# Glacier Monitoring for Climate Change Detection in Nunavut

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## SUMMARY

Nunavut contains approximately 75% of Canada's total glacierized area. The high arctic ice caps have received the most consistent monitoring, whereas glaciers on Baffin Island have been monitored for shorter intervals since the 1960s. Although mass balance data for selected Baffin glaciers show no clear trend over the monitoring period, there appears to be reasonable agreement between summer temperature and annual mass balance. In contrast to global warming trends, the Baffin region has experienced a general cooling over the last 30 years, particularly in winter. The cause of this cooling is not fully understood and its impact on the local ice cover is uncertain. In order to address these issues, mass balance observations should be resumed on a suitable glacier as part of an integrated environmental monitoring program in the region.

## RÉSUMÉ

Environ 75 % des territoires englacés du Canada sont situés dans le territoire du Nunavut. Les calottes glacières du haut-Arctique sont les zones qui ont fait l'objet de suivis plus réguliers, alors que les glaciers de l'île de Baffin ont été étudiés sur des périodes plus courtes à partir des années 1960. Bien que les données sur le bilan de masse de certains glaciers de l'île de Baffin montrent qu'il n'existe pas de tendance pour la période étudiée, il semble bien qu'il y ait concordance entre la température estivale et le bilan de masse annuel. Contrairement à la tendance du réchauffement global, la région de Baffin a subi un refroidissement généralisé au cours des derniers 30 ans, particulièrement en hiver. On ne comprend pas complètement les causes de ce refroidissement et les répercussions sur la couverture de glace sont encore incertaines. Dans le but de trouver réponses à ces questions, on doit reprendre les études de bilan de masse sur un glacier approprié, dans le cadre d'un programme intégré de surveillance environnementale dans la région.

## INTRODUCTION

The association between climate change and the advance and retreat of glaciers has long been recognized, prompting the scientific study of glaciers from a climatological point of view (Ahlmann, 1953). For more than 30 years a concerted, international effort has been under way to systematically measure and compile standard parameters on glaciers in all parts of the world as a means of detecting regional responses to climate change (Haeberli and Hoelzle, 1993). A significant contribution to these studies has come from Canada (Young and Ommanney, 1984), which is not surprising in view of the large ice volumes in the Canadian Western Cordillera and Arctic Archipelago. The latter area, lying for the most part within the designated territory of Nunavut, includes nearly 152,000 km² of ice, or about 75% of Canada's total glacierized area (Table 1).

The glaciers of Nunavut include many forms: from the small (*ca.* 290 km²) Grinnell and Terra Nivea subpolar glaciers of southernmost Baffin Island (Mercer, 1956) to the 17,000 km² Agassiz Ice Cap on northern Ellesmere Island. They are distributed over a span of more than 20° of latitude. For the most part, these ice masses are centred on the higher and more mountainous areas of the eastern islands; however, there is variation in their volume and thickness which for the most part is related to accumulation patterns (Koerner, 1977, 1979). The thickest and most continuous ice cover lies on slopes facing Baffin Bay and Davis Strait, coinciding with the area of greatest accumulation, whereas thinner and less-extensive ice caps occur in the drier regions to the northwest (Koerner, 1979).

In this review, prepared for the Nunavut Environment Assessment Transect workshop, we summarize the record of glacier monitoring in Nunavut and discuss the relationship between glacier variations and climate change during this observational period. Specifically, we focus on the Baffin Island region because it has received less attention in the last couple of decades and has experienced a cooling trend not observed elsewhere in Nunavut. Our emphasis on traditional, field-based glacier monitoring fits the general theme of the workshop; however, we recognize that such an approach will only be one part of a larger integrated monitoring program. Likewise, the criteria for the selection of suitable glaciers for monitoring are presented in the context of a field-based program for Baffin Island.

## REVIEW OF SELECTED GLACIER MONITORING ROGRAMS

A number of glaciers and ice caps in Nunavut have been studied over the years. Those discussed here are the principal ones in terms of continuity or length of observations or because they otherwise have some regional significance. Summary information is given in Table 2, with locations shown in Figure 1. Although records of past glacier balance have been reconstructed from ice core data, this review focusses on observational data from glacier monitoring programs. The glacial and climate records in ice cores from Nunavut have been reviewed elsewhere by Koerner (1989), Bradley (1990), Fisher and Koerner (1994) and Fisher *et al.*, (1995).

### St. Patrick Bay Ice Caps

In northeastern Ellesmere Island, a pair of small (<10 km²) ice caps occupy an otherwise ice-free portion of the Hazen Plateau, overlooking St. Patrick Bay, Robeson Channel (Table 2 and Fig. 1). These glaciers were first studied in 1972 by Hattersley-Smith and Serson (1973)

**Table 1** Summary of glacierized areas within Nunavut (adapted from Haeberli *et al.*, 1989).

| | km² |
|---|---|
| Ellesmere Island | 80,500 |
| Baffin Island | 37,000 |
| Axel Heiberg Island | 11,700 |
| Devon Island | 16,200 |
| Bylot Island | 5,000 |
| Others | 1,600 |
| Total | 152,000 |

