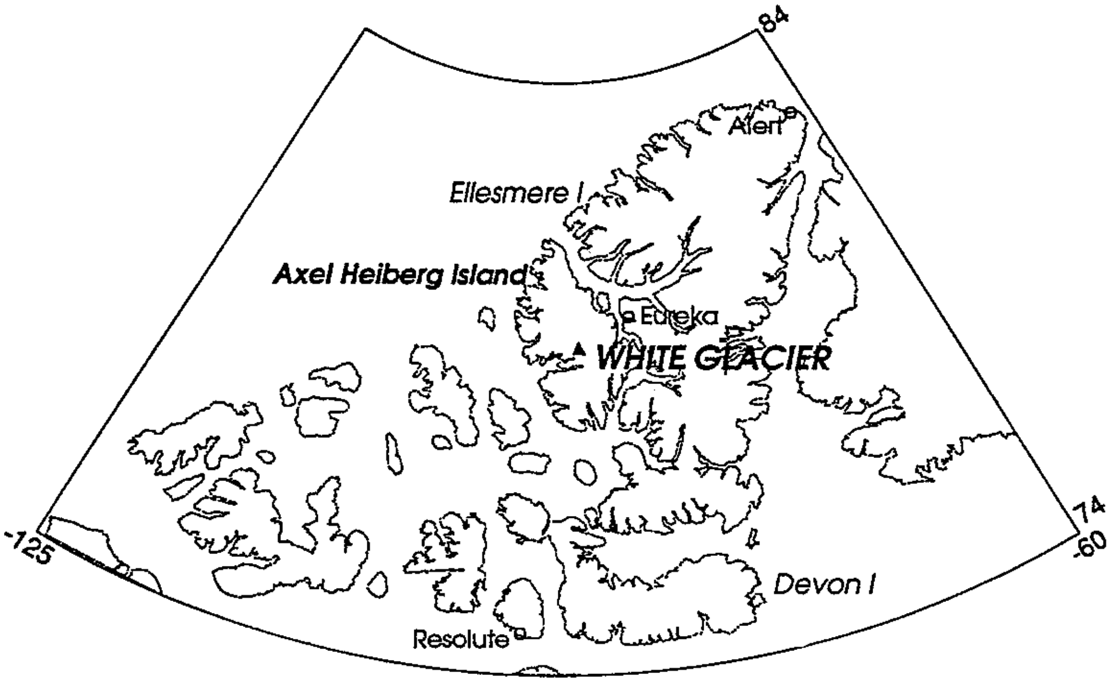

Figure 1. *Location within the Canadian High Arctic of White Glacier and Thompson Glacier. In the main panel, showing the catchments of the two glaciers, glacier ice is shaded grey and lakes are black. Note that several glaciers in the eastern part of the Thompson catchment are dynamically independent of Thompson Glacier. Coordinates (km) are those of UTM Zone 15.*

particular reference to Axel Heiberg Island.

Operation Polaris, conducted by the U.S. Army, produced the first oblique (trimetrogon camera) air photo coverage of Axel Heiberg Island, beginning in 1947. Between 1950 and 1953, the Royal Canadian Air Force trimetrogon coverage of Canada was extended to include Axel Heiberg Island. Ommanney (1969) includes a number of excellent examples including (Table 1; see his Figure 2) a Polaris view of White and Thompson Glaciers from August 1948 and an RCAF view (his Figure 26) taken in July 1952. We have located one other oblique photo of the two glaciers from 1952; unfortunately there is no early vertical imagery.

In 1958 and 1959, vertical air photo coverage was completed for Axel Heiberg Island (Ommanney 1969). In 1960, a special series of low-altitude verticals was obtained for the Expedition Fiord area (Haumann 1963). This series was designed (Blachut 1963; Blachut and Müller 1966) as the basis for large-scale maps (National Research Council 1962a,b) of the lower parts of White and Thompson Glaciers. These maps are our datum for observations of changes in the glacier margins.

Since 1960, numerous ground and air photos have been taken of the glaciers. Some are listed in Table 1 and are discussed below. Others, like those of Post (taken in 1964, examples shown by Post and LaChapelle 1971), were not available to us. We have chosen air photos from 1972 and 1977 for detailed analysis.

