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# On the Glaciers of Bylot Island, Nunavut, Arctic Canada

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## Abstract

The present extent of glacier ice on Bylot Island, Arctic Canada, is mapped using high-resolution Landsat 7 ETM+ satellite imagery. The island is 43% ice covered, with 4783 km$^2$ of ice. Most ice is centered on the northwest-southeast–trending Byam Martin Mountains, flowing outward as radial valley glaciers and piedmont lobes. The largest glacier is 49 km long and 6.5 km wide. The majority of glaciers terminate on land, but many have margins ending in lakes and two calve into the sea. The late summer snowline, mapped from satellite imagery, is highest along the southern and central parts of the island at about 1050 m, with lower values along the east-northeastern margin of the ice down to about 700 m. These snowline-elevation differences suggest a predominant moisture source from the northeast. Several valley glaciers and piedmont lobes have deformed medial moraines and ice-surface foliation suggesting past surge activity. Ten glaciers are interpreted to be of possible surge-type. The modern extent of glaciers is compared with that of two earlier time intervals. First, we have mapped glacier margins in several areas of Bylot Island from aerial photographs acquired in 1958 and 1961. Secondly, former positions of ice fronts are mapped from moraine systems deposited during the Neoglacial maximum and identified on satellite data. Glaciers have retreated from 0.9 to 1.8 km since the Neoglacial maximum about 120 years ago, with most retreat occurring between 1958/1961 and 2001. Approximately 253 km$^2$ or 5% of the 1958/1961 ice-covered area has been lost. Overall, marked glacier retreat has occurred, although a few glaciers, possibly of surge-type, show small readvances. This retreat is consistent with observed climate warming in the Canadian Arctic, especially since the 1960s.

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## Introduction

The climate of the Arctic has warmed since the early 20th century, from the end of the relatively cold period sometimes known as the 'Little Ice Age' (Grove, 2001). Temperatures rose generally from about 1900 to the mid-1940s, then decreased to the mid-1960s, and increased once more after this by about 0.4°C per decade (Global Historical Climate Network dataset [GCHN]; Peterson and Vose, 1997; Jones and Moberg, 2003; McBean et al., 2005). The Arctic surface temperature trends indicate that Bylot Island may be situated at a transition zone between warming in the Queen Elizabeth Islands and cooling to the south and east for the interval 1946 to 1965 (McBean et al., 2005). However, there is considerable regional variability in the surface temperature signal within the Arctic. Precipitation is more difficult to measure than temperature, and glacier mass balance studies have the advantage of integrating the effects of both these parameters.

The Canadian Arctic archipelago has over 150,000 km$^2$ of ice-covered area, representing about 60% of the glaciers and ice caps in the Arctic outside Greenland (Dowdeswell et al., 1997; Dowdeswell and Hagen, 2004). Several Canadian ice masses, including White Glacier and Devon, Meighen, and Agassiz ice caps, have been investigated in detail and have been shown to have had a consistently negative net mass balance over the last 40 years or so (Koerner, 1996; Dowdeswell and Hagen, 2004). However, many glaciers in the Canadian Arctic islands have not been investigated previously in terms even of their dimensions, and rates of change in extent are seldom available. This is a significant gap in our knowledge of the ice masses of the Arctic and the way that they are responding to environmental change.

The purpose of this paper is (1) to present accurate baseline data on the modern extent and characteristics of the glaciers on Bylot Island, and (2) to examine the changes that have occurred between 2001, 1958/1961, and the Neoglacial maximum in the context of the changing climate of the Canadian Arctic islands.

## Study Area and Methods

### STUDY AREA AND GLACIAL HISTORY

Bylot Island is located east of northern Baffin Island, between latitudes 72.5° and 74°N, and longitudes 76° and 81°W (Fig. 1; Andrews, 2002). It is dominated by the Byam Martin Mountains, which extend the length of the island in a northwest-southeast direction. The highest mountain peaks, Angilaaq (1844 m) and Malik (1905 m), are found in the center of the island (Fig. 1). Elevations decrease in all directions from this central highland, with only isolated locations reaching above 1500 m elsewhere. Low-lying areas occur along the outer margins of Bylot Island in the southwest, the north, and on a small portion of the northwestern tip. Other areas of low relief are represented in the northeast by glacial valleys with outwash plains bordered by mountainous terrain.

