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Remote-sensing Resources for Monitoring Glacier Fluctuations on Axel Heiberg Island

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ABSTRACT. We document the abundant resources available for the photographic reconstruction of glacier terminus positions in the Canadian High Arctic, with particular reference to Axel Heiberg Island. Early terrestrial photographs may yet be discovered in the archives of explorers, but systematic photography of the High Arctic began with aerial coverage by the U.S. Air Force's Operation Polaris in the early 1940s. This oblique (trimetrogon) coverage was completed by the Royal Canadian Air Force in the early 1950s, and the coverage of vertical photography was completed in the late 1950s. Thereafter the resources become intermittent, but Axel Heiberg Island glaciers have been imaged quite frequently from the air. Visible-band satellite imagery is available from as early as 1962, but the number of useful archived images is limited by persistent, extensive cloud cover and, for some satellites, by distance of the region from ground receiving stations. Radar imagery, which is free of the cloud constraint, has recently become available both from the air and from space. We illustrate the potential of the photographic record by extending back to 1948 an earlier analysis of the terminus fluctuations of White and Thompson Glaciers. Analysis of an oblique photograph demonstrates a significantly more rapid retreat of White Glacier during 1948–60 than during 1960–95, while the advance of Thompson Glacier between 1948 and 1960, at 58 m a^{-1}, was almost three times faster than thereafter.

Key words: Axel Heiberg Island, glacier monitoring, remote sensing, terminus fluctuations

RÉSUMÉ. Nous documentons les importantes ressources disponibles pour la reconstruction photographique des positions du front des glaciers dans l'Extrême-Arctique canadien, en particulier sur l'île Axel Heiberg. On peut encore découvrir d'anciennes photographies terrestres dans les archives des explorateurs, mais les premières photographies systématiques de l'Extrême-Arctique ont été prises par des avions américains dans le cadre de l'opération Polaris au début des années 1940. Cette couverture par prise de vue oblique (trimétrogon) a été achevée par l'Aviation royale du Canada au début des années 1950 et celle par photographie verticale a été terminée à la fin des années 1950. Pour la période qui suit, les ressources deviennent intermittentes, mais des images aériennes des glaciers de l'île Axel Heiberg ont été prises assez souvent. Dès 1962, les capteurs de satellite ont fourni des clichés dans la bande du visible, mais le contenu utilisable de l'archive est limité par la couverture nuageuse étendue et persistante de cette région et, pour quelques satellites, par la distance entre la région et les stations de réception. L'imagerie radar, qui n'a pas à s'inquiéter des nuages, a récemment fourni des clichés pris des airs comme de l'espace. Nous illustrons les possibilités des dossiers photographiques en faisant remonter jusqu'en 1948 une analyse antérieure des déplacements du front des glaciers White et Thompson. L'analyse d'une photographie oblique montre un recul significativement plus rapide du glacier White durant la période 1948–1960 que durant la période 1960–1995, tandis que, entre 1948 et 1960, l'avancée du glacier Thompson, à 58 mCa^{-1}, a été près de trois fois plus rapide que par la suite.

Mots clés: télédétection, surveillance des glaciers, déplacements du front des glaciers, île Axel Heiberg

INTRODUCTION

This paper documents and illustrates the great potential of the available and nearly available photographic database for the monitoring and historical reconstruction of high-latitude glaciers. It was stimulated by a recent article (McMillan, 1998) based on ground-level photographs, taken in 1955 and 1983, of the terminus of Bunde Glacier, Axel Heiberg Island, Nunavut, Canada. McMillan used the photographs to interpret the behaviour of the terminus over the 28-year interval. In fact, systematic aerial photography of Axel Heiberg Island (AHI) began in the year of the first issue of *Arctic*, 1947. Since then, a remarkable amount of aerial photography and satellite imagery of High Arctic glaciers has become available. This imagery, now spanning more than 50 years, provides a valuable basis for interpreting careful ground-level photographs and observations of glaciers such as those of McMillan (1998) and, even with simple measurement techniques, for much more comprehensive monitoring of remote glaciers than has yet been attempted.

In the following section, we review the glaciologically relevant imagery available for AHI, our principal concern being with the older sources. The third section illustrates the potential of the historical photographic record through a simple but accurate quantitative analysis of a 1948 oblique air photograph of the terminuses of two adjacent glaciers, one of which is advancing while the other is retreating. The final section reflects on our experience with these images and attempts to assess the potential of

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the remote-sensing record as a whole. An appendix provides information on the whereabouts and accessibility of some of the older information.

HISTORICAL SURVEY — AXEL HEIBERG ISLAND

Early Visitors

Knowledge of AHI (Fig. 1) appears to be a 20th-century phenomenon. Members of an expedition led by Sverdrup (1904) discovered the island in 1899. Dunbar and Greenaway (1956) describe the early history of exploration. All of the early visits were confined to the outer coast; they did not penetrate to the more glacierized interior. Glaciologically useful photographs or sketches may yet be found among the papers of early explorers, but the publications we have examined contain little visual material of glaciological value. For example, Sverdrup has photographs of only two glaciers in the vicinity of Bache Peninsula, Ellesmere Island. One, Beitstad Glacier, receded by about 2.5–3.0 km between 1899 (Sverdrup, 1904:Vol. I:187) and 1959, the date of the photography on which NTS map sheet 39G (1:250 000 scale) is based. MacMillan (1918), who visited AHI in 1914 and 1916–17 from a base camp in Greenland, mentions having taken more than 5000 photographs during his time in the High Arctic.

Airborne Sensors

The first known aerial photographs of the island were taken in 1947 and 1948 during Operation Polaris, the U.S. Army Air Force's trimetrogon survey of the High Arctic (Fig. 2a,b). ("Trimetrogon" is the name of an air-photographic survey method, used until about the mid-1950s, in which three cameras, originally of the Metrogon brand, were mounted along a line transverse to the flight path of the aircraft. One camera pointed to the nadir and one to either side of the flight path at a depression angle from the horizontal of about 30°.) The survey focused initially on the coastline, with some later traverses across the interior. Flying heights vary from 19 500 feet to 22 000 feet (5944 m to 6706 m), so that, in each set of three photographs, the vertical covers about 14 km × 14 km on the ground. The left-oblique and right-oblique photographs have fields of view about 102° wide extending all the way to the horizon, but our experience is that accurate measurements of glacier terminus positions can be made only within a swath about 40 km wide and centred on the flight line. This explains the shape of the unobscured region at either end of each flight line in Figure 2.