Beginning in the early 1970s satellite coverage of Axel Heiberg Island became available (Jung-Rothenhäusler *et al.* 1992, Jung-Rothenhäusler 1993). Later satellites in the Landsat series did not overfly latitudes as far north (79.5°N) as our study area, but even the earlier satellites yielded few cloud-free images. Jung-Rothenhäusler (1993) studied a Landsat-1 MSS image of White Glacier from map, September 1974 (image 1-0780-19541-10, path 67, row 1). He was able to generate a surface reflectance but the coarse resolution (80m pixels) would have precluded analysis of terminus fluctuations even had more than one image been available. More recent satellite imaging systems, such as those of the SPOT series, have greatly enhanced resolution, but they remain at the mercy of the clouds for viewing opportunities. It is reasonable to hope for much better results from the microwave imagery now available from the ERS satellites and from Radarsat in particular. We demonstrate below, using airborne SAR images, that radar is viable as a tool for monitoring glacier terminus fluctuations.

TABLE 1
Imagery of the White-Thompson terminus complex

Date	*Flightline*	*Frames*	*Nominal scale*	*Type*	*Comments*
11-08-48	8M 219	60L		obl	Ommanney 1969
?-52	T487	L33		obl	Ommanney 1969
28-07-52	T498	R45	1:37000	obl	Trimetrogon
13-08-59	A16864	36-37	1:60000	b/w	
2-08-60	10		1:8000	b/w	Haumann 1963
14-08-67				b/w	Kälin 1971
9-06-72	A23093	190-191	1:20000	b/w	
08-72	A23057	9	1:20000	b/w	
08-72	A23045	95-96	1:20000	b/w	
07-73	A30860	140-142	1:20000	clr	
08-74	A30995	75-81	1:20000	clr	
08-75	A31066	130-134	1:9000	clr	
08-75	A31066	141-147	1:12500	clr	
9-08-77	A24755	9	1:20000	b/w	
9-08-77	A24791	124 170-171	1:20000	b/w	
9-08-77	A24793	87-90	1:15000	b/w	
9-08-77	A31165	90-94	1:15000	clr	
07-78	A31220	56-65	1:7000	clr	
18-02-88			1:124000	sar	Resolution 6m along track, 16m across track
08-90				clr	Flown for Geological Survey of Canada, not yet numbered
26-04-95			1:63000	sar	Resolution 10m along track, 20m across track

Type: obl – oblique monochrome air photo; b/w – vertical monochrome air photo; clr – vertical colour air photo; sar – Synthetic Aperture Radar image.

On 18 February 1988, a SAR image of the Expedition Fiord area was obtained with the STAR-2 SAR system of Intera Technologies Ltd., as part of the Winter Arctic Atlas project. The system is based on an X-band SAR which, at the flight altitude of 8530m, provided a range resolution of 16m and an azimuth resolution of 6m. The image print made available to us has a nominal scale of 1:124000 at the White-Thompson terminus complex.

On 26 April 1995, a C/X-band SAR image of White Glacier was obtained by Canada Centre for Remote Sensing from an altitude of 7000m. Swath width was 65km and resolution was 10m in azimuth and 20m in range. The print from which we worked has a nominal scale of 1:63000.

The data base for the present work thus consists of five images between August 1960 and April 1995:

reference maps (National Research Council 1962a,b) drawn at 1:5000 scale from August 1960 photography;
air photos from August 1972 and August 1977; and
airborne SAR images from February 1988 and April 1995.

PHOTOGRAMMETRIC ANALYSIS

Our initial approach to the problem of estimating rates of terminus advance was based on hand copying of later terminus or source images to a reference image. We used a Procom-2 enlarger (Gregory Geoscience Ltd., Kanata, Ont.), an instrument which enables the user to enlarge and scan one set of data and if desired to merge and register two sets of data at one common scale. By careful registration of stable landscape features in the source image to corresponding features in the reference image it is possible to accommodate quite accurately the differences of origin, orientation and scale between the two images. Unstable features which have changed in the interval between the images will appear in their new locations when transcribed onto the reference image (Figure 2). Thompson Glacier has clearly advanced in the interval between the first (reference) image and the most recent source image, at a rate which appears to have been moderate from 1959 to 1972, slow from 1972 to 1988, and rapid from 1988 to 1995. White Glacier has apparently retreated steadily over the same time span, possibly faster after 1972 than before. Moreover Thompson Glacier has been encroaching on White Glacier, the lower tongue of which is now much narrower and has also been displaced to the north and east by as much as 300m.

Although it is not our primary focus, the push moraine in front of Thompson Glacier (Figure 2) has also been displaced by the advancing front of Thompson Glacier. Its shape has changed somewhat, but the displacement is most simply understood as a rigid down-valley motion over roughly the same distance as the advance of the glacier terminus, about 400 to 600m in 35 years. The push moraine has been studied in detail by Kälin (1971) and Moisan and Pollard (1992).

