MASS BALANCE AND AREA CHANGES OF FOUR HIGH ARCTIC PLATEAU ICE CAPS, 1959–2002

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ABSTRACT. Small, stagnating ice caps at high latitudes are particularly sensitive to climatic fluctuations, especially with regard to changes in ablation season temperature. We conducted mass balance measurements and GPS area surveys on four small High Arctic plateau ice caps from 1999–2002. We compared these measurements with topographic maps and aerial photography from 1959, and with previously published data. Net mass balance (b_n) of Murray Ice Cap was –0.49 (1999), –0.29 (2000), –0.47 (2001), and –0.29 (2002), all in meters of **water equivalent** (**m w.eq.**). The mass balance of nearby Simmons Ice Cap was also negative in 2000 (b_n = –0.40 m w.eq.) and in 2001 (b_n = –0.52 m w.eq.). All four ice caps experienced substantial marginal recession and area reductions of between 30 and 47% since 1959. Overall, these ice caps lost considerable mass since at least 1959, except for a period between the mid-1960s and mid-1970s characterized regionally by reduced summer melt, positive mass balance, and ice cap advance. The regional **equilibrium line altitude** (**ELA**) is located, on average, above the summits of the ice caps, indicating that they are remnants of past climatic conditions and out of equilibrium with present climate. The ice caps reached a Holocene maximum and were several times larger during the **Little Ice Age** (**LIA**) and their current recession reflects an adjustment to post-LIA climatic conditions. At current downwasting rates the ice masses on the Hazen Plateau will completely disappear by, or soon after, the mid-21st century.

Introduction

Small, stagnant ice caps at high latitudes without appreciable iceflow are particularly sensitive to climatic fluctuations, especially with regard to variations in ablation-season temperature (Paterson 1969; Hattersley-Smith and Serson 1973; Rosqvist and Østrem 1989; Grudd 1990). In a general sense, the position of the ice margin and the areal extent of a stagnant ice cap are strongly related to its annual mass balance (Paterson 1969). Here we report the results of recent mass balance and GPS area measurements on four small, stagnant plateau ice caps located on the Hazen Plateau of Ellesmere Island, Nunavut, Canada (Fig. 1). Most of the plateau is currently unglacierized and the ice caps persist today at about the same elevation as adjacent ice-free areas, indicating that the plateau surface is close to the regional equilibrium-line altitude (ELA) or glaciation level (Miller *et al.* 1975). Therefore, relatively small changes in climate could lead to profound changes in the extent of snow and ice cover on the Hazen Plateau. Aerial

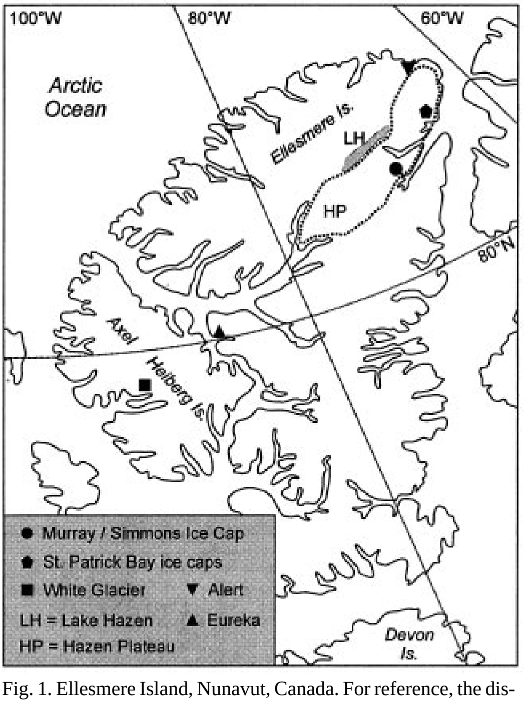

Fig. 1. Ellesmere Island, Nunavut, Canada. For reference, the distance from Murray/Simmons Ice Cap to the St. Patrick Bay ice caps is *c.* 110 km, to Alert *c.* 160 km.