Trimetrogon photography was repeated by the Royal Canadian Air Force in 1950 and 1952 (Fig. 2c, d), which also flew a single flight line in each of 1951 and 1953. RCAF coverage was more complete than that of Operation Polaris. Dunbar and Greenaway (1956) and Ommanney (1969) show numerous examples of this imagery.

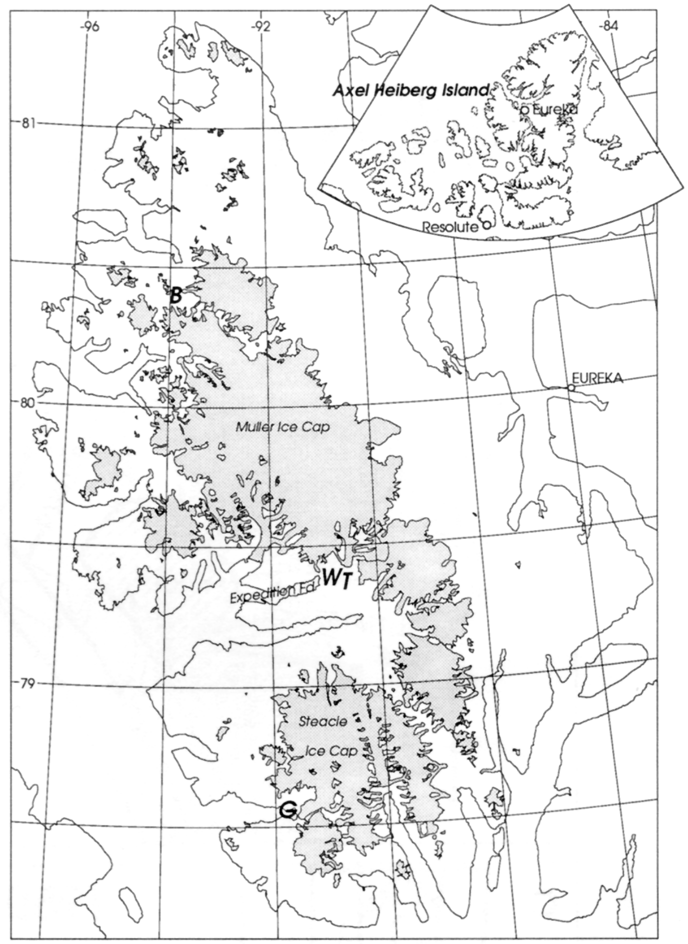

FIG. 1. Axel Heiberg Island. Glacier cover is stippled. Letters B, T, W, and G lie south or west of the terminuses of Bunde Glacier, Thompson Glacier, White Glacier, and Good Friday Glacier, respectively. Universal Transverse Mercator projection (zone 15).

Comparison of the panels of Figure 2 shows that different parts of the glacier cover of the island were imaged from 0 to 4 times between 1947 and 1953. However no account is taken here of obscuration by clouds. Much of the Operation Polaris photography of 1947 and 1948 is of limited value because of clouds, although we report below an analysis of a partially cloudy image from August 1948 that has yielded valuable quantitative information. The RCAF coverage of 1950 to 1953 is little affected by cloudiness.

Complete coverage of AHI by vertical photographs was obtained in 1958 and 1959. Ommanney (1969) used these photographs for his meticulous inventory of the island's ice masses. The photographs are of excellent quality and are the basis for the standard 1:250 000 scale topographic maps of the island. The 1959 photographs are also the basis for a 1:50 000 scale map of the Thompson Glacier area (National Research Council, 1962).

In 1964 Austin Post, then of the U.S. Geological Survey, made a low-altitude oblique-photographic survey of glacier terminuses in the Canadian High Arctic and Greenland. Post's collection includes more than 250 views of AHI glaciers (Fig. 3); one appears as Figure 121 of Post and LaChapelle (2000).