**Table 2** Location and summary information for selected glaciers in Nunavut.

| Name | Lat (N) | Lon (W) | Area (km²) | Period of Surveys | References |
|---|---|---|---|---|---|
| St. Patrick Bay ice caps | 81.95 | 64.17 | 10 | 1972-85 | 1,2 |
| Agassiz Ice Cap | 80.42 | 75.00 | 17,326 | 1976-95 | 3 |
| Meighen Ice Cap | 79.95 | 99.13 | 85 | 1960-94 | 3 |
| White Glacier | 79.43 | 90.67 | 39 | 1959-95 | 3,4,5 |
| Baby Glacier | 79.43 | 90.67 | 0.6 | 1959-76,1989-95 | 3,4,5 |
| Devon Ice Cap | 75.33 | 82.50 | 12,825 | 1960-95 | 3,4 |
| Barnes Ice Cap | | | | | |
| at Lewis Glacier (NW) | 70.43 | 74.77 | 170 | 1963-66, 1989-90 | 6,7,8,9 |
| at South Dome | 69.75 | 72.40 | 500 | 1950,1963-84 | 10,11,12 |
| Decade Glacier | 69.64 | 69.83 | 8.7 | 1965-73 | 13,14 |
| Boas Glacier | 67.58 | 65.27 | 1.4 | 1969-74 | 15 |
| Penny Ice Cap | 67.28 | 65.93 | 6,000 | 1953, 1979, 1992-95 | 16,17,18 |
| Grinnell and Terra Nivea ice caps | 62.50 | 66.67 | 290 | 1951-53 | 19 |

**References**

1 Hattersley-Smith and Serson, 1973
2 Bradley and Serreze, 1987
3 Koerner, 1995
4 Haeberli *et al.*, 1989
5 Cogley, *et al.*, 1995
6 Sagar, 1966
7 Anonymous, 1967
8 Andrews and Barnett, 1979
9 Jacobs *et al.*, 1993
10 Orvig, 1954
11 Hooke *et al.*, 1987
12 Jacobs *et al.*, in press
13 Stanley and Hodgson, 1968
14 Kasser, 1973
15 Weaver, 1975
16 Ward and Baird, 1954
17 Holdsworth, 1984
18 Wake *et al.*, 1996
19 Mercer, 1956

and in 1982-1983 by Bradley and Serreze (1987), who concluded that they were losing mass now and would vanish within a century or two if current climatic conditions persisted. Bradley and Serreze (1987) suggested that, because the two small ice caps are not in equilibrium with present climate, they are not likely to be useful for purposes of monitoring long-term regional climate change.

### Agassiz Ice Cap

Of the principal ice masses on Ellesmere Island, the Agassiz Ice Cap (Fig. 1) has received the most attention in recent years. A stake network on part of the ice cap has been maintained since 1977 to investigate mass balance/elevation relationships and improve the interpretation of three surface-to-bedrock ice cores drilled in 1977, 1979 and 1984 (Koerner, 1995). Existing maps of the ice cap are not accurate enough to compute an annual mass balance and the stake network extends only into the superimposed ice zone; therefore, the average annual net balance of -0.38 m water equivalent (w.e.) for the period 1977-1993 is not representative of the entire ice cap (Koerner, 1995).

### White and Baby Glaciers

White Glacier is a valley glacier draining from the Müller Ice Cap on west-central Axel Heiberg Island (Fig. 1). It is more than 15 km long and has an elevation range of 1700 m. Glacier mass balance measurements were initiated by the Jacobsen-McGill Arctic Research Expedition in 1959 and continued first by Eidgenössische Technische Hochschule (ETH), Zürich and later by Trent University. The mass balance record, which extends over 32 years, with one gap of 3 years, represents one of the longest such records in Nunavut and in the high Arctic in general. White Glacier has also been the focus of studies dealing with aspects of glaciology, including meteorology, climatology, glacier movement and thermal regime, and Quaternary history (*cf.*, Ommanney, 1987a, b). A recent reassessment of the mass balance series 1960-1991 provides an average annual net balance of -0.1 m w.e., with no obvious trend in the data (Cogley *et al.*, 1995). Occasional extreme years have a significant effect on the mass balance record and are an important consideration in understanding the glacier's response to climate change. For example, the 2 highest net-loss years (1962, 1987) together exceed the entire net gains of the positive years (Cogley *et al.*, 1995).

Baby Glacier is a small niche glacier (0.6 km²) within 10 km of the White Glacier (Fig. 1). Mass-balance measurements were made more or less consistently from 1959 to 1976 and 1989 to present (Cogley *et al.*, 1995). Although both Baby and White glaciers have similar mass balance normals, Cogley *et al.*, (1995) emphasized the importance of Baby Glacier as a "sensitive" indicator of climate change because it spans an elevation range which contains the regional average equilibrium line altitude (974 m) and has a response time that is sufficiently short for climate change detection.

### Meighen Ice Cap

Meighen Ice Cap is located on Meighen Island on the northwestern edge of Nunavut bordering the Arctic Ocean (Fig. 1). It covers *ca.* 85 km², has a maximum thickness of 120 m and rises to only 268 metres above sea level (masl; Alt, 1979). The existence of an ice cap at such a low elevation, even at 80°N, prompted the Polar Continental Shelf Project in 1959 to initiate scientific investigations.