The present distribution of ice on Bylot Island reflects the topography of the island. The ice cover takes a variety of forms including outlet glaciers emanating from the ice cap and terminating either on land or at the coast, isolated mountain



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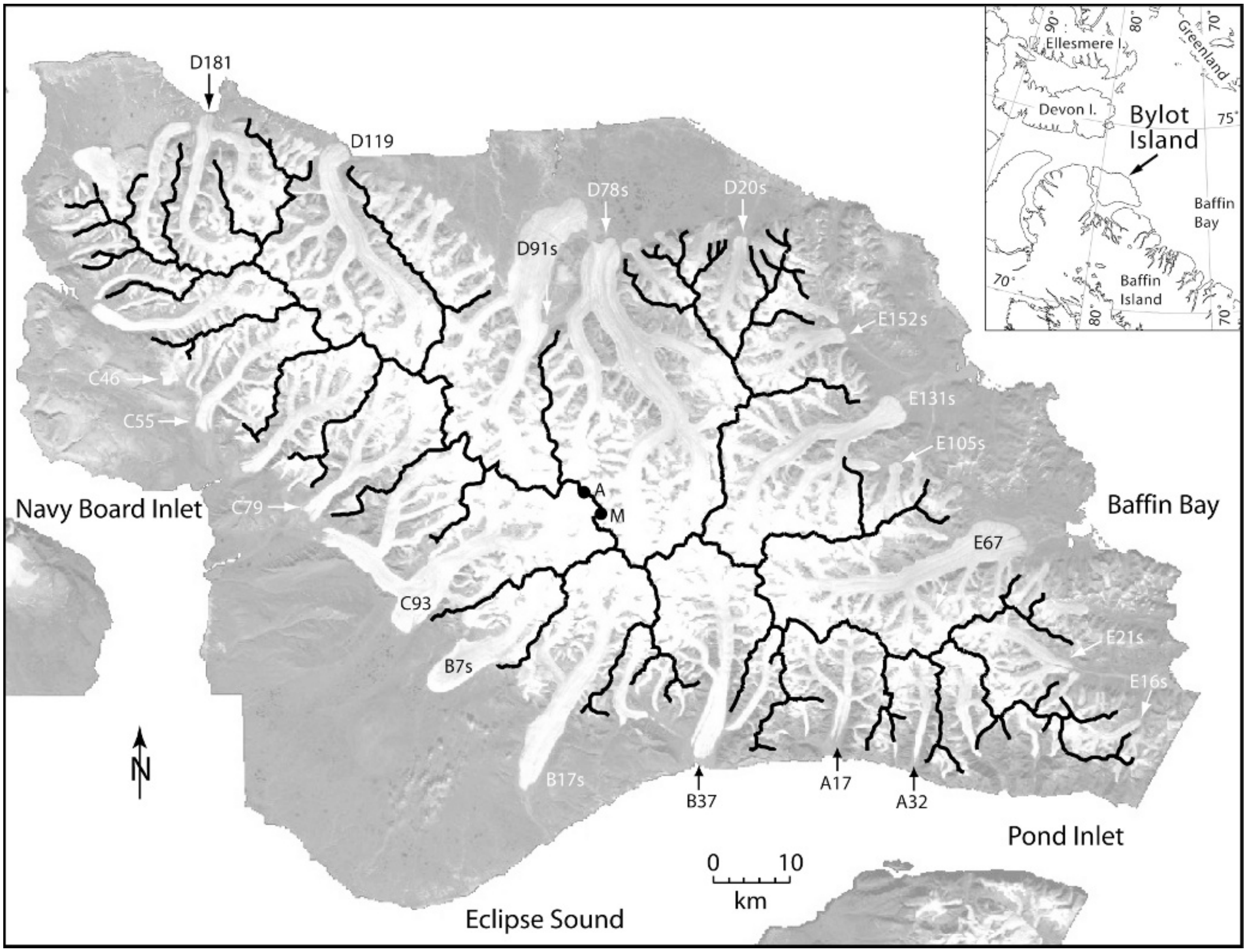


**FIGURE 1. Location map of Bylot Island in the Canadian Arctic showing the major drainage basins on the ice cap. The largest outlet glaciers are identified using the numbering system given in Ommanney (1980). Glaciers of probable surge-type have an 's' after their identification number. 'M' = Malik Mountain; 'A' = Angilaaq Mountain.**

glaciers which have become detached from the main ice cap, and small perennial ice patches found predominantly in lowland areas.