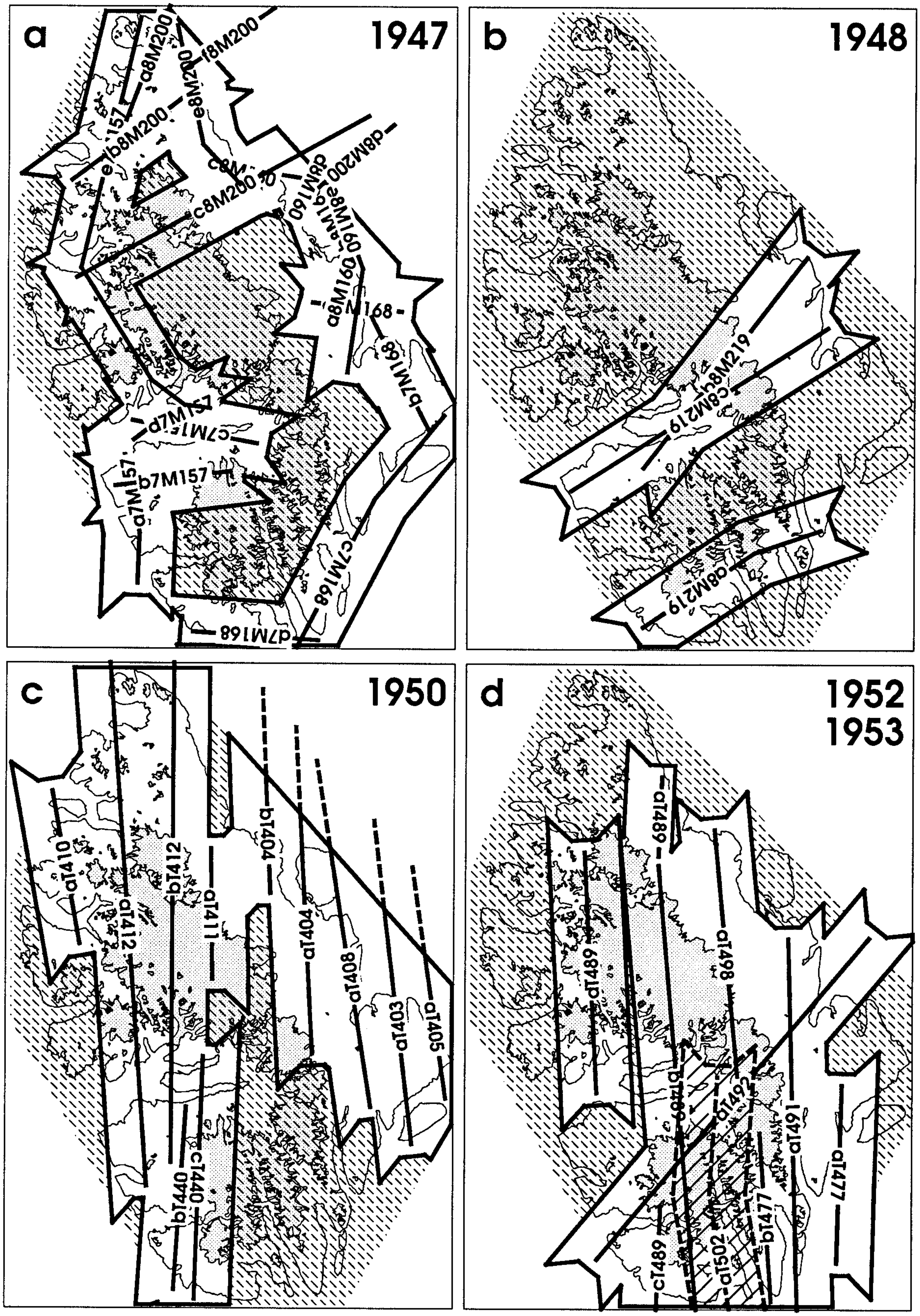

FIG. 2. Early trimetrogon photographic coverage of Axel Heiberg Island. In each panel, dashed diagonal lines obscure those regions *not* covered during the indicated year. Flight lines are labelled with their official numbers, to be read in the direction of flight-line travel. Each official number is prefixed by an unofficial, lower-case letter to identify separate legs of the flight line. a: Operation Polaris coverage, 1947. b: Operation Polaris coverage, 1948. c: R.C.A.F. coverage, 1950. d: R.C.A.F. coverage, 1952; flight line T502 (continuous hatching) was flown in 1953.

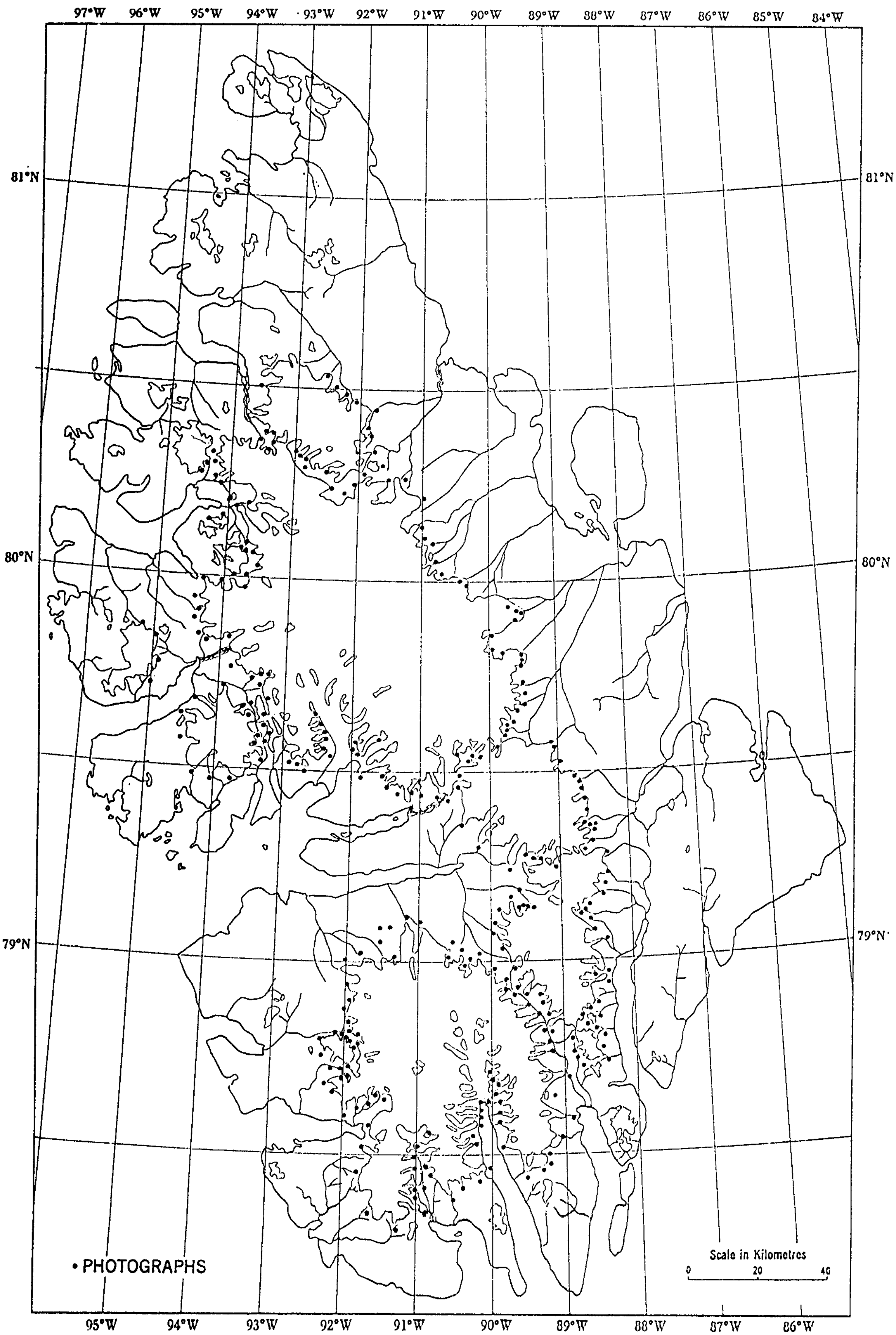

FIG. 3. Locations (dots) of low-altitude oblique photographs taken by Austin Post in 1964. Coverage of the island's glacier terminuses is almost complete. Reproduced, with permission, from Figure 7 of Ommanney (1969).