An ice core drilled to a depth of 112 m in 1965 revealed that the ice cap consists almost entirely of superimposed ice that forms each spring by the refreezing of meltwater under the snow pack (Paterson, 1969; Koerner and Paterson, 1974). Koerner's (1968) analysis of ice texture and fabric from the core revealed that the ice cap has been stagnant thoughout its history and has never been much bigger than it is at present. The ice cap has experienced an average annual net balance of -0.13 m w.e. over the period 1960-1993 (Koerner, 1995), which is similar to that of the White Glacier on adjacent Axel Heiberg Island. Analysis of summer synoptic climate controls of the Meighen Ice Cap mass balance revealed a link between the general atmospheric circulation (particularly the position of the dominant 500-mb cold low influencing Meighen Island) and mass balance variations over a period of fourteen years (Alt, 1979). In essence, the ice cap owes its existence to the summer cooling effect of the Arctic Ocean.

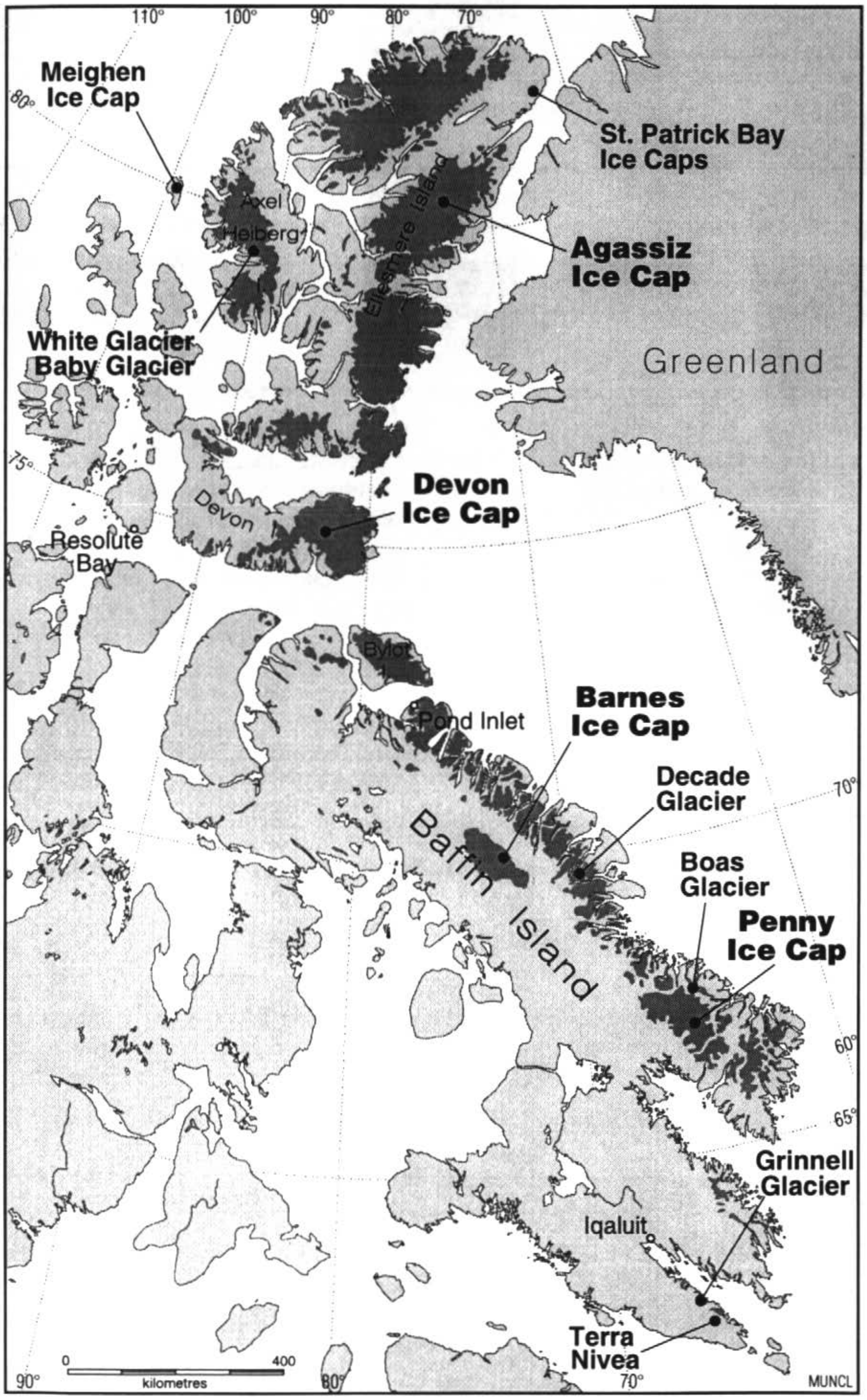

**Figure 1** *Location map showing glacierized areas of Nunavut, and selected ice caps and glaciers discussed in the text.*

### Devon Ice Cap

Devon Ice Cap, on the eastern part of Devon Island (Fig. 1), has received the most consistent attention of Canadian high arctic glaciers through annual surveys by the Polar Continental Shelf Project. Mass balance measurements have been conducted since 1961 (except in 1968) and several surface-to-bedrock ice cores were drilled in the 1970s (Koerner, 1977). The northwest region of the ice cap (including its outlet glacier, the Sverdrup Glacier), which has been studied in most detail, has an average annual net balance of -0.05 m w.e. for the period 1961-1993 (Koerner, 1995). Repeated gravity measurements show no significant changes of thickness in the accumulation zone of the ice cap which suggests that accumulation rates have not changed significantly for several decades (Koerner, 1989).