Figure 2 suffers the limitations of being drawn by hand. Quantitative comparison of the terminus outlines would not be difficult, but it would be time-consuming unless they were digitized. Estimating positional errors is also next to impossible, an important issue since the inferred changes in terminus position may well be of the same order of magnitude as the errors. Accordingly we turned to a more direct approach (Cogley 1992), in which we digitized both the successive terminus outlines and a substantial number of control points from the reference and source images.

About thirty control points were first identified and digitized on the reference maps (National Research Council 1962a,b). By comparing the independent efforts of three different workers we estimated the accuracy of the digitized reference locations as significantly better than 1 metre root-mean-square (with respect to the points on the map rather than to the absolute locations). The terminus outlines were also digitized from the reference maps. For each successive source image in the time sequence we then digitized the terminus outlines and as many of the control points as were within the field of the image and could be identified reliably.

Each source image was registered to the reference image by a simple polynomial-fitting algorithm. Given reference and source coordinates for each of several control points, we estimated the parameters of two polynomials, one for *X* coordinates and one for *Y* coordinates:

$$X_r = a_x + b_x X_s + c_x Y_s + \dots \qquad (1)$$

$$Y_r = a_y + b_y Y_s + c_y Y_s + \dots \qquad (2)$$

where the *a*,*b*,*c* are the unknown parameters and subscripts *r*,*s* refer to reference and source images respectively. In no case was it necessary to fit a polynomial of order higher than one. Average distances between the known points (X_r,Y_r) and their estimates (i.e. positions calculated from the right-hand sides of eqs. 1 and 2) ranged between 40m and 90m.