No extensive photographic survey of AHI has been attempted since the work of Post. One part of the island, however, has continued to be a focus of scientific attention and has an excellent, if increasingly sporadic, record of repeated photography. This is the Expedition Fiord area (Fig. 1), which was the subject of the Jacobsen-McGill University expedition beginning in 1959 (Müller and Members of the Expedition, 1963) and has been studied, mainly by glaciologists, ever since. Cogley et al. (1995) reassess the studies of mass balance done on Expedition Fiord glaciers, while Cogley et al. (1996a) address White Glacier in particular and Adams et al. (1998) study Baby Glacier in particular. Cogley et al. (1996b) list the photography flown over the Expedition Fiord glaciers on summer dates in 1960, 1967, 1972–75, 1977–78 and 1990. The photographs are at scales from 1:7000 to 1:20 000, and some are in colour.

The photographs of 1960 were used to produce a 1:100 000 scale map of the Expedition Fiord area (McGill University, 1963), a 1:10 000 scale map of White Glacier (National Research Council, 1965), and several maps of terminuses at a scale of 1:5000. The success of this mapping effort depended on accurate ground control (Haumann, 1963), as does the photogrammetric work described below. An orthophotomap of the terminus of Thompson Glacier at 1:5000 scale, based on the photography of 1977, has recently been published (Institute of Cartography, 1998).

Cogley et al. (1996b) developed a preliminary chronology of advance rates for White and Thompson Glaciers from a subset of the photographic record summarized above. They used maps based on 1960 photographs, photographs from 1972 and 1977, and airborne synthetic aperture radar (SAR) imagery obtained in February 1988 and April 1995. These opportunistic SAR flights were made under the auspices of unrelated projects through the kindness of other investigators, from the Canarctic Shipping Company, which was managing the Canadian Ice Service's Winter Arctic Ice Atlas project, in 1988, and from the Canada Centre for Remote Sensing in 1995.

Spaceborne Sensors

In 1995, the U.S. government declassified large amounts of film-based imagery from the CORONA series of intelligence satellite missions, which were flown between 1960 and 1972 (McDonald, 1995). The Canadian High Arctic is covered in abundant CORONA imagery from 1962 and 1963, but low resolution and extensive cloud cover limit its usefulness. However, there is excellent coverage of many AHI glaciers on medium-resolution photographs of the KH-4A series, taken on 14 August 1966, as well as more spatially limited coverage on three other dates in 1966–67. Features as small as 3 m are resolvable on suitable enlargements.

The former Soviet (now Russian) Kosmos satellites have carried a number of high-resolution cameras that have recorded imagery of high latitudes on film. This imagery is evaluated by Dowdeswell et al. (1993) for Svalbard. They report that resolutions as fine as 2–3 m, more than adequate for the mapping of glacier terminus fluctuations, are attained by the KFA-1000 camera. AHI is covered by KFA-1000 photographs taken in July 1993, although cloud cover is about 70%, and also by KATE-200 multispectral photographs of 20 m resolution from 1976.

To assess the extent and quantity of coverage of AHI by spaceborne digital sensors, we searched the archives of the Canada Centre for Remote Sensing for scenes dated between 1 August and 15 September that had cloud cover of 10% or less. Landsats 1 to 3 gave at least partial Multi-Spectral Scanner (MSS) coverage of AHI in each year from 1974 to 1982, and a single Landsat 1 scene in 1972. Landsat 4 and Landsat 5 orbited at lower altitudes than their predecessors, and the limitations of onboard data storage (between the time of imaging and the time of passage over telemetry receiving stations such as those at Prince Albert, Canada or Kiruna, Sweden) reduce the number of available images. There is good coverage of AHI in 1983, but in and after 1984 there are only four MSS scenes covering AHI. From the Thematic Mapper flown on Landsats 4 and 5, there are only two scenes, one each in 1985 and 1987, that cover parts of AHI.

The Thematic Mapper has 30 m resolution, but the resolution of the MSS—pixel sizes of the order of 80 m × 50 m—is inadequate to detect typical rates of terminus advance (only a few metres per year) over spans of only a few years. Howarth and Ommanney (1983) also found the MSS inadequate for glacier inventory. Jung-Rothenhäusler (1993) and Cogley (1992) studied a Landsat 1 image of AHI obtained in September 1974, with the aim of extracting information relevant to the estimation of glacier mass balance from space.

Archived late-summer coverage of AHI by the SPOT High Resolution Visible (HRV) sensor, with a ground resolution of the order of 10 m, is abundant for 1988–92 and 1994–95, but not for other years since the launch of SPOT-1 in 1988.

The persistent, extensive cloud cover that prevails during the Arctic summer limits the glaciological value of all the visible-wavelength satellite sensors discussed above. For example, of the 228 SPOT HRV images of AHI archived from the period 1 August–15 September 1995, only 18 show glaciological information. Most of the rest are too cloudy or do not cover glacierized parts of the island, while some are compromised by snow cover. The 18 useful images include several repeated scenes. In sum, the effective HRV coverage of AHI glacier terminuses for 1995 is less than 20%. This estimate is typical for other summers and other sensors. Marshall et al. (1993) show quantitatively for Svalbard that the ratio of useful to available visible-band images is very small because of cloud cover, and this conclusion evidently applies also to AHI.

Cloud cover is not a limiting factor for synthetic aperture radar (SAR) sensors. ERS-1, the first of these to image

AHI, was launched in 1991. However ERS SAR images of AHI have not been archived in large numbers. There is moderately good ERS coverage of AHI for 1993, but little or no imagery of glaciological value before or after that year. There is no archived coverage of AHI glaciers by JERS-1, the Japanese Earth Resources Satellite that operated from 1992 to 1998. Abundant images from Radarsat, launched in 1995, are available for dates from 1997 onward. Most were obtained in the ScanSAR mode, with swath widths of 500 km and resolutions of 100 × 100 m, although special investigations (e.g., Budkewitsch et al., 1999) have yielded a modest number of higher-resolution scenes, particularly for the Expedition Fiord area and for the Wolf Fiord area in southern AHI.