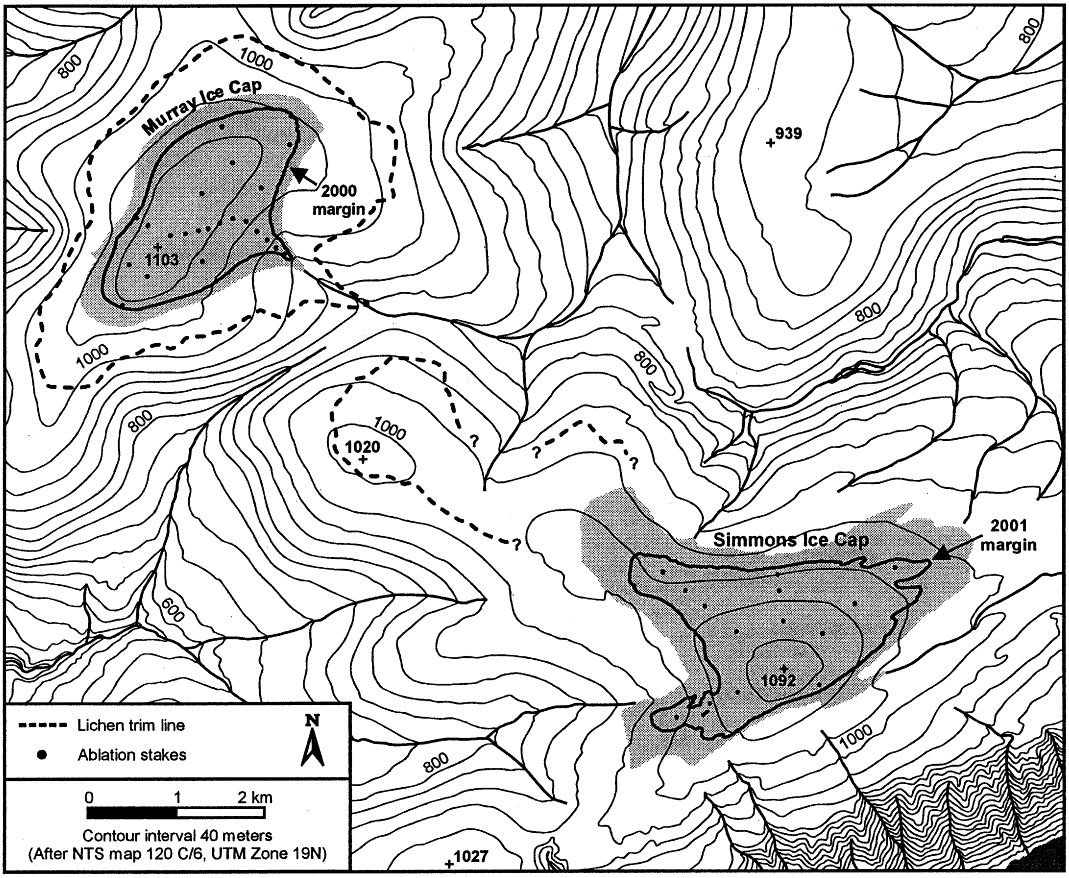

Fig. 2. Murray and Simmons Ice Caps, Ellesmere Island, Nunavut, Canada. The summits are at 81°21'N, 69°15'W and 81°21'N, 68°50'W respectively. Ice extent on Canada National Topographic System (NTS) map sheet 120 C/6 (gray shading) is based on aerial photographs from 6 July 1959. The lichen trim line (dashed line) was mapped by field observations using GPS.

photographs and topographic maps from 1959 and two earlier studies of Hazen Plateau ice caps (Hattersley-Smith and Serson 1973; Bradley and Serreze 1987a) provide a temporal context for the current data. We are specifically interested in assessing how snow and ice conditions on the ice caps and the surrounding plateau have changed since they were last visited some 20 years ago.

Background – previous studies

The Hazen Plateau forms a large upland region, gently rising from *c.* 300 m above sea level (a.s.l.) near Lake Hazen to over 1000 m a.s.l. along the northeast coast of Ellesmere Island (Fig. 1). This part of Ellesmere Island is characterized by some of the lowest accumulation rates (<0.15 m; Koerner 1979) and highest glaciation levels or ELAs (*c.* 800–1000 m a.s.l.; Miller *et al.* 1975) in the Canadian High Arctic. The plateau is largely unglacierized today, except for two pairs of thin, stagnant ice bodies along its northeastern margin (Figs 1, 2, 3) which we unofficially term the Hazen Plateau ice caps. Murray and Simmons Ice Caps together range in elevation between *c.* 960 and 1100 m a.s.l. and are surrounded by ice-free plateau areas up to *c.* 1030 m a.s.l. (Fig. 2). The St. Patrick Bay ice caps (Fig. 3; unofficial name) are located *c.* 110 km to the northeast at lower elevation (*c.* 750–900 m a.s.l.), possibly related to local moisture sources (Hattersley-Smith and Serson 1973). Our studies (1999–2001) focused on Murray Ice Cap (e.g. Braun *et al.* 2001) and also included mass balance measurements on Simmons Ice Cap in 2000 and 2001. We visited the St. Patrick Bay ice caps in a reconnaissance survey on 15 July 2001. We re-meas-