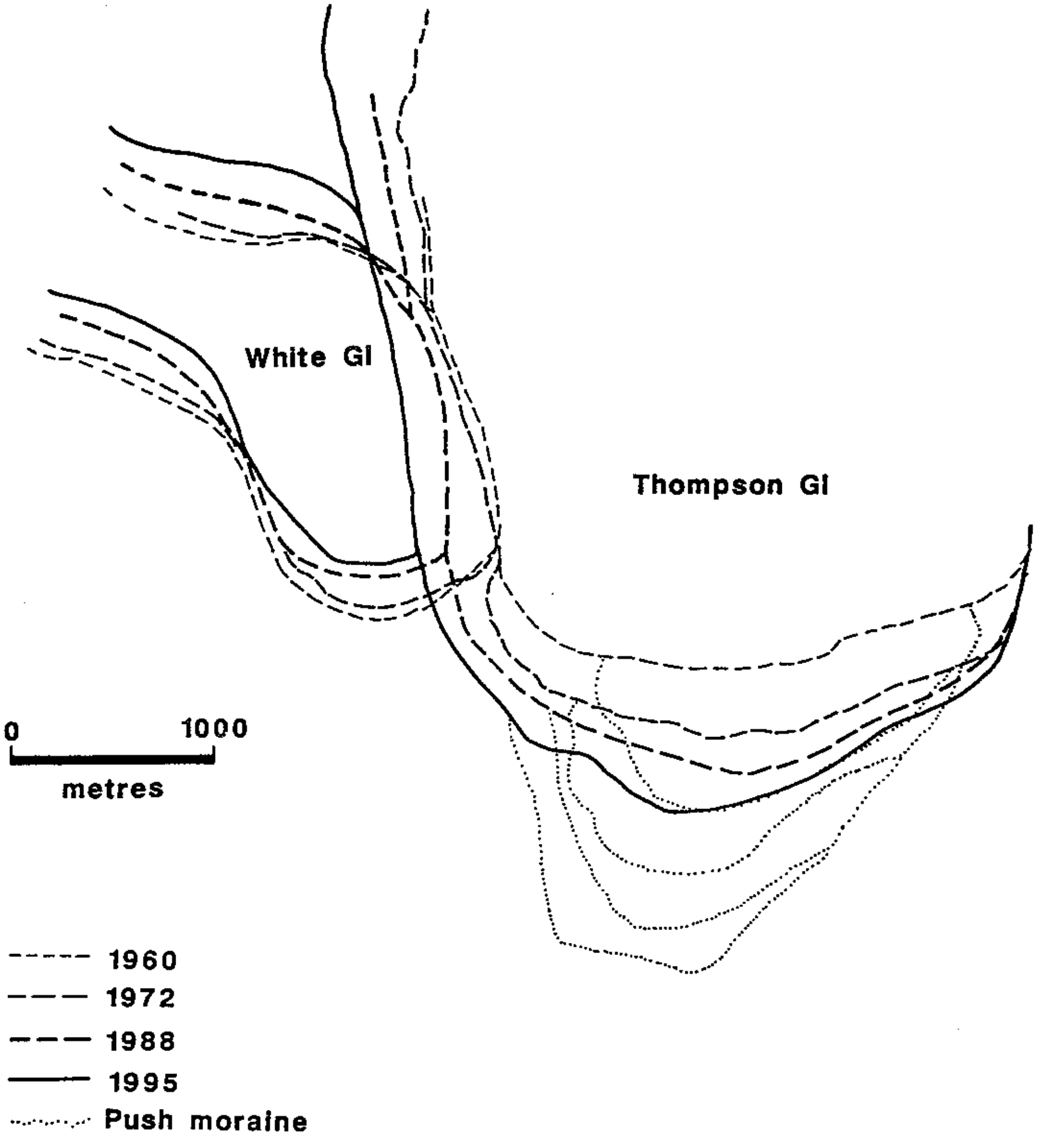

Figure 2. *Reconstruction of the White-Thompson terminus complex from a reference map (National Research Council 1962c), aerial photography, and SAR imagery at four different dates between 1959 and 1995. Terminus outlines were traced by hand using a Procom-2 enlarger, selected fixed landscape elements being registered to the reference map by eye. The reference map is based on 1959 photography.*

(Several control points with consistently large errors were rejected during the analysis.) However the estimates of X_r and Y_r considered separately were (in the nature of least-squares fitting) unbiased. Thus when we turn to estimating the error of the unknown (X_r,Y_r) for *terminus-outline* source coordinates the random errors cancel out, and the appropriate calculation is to sum the squares of the errors in the parameters a,b,c. Nearly all of these terminus-outline errors were between 2m and 10m.

We propagated these errors through the remainder of the analysis in a conventional way. In particular we assume that the parameter errors, or in effect the errors in identification of control points, are uncorrelated. It is possible that this is not a good assumption. The terrain surrounding the White-Thompson terminus complex is a landscape without artefacts, and therefore without sharp features. The sharpest features are mostly hilltops, and in any image their apparent sharpness and perhaps the apparent locations of their summits depend on the prevailing illumination. Apparent differences between control-point locations may therefore arise between different images which are illuminated differently. We suspect that this is not a serious bias, but cannot as yet support such a claim quantitatively. Future ground surveys, preferably at the same time as remote sensing, will settle the question.

Georeferenced terminus outlines at the five dates of our analysis are shown in Figure 3. Broadly, the same pattern is seen as in Figure 2, with Thompson Glacier advancing and also encroaching upon the retreating White Glacier, but there are significant differences of detail. Figure 3c suggests that the advance of Thompson Glacier may not be as rapid now as formerly, and the retreat of White Glacier (Figure 3b) may be more rapid. But this depends on what we mean by "terminus". In 1960 White Glacier had a well-defined front, gently arcuate to the south and 1100m wide. By 1995 this front was only 450m wide at most, having lost about 300m by differential recession on its western side and about 400m on the eastern side where ice formerly belonging to White Glacier has been transferred en bloc to Thompson Glacier. The former suture between the two terminuses has been replaced by a new suture at the locus of drainage (both subglacial and supraglacial) of Between Lake (Maag 1969). (Between Lake is an ephemeral body of meltwater which used to develop in spring and early summer above the confluence of the two glaciers. The position, shape and capacity of this lake, and its regime, have changed considerably over the years in response to changes of the two glacier terminuses. At present its maximum annual volume is far smaller than formerly because the new suture is a less complete barrier than the old.)

For the calculation of rates of advance we chose baselines (Figure 3a) on the tongue of each glacier so as to avoid both the immediate zone of interaction between them and the lateral zones where edge effects might be expected. On Thompson Glacier, 2300m is available after these deductions, but on White Glacier the 480m-long baseline includes a western portion where retreat has been much more rapid than in the centre of the 1960 front. There appears to be no non-arbitrary definition of a terminus in the context presented by White Glacier over the last three decades.

The rates of advance are listed in Table 2 and illustrated in Figure 4. The four intervals of the photogrammetric analysis have been augmented by including annual ground surveys from the 1960s by Müller (1963) and Kälin (1971). The number of profiles in each of these surveys was small, but Kälin also gives an average rate of advance of 23 m a^{-1} for Thompson Glacier from 1960 to 1967. This rate, based on georeferencing of an air photo from August 1967 (Table 1), is comparable both with Kälin's own annual estimates and our overlapping photogrammetric estimate. Kälin's estimates for Thompson Glacier are made along the average azimuth of the glacier's advance, which he gives as 210°, whereas ours are made parallel to the margins above the White Glacier suture, along an azimuth of 196°. Trigonometry indicates that our rates will therefore be a few percent less, but we have not corrected for this small discrepancy.