Our purpose here is to describe the actual historical archive, and not the enormous *potential* of radar for future surveys. The existing archive of SAR images is likely to be of limited value for the mapping of pre-1997 terminus positions, but should grow in value for later dates as Radarsat imagery accumulates. However, two problems relating to horizontal positioning remain unresolved. First, AHI glaciers, being cold and stiff, tend to terminate in steep, often vertical, slopes with heights of up to tens of metres. Second, most potential control points in terrain like that of AHI are mountaintops. Thus, radar image positions are in general affected by foreshortening and shadowing (e.g., Olmsted, 1993), and it is not yet clear whether satellite SAR imagery will be registrable to the same accuracy that we can achieve with large-scale aerial photographs. For example, Adam et al. (1997) were able to register glacier margins only to a horizontal accuracy of ± 75m.

Future Sensors

Imagery from the Enhanced Thematic Mapper on Landsat 7, launched in April 1999, is now becoming available. Excellent coverage of AHI was acquired during July 1999. Sensor resolution in the panchromatic band is 15 m.

The 15 m resolution ASTER radiometer, a joint U.S.-Japanese venture on the EOS Terra satellite launched in December 1999, will be the primary source of information for the Global Land Ice Measurements from Space (GLIMS) project. Coordinated by the U.S. Geological Survey, Flagstaff, Arizona (Kargel and Kieffer, 1995), GLIMS aims to monitor the world's glaciers regularly and frequently. Two parts of the Canadian High Arctic—central AHI and the Ward Hunt Ice Shelf, Ellesmere Island—are designated for high-priority ASTER imaging by GLIMS; the remainder of the region has medium priority. As a short-wavelength sensor, ASTER will be constrained by cloud cover, darkness, and perhaps snow cover, but the attentive targeting of glaciers by GLIMS may offset these disadvantages in part.

Appraisal

For a "typical" glacier terminus on AHI, there are up to six cloud-free images between 1947 and 1966. The SPOT satellites are likely to yield a small number of additional images for 1988 to 1995, and the likelihood of the terminus having been imaged at high resolution by Radarsat from 1997 onward is fair to good. Landsat satellite imagery in and after 1972 does not add appreciably to the useful historical record, because of its low resolution and sparse cloud-free coverage. For selected terminuses, especially in the Expedition Fiord area, the actual frequency of coverage is significantly greater than the typical frequency. In sum, remotely sensed imagery of AHI glaciers represents a substantial repository of spatially extensive historical information about glacier fluctuations and therefore, in principle, about climatic change. We turn next to an illustration of recent work intended to make this information easier to exploit.

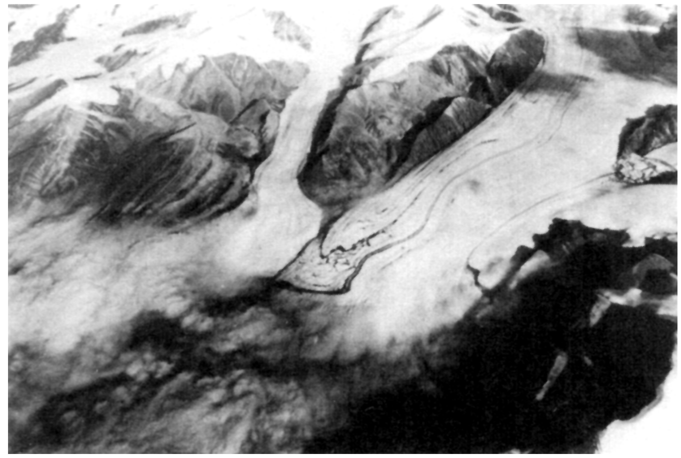

FIG. 4. Part of photograph 60LT-72PL-C-8M219-72RS-11 AUG. 48-14C (National Archives of Canada), showing the contiguous terminuses of White Glacier (left) and Thompson Glacier (right). The look azimuth is 313°, or northwest.

WHITE AND THOMPSON GLACIER TERMINUS POSITIONS IN 1948

Figure 4 is a left-oblique, northwest-looking image from 11 August 1948 showing parts of central and northern AHI. In the foreground, partly obscured by a thin layer of valley fog, are the contiguous terminuses of White Glacier (left) and Thompson Glacier (right). Close inspection of the original prints reveals that most of the ice edge is discernible. Although its quality leaves something to be desired, this photograph is probably the oldest surviving artefact containing information on the history of the two glaciers. We therefore decided to try to extract the information in a form appropriate for quantitative interpretation. The principles of oblique photogrammetry are set out by Imhof and Doolittle (1966). Our method deviates somewhat from their mapping-oriented approach and exploits the power of modern computers, but it is an updating of the old technology rather than a fully general algorithm for rectification of oblique imagery. The procedure in general has been little used for 40 years, so we summarize it briefly here. The interested reader is referred to Cogley (1999) for geometrical details.

We model the relationship between image points and corresponding points on the ground using a set of control points whose ground coordinates are known accurately. We obtained good results by measuring carefully chosen points on a large-scale map (National Research Council, 1962), which was itself based on reliable ground surveys (Haumann, 1963). The first image parameter, the swing angle or rotation of the photograph in its own plane about the optical axis of the camera, is obtained by locating on the photograph the tangent to the gently curved image of the horizon. This tangent and the perpendicular that connects the point of tangency A with the centre of the photograph P together define the coordinate system in which subsequent measurements are made. The length of AP and the known focal length of the camera, f, are used to estimate the photograph's depression angle (from the horizontal), which is then corrected for atmospheric refraction and the curvature of the Earth. The nadir of the photograph is the point in the image plane vertically below the camera; it lies on the continuation of AP at a distance that depends on the depression angle and on f.