Recent work showed that some glaciers on Bylot Island have receded over a kilometer from their Neoglacial moraines, whereas other modern ice margins are not significantly different from their Neoglacial maximum positions (Klassen, 1985, 1993a). Earlier work indicated that much of the terminal retreat occurred between 1851 and 1948 (Falconer, 1962). Falconer's comparison of the existing photographic data, pictures, and maps prior to 1961 showed that the glaciers on the northern coast of Bylot Island remained largely unchanged between 1948 and 1958. Glaciers on the southern and western coasts gave a mixed signal, with some showing retreat of about 50 m and others showing only a slight change in terminus position during this 10-year period.

The Quaternary glacial history of Bylot Island has been investigated in the field. Six Quaternary glacial episodes were recognized prior to the Neoglacial maximum (Klassen, 1981, 1982, 1985, 1993a). Stratigraphic relationships between surficial deposits of varying lithological composition, the nature and distribution of marginal marine deposits, and chronological evidence from radiocarbon and amino-acid dating techniques have identified three of these events as being confined to local mountain glaciers and three involving regional ice sheets. The Neoglacial maximum, which occurred approximately within the last 120 years, falls into the former category (Klassen, 1993a).

The numbering system used in this paper to identify the glaciers of Bylot Island originated in the 1960s as the Canadian Glacier Inventory Project, which was part of the world inventory of glaciers program sponsored by UNESCO (Ommanney, 1980; Klassen, 1993b).

## *IMAGERY*

Landsat ETM+ (Enhanced Thematic Mapper) and ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer on board the Terra satellite) imagery was used to map the present extent of glaciers on Bylot Island. The base image for the modern data was Landsat 7 image L71032008008200100809, which was acquired on 9 August 2001. Although the Global Land Ice Measurements from Space (GLIMS) project, of which this study is part, is primarily involved with ASTER data, this Landsat image was the only available scene that provided a cloud-free view of Bylot Island. Other Landsat and ASTER images were used for clarification (e.g. where an area was obscured by shadow in the base image). The spatial resolution for the visible and near-infrared bands of Landsat ETM+ and ASTER imagery is 30 and 15 m, respectively. The panchromatic band of the Landsat data has a pixel size of 15 m. The main source of error in the evaluation of ice extent from Landsat and ASTER images was in errors introduced by the operator during digitization and in the difficulty of obtaining imagery showing the glacier margins at their minimum extent, when they were not obscured by summer snow cover.

Aerial photographs at a scale of 1:60,000 provided data from which the 1958 and 1961 ice margins were obtained. These were orthorectified to UTM Zone 17, WGS 84 using ground control points from the Landsat 7 image and processed with digital elevation data using ERDAS Imagine image processing software. Elevation data (Canadian Digital Elevation Data—CDED) were obtained from Geomatics Canada (Department of Natural Resources, Centre for Topographic Information) and the University of Alberta data library. They were derived from 1:250,000 topographic map sheets (National Topographic Database—NTDB) created from aerial photographs acquired from June to July 1958 (flight lines A16018, A16047, A16214, A16294, A16295, A16350) and July 1961 (flight line A17040). Although not from the same year, the mosaiced CDED provided the most comprehensive early data set available for this area as a whole.