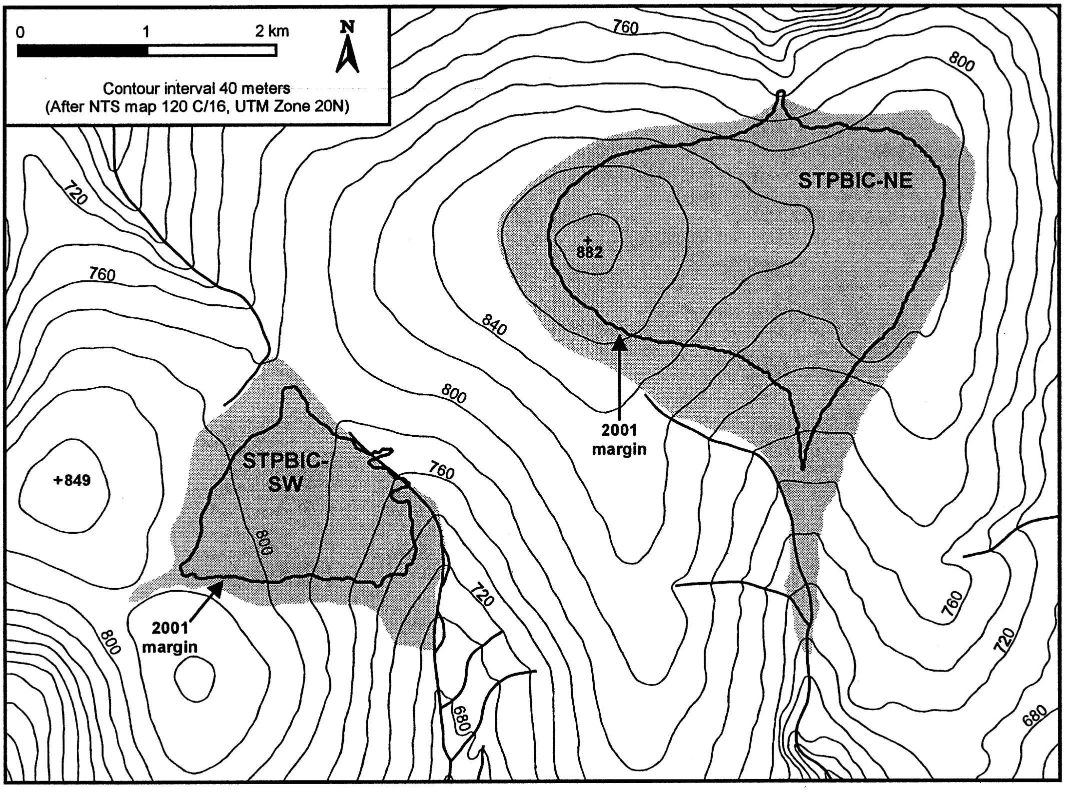

Fig. 3. St. Patrick Bay ice caps, Ellesmere Island, Nunavut, Canada. The summit of the larger (NE) St. Patrick Bay ice cap (STPBIC-NE) is at *c.* 81°57'N, 64°10'W; the summit of the smaller (SW) St. Patrick Bay ice cap (STPBIC-SW) is at *c.* 81°54'N, 64°25'W. Ice extent on Canada National Topographic System (NTS) map sheet 120 C/16 (gray shading) is based on aerial photographs from 6 July 1959.

ured the main ablation stake transect on Murray Ice Cap on 28 July 2002. Aerial photographs from 6 July 1959 show all four ice caps fully in the ablation zone and the Hazen Plateau entirely free of seasonal snow.

Previous studies: Murray and Simmons Ice Caps

Prior to this study, no specific glaciologic studies had been conducted on Murray Ice Cap. An ablation stake network was established on nearby Simmons Ice Cap (Fig. 2) in early June 1976 (Bradley and England 1977) when winter snow accumulation across the ice cap ranged between 0.1 and 0.18 meters of water equivalent (m w.eq.). The authors inferred that Simmons (and Murray) Ice Cap had probably gained mass over the 1975/76 balance year (Table 1) and experienced overall positive mass balance and lateral ice margin advance for some time before 1976. Only six of the original 18 ablation stakes were located during a return visit on 11 July 1983 (Bradley and Serreze 1987a). They assumed that the other 12 stakes had melted out and estimated a minimum net mass loss of 0.49 m w.eq. between 1976 and 1983 (Table 1). Field observations also indicated a recession of the 1983 Simmons Ice Cap margin relative to its 1959 position (Table 2) (Bradley and Serreze 1987a).

Previous studies: St. Patrick Bay ice caps

G. Hattersley-Smith and others visited the St. Patrick Bay ice caps (Fig. 3) in July/August 1972 (Hattersley-Smith and Serson 1973). They estimated net accumulation on the larger (NE) ice cap for the 1971/72 balance year of *c.* 0.14 m w.eq. (Table 1). The seasonal snowpack overlaid icy firn and superimposed ice (*c.* 0.39 m w.eq.), which in turn rested on a distinct older ablation surface. This stratigraphy was interpreted as evidence that the ice cap experienced net ablation for an extended period until at least 1959 and more likely until the unusu-

Table 1. Net mass balances (m w.eq.) of the Hazen Plateau ice caps. Where a value represents a multiyear period, the average annual value is shown in parentheses. * denotes a minimum estimate. Qualitative field observations are indicated by *italics*.