Given the quantities determined so far, it is a straightforward exercise in trigonometry to estimate the horizontal coordinates on the ground that correspond to any given point in the image plane. The unknown ground coordinates depend on the elevation of the ground point and on four model parameters. One of these is the elevation of the camera, for which reported flying height is a first guess. Two parameters represent the location of the nadir in the ground coordinate frame, and the final parameter is a rotation to align the ground and image coordinate frames. Our model estimates these parameters with a nonlinear least-squares inversion algorithm applied to the set of control points.

The reliance on existing ground control is a limitation of the procedure, but it is not necessarily fundamental. A further limitation is the need to supply a moderately accurate estimate of the elevation of each ground point. In practice, this is not a serious constraint for glacier terminuses, which vary little in elevation across their width, although the steeper lateral margins behind the terminuses can be seriously mislocated without the elevation information. A principal advantage of the analysis is that it is not stereoscopic. That is, it avoids the need to work with the accompanying vertical or adjacent oblique photographs. The accompanying vertical is used only for a first guess at the location of the nadir of the oblique photograph (the second and third parameters of the model).

The result of our analysis is shown in Figure 5. We estimate advance rates of +58.5 ± 2.0 m a^{-1} for Thompson Glacier and -12.6 ± 1.2 m a^{-1} (that is, a retreat) for White Glacier between 1948 and 1960. (Error ranges are twice the standard error; they derive from an estimate, based on repeated trial measurements, of 0.1 mm for the standard error of any distance measured on a photograph or map, and we assume the same uncertainty for the focal length of the camera.) Cogley et al. (1996b) illustrate in greater detail the evolution after 1960. The terminus advance of Thompson Glacier has slowed steadily. It was only +7 m a^{-1} in 1988–95, and the total advance in the 35 years following 1960 is roughly the same as that in the 12 years before 1960 (Fig. 5). White Glacier has retreated throughout the period of observation, but at a variable rate. From 1972 to 1977, the estimated rate was not significantly different from zero, a result that agrees with the terrestrial-photogrammetric estimate of Arnold (1981) for a 12-month interval in 1969–70. More recently, the rate of retreat of White Glacier has increased moderately, to -10 m a^{-1} in 1988–95. (Airborne SAR imagery for these two dates was available to us in the form of paper prints. We treated the prints as if they were air photographs, taking care to avoid control points that might be compromised by layover or foreshortening.) Thus, the magnitude of rates of fluctuation was greater for both glaciers before 1960 than it has been since that date. Figure 6 shows the recent appearance of the two terminuses as seen by the airborne SAR in 1995. Inspection of 1998 and 1999 Radarsat images (not shown) suggests that the two terminuses have maintained their patterns of behaviour since the date of Figure 6.

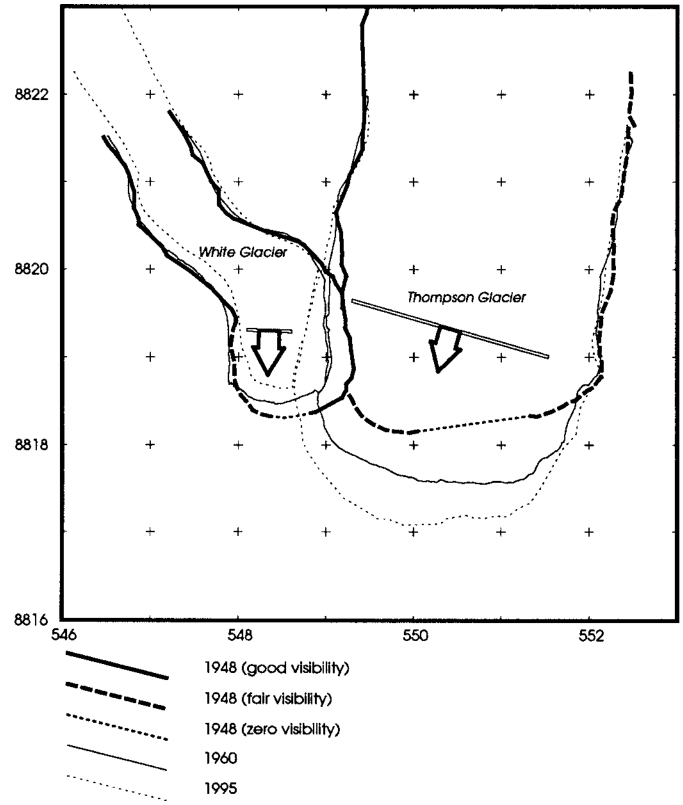

FIG. 5. Mapped terminus positions of White and Thompson Glaciers in 1948, 1960 and 1995. The 1948 positions were obtained as described in the text (see also Cogley, 1999) from the photograph shown in Figure 4. The 1960 and 1995 positions are from Cogley et al. (1996b). The transverse bars, with arrows pointing down-glacier, are the baselines used to measure terminus positions and advance rates. Coordinates (km) are those of UTM zone 15.

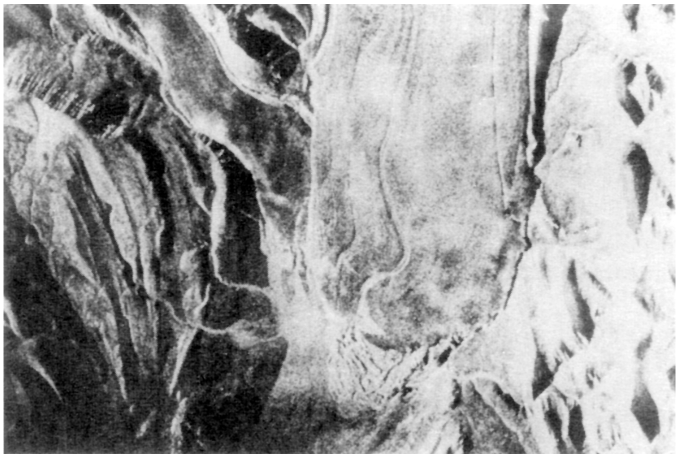

FIG. 6. Part of an image of White and Thompson Glaciers obtained with an airborne C-band SAR on 26 April 1995 by Canada Centre for Remote Sensing. Flying height was 7000 m and resolution was 20 m in range (approximately along the axis of White Glacier) and 10 m in azimuth. Photogrammetric procedures used to generate the terminus map of Figure 5 are described by Cogley et al. (1996b).