DISCUSSION

We have not attempted quantitative analysis of the early oblique images listed in Table 1. However careful inspection, and comparison with later vertical images, persuade us that the early obliques are consistent with rates of advance having been similar during the 50s to those measured for the 60s. The most persuasive comparison is of the position of the convoluted medial moraines on Thompson Glacier relative to the suture between the glaciers, as seen especially on images from 1948 and 1959. This informed guess is marked appropriately on Figure 4.

Arnold (1981), as a byproduct of another study, estimated a terminus retreat rate for White Glacier of 5 m a^{-1} between summer 1969 and summer 1970. This is consistent with other estimates.

Moisan and Pollard (1992) reproduced information from an unpublished map at 1:10000 scale prepared by L. King during 1988. We digitized King's terminus positions and compared them with our SAR-image positions obtained about six months earlier. For Thompson Glacier the two positions are consistent in that the summer 1988 outline is almost everywhere intermediate between our February 1988 and April 1995 outlines, although it tends to be closer to the April 1995 than to the February 1988 outline. For White Glacier the summer 1988 outline is 50-100m more advanced than either the February 1988 or the April 1995 outlines. Nothing is known of the methods used by King to produce the summer 1988 outlines. We think it improbable that our positional estimates are in error by as much as this comparison would suggest, several tens of metres, but we recall (see the previous section) that we cannot exclude the possibility of bias due to illumination effects on control point identification.