Balance year or period	Murray Ice Cap	Simmons Ice Cap	STPBIC-NE	STPBIC-SW
1963–1971			0.39 (0.04)[1]	
1972			0.14[1]	
1973			0.14[2]	
1974			0.14[2]	
1975			–0.08[2]	
1976	*positive*[3]	*positive*[3]	–0.07[2]	
1972–1982			–1.3 (–0.14)[4]	
1976–1983		*–0.49 (–0.08)[4]		
1982			–0.14[4]	
1983		*positive*[4]	0.14[4]	0.17[4]
1984–1998		*–0.49 (–0.03)		
1984–2000			*–1.01 (–0.06)	*–1.26 (–0.07)
1999	–0.49	*negative*		
2000	–0.29	–0.40		
2001	–0.47	–0.52	*negative*	*negative*
2002	–0.29	*negative*		

Sources: [1] Hattersley-Smith and Serson (1973), [2] Ommanney (1969, 1977), [3] Bradley and England (1977), [4] Bradley and Serreze (1987a). Data for STPBIC-NE are available at ftp://ftp.trentu.ca/pub/gghydro (Cogley and Adams 1998).

ally warm summer of 1962. In contrast, *c*. 1963 to 1972 represented a phase of net accumulation on this ice cap, possibly interrupted by some years with net ablation. They reported that the ice cap in 1972 'appears to be in a healthy state and is spreading laterally as well as thickening' (Table 2). This positive regime however did not persist, as net annual mass balance was again negative for the 1974/75 and 1975/76 balance years (Table 1). The original 1972 stake network was re-surveyed in 1982 by a research group from the University of Massachusetts (Bradley and Serreze 1987a) as part of a 2-year topoclimatic study of the St. Patrick Bay ice caps and surrounding Hazen Plateau (Bradley and Serreze 1987b; Serreze and Bradley 1987). Net mass balance between 1972 and 1982 was –1.3 m w.eq. (Table 1); this mass loss led to a reduction in area of both ice caps (Table 2). Mass balance conditions and summer climate differed markedly between 1982 and 1983, with 1983 being notably colder and having more summer snowfall, resulting in a positive annual mass balance for the 1982/83 balance year on both ice caps (Table 1).

Methods

Ice-cap mass balance

We measured ice-cap mass balance using conventional glaciological techniques as described by Østrem and Brugman (1991). We established a network of 11 ablation stakes on Murray Ice Cap in 1999 and expanded the network in 2000 to 29 stakes (Fig. 2). We established a network of 15 stakes on Simmons Ice Cap in 2000 (Fig. 2). Winter snow accumulation was measured each year in late May (1999–2001) and summer ablation was measured in late July/early August (1999–2002) and confirmed the following May (2000/2001 only). Individual stake measurements for each ice cap were grouped into 20 m elevation bands to determine a linear ablation gradient for each year (cf. Rosqvist and Østrem 1989). This ablation gradient was used to integrate the net specific ablation measurements over the entire ice cap surface, based on a 10 m digital elevation model constructed from a 1:50 000 topographic map (Fig. 2) (cf. Jansson 1999). We consider ±0.2 m as a conservative uncertainty estimate for the annual net mass balance values following Cogley and Adams (1998). We calculated minimum mass balance estimates for Simmons Ice Cap (1984–1998) and the St. Patrick Bay ice caps (1984–2000) using the mean remaining depth of stake insertion into the ice in 1983 (M. Serreze, pers. comm.) and assuming a relative ice density of 0.9 (Table 1).

Table 2. Ice cap area (km^2) of the Hazen Plateau ice caps and uncertainty estimates 1959–2002. Qualitative field observations are indicated by *italics*.

Year	Murray Ice Cap	Simmons Ice Cap	STPBIC-NE	STPBIC-SW
Area				
1959	4.37[1]	7.45[1]	7.48[1]	2.93[1]
1972			*advance*[2]	
1976	*advance*[3]	*advance*[3]		
1978			6.69 (89%)[4]	2.74 (93%)[4]
1983			*recession*[5]	
1999	3.28 (75%)			
2000	3.15 (72%)			
2001	3.05 (70%)	3.94 (53%)	4.61 (62%)	1.72 (59%)
2002	*recession*	*recession*		
Uncertainty estimate				
1959	±1.3%	±1.3%	±1.1%	±1.7%
1978			N/A	N/A
1999	±1.7%			
2000	±1.8%			
2001	±2.7%	±3.2%	±2.2%	±3.8%

Sources: [1] Topographic map, [2] Hattersley-Smith and Serson (1973), [3] Bradley and England (1977), [4] Bradley and Serreze (1987a).
The updated values for 2003 are available at www.geo.umass.edu/climate/hazen/field23.html

Ice-cap area

We digitized the 1959 ice margins of the four Hazen Plateau ice caps directly from available 1:50 000 topographic maps (Figs 2, 3), scanned at 600 dpi and registered to UTM zone 19N (20N for the St. Patrick Bay ice caps). The topographic maps used are based on aerial photography from 6 July 1959. We visually confirmed the accuracy of the ice-cap outlines depicted on the topographic maps by detailed comparison with the original aerial photographs (see below).

We surveyed the 1999–2001 ice-cap margins and lichen trim lines on foot (or snowmobile) using a portable GPS receiver, logging discreet positions every 3–10 s (10–15 m). The points along each ice-cap 'trace' were imported into a geographical information system (GIS) software package and connected as polygons for area calculations. The 1999 and 2000 GPS positions collected for Murray Ice Cap were differentially corrected using data from the nearest available GPS base station (Thule AFB, Greenland, 76°20'N, 68°48'W). This 'low-tech' technique eliminates the need to operate a dedicated GPS base station on-site, a significant advantage in remote environments. The main disadvantages are (1) greater uncertainties associated with the differentially corrected GPS positions compared to more sophisticated techniques, and (2) the dependence on consistent base station data availability. The latter problem was illustrated in 2001, when we were not able to correct the four collected ice-cap traces because of partially missing base station data.