DISCUSSION

Evolution of the Two Terminuses

A naive but not improbable interpretation of the historical changes documented in Figure 5 is that Thompson Glacier is now close to its maximum advance in response to the cooling of the Neoglacial, while White Glacier is beginning to respond to more recent warming. The rate of advance of the terminus of Thompson Glacier has been decreasing since 1948, and can be expected to slow in perhaps a decade or two to a stillstand not very far forward from its present position. This speculation is consistent with the 200-year response time estimated by Cogley et al. (1995). The near-stillstand of White Glacier during the 1970s may be a response to the cooling of the 1940s to 1960s (e.g., Jones, 1988). The most positive mass balances of the Neoglacial are inferred (Fisher and Koerner, 1994) to have occurred during the early 19th century, so that a response time of 100 years (Cogley et al., 1995) would place the date of the furthest forward position of White Glacier in the early 20th century.

Müller (1963) gives a ^{14}C age (B-464) of 240 ± 200 BP (^{14}C years ± 2-σ laboratory error) as the oldest age for the last advance of White Glacier beyond its 1960 position. The outer margin of a terminal moraine, about 300 m forward of the 1960 position, probably represents the limit of this advance. Parent (1991) gives a ^{14}C age (GSC-5160) of 180 ± 60 BP, which indicates the earliest time at which this limit could have been reached. These ages, from organic materials buried by the terminal moraine, show that the terminal moraine is a product of Neoglacial advance. Whatever the date of the limit, about 150 m of retreat occurred from it before 1948 and about 150 m between 1948 and 1960.

The recent advances of both glaciers probably represent their furthest forward positions during the entire Holocene (Koerner, 1997).

Other Glacier Terminuses

Müller (1969) documented the behaviour of the advancing terminus of Good Friday Glacier, a major outlet (641 km^2; Ommanney, 1969) of Steacie Ice Cap in southern AHI (Fig. 1). Recently McMillan (1998) suggested that Bunde Glacier (24.8 km^2) in northern AHI had exhibited practically no change in terminus position between 1955 and 1988. To judge from his terrestrial photographs, this suggestion is qualitatively reasonable. On the other hand, we were surprised by the magnitudes of the rates measured for White Glacier and Thompson Glacier in the last section. Visual comparisons had persuaded us (Cogley et al., 1996b) that the rates for 1948–60 would be comparable with rates measured after 1960. In this we were wrong, and we conclude that an attempt to quantify the conclusion reached by McMillan (1998) would be worthwhile. Given actual rates of fluctuation of glacier terminuses on AHI, visual inspection is too imprecise as a means of resolving the regional signal, if any, of change in glacier dynamics or climate over intervals of a few years or perhaps even decades. The tiny sample available now from AHI consists of four glacier terminuses, of which two exhibit marked but decelerating advance, one exhibits moderate retreat, and one appears to exhibit no change. Thus, in addition to obtaining greater precision, it will be necessary to increase the sample size before any regional signal can be identified with confidence.

Prospects

Our photogrammetric analysis was comparatively luxurious, in that excellent ground control is available for Expedition Fiord. Elsewhere on AHI, and in the Canadian High Arctic generally, reliable ground surveys have never been carried out. Much can still be done in the analysis of other glacier terminuses, however, if one image is of sufficient quality to provide a reference coordinate frame to which terminus positions from other images can be transformed or "warped." In future work, we hope to extend the analysis of the Expedition Fiord glaciers to less well surveyed glaciers, and thus to collect a more broadly based sample of regional response to climatic changes.

We have considered the imaging records only as a source of information on terminus fluctuations. It might also be possible to use the older records to map glacier surface elevations at scales larger than the standard 1:250000 of published maps. Such work would be time-consuming and, especially on nearly featureless photographs of accumulation areas, quite difficult. If it were successful, however, it would become possible, by relying on radar interferometry (Mattar et al., 1998) or laser altimetry (Aðalgeirsdóttir et al., 1998) of more recent states, to estimate long-term volumetric change.

Assembling the available photographic records, whether terrestrial, aerial or spaceborne and whether governmental or not, can be difficult. The older records are little known and little used. Costs can be restrictive or prohibitive for those modern products that are available only on commercial terms. For the less formal records, usually only those who have taken the photographs know of their existence, and McMillan (1998) is to be commended on his initiative in making his record public. It is likely that a modest number of useful photographic records of glaciers lie dispersed among the papers of visitors to the Canadian High Arctic. The prospect of such photographs yielding objective information on glacier terminus fluctuations appears to be good, and we encourage those who hold them to consider placing them in suitable archives. However, more consideration needs to be given to how best to diffuse knowledge of the preserved resources through the interested community. The Appendix documents what we have learned about the present state of the resources in the course of the work reported here.

Glacier monitoring in the future will rely on rapid analyses of large volumes of digital information, but more work is needed on the means of analyzing larger numbers of historical photographs more economically. However, we made our measurements without sophisticated hardware or software, and the mathematical basis of the method is well developed. The problem is therefore one of productivity, not lack of understanding, and still less lack of material.

Other specialists will no doubt have their own uses for repeated extensive surveys of uninhabited high-latitude regions such as AHI. As glaciologists, however, we wish to emphasize the critical role of such surveys in deepening and extending our understanding of cryospheric change. The slow timescales that govern glacier dynamics introduce a fundamentally historical dimension to the problem of understanding glacier terminus fluctuations and placing them in climatological perspective. Therefore, given the almost complete absence of historical records in the High Arctic, the archive of glacier photography documented above is in need of careful curation. It deserves to be more widely known and used, and has yet to yield even a small fraction of its glaciological potential.

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APPENDIX: AVAILABILITY OF HISTORICAL GLACIER IMAGERY FOR CANADA

We do not attempt here to document the extensive regular holdings of the National Air Photo Library (NAPL), but focus rather on glacier images, especially older images, which may be harder to find. In most cases it is not practical to separate Arctic material from cordilleran material, and most of the collections contain (rather than consist of) glaciological subjects. We include the information because of the probable diversity of readers' interests. Contact information for the major repositories is given in Table A1.