### *SNOW AND ICE CLASSIFICATION*

In order to define the present extent of glacier ice on Bylot Island, an initial unsupervised classification was carried out on the 9 August 2001 Landsat image, as is standard for the Canadian Arctic GLIMS data (L. Copland, personal communication, 2004). This classification was based on the normalized-difference snow index (NDSI) which exploits the difference between the high reflectivity of snow and ice in band 2 and its low reflectivity in the near-infrared band 5 (Dozier, 1984):

$$\mathrm{NDSI} = \frac{\text{band } 2 - \text{band } 5}{\text{band } 2 + \text{band } 5.} \qquad (1)$$

The NDSI classification method has the advantage of being automated. L. Copland (personal communication, 2004) also found that the NDSI worked particularly well for areas misclassified in both the unsupervised Landsat 7 panchromatic band and the Landsat Thematic Mapper ratio (TM4/TM5) classification methods. Although this was the case for the Devon Island Ice Cap, with its relatively simple outline, extensive manual editing was required when the NDSI classification was applied to the more complex ice margin on Bylot Island in this paper. Incorrect classifications occurred due to shadowing along steep topographic features, such as mountain peaks and ridges, and moraine crests. Ice-covered water bodies were also often misclassified. Therefore, in this study, all areas of ice that were initially classified using the NDSI method were thoroughly edited manually. These included all ice bodies greater than 0.008 $km^2$ in area.

### *SNOWLINE ESTIMATES*

Snowline data were determined using the 9 August 2001 Landsat ETM+ image combined with digital elevation data provided by Geomatics, Canada. Elevation changes due to ice cap thinning, which occurred between the Landsat imagery and the CDED acquisition dates, were not considered to be problematic for the determination of the overall snowline pattern. The regional snowline is, of necessity, generalized to account for medium- and small-scale variability due to factors such as aspect and shadowing.

More important to the accuracy of regional snowline elevation data is the date of the source imagery. The end of the balance year as defined by the cessation of melting and the beginning of snow accumulation occurred between 9 and 25 August in 2001. The substantial new snow cover visible on an image from 25 August is unlikely to have melted so late in the season. Therefore, although the snowline data given here are minimum estimates for the year 2001, 25 August provides the likely maximum length of the balance year 2000–2001.

## Modern Ice Extent

### *ICE COVERED AREA*

The extent of ice on Bylot Island at the end of the 2001 balance year was 4783 $km^2$, which represents 43% of the island's total area of 11,122 $km^2$. This ice-covered area includes (1) the main ice cap (4620 $km^2$), (2) ice-covered areas immediately adjacent to the main ice cap but not directly connected to it (114 $km^2$ of ice), and (3) other remnant glaciers, ice bodies, or perennial ice fields that are found in isolated positions at some distance from the main ice cap (49 $km^2$ of ice), and located predominantly along the northeast coast (Fig. 1). These values exclude bedrock outcrops, nunataks, and unglacierized interfluves lying within each of these three ice-covered areas. About 15.3% of the interior of the main ice cap is exposed bedrock. Values for the main ice cap and the ice immediately adjacent to it are combined in the remainder of the paper to give an area of 4734 $km^2$. It is assumed that these immediate outliers were connected to the main ice cap until recently.

### *OUTLET GLACIERS*

Glaciers centered on the uplands of Bylot Island flow radially outward as a series of valley glaciers emanating from cirque headwalls. The cirques can be discerned from the pattern of nunataks and upland highs with relatively thin ice cover and are visible when looking at individual drainage basins (Fig. 1). Those glaciers that descend onto relatively flat coastal plains characteristically form piedmont lobes.

The dimensions of the larger outlet glaciers are given in Table 1. Length and width measurements were made parallel and perpendicular to glacier flow, respectively. In situations where tributary glaciers merged, measurements where taken only where the flowlines of the confluent glacier regained perpendicularity to glacier width. The longest outlet glacier, D78, is 49 km in length and has a maximum width of 6.5 km (Fig. 1). The length distribution of the outlet glaciers points to the slightly asymmetric nature of the underlying topography, with shorter glaciers generally situated on the southwestern portion of Bylot Island. Two length values are given for Glacier C93, the longer value accounting for its larger limb to the west (Fig. 1). The extensive area of stagnation deposits in the proglacial area of this glacier suggests that it extended much farther south in the past. Deglaciation by thinning and down-wasting had a predominant southwest/northeast component relative to the more protected western tributary. Large areas of kettle lakes are also observed in the proglacial areas of glaciers B7, D91, and D78.