Ice-cap area – uncertainties

We assessed the uncertainties associated with our ice-cap area measurements (Table 2) by first quantifying each individual contributing error source (Table 3) and then calculating the resultant uncertainty for the position of the ice margin (Table 4). It is important to note that some of the absolute values assigned to individual uncertainties listed in Table 3 are themselves estimates. Furthermore, possible human errors and subjectivity associated with the creation of the topographic maps from aerial photographs cannot be rigorously quantified.

Uncertainties for the 1959 ice-cap area measurements were a combination of (1) registration errors of the scanned topographic maps relative to their respective coordinate system, and (2) generalization of the ice-cap margins during the digitization process. Inherent in this type of study are errors and uncertainties associated with the delineation of the ice-cap margin, whether it is on the original aerial photograph, the topographic map, or directly in the field. A certain amount of subjective generalization and human error is inevitable in this process and we

Table 3. Types and magnitudes of individual uncertainties associated with ice-cap area measurements.

Source of uncertainty	Type of uncertainty	Magnitude of uncertainty
Coordinate system registration	Registration error	±2 pixel[1] (generated by GIS software)
Ice margin delineation	Generalization/subjectivity	±2 pixel[1] (map), ±5 m (field) (both estimated)
Differential GPS	Individual position	±5 m (1999), ±5.2 m (2000) (generated by DGPS software)
Uncorrected GPS	Individual position	±9.4 m (2001) (estimated)

[1] Pixel size: 2.1 m.

Table 4. Individual contributions of the uncertainties and resultant ice margin buffer.

Year	Ice cap	Registration	Generalization	DGPS	GPS	Buffer
1959	All	±4.2 m	±4.2 m			±6 m
1999	MIC		±5 m	±5 m		±7.1 m
2000	MIC		±5 m	±5.2 m		±7.2 m
2001	All		±5 m		±9.4 m	±10.6 m

MIC, Murray Ice Cap

estimated this uncertainty at ±2 pixel or *c.* 5 m (Table 3), based on careful comparisons of the original aerial photographs, the topographic maps, and the actual ice margin in the field. Wind-drifted snow accumulations along the northeast margin of STPBIC-SW and along the terminus of STPBIC-NE, both on the 1959 aerial photographs and in 2001, made it difficult to determine the precise positions of the ice margins at these locations. For consistency, we mapped 'maximum area' solutions in both cases in 2001. The uncertainty for each differentially corrected GPS position collected in 1999 and 2000 was *c.* 5 m (Table 3), which represents the maximum 99% confidence interval for the corrected GPS positions (generated by the differential-correction software). The horizontal error associated with the 2001 uncorrected GPS positions was estimated to be *c.* 9.4 m (99% confidence limit of 22739 positions collected over 5 days at a fixed point). It is interesting to note in this context that the difference in Murray Ice Cap area between the differentially corrected and the uncorrected 2000 trace was less than 100 m^2 (<0.1‰). We determined the resulting uncertainty for ice-cap area by applying an area-buffer around the digitized ice-cap margins using a GIS software package, calculated as the quadratic sum of the individual contributing uncertainties (Table 4). The final values for the ice-cap area uncertainty estimates (Table 2) are a function of the applied area-buffer, but are also affected by ice-cap area and the length/irregularity of each ice-cap margin. They clearly represent worst-case estimates, as the area-buffer assumes that all points defining the ice margin are systematically displaced to induce maximum area change. In reality, we can expect a certain amount of error cancellation in terms of total ice-cap area.

Results

Ice-cap mass balance

Murray and Simmons Ice Caps experienced highly negative annual mass balances (–0.29 to –0.49 m w.eq.) for at least the past four years (Table 1). Winter snow accumulation on both ice caps was relatively constant each year (0.06–0.1 m w.eq. 1999–2001), and variations in annual net mass balance were mainly a function of summer conditions. Summer climatic conditions in 2000 and 2002 were generally colder and snowier than in 1999 or 2001, leading to less negative annual mass balance on the ice caps (Table 1). We were not able to recover the six ablation stakes remaining on Simmons Ice Cap in 1983 (from the original 1976 network), but one was found melted 10–20 cm horizontally into the glacier surface. We were also unable to locate any of the ablation stakes from the 1972 and 1982 networks on the St. Patrick Bay ice caps during our visit on 15 July 2001 and assume that they had melted out as well. These observations suggest an overall negative mass balance for these three ice caps since at least 1984 (Table 1). The Hazen Plateau ice caps presently do not retain any accumulation of snow, firn, or superimposed ice, even on their highest or most-sheltered parts. The entire surface of Murray and Simmons Ice Caps at the end