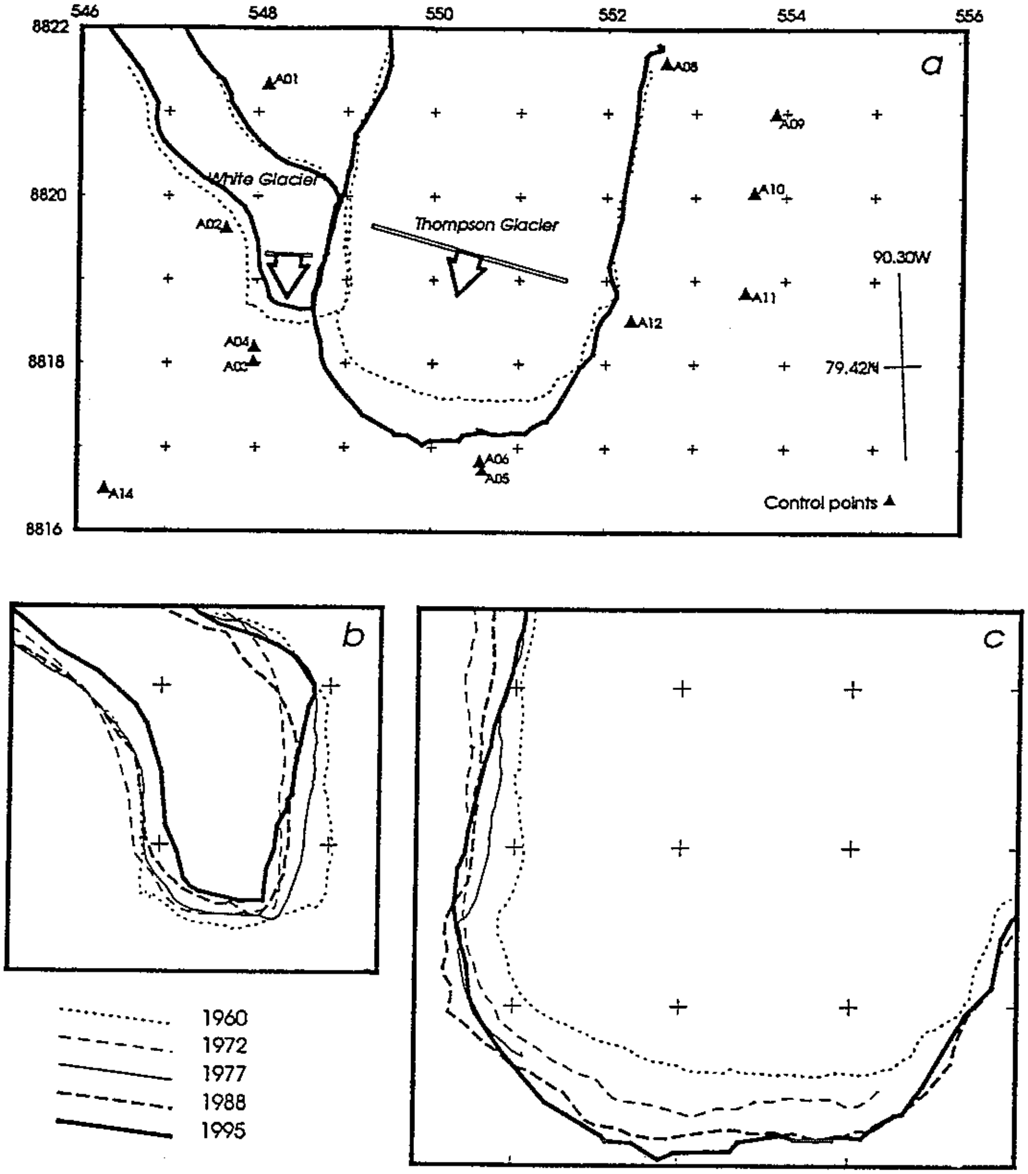

Figure 3. *Quantitative photogrammetric reconstruction of the White-Thompson terminus complex from reference maps (National Research Council 1962a,b), aerial photography and SAR imagery at five different dates, 1960—1995.*

a: Sketch of the terminus complex showing selected control points; terminus outlines in 1960 (dotted lines) and 1995 (thick solid lines); and baselines (hollow bars with arrows). Baselines were chosen arbitrarily. Distances of each terminus from its baseline were calculated in the directions given by the arrows, at each date and at every 30m (White Glacier) or 50m (Thompson Glacier) along the baseline; they were then differenced and divided by the difference in date to obtain rates of advance (Table 2). Tick marks every kilometre are 100m high and wide.

b: Terminus of White Glacier at five different dates.

c: Terminus of Thompson Glacier at five different dates. Photographic coverage is incomplete for 1972 and 1977.

TABLE 2
Rates of advance of glacier terminuses

	Thompson			White		
Interval	*du/dt*	σ	*n*	*du/dt*	σ	*n*
1959.65 – 1960.53	26.9 ± 2.40		1	-1.9 ± 1.40		3
1960.59 – 1972.62	19.4 ± 0.63	4.0	47	-5.8 ± 0.38	1.5	17
1960.53 – 1961.56	18.5 ± 2.40		2	-3.0 ± 1.40		3
1961.56 – 1962.67	20.9 ± 2.40		2	-6.1 ± 1.40		3
1962.67 – 1963.66	26.7 ± 2.40		1			
1963.66 – 1964.73	16.4 ± 2.40		1			
1964.73 – 1965.66	13.8 ± 2.40		1			
1965.66 – 1966.71	18.2 ± 2.40		1			
1966.71 – 1967.67	26.8 ± 2.40		1			
1967.67 – 1968.66	12.5 ± 2.40		1			
1968.66 – 1972.62	19.5 ± 6.80		47			
1962.65 – 1972.62				-6.1 ± 2.00		17
1972.62 – 1977.62	21.2 ± 1.21	3.7	7	-0.3 ± 0.94	3.8	17
1977.62 – 1988.13	8.1 ± 0.48	1.2	7	-7.4 ± 0.73	3.2	17
1988.13 – 1995.32	7.2 ± 1.13	8.0	47	-9.8 ± 1.70	5.9	17

du/dt: rate of advance (m a^{-1});
σ: standard deviation of rate of advance (m a^{-1});
n: number of profiles.

Intervals with $n \leq 3$ are from annual ground surveys (Müller 1963; Kälin 1971). Others are from photogrammetric analysis; for two which end at 1972.62, rate estimates are from photogrammetric analysis adjusted by removing the contribution of several annual surveys.