Bradley and England (1978a) demonstrated that mass balance on the Devon Ice Cap is closely related to summer temperature conditions, specifically, average minimum temperature melting degree day ($MDD_N$) totals at the two nearest weather stations, Thule and Resolute ($r = 0.94$). Positive mass balance years appear to correspond with strong cyclonic activity in Baffin Bay, which reduces melting and causes summer snow accumulation, whereas fully developed anticyclonic conditions result in a high negative mass balance (Alt, 1978). Because the magnitude of mass balance gains is limited by low accumulation amounts, even when mean summer temperatures are very low, an occasional warm summer may remove cumulative mass gains over many years (Bradley and England, 1978b). Alt (1978) has shown that one summer of anticyclonic dominance can produce melting equivalent to three times the modal winter accumulation, therefore, if more than 1 year dominated by anticyclonic conditions occurs in a decade, the mean mass balance of that decade will be negative. Consequently, Bradley and England (1978a) suggest that significant growth of Devon Ice Cap is unlikely without marked increases in accumulation.

On the basis of the linear relationship between mass balance and $MDD_N$, Bradley and England (1978b) reconstructed the mass balance record of Devon Ice Cap back to 1947-1948 when instrumental observations were first kept at Thule and Resolute. They showed that since 1963 a marked change in the frequency of positive balance years has occurred and that, from 1947-1948 to 1963-1964, the estimated average annual mass loss on the ice cap was six to seven times greater than during the later period. They attributed this mass balance change to the cooling effects of a massive increase in volcanic dust in the upper atmosphere, primarily due to the eruption of Mt. Agung (in 1963), which may have affected solar radiation receipts and the general circulation.

### Barnes Ice Cap

Barnes Ice Cap is located at 70° N latitude on the central plateau of Baffin Island (Fig. 1). It is about 1050 masl at its summit and occupies an area of about 6000 km². Ives and Andrews (1963) determined that Barnes Ice Cap attained its present configuration around 5000 B.P. Further studies by Andrews and Barnett (1979) added detail to the chronology of retreat and showed that the ice cap had readvanced in some sectors as recently as 100 years ago. Maps of regional deglaciation complied by Dyke and Prest (1987) indicate that Barnes Ice Cap is the last contiguous remnant of the Laurentide Ice Sheet, an interpretation supported by evidence of Pleistocene ice at its base (Hooke, 1976). Initial studies (Baird *et al.*, 1952; Ward and Orvig, 1953) concluded that, while the winter snow pack melts entirely in most summers, the ice cap is maintained near equilibrium by formation of superimposed ice. Løken and Andrews (1966) concluded that, although the ice cap may be self-maintaining, if removed under present climatic conditions it would not reform. Subsequent field investigations in the southeast sector (Hooke *et al.*, 1987) and on the northwest margin (Jacobs *et al.*, 1993), as well as recent satellite studies of the southern half of the ice cap (Jacobs *et al.*, in press), provide strong evidence for sustained attrition over most, if not all, of the ice cap surface. This recession has continued during the past three decades, at a time when the regional climatic record has shown a trend toward lower temperatures (Jacobs *et al.*, 1993).

### Decade Glacier

The Decade Glacier is a relatively small (8.7 km²) cirque glacier located between 400 masl and 1450 masl on the southeast side of Inugsuin Fiord in northeastern Baffin Island (Østrem *et al.*, 1967) (Fig. 1). The glacier was selected for mass balance studies during the International Hydrological Decade because it was found to meet the criteria for long-term monitoring (see below). The glacier is accessible from the hamlet of Clyde River. In addition to intensive glaciological and hydrologic studies conducted in 1965 and 1967 (Østrem *et al.*, 1967; Stanley and Hodgson, 1968), mass balance surveys were conducted from 1965 to 1971 and again in 1973 (Østrem and Brugman, 1991). Winter accumulation was found to be about 0.25 m w.e., and both winter accumulation and summer ablation were found to be comparable to that on the south end of the Barnes Ice Cap, 80 km to the west (Østrem *et al.*, 1967). Annual net balance data obtained on the Decade Glacier over the 1965-1973 period revealed large interannual variations closely associated with summer temperatures (Fig. 2), as has been found to be generally characteristic of eastern arctic glaciers.

### Boas Glacier

Boas Glacier (unofficial name for glacier 46204J68 in the Canadian Glacier Inventory) is one of two cirque glaciers on a high (1300 m) plateau northeast of the Penny Ice Cap, within the Auyuittuq National Park Reserve. Studies were initiated there in 1969 to explore ideas concerning past and present associations between regional climate and glacierization (Andrews *et al.*, 1970). The glacier was first surveyed in 1969 and more intensively in 1970 as part of a program of Quaternary studies by the University of Colorado, which continued over a number of years from a base in the community of Broughton Island (Jacobs *et al.*, 1972). Resurveys of the Boas Glacier in 1973 and 1974 provided the basis for a five-year analysis which revealed large interannual variations in annual net mass balance and a strong dependency on summer climate (Fig. 2). During the period from 1969 to 1974, the glacier lost an estimated 0.16 m w.e. (Weaver, 1975).