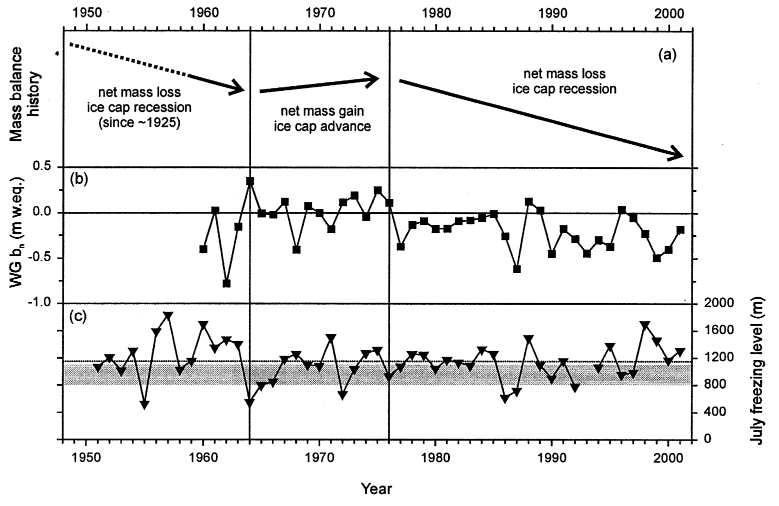

Fig. 4. (a) Generalized mass balance history of the Hazen Plateau ice caps. (b) Annual net mass balance of the **White Glacier** (**WG**) (cf. Fig. 1). (c) July freezing level heights at Alert (1951–2001), with mean of 1150 m a.s.l. shown as a dotted line (1993 data missing). Gray shading indicates the elevation range of the Hazen Plateau ice caps (*c.* 800–1100 m). Mass balance data for White Glacier are from www.trentu.ca/geography/glaxmbal.htm; White Glacier is considered a representative example of Canadian High Arctic glaciers (Cogley *et al.* 1996). Vertical lines through all three plots represent the period of reduced summer melt and increased glacierization in the High Arctic from *c.* 1964 to 1976.

of each summer (1999–2002) and of the St. Patrick Bay ice caps (observed only 2001) was dirty, bare glacier ice characterized by accumulations of wind-blown dust in well-developed cryoconite holes – all suggesting net ablation over an extended period of time.

Ice-cap area changes

All four Hazen Plateau ice caps experienced considerable marginal recession since at least 1959 (Figs 2, 3). Marginal recession was greatest (up to *c.* 700 m) for the flat, low-lying parts of the ice caps and less along the steeper and sheltered sections of the ice margins. This presumably was due to local increases in snow accumulation related to wind drifting. This retreat of the ice margins led to decreases in overall ice-cap area amounting to between 30 and 47% since 1959 (Table 2). The margin of Murray Ice Cap retreated 10–30 m each year in 1999–2001, resulting in an annual area reduction of *c.* 2.5% (Table 2). The margins of all four ice caps were visually thinning and rapidly disintegrating over the course of each summer. This was visibly illustrated by one section of the Simmons Ice Cap margin which retreated *c.* 10 m over 15 days in late July 2001. In addition, two small holes (*c.* 200 m^2) developed in the SW-lobe of Simmons Ice Cap at *c.* 1030 m a.s.l. during July/August 2001 (i.e. ice-free area), which are likely to accelerate ice margin disintegration and retreat in the coming years. We were unable to conduct quantitative area measurements in 2002, but field observations indicated a continued recession of Murray Ice Cap of *c.* 40 m at its terminus in this year. The SW lobe of Simmons Ice Cap in 2002 was almost completely separated from the main ice cap at an elevation of *c.* 1030 m a.s.l. (Fig. 2; see also: www.geo.umass.edu/climate/hazen/sic_99_02.html).

Discussion

Our new data, in combination with previously published work (Tables 1, 2) allow a generalized reconstruction of the Hazen Plateau ice caps' mass balance history for the last four decades (Fig. 4a). The ice caps experienced net ablation and shrinkage for an extended period of time until some time in the early to mid-1960s (Hattersley-Smith and Serson 1973). This was followed by a phase of net accumulation and ice-cap growth until the early to mid-1970s (Hattersley-Smith and Serson 1973; Bradley and England 1977). Since that time, the ice caps have again experienced overall net mass loss and marginal recession. There is evidence for some inter-annual variations in mass balance superimposed on the general trend (e.g. 1982/83), as well as for spatial variability across the Hazen Plateau (e.g. 1976) (Table 2).

This general temporal pattern was also exhibited by other glaciers studied in the Canadian High Arctic, with generally positive mass balances from the mid-1960s to the mid-1970s, followed by generally negative mass balances thereafter (e.g. Fig. 4b). This documented increase in glacierization across much of the High Arctic coincided with a period of reduced summer melt conditions and increased annual precipitation (Bradley and Miller 1972; Bradley 1973; Bradley and England 1978; Alt 1987). Corroborating this are upper air sounding data (Fig. 4c) from the closest official Canadian weather station at Alert (Fig. 1), which show a decrease in July freezing level height of *c.* 100 m between 1964 and 1976 relative to the long-term (1951–2001) mean of 1150 m a.s.l. July freezing level heights have also been shown to be highly correlated with glacier ELAs and mass balance (Bradley 1975; Bradley and England 1978) in the Canadian High Arctic. This comparatively small shift in climate and lowering of the ELA was evidently sufficient for the Hazen Plateau ice caps to experience predominantly positive mass balance years and expansion during this period from the mid-1960s to the mid-1970s (cf. Bradley 1975). However, the regional ELA appears to be located, on average, above the summits of the ice caps for at least the last *c.* 50 years (Fig. 4c). This suggests that the contemporary climatic conditions on the Hazen Plateau are not severe enough to sustain permanent ice cover on the plateau (cf. Ohmura *et al.* 1992). These findings support the interpretation by Bradley and Serreze (1987a) that the Hazen Plateau ice caps are out of equilibrium with current climate.