The majority of glacier margins terminate on land. However, two of the larger outlet glaciers terminate in marine waters, and

TABLE 1

**Size characteristics of the larger outlet glaciers on Bylot Island. The glaciers are located in Figure 1.**

| Glacier Number/Name | Length (km) | Max. width (km) | Drainage basin area+ ($km^2$) | Ice in drainage basin ($km^2$) |
|---|---|---|---|---|
| D119 | 35.9 | 3.2 | 364 | 272 |
| D91 | 46.4 | 5.8 | 383 | 338 |
| D78 | 49.4 | 6.5 | 708 | 571 |
| E131 | 35.2 | 4.4 | 347 | 293 |
| E67 | 37.0 | 4.1 | 403 | 340 |
| B37 Sermilik | 33.3 | 3.2 | 251 | 221 |
| B17 Aktineq | 36.5 | 4.2 | 258 | 233 |
| B7 | 23.6 | 4.7 | 130 | 125 |
| C93 | 43.0/30.4* | 4.8 | 469 | 403 |

* Glacier C93 bifurcates. The second number given represents the shorter terminus.

+ Drainage basin divides do not generally intersect glacier frontal margins. In order to close the area polygon, the intersection of the first tributary glacier with the drainage divide was used. Area calculations are therefore minimum values.

portions of many termini and lateral margins end in lakes (Fig. 2). Glaciers D181 and D119 in the northwestern part of Bylot Island are currently calving into Baffin Bay (Fig. 1). The suspended sediment plume emanating from the terminus of Glacier D181 and the presence of icebergs immediately offshore can be seen in Figure 2A. The glaciers calving into the sea have a combined marginal width of about 4.5 km and drain 9% or 430 $km^2$ of the interior ice. A further 28 km of ice margin is situated adjacent to lakes. These include smaller glaciers flowing from local uplands which terminate in lakes (Figs. 2B and 2C). Features such as the