### Penny Ice Cap

The Penny Ice Cap dominates the Cumberland Peninsula of eastern Baffin Island. Of somewhat lesser area than the Barnes Ice Cap, but about 800 m higher and well above the 0°C July isotherm, it has a more polar regime. First investigated in the 1950s by teams from the Arctic Institute of North America (Ward and Baird, 1954), the Penny Ice Cap has since been the subject of a number of short-term studies rather than any long-term monitoring. From the early surveys, Orvig (1954) concluded that while outlet and cirque glaciers were in retreat from what have since been recognized as recent (19th century) neoglacial maximum positions, the ice cap was in a "healthy state." Based on reconnaissance surveys and shallow cores taken near the summit, Holdsworth (1984) estimated an average annual net accumulation of 0.43 m w.e. for the period from 1949 to 1979. An international drilling effort at the summit in 1994 and 1995 is providing new information on the history of the ice cap, and an indication of mass balance trends in the recent past (Wake *et al.*, 1996). The Penny Ice Cap is within Auyuittuq National Park, and park personnel have

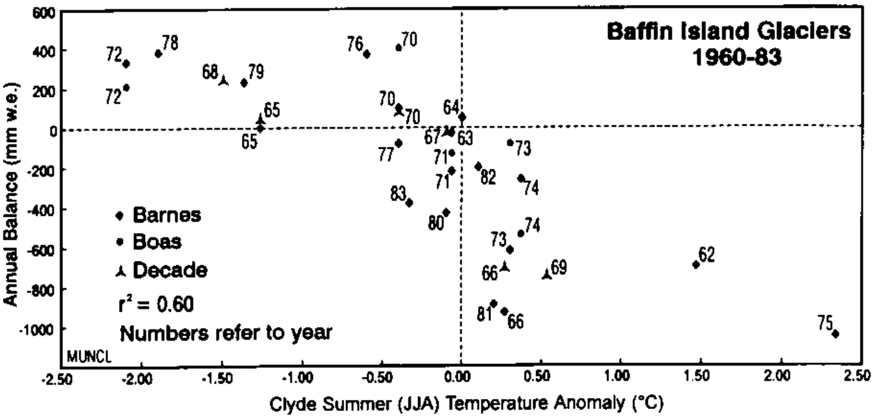

**Figure 2** *Annual mass balance of Decade Glacier (triangle symbol), Barnes Ice Cap (solid diamond symbol), and Boas Glacier (solid circle symbol) plotted against annual departure of Clyde summer temperature from the mean of 1960-1993. JJA = June, July, August.*

been involved as observers in these recent studies. Although no sequential mapping of the Penny Ice Cap margin has been undertaken, it is noteworthy that the recent retreat of many of its outlet glaciers has been observed and commented on by Inuit of the region (G. Eeseemailiee, pers. comm., 1993).

### Grinnell and Terra Nivea Ice Caps

The southernmost ice caps in Nunavut are Grinnell Glacier and Terra Nivea, on the south side of Frobisher Bay in Baffin Island. Despite their relative proximity to the community of Iqaluit, they have not been systematically surveyed. Mercer (1956) described the Grinnell Ice Cap as a thin highland (870 masl) ice body with eight outlet glaciers of which four reach tidewater in Frobisher Bay. Over the three years of observations, he concluded that, while there is a large superimposed ice zone, the upper reaches of the ice cap are in the firn zone in most years, in contrast to the situation on the Barnes Ice Cap. He noted large interannual differences in mass balance and climate and suggested that summer temperature played a larger role in these variations than winter balance. Mercer (1956) made a qualitative comparison of the extent of one of these glaciers with photographs from 1897, and concluded that a significant decrease in volume had occurred over the intervening period.

## GLACIER CHANGE AND CLIMATE CHANGE IN NUNAVUT

From southern Baffin Island to northern Ellesmere Island, there is widespread evidence of significant recent neoglacial events, ending in the late 19th century. The 20th century glaciological record is one of more-or-less renewed retreat of glaciers from recent terminal moraines. These recent changes are of considerable interest when viewed in relation to the regional climatic record.

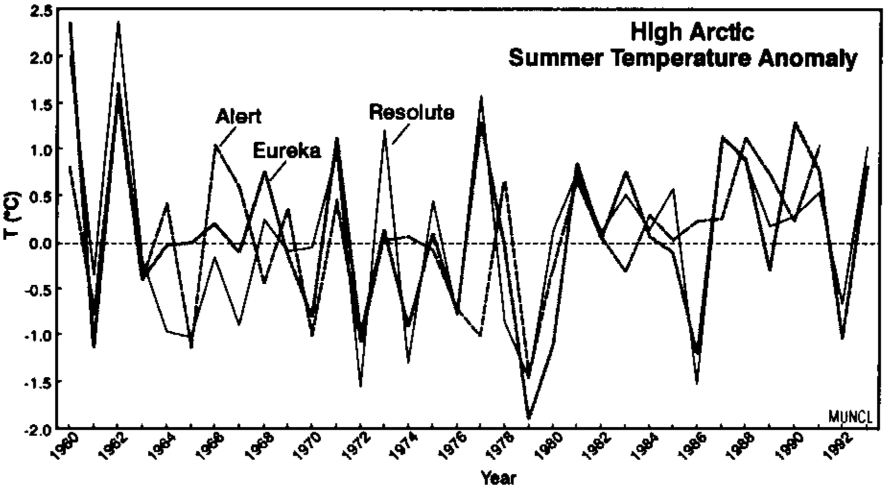

**Figure 3** *Summer temperature anomalies for Alert, Eureka and Resolute weather stations for the period 1960-1993. The record shows no trend, but large interannual variability.*