The overall cumulative mass balance of the Hazen Plateau ice caps and other Canadian High Arctic glaciers (Koerner 1995; Dowdeswell *et al.* 1997; Serreze *et al.* 2000) has been negative for the last *c.* 40 years, with a turn towards even more negative values during the 1990s. This mass loss has led to a retreat of the ice margins and resulted in shrinkage of the Hazen Plateau ice caps since at least 1959 (Fig. 5). There is additional evidence from snow-pit and firn-core studies (Hattersley-Smith 1963) for elevated summer temperatures and increased melting in the period from *c.* 1925 to 1961, suggesting overall more negative glacier mass balances in the Canadian High Arctic during the first part of the 20th century, compared to the last 40 years of direct measurements (Koerner 1995).

The Hazen Plateau ice caps are to some extent end-members of the full glacier–climate response spectrum in the sense that their response to a given climatic perturbation is relatively more extensive and rapid than in the case of larger, more dynamic High Arctic ice caps or glaciers. These ice caps appear to have formed relatively recently (Koerner 1989) during the so-called ‘Little Ice Age’ (LIA, *c.* 1600–1850). They probably maintained their maximum Neoglacial extents as late as *c.* 1925, similar

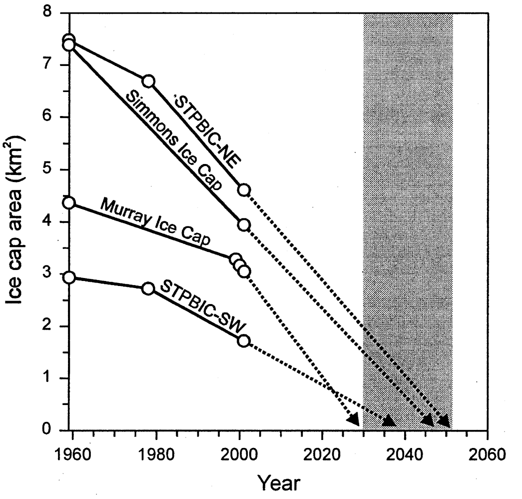

Fig. 5. Area reduction of the Hazen Plateau ice caps 1959–2001, with a generalized linear projection suggesting complete disappearance of the ice caps by mid-21st century or soon thereafter.

to other small glaciers and ice caps on northern Ellesmere Island (Hattersley-Smith 1969). Evidence for an increased extent of ice and/or perennial snow on the Hazen Plateau at some point in the recent past, probably the LIA, is also provided by a well-defined lichen trim line around Murray Ice Cap (*c.* 9.6 km^2) and on the plateau between Murray and Simmons Ice Caps (Fig. 2). A similar lichen trim line is evident around Simmons Ice Cap and the St. Patrick Bay ice caps, but has not yet been mapped in detail. Additional plateau surfaces of comparable elevation in this region probably also supported small ice caps or perennial snowfields at that time. In this context the period of overall positive glacier mass balances from the mid-1960s to mid-1970s may provide a useful analogue for the reduced summer melt conditions in the High Arctic during the LIA (cf. Alt 1987).

Conclusions

The Hazen Plateau ice caps have experienced considerable marginal recession and significant overall mass loss since at least 1959. The sensitivity of these ice caps to changes in climate is enhanced by (1) the low amounts of winter snow accumulation, (2) the absence of iceflow, and (3) the small vertical relief. They are out of equilibrium with modern climate and considered to be relicts of past climatic conditions with reduced summer melt and/or increased snowfall although winter snowfall variations appear to be largely inconsequential in terms of annual mass balance today. The ice caps probably formed during the LIA and will continue to lose mass and retreat under current climatic conditions. They are likely to disappear over the next few decades, unless climatic conditions deteriorate as they did in the mid-1960s. The decay of these ice caps is likely to accelerate in the near future due to feedback processes such as ice-margin disintegration. This study demonstrates that even infrequent mass balance and ice-area measurements can be useful in assessing the general mass balance regime of High Arctic glaciers, especially if some additional historical information is available.

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References

Alt, B.T., 1987: Developing Synoptic Analogs for Extreme Mass Balance Conditions on Queen Elizabeth Island Ice Caps. *J. Clim. Appl. Meteorol.*, 26(11): 1605–1623.

Bradley, R.S., 1973: Recent Freezing Level Changes and Climatic Deterioration in the Canadian Arctic Archipelago. *Nature*, 243: 398–400.

Bradley, R.S., 1975: Equilibrium-line altitudes, mass balance, and July freezing-level heights in the Canadian High Arctic. *Journal of Glaciology*, 14(71): 267–274.