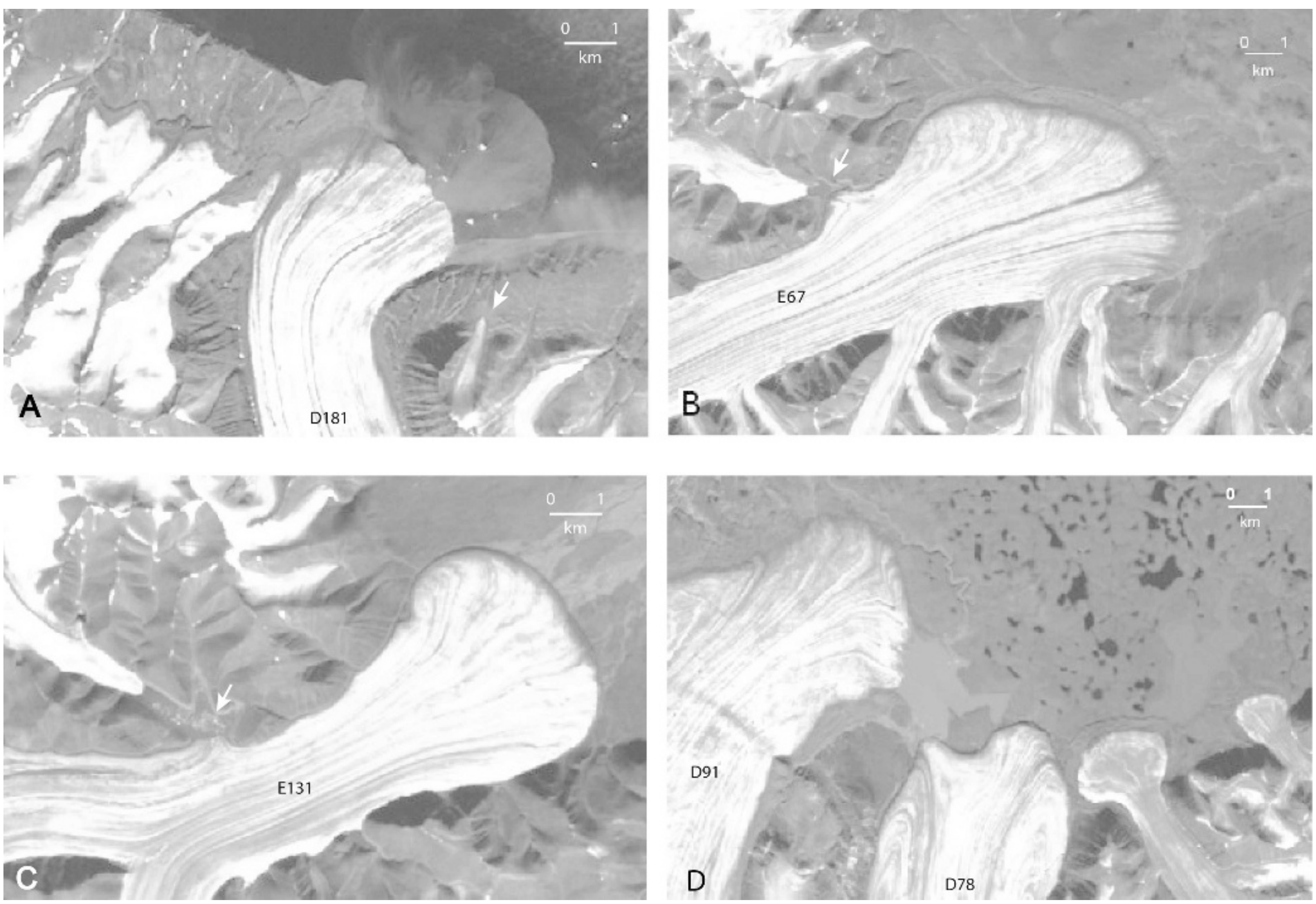


**FIGURE 2. The forms of glacier termini on Bylot Island (locations shown in Fig. 1). (A) Glacier D181 terminates in Baffin Bay. The image shows calved icebergs and a well-defined suspended sediment plume derived from turbid glacial meltwater. The arrow denotes a smaller glacier with no Neoglacial terminal moraine. (B) Glacier E67 shows undisturbed recessional features, whereas the smaller glacier to the east shows an over-steepened front with no end moraine visible. Arrow shows glacier terminal/lateral margins in a lake. (C) Glacier E131 has an over-steepened front with calving taking place into a lake along its northern lateral margin (marked with an arrow). (D) Glaciers D91 and D78 exhibit a combination of deformed medial moraines, termination into lakes and an over-steepened front. The smaller glacier to the east shows undeformed recessional end moraines.**

presence of icebergs and concave marginal outlines also indicate that calving has occurred into these lakes (Fig. 2C).

## Surge-Type Glaciers

There are now recognized to be large numbers of surge-type glaciers in the Canadian Arctic islands (Copland et al., 2003), although none have been identified previously on Bylot Island (Andrews, 2002). The glaciers of Bylot Island that terminate on land can be divided broadly into those that display largely undeformed recessional features and those that exhibit evidence of differential flow velocity and possible surge activity. Compound glaciers often have both undeformed and deformed components. Surge activity is generally recognized by a combination of features, such as looped or deformed moraines, anomalous and/or widespread crevassing, pronounced ice ramps, stagnant ice, potholes, and over-steepened termini (Meier and Post, 1969; Sturm, 1987). Distorted medial moraines and over-steepened margins are the two surge indicators most commonly observed in satellite imagery of Bylot Island glaciers. The distortion of medial moraines takes place when faster-flowing glacier components encounter slower-moving sections, as can be the case with tributary and trunk glaciers.