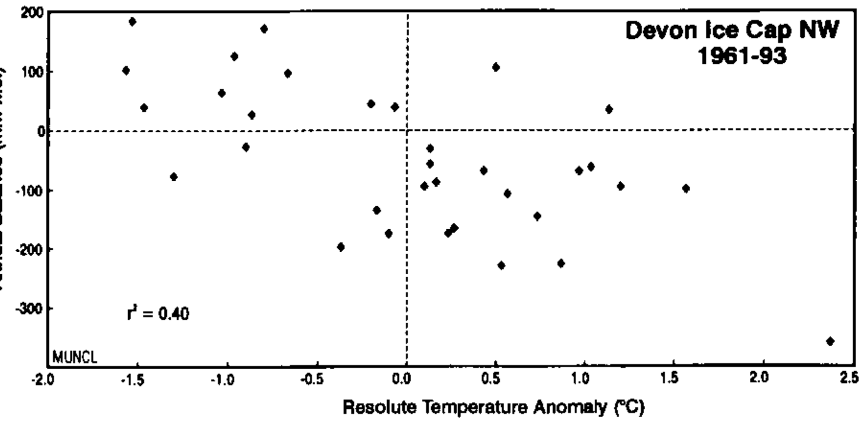

**Figure 4** *Annual mass balance of Devon Ice Cap plotted against annual departure of Resolute summer temperature from the 1960-1993 mean.*

For subpolar and polar glaciers in areas of relatively sparse winter precipitation there is ample evidence that the summer energy balance, most simply expressed in terms of summer near-surface mean air temperature or of cumulative melting-degree days, is the variable most closely linked to interannual variations in glacier mass balance, with winter precipitation of secondary importance (*e.g.*, Johannesson *et al.*, 1995). Observations on glaciers in Nunavut, such as the Boas (Weaver, 1975), the Grinnell (Mercer, 1956), and the White (Cogley *et al.*, 1995) have shown that a single warm summer can undo the net accumulation of a number of successive positive mass-balance years.

The instrumental record for the Canadian eastern and high Arctic is limited mainly to the last 40-50 years. These records, supplemented by the much longer Greenland record, show a warming trend in annual temperatures from about 1890, peaking around 1930, followed by a cooling trend, which has persisted into the early 1990s (Kelly *et al.*, 1982; Jones, 1988; Chapman and Walsh, 1993). For Baffin Island this trend is dominated seasonally by fall, winter and spring cooling, with little change in summer (Environment Canada, 1995). The recent cooling does not appear to extend to the high Arctic, rather the influence of a warming in the western continental interior may have extended to the western island region (Environment Canada, 1995). A review of summer temperatures for the last three decades from three high arctic weather stations, Alert, Eureka and Resolute, shows no trend, but large interannual variability (Fig. 3).

The high spatial variability of precipitation combined with the low density of observing stations in the region discourages any regional analysis of snowfall trends. The best source of winter mass balance data is surveys of spring snowcover on the glaciers and ice caps, as part of a systematic survey program (Koerner, 1986). While such surveys have been carried out over many years in some parts of the Arctic (Haeberli *et al.*, 1989), continuous mass balance series in Nunavut are confined to a few glaciers in the high Arctic (Østrem and Brugman, 1991; Koerner, 1995). These records can be used to test the relationship between regional ablation season climate and glacier mass balance. A strong association is seen, for example, between the annual mass balance on the

Devon Ice Cap and Resolute summer temperatures (Fig. 4), with similar associations found for other glaciers in the region (Fig. 2). A similarly strong association ($r^2 = 0.86$) was found by Hooke *et al.*, (1987) between annual mass balance on Barnes Ice Cap and summer temperatures in central Baffin Island at Dewar Lakes between 1962 and 1983, the last year in which a long-established net on the southeast side was surveyed. Hooke *et al.* (1987) found a general thinning of the ice cap along that profile, and analysis by Jacobs *et al.* (in press) of recent satellite imagery of the southern half of the Barnes has shown that recession is occurring around most of the margin.

## MONITORING FUTURE CHANGES

In 1991, the International Association of Hydrological Sciences (IAHS) recommended that, "in order to document glacier signals of present [climate] warming and to understand the sensitivity and representativity of glacier responses in various parts of the world, the existing network of glacier mass balance measurements should not only be kept intact, ... but also expanded to cover key areas, especially at polar latitudes..." (Haeberli and Hoelzle, 1993, p. 104). In making this recommendation, it recognized that "glacier mass studies form an essential part of the continuous monitoring of the global environment" and in particular, "fluctuations of mountain glaciers clearly reflect changes in the energy balance of the earth's surface and belong to the key phenomena for monitoring climate change" (Haeberli and Hoelzle, 1993, 103). The sensitivity of glaciers and small ice caps to global warming has been estimated by Oerlemans and Fortuin (1992) using a modelling approach on selected glaciers in widely differing climatic regimes. They showed that for a uniform 1 K warming the area-weighted glacier mass balance will decrease by 0.4 $m \cdot a^{-1}$, which corresponds to a sea level rise of 0.58 $mm \cdot a^{-1}$. During the past century, glaciers in the Alps have lost roughly half their total mass due to a rise in temperature of about 0.5° C (Haeberli and Hoelzle, 1993; Berger and lams, 1996).