Bradley, R.S. and England, J., 1977: The Simmonds Ice Cap. *In*: Bradley, R.S. and England, J., (eds): Past glacial activity in the High Arctic. Contribution No. 31. Department of Geology and Geography, University of Massachusetts. 177–182.

Bradley, R.S. and England, J., 1978: Recent climatic fluctuations of the Canadian High Arctic and their significance for glaciology. *Arctic and Alpine Research*, 10(4): 715–731.

Bradley, R.S. and Miller, G.H., 1972: Recent Climatic Change and Increased Glacierization in the Eastern Canadian Arctic. *Nature*, 237: 385–387.

Bradley, R.S. and Serreze, M.C., 1987a: Mass balance of two High Arctic plateau ice caps. *Journal of Glaciology*, 33(113): 123–128.

Bradley, R.S. and Serreze, M.C., 1987b: Topoclimatic studies of a High Arctic plateau ice cap. *Journal of Glaciology*, 33(114): 149–158.

Braun, C., Hardy, D.R. and Bradley, R.S., 2001: Recent recession of a small plateau ice cap, Ellesmere Island, Canada. *Journal of Glaciology*, 47(15): 154.

Cogley, J.G. and Adams, W.P., 1998: Mass balance of glaciers other than ice sheets. *Journal of Glaciology*, 44(147): 548–563.

Cogley, J.G., Adams, W.P., Ecclestone, M.A., Jung-Rothenhaeusler, F. and Ommanney, C.S.L., 1996: Mass balance of White Glacier, Axel Heiberg Island, N.W.T., Canada, 1960–91. *Journal of Glaciology*, 42(142): 548–563.

Dowdeswell, J.A. et al., 1997: The Mass Balance of Circum-Arctic Glaciers and Recent Climate Change. *Quaternary Research*, 48*:* 1–14.

Grudd, H., 1990: Small glaciers as sensitive indicators of climatic fluctuations. *Geografiska Annaler*, 72A(1): 119–123.

Hattersley-Smith, G., 1963: Climatic inferences from firn studies in northern Ellesmere Island. *Geografiska Annaler*, 45(2–3): 139–151.

Hattersley-Smith, G., 1969: Glacial features of Tanquary Fiord and adjoining areas of northern Ellesmere Island, N.W.T. *Journal of Glaciology*, 8(52): 23–50.

Hattersley-Smith, G. and Serson, H., 1973: Reconnaissance of a small ice cap near St Patrick Bay, Robseson Channel, Northern Ellesmere Island, Canada. *Journal of Glaciology*, 12(66): 417–421.

Jansson, P., 1999: Effect of uncertainties in measured variables on the calculated mass balance of Storglaciaren. *Geografiska Annaler*, 81A(4): 633–642.

Koerner, R.M., 1979: Accumulation, ablation and oxygen isotope variations on the Queen Elizabeth Islands ice caps, Canada. *Journal of Glaciology*, 22(86): 25–41.

Koerner, R.M., 1989: Queen Elisabeth Islands Glaciers. *In*: Fulton, R.J., (ed.): Quaternary Geology of Canada and Greenland. Geology of Canada, (No. 1). Geological Survey of Canada. 464–477.

Koerner, R.M., 1995: Canadian Arctic. *In*: Jania, J. and Hagen, J.O., (eds): Report on mass balance of Arctic glaciers. Sosnowiec/Oslo, International Arctic Science Committee. Working Group on Arctic Glaciology. 5–8.

Miller, G.H., Bradley, R.S. and Andrews, J.T., 1975: The glaciation level and lowest equilibrium line altitude in the High Canadian Arctic: Maps and climatic interpretation. *Arctic and Alpine Research*, 7(2): 155–168.

Ohmura, A., Kasser, P. and Funk, M., 1992: Climate at the equilibrium line of glaciers. *Journal of Glaciology*, 38(130): 397–411.

Ommanney, C.S.L., 1969. A study in glacier inventory: The ice masses of Axel Heiberg Island, Canadian Arctic Archipelago. Axel Heiberg Island Research Reports, Glaciology 3. McGill University, Montreal. 105 p.

Ommanney, C.S.L., 1977: Quadrennial report to the Permanent Service on the Fluctuations of Glaciers on Canadian glacier variations and mass balance changes. Fisheries and Environment Canada. Inland Waters Directorate, Glaciology Division. Ottawa.

Østrem, G. and Brugman, M., 1991: Glacier mass-balance measurements. A manual for field and office work. National Hydrology Research Institute Science Report 4. Environment Canada, Saskatoon. 224 p.

Paterson, W.S.B., 1969: The Meighen Ice Cap, Arctic Canada: Accumulation, Ablation and Flow. *Journal of Glaciology*, 8(54): 341–352.

Rosqvist, G. and Østrem, G., 1989: The sensitivity of a small ice cap to climatic fluctuations. *Geografiska Annaler,* 71A(1): 99–103.

Serreze, M.C. and Bradley, R.S., 1987: Radiation and cloud observations on a High Arctic plateau ice cap. *Journal of Glaciology*, 33(114): 162–168.

Serreze, M.C. et al., 2000: Observational evidence of recent change in the Northern High-Latitude environment. *Climatic Change,* 46: 159–207.

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