The outlet glaciers on Bylot Island are complex and commonly have numerous tributaries. In 10 cases, medial moraines exhibit deformation indicating possible non-steady flow. These glaciers of possible surge-type are labeled in Figure 1. The two largest of these glaciers, D91 and D78, drain an ice-covered area of 909 $km^2$ or just over 19% of the total area of the ice cap (Fig. 1). Both of these glaciers show deformed medial moraines, particularly in the snout area of the westernmost sections (Fig. 3). Other areas of moraine distortion occur near the central part of the terminus on Glacier D91 and in the eastern snout sections of both glaciers. The distorted moraines evident farther up-glacier on D78 may be complicated by obstruction of flow due to topographic constraints which do not occur in front of Glacier D91 or Glacier D78. The over-steepened front margin which is also visible in Glacier D78 suggests a readvance. The Neoglacial terminal moraines evident for the glacier immediately to the east are not present at Glacier D78 and may have been overrun during

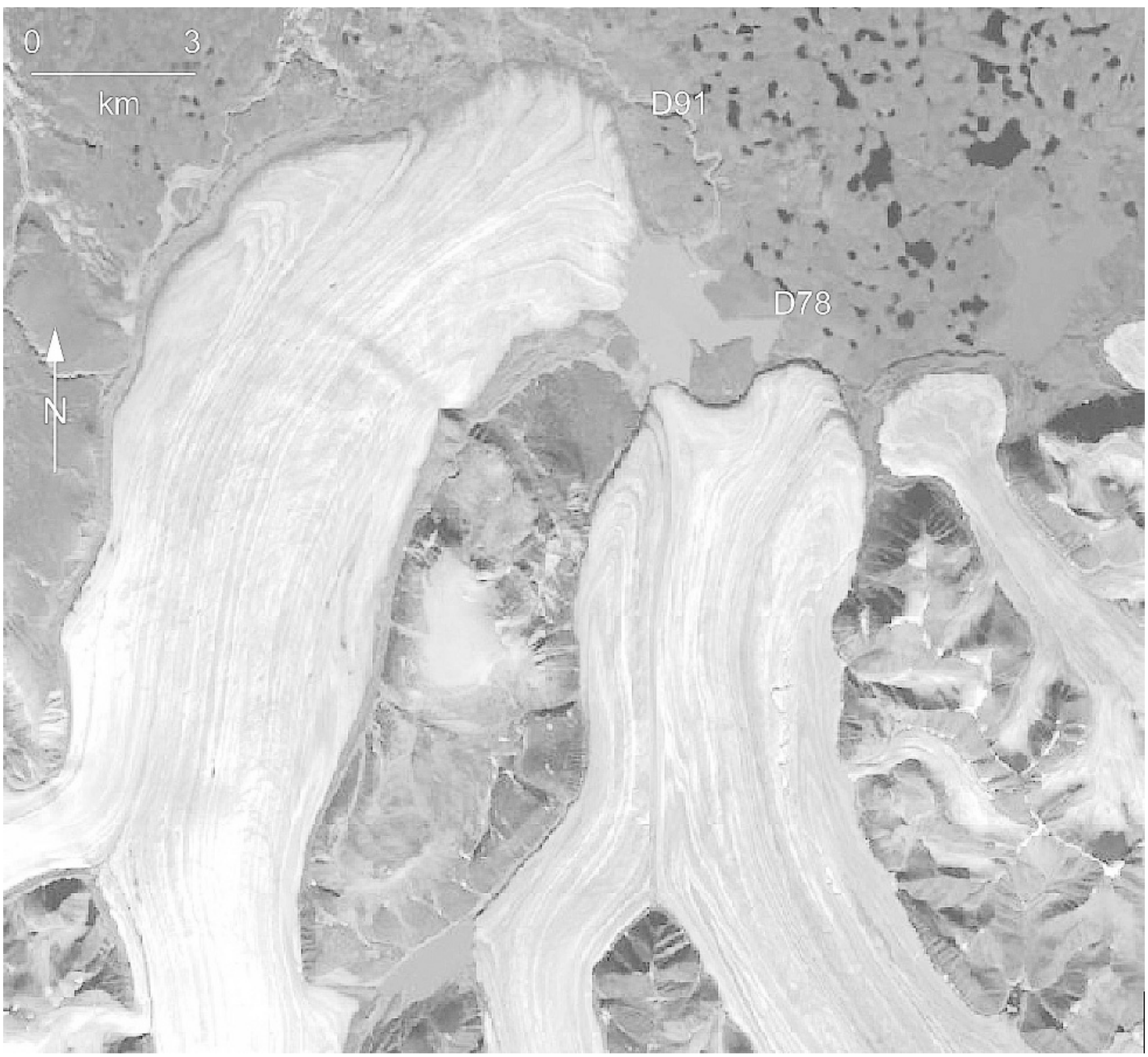


**FIGURE 3. The deformed medial moraines indicative of possible surge episodes are visible on glaciers D91 and D78 (located in Fig. 1).**