### Glacier Mass Balance

Changes in glacier mass balance are the direct and immediate response to climate change; however, glaciers can be logistically difficult and expensive to monitor, especially in remote arctic regions. In Nunavut, ongoing glacier mass balance programs are confined to the Queen Elizabeth Islands. The Geological Survey of Canada monitors the Agassiz, Devon and Meighen ice caps (Koerner, 1995) while Trent University, Ontario conducts annual surveys of White and Baby glaciers (Cogley *et al.*, 1995). Both projects receive logistical support from the Polar Continental Shelf Project, Natural Resources Canada. Mass balance measurements are usually made once a year, during the spring, using the "stratigraphic" method of Østrem and Brugman (1991). A survey may take up to several weeks to complete depending on the stake network and field conditions. The incorporation of remote sensing (see below) and state-of-the-art surveying technology should improve the quality and reduce the labour-intensive nature of glacier mass balance surveys.

### Glacier Length Variations

Although fluctuations in glacier length represent the indirect and delayed response to climate change, they are considered the most easily detectable, unequivocal proof of climate change in cold regions (Haeberli *et al.*, 1989). Unlike ice sheets and large ice caps, typical response periods of mountain glaciers are several decades (Johannesson *et al.*, 1989), which provide an opportunity to assess glacier responses to recent and potential future climate change (Haeberli, 1990). Airborne remote sensing technology has been used since the 1930s as a means of acquiring data on glacier fluctuations on a regional basis and, if aerial photographs are available for different dates, areal and volumetric changes in glaciers can be monitored (*e.g.*, Haakensen, 1986). In Nunavut, historical variations in glacier margins have been recorded from systematic aerial photographic surveys from as early as the 1940s and 1950s (*e.g.*, White Glacier, Moisan and Pollard, 1992), and from expedition engravings and photographs dating back to the mid 1800s (*e.g.*, northern Baffin and Bylot islands, Falconer, 1962). Jacobs *et al.*, (1993) published the first satellite images illustrating marginal variations of the Barnes Ice Cap. They determined that the Lewis Glacier, an outlet lobe along the northwestern margin, had retreated about 680 m between 1961 and 1988, or about 25 $m \cdot a^{-1}$, compared with an estimate of 20 $m \cdot a^{-1}$ obtained by earlier workers from detailed surveys of the glacier snout in 1963 and 1965 (Anonymous, 1967). Longer records of glacier fluctuations can be deduced from geomorphic, sedimentologic and botanical evidence (*e.g.*, Løken and Andrews, 1966; Jacobs *et al.*, 1993).

### Satellite Remote Sensing

The advent of high-resolution earth-observing satellites such as Landsat and SPOT opened a new dimension in the remote sensing of glaciers (Ferrigno and Williams, 1983; Rees and Squire, 1989). Large ice sheets as well as smaller ice caps and glaciers could be viewed with a resolution on the order of 30 m in several visible and near-infrared bands, and the potential existed for mass balance estimates, at least on glaciers with a clearly defined summer snowline (Østrem, 1975). The generally high reflectances typical of snow and ice in the visible bands presented problems initially in the analysis of Landsat multispectral scanner (MSS) imagery, as there was a tendency for the sensors to be near saturation, but this could be mitigated by contrast stretching in the digital analysis (Dowdeswell and McIntyre, 1986). Spectral capabilities improved in 1982 with the availability of Landsat Thematic Mapper (TM) data, which together with SPOT imagery have proven useful in glacier reflectance studies (Winther, 1993), in mapping surface topography on larger ice sheets (Dowdeswell and McIntyre, 1987), in determining the different snow and ice zones or "glacier facies" (*sensu* Benson, 1961) during the summer melt season (Hall *et al.*, 1987), and in the analysis of ice-marginal landforms and surficial deposits adjacent to glaciers (Ronnert and Nybourg, 1994).

The ability of synthetic aperture radar (SAR) to penetrate cloud cover permits the imaging of glaciers that are almost continually cloud-covered, whereas its penetration through surface layers of snow may reveal boundaries that are not visible from the surface (Østrem and Brugman, 1991; Rees *et al.*, 1995). SAR is also potentially useful for determining the marginal position of a glacier and distinguishing differences in its surface conditions, provided relief is not too complex (Jacobs and Simms, 1996). A combination of SAR data and visual imagery such as Landsat TM may prove to be a powerful tool for glaciological investigations (*e.g.*, Dowdeswell *et al.*, 1995; Brugman *et al.*, 1996, Jacobs and Simms, 1996).