A. Joint American/Canadian Aerial Photography, 1931–48

The Visual and Sound Archives (VSA), National Archives of Canada, hold a collection of some 200 000 trimetrogon aerial photographic prints (not negatives) of various parts of Canada taken between 1931 and 1948 by the U.S. Army-Air Force Task Force and other agencies. The Archives acquired this collection from the NAPL in 1968 and 1969. The photographs are accompanied by flight-line maps and a card index. About a quarter of the photographs are of the High Arctic and were taken during Operation Polaris (1943–44 and later). This accession is in Record Group ("RG") RG21M/1968-00002-X.

Accession RG85M/934022 ("Northern Administration Branch") contains the flight-line maps for the U.S. photography. The earliest northern holdings appear to be those for Newfoundland and northern Alberta, which date from late 1941. Flight-line maps of the Canadian High Arctic are all dated 1948, but at least some of the photography was obtained earlier, for example in 1947 for Axel Heiberg Island (Ommanney, 1969).

B. Royal Canadian Air Force Aerial Photography, 1941–63

The Records Disposition and Government Archives Division (contact information as for VSA) holds textual files (for example, accession RG24/17702/071-2) relating to aerial photography of the Arctic by the Royal Canadian Air Force for surveying purposes between 1941 and 1963. These records were acquired as part of the RCAF central registry files.

TABLE A1. Major repositories of historical photographic records.

NAPL	
National Air Photo Library, Geomatics Canada, Natural Resources Canada, 615 Booth Street, Ottawa, Ontario K1A 0E9.	
Web:	http://airphotos.nrcan.gc.ca/contact.html
Tel:	(613) 995-4560
Fax:	(613) 995-4568
NWRI	
Canadian Glacier Information Centre, Library, National Water Research Institute, 11 Innovation Boulevard, Saskatoon, Saskatchewan S7N 3H5.	
Email:	heather.popoff@ec.gc.ca
Tel:	(306) 975-5718
Fax:	(306) 975-5143
VSA	
Researcher Services Division, Visual and Sound Archives, National Archives of Canada, 395 Wellington Street, Ottawa, Ontario K1A 0N3.	
Web:	http://www.archives.ca/www/svcs/english/contactingus.html
Tel:	(613) 996-7613
Fax:	(613) 995-6226

Negatives and prints of trimetrogon photographs taken by the Royal Canadian Air Force from 1945 to the mid-1950s are held at the NAPL. Axel Heiberg Island was photographed in 1950 and 1952, with one flight over the extreme east of the island in 1951 and one over the south in 1953.

C. Photographs Taken by Austin Post, 1964

In 1964, with the support of the Polar Continental Shelf Project, Austin Post took a large number of oblique aerial photographs of glaciers in the High Arctic of Canada and in Greenland. The photographs are stored in the NAPL collection. Many of the prints are annotated with place-names, and some with coordinates. The collection, which is neither catalogued nor indexed, is in three boxes: *PSF 164* (173 prints of eastern Axel Heiberg Island and Ellesmere Island); *PSF 264* (203 prints of Greenland, Axel Heiberg Island, and Ellesmere Island); and *PSF 364* (207 prints of Axel Heiberg Island, Ellesmere Island, Greenland, and Devon Island). We have not yet succeeded in locating the negatives of these photographs. They are not at the National Snow and Ice Data Center (University of Colorado, Boulder, CO80309, U.S.A.; http://www-nsidc.colorado.edu). That repository does, however, hold the American Geographical Society Collection of about 10 000 photographs, dating from the 1880s to 1975, of glaciers in western North America.

D. Glacier Imagery and Other Information at the National Water Research Institute

Beginning in the 1960s, various government departments and other organizations transferred data on glaciers, including many thousands of aerial photographs and maps, to the Glacier Inventory Section, Glaciology Subdivision, of what is now the National Water Research Institute (NWRI). Regrettably, the Glacier Inventory Section no longer exists. Its magnificent collection is still stored in the Canadian Glacier Information Centre at NWRI; however, only very limited resources are at present allocated to its curation.

The Canadian Glacier Information Centre collection includes:

- several thousand photographs from "phototop" stations occupied on the Canada-Alaska border during the International Boundary Survey near the beginning of the 20th century;
- photography and maps from the Alberta-British Columbia Interprovincial Boundary Commission Survey (1917);
- material gathered for the International Geophysical Year (1957–58) glacier inventory;
- the raw materials used for the Canadian Glacier Inventory, which was intended to identify every perennial body of snow or ice in Canada. These include tens of thousands of aerial photographs that provide complete coverage of glacierized areas of Canada, including those described in A and B above, and data (including a large bibliography and software designed to retrieve all quantitative material) on 40 000 of the more than 100 000 glaciers in Canada;
- records, including field survey records, from the Defence Research Board (Department of National Defence) glaciological programme on Ellesmere Island (1950s–1970s);
- material gathered for the International Hydrological Decade (1965–74);
- field survey records and terrestrial photographs of glaciers obtained by the Dominion Water and Power Bureau (1945–60) and its successor, the Water Survey of Canada, Environment Canada (1960–80);
- a collection that includes the largest-scale maps available for all glacierized areas of Canada.

E. Terrestrial Photography of Western Canada

The Visual and Sound Archives hold, as accession RG24M/85603/64, some 15 000 glass-plate negatives and some 7000 prints of a mountaintop survey done in British Columbia and the Yukon by the Army Charting Establishment from 1947 to 1957.

F. Satellite Imagery

CORONA imagery is available from the U.S. Geological Survey Global Land Information System (http://edcwww.cr.usgs.gov/webglis/). Landsat, SPOT, ERS, and Radarsat imagery is available from the Canada Centre for Remote Sensing (http://www.ccrs.nrcan.gc.ca/). Both of these sources offer advanced search and browse facilities and accept orders electronically. KFA-1000 and KATE-200 photographs are available from the Remote Sensing Laboratory, Institute of Geography, Russian Academy of

Sciences, Staromonetny pereulok 29, 109107 Moscow, Russia.

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