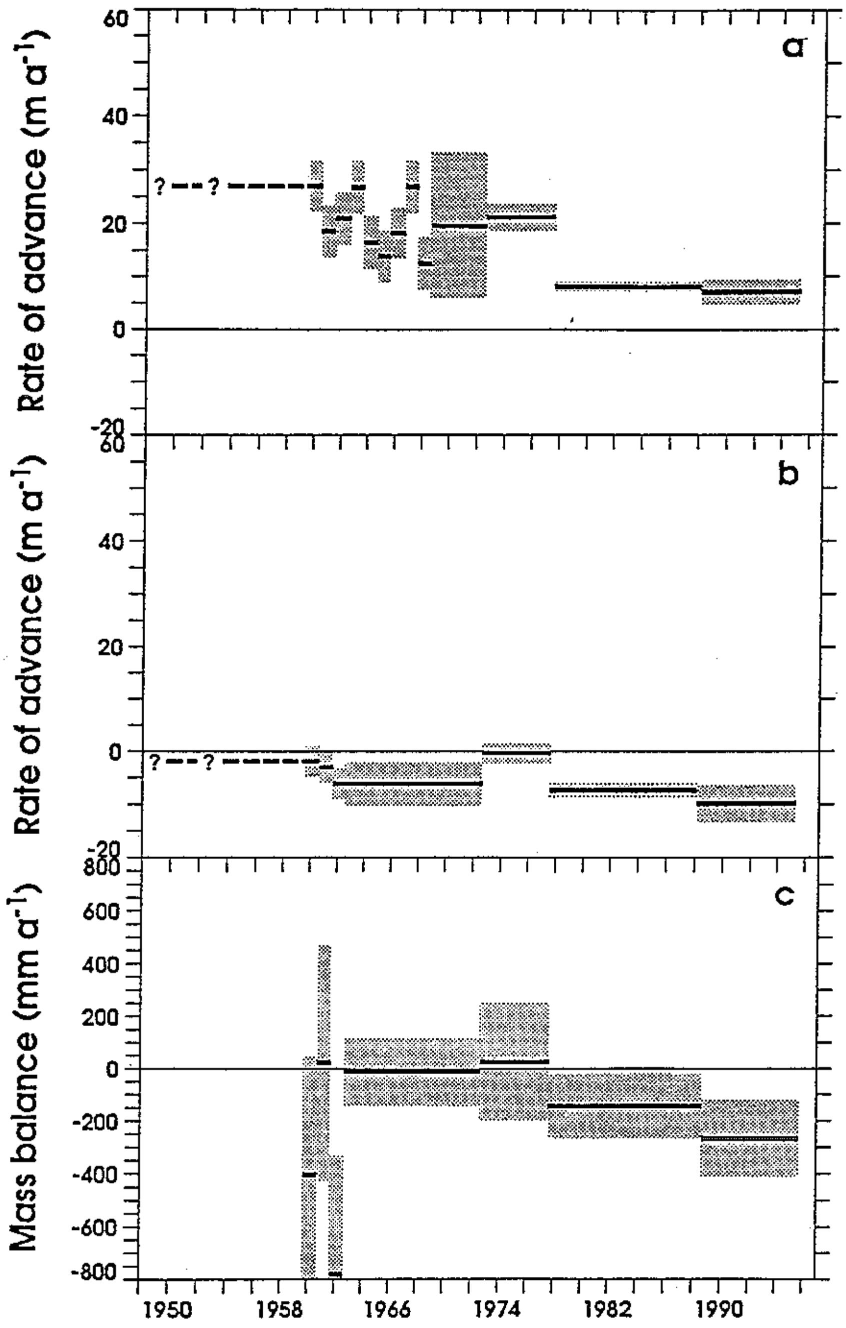

Figure 4. *Rates of advance of White and Thompson Glaciers.*

a: Thompson Glacier. Horizontal lines: estimated rates of advance. Shading: confidence regions of ±2 standard errors about each estimate, incorporating both intrinsic positional errors and sampling errors due to rate variations along the baseline. Question marks indicate a guess at early rates of advance based on inspection of images from 1948 and 1952. One-year-long estimates for 1959 to 1968 are from Müller (1963) and Kälin (1971).
b: White Glacier. Symbolism as in panel b. One-year-long estimates for 1959 to 1962 are from Müller (1963).
c: Mass balance of White Glacier (Cogley et al. *1995, and recent unpublished measurements), degraded to the resolution of panel b by averaging annual estimates.*

Moisan and Pollard (1992) estimated rates of advance for Thompson Glacier varying from 9 to 19 m a^{-1} over the interval 1959—1988. Considering the higher rates observed by Kälin (1971) in the 60s, they suggested that the advance might have decelerated, and we can now confirm that suggestion (Figure 4).

Figure 4 shows that genuine variations in advance rate, exceeding the uncertainty of the measurements, can be identified at both interannual and decadal time scales. The short-term variations can presumably be accounted for by short-term and local variations in forcing factors, including variations in ablation rate and, where the terminus is cliffed as along part of the front of Thompson Glacier, in the "calving" rate of ice blocks. Glacier flow velocities are also known to vary over short periods (e.g. Iken 1974), and so some of the short-term variation in advance velocity of the terminus may arise directly from glacier dynamics.

Decadal and longer-term variations in terminus position are of interest in a broader, climatic context. The problem is to relate the observed changes to long-term changes in forcing, with allowance for the dynamic response of the glacier. This interaction between forcing, dynamics and fluctuations of glacier length is not well understood, although Jóhannesson *et al.* (1989) offer a simple but well-grounded way of estimating dominant timescales of response. They suggest, as an estimate of glacier response time, the ratio of a typical glacier thickness to the typical mass balance at the terminus (in m a^{-1}). This yields response times to climatic forcing of about 100 years for White Glacier and 200 years for Thompson Glacier, since both have a mass balance of about —2 m a^{-1} at their terminuses (Cogley *et al.* 1995) and their thicknesses are about 200m and 400m respectively (e.g. B.S. Müller 1961; Iken 1974; Blatter 1985, 1987).