In late 1995, Canada launched RADARSAT, a SAR satellite operating at C-band frequency. It will provide 1-3 day repeat coverage for arctic regions (above 60° latitude) at various incidence angles and swath widths, and has the potential for producing stereoimages. RADARSAT SAR interferometry from sequential repeat-orbit data can provide detailed mapping capabilities on ice caps and glaciers and magnitude estimates of surface changes for glacier movement and mass balance monitoring (*e.g.*, Vachon *et al.*, 1996). Satellite laser altimeters may also prove useful in this regard (Williams and Hall, 1993). Other SAR satellites include ERS-1, flown by the European Space Agency, and the Japanese Earth Resources Satellite (JERS-1).

### Traditional Knowledge

Although traditional ecological knowledge (TEK) has more commonly been applied to issues of wildlife management and renewable resources in Nunavut (*e.g.*, Gunn *et al.*, 1988; Finley, 1994), it has an important contribution to make to glacier monitoring for climate change detection. Native hunters are perceptive observers of their environment, including changes in the position of glacier margins (G. Eeseemailiee, Pangnirtung, pers. comm., 1993; N. Maktar, Pond Inlet, pers. comm., 1996). This TEK database could be developed and promoted in selected communities, much like the Icelandic glacier observation program, in which trained laypeople, often farmers or sheepherders in remote areas, form the network of observers (Williams and Hall, 1993). They report annual measurements of glacier advance or recession, and unusual glaciological phenomena, such as glacier surges and jökulhlaups. These observations are collated (*e.g.*, Sigurdsson, 1988), and submitted to the World Glacier Monitoring Service in Zurich, Switzerland.

TEK can also play an important role in understanding how glacier variations impact the local ecosystem. As Feit (1988, p. 76) points out, "there is no reason not to expect that indigenous peoples, any less than people of European descent, would develop a realistic body of knowledge about an environment with which they intensively interact..." For example, traditional ecological knowledge of local ecosystems could be integrated with scientific observations to address such questions as: How would changes in the magnitude and seasonal pattern of glacier meltwater discharge affect fish habitats and water resources? How would the changing discharge affect estuarine circulation and the formation and breakup of sea ice?

## SELECTING A SUITABLE GLACIER FOR MONITORING

The selection of a suitable glacier for field monitoring is critical considering that the results obtained should be applicable to, and representative of, the broader region. Østrem and Brugman's (1991) criteria for this selection process are summarized below under two themes; the first deals with the representiveness of a selected glacier and catchment area, the second is concerned with logistical considerations (see also Cogley *et al.*, 1995).

### *Representativeness*

A selected glacier should: 1) have a well-defined, highly glacierized catchment; 2) be comparable with other glaciers in the area (*e.g.*, hypsometry); and 3) be drained by one meltwater stream which is suitable for discharge measurements close to the glacier snout. This may be particularly important if the glacier is part of an integrated, basin-wide environmental monitoring program.

### *Logistical considerations*

A selected glacier should: 1) be small enough that it can be surveyed by two or three people. The upper limit is probably 10-15 km$^2$. With improved technology, a larger glacier can be selected; 2) have relatively easy access so that it can be visited throughout the year without the use of helicopters, *etc;* 3) be relatively safe to work on (*e.g.*, few crevasses); 4) be situated in an area for which reliable maps, air photographs and satellite imagery are available. Ideally, digital elevation models should be constructed.

Other criteria that should influence the selection process include: 1) the duration and reliability of any previous mass balance measurements. An existing record, irrespective of its age, would provide an important reference for current conditions; 2) the proximity to a local community for human resources and logistical support. Also, the local community likely has traditional knowledge of the glacier's mass balance, marginal fluctuations and meltwater discharge; 3) the proximity to weather stations and ideally, automatic weather stations operating on the glacier, to relate climate and mass balance (*cf.*, Jania and Hagen, 1995).

## CONCLUSIONS

The Arctic contains about two-thirds of the world's small glaciers. Given that global warming is predicted to be most marked in high latitudes (*e.g.*, Houghton *et al.*, 1990, 1992) and that changes in the mass balance of small glaciers can provide the first indication of climate change, the IAHS strongly recommended expansion of the glacier monitoring network in polar regions (Haeberli and Hoelzle, 1993). At present, only 14 glaciers in the entire Arctic have mass balance records longer than 20 years and less than ten of these have ongoing monitoring programs (Jania and Hagen, 1995). Although Nunavut contains half of these programs, they are not evenly distributed and, in some cases, they are not designed for climate change detection (*e.g.*, Agassiz Ice Cap). The Baffin region represents an obvious gap in the glacier monitoring network of Nunavut and, in contrast to global warming trends, the region has experienced a general cooling over the last 30 years, particularly in winter. The cause of this cooling is not fully understood; however, it does raise some interesting questions concerning glacier mass balance in the region. For example, how are glaciers responding to increased winter cooling? Will reduced precipitation, resulting from cooler winters, accelerate the negative mass balance trend of recent decades? The record of glacier mass balance observations on central Baffin Island extends back to 1962 and there appears to be a consistent relationship between climate (summer temperature) and annual balance for the principal glaciers (Fig. 2). It is our recommendation, therefore, that this series of mass balance observations be revived as part of an integrated environmental monitoring program in the region and an international monitoring network for climate change detection in arctic regions (*cf.*, Jania and Hagen, 1995).

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