If this calculation is meaningful it implies that the close coherence between Figures 4a and 4b is coincidental: the time series of either glacier can be reproduced well by translating that of the other upward or downward as appropriate, but the similarity of shape has no physical significance because White Glacier and Thompson Glacier are responding to climatic forcing integrated over different amounts of past time.

To the extent that the terminus fluctuations of Thompson Glacier are governed by long-term climatology, as opposed to short-term effects and to its local interaction with the tongue of White Glacier, an explanation of the fluctuations must account for forcing over the last several centuries. A plausible explanation is that Thompson Glacier is still responding to the Neoglacial cooling. The slowing of its advance may be an early indication of its emergence from the Little Ice Age. This speculation, however, will not do for White Glacier because it should already have adjusted to post-Neoglacial conditions. It is tempting to see the recent acceleration of retreat as a response to anthropogenic global warming, but considering the difficulty of defining its terminus under present conditions this is probably going too far. Moreover Cogley *et al.* (1995) show that in fact there has been no significant change in climatological forcing, at least in recent decades. Thus to the extent that the terminus fluctuations of White Glacier are governed by long-term climatology, its recent behaviour is puzzling. It is perhaps more probable that Figure 4b documents short-term and local behaviour.

For White Glacier, but not for Thompson Glacier, we have a long mass-balance record (Figure 4c) with which to compare terminus fluctuations. Cogley *et al.* (1995) concluded that the series of annual balances for 1960—1991 exhibits no significant linear trend, but at the degraded resolution of Figure 4c it is possible to appreciate that at the decadal scale the mass balance may in fact vary significantly. However these variations are an immediate, year-by-year response to climatic forcing in the form of mass and energy receipts at the glacier surface, and they are not influenced by slow glacier dynamics. There is an apparent correspondence of patterns between Figures 4b and 4c, but because of the disparity of timescales it is surely fortuitous.

Were it permissible to extrapolate backwards from the half-century of photographic coverage and the analysis above, we would conclude that about 100 years ago the terminus of White Glacier must have been separated from that of Thompson Glacier. The latter would have been 1—2km shorter than at present, and White Glacier would have been an "expanded-foot glacier" (Ommanney 1969) of a type which is very common elsewhere in the Canadian high Arctic. Were it permissible to extrapolate *forwards*, we would expect the pattern of advance and retreat to eliminate, over the next 50 years or so, the distinct status of White Glacier, which is well on the way to becoming simply a tributary of Thompson Glacier.

CONCLUSION

We have documented the terminus fluctuations of two High Arctic glaciers for which a wealth of related glaciological information is already available. Further detail can be added to the record of terminus fluctuations by analysis of imagery from other dates, but this will probably require improvements in photogrammetric accuracy. Shorter intervals between images make the errors larger as a proportion of the length-change signal which is being sought. Positional errors of up to 10m are unacceptable when measuring advance rates of about 10 m a^{-1} over intervals as short as 1—2 years. The most intriguing aspects of terminus fluctuations, however, are in the lower-frequency range of decades and longer. Our results show that on these time scales the advance of the larger of our two study glaciers is slowing down while the retreat of the smaller is speeding up. The information presently available does not permit a physical explanation of why this should be so, but the most plausible rationalization is that much of the signal we have detected is due to the interaction between the two terminuses. White Glacier, in particular, continues to suffer dramatic reorganization of its terminus and lower tongue as Thompson Glacier takes over space which formerly belonged to it. The decelerating advance of Thompson Glacier is generally consistent with what is known about recent climatic history, and about the response times of glaciers, but a fuller understanding of its kinematics will probably require modelling of its dynamics.

It is encouraging that our radar images yielded very useful information. Satellite radar is likely to become a very valuable tool in glacier monitoring if, as now seems probable, it can provide frequent imagery comparable with the airborne imagery which we have used. Advances in control technology and in the accuracy of platform position and attitude information, together with developments in radar interferometry, will reduce the complexity of georeferencing and the magnitudes of positional errors, and will tend to shift measurements such as ours into the realm of routine. Better ground truth will also be obtainable with GPS technology, and in general the outlook for advances in quantitative understanding of glacier fluctuations is very promising. The measurements reported above will, we hope, be part of the groundwork for these advances.

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