an active surge phase. Other glaciers on Bylot Island exhibit only slight disturbance of their medial moraines (Figs. 2B and 2C). Although this is evidence of differential flow velocities, whether or not these are considered to have "surged" is debatable. It is clear, however, that the medial moraines have been deformed relative to the typical, parallel medial moraines observed elsewhere (e.g. Fig. 2A). Glacier E131, which shows only slight moraine deformation, also has an over-steepened margin (Fig. 2C).

The majority of glaciers displaying ice-surface features indicative of possible surge activity are situated along the northeast-trending coastline of Bylot Island. None of the surge-type glaciers are located along the northwestern portion of the island or the southern, Pond Inlet margin.

## Regional Snowline

The snowline elevation on Bylot Island varied from just over 1000 m to just under 700 m in 2001 (Fig. 4). The regional pattern shows the lowest elevations occurring along the east-northeastern coastline. Of the 291 individual snowline elevation points measured, all of those below 700 m are situated here (2.4%). This reflects a probable northeasterly moisture source from Baffin Bay (Koerner, 1979). Interestingly, the glaciers along the northern coast, which would also receive moisture from Baffin Bay, do not exhibit similarly low snowline elevations. This may be due to their closeness to the shoreline itself, which could result in enhanced warming in summer. Higher snowline elevations are found in the southern and central portion of Bylot Island. The highest snowline elevations occur along the southeastern, Pond Inlet margin. Here, areas as high as 1270 m are snow free, which reflects, for example, the local occurrence of steep slopes. However, this is uncommon, and less than 5% of the points measured exceed 1050 m in snowline elevation.

The map of regional snowline elevations given in Figure 4 is for August 2001. Snowline elevations are a product of the winter accumulation minus the summer loss of mass in that year. The balance year 2000–2001 was more negative than any observations since 1961, according to mass balance records from northwest Devon Ice Cap (Fig. 1; R. M. Koerner, personal communication, 2006). On Devon Island, mass balance values for the period 1998 to 2001 were significantly lower than the period from 1961, with the balance year 2000–2001 falling below the standard deviation even for this warmer 4-year interval. This suggests that the 2000–2001 balance year may have been unusually warm. We may therefore expect that the snowline elevations in Figure 4 represent maximum values relative to the preceding decades. However, the absolute elevation of the snowline was determined on 9 August 2001, slightly before the end of the balance year 2000–2001. A Landsat image acquired on 25 August 2001 showed fresh snow cover on all glacier surfaces and above about 300 m to 450 m on unglaciated terrain (north and south coasts, respectively). Mean daily temperatures at Pond Inlet fell below freezing for the first time that month on 19 August, suggesting that 2001–2002 balance year began in the second half of August.

## Post-Neoglacial Changes in Ice Extent

### *CHANGES IN OVERALL ICE EXTENT*

The majority of glaciers on Bylot Island exhibit clear evidence of retreat from their Neoglacial maximum positions. The larger glaciers, which extend from the mountains onto flat-lying terrain, have end moraines situated beyond their present ice margins (e.g. Fig. 2B). The most notable exception to this is the case of possible surge-type glaciers (e.g. Fig. 2D) where steep margins indicate possible readvance. Some smaller mountain glaciers, especially those which have become detached from the main ice cap, do not always exhibit terminal moraines at their margins (e.g. Fig. 2A). However, it is often possible to discern other indications of area change for these smaller glaciers, such as differences in rock weathering and/or degree of vegetation, both of which result in higher brightness values for the more recently exposed bedrock.

The satellite and aerial photographic data presented show that most of the glaciers on Bylot Island have been in retreat since the Neoglacial maximum. Comparisons are made using the 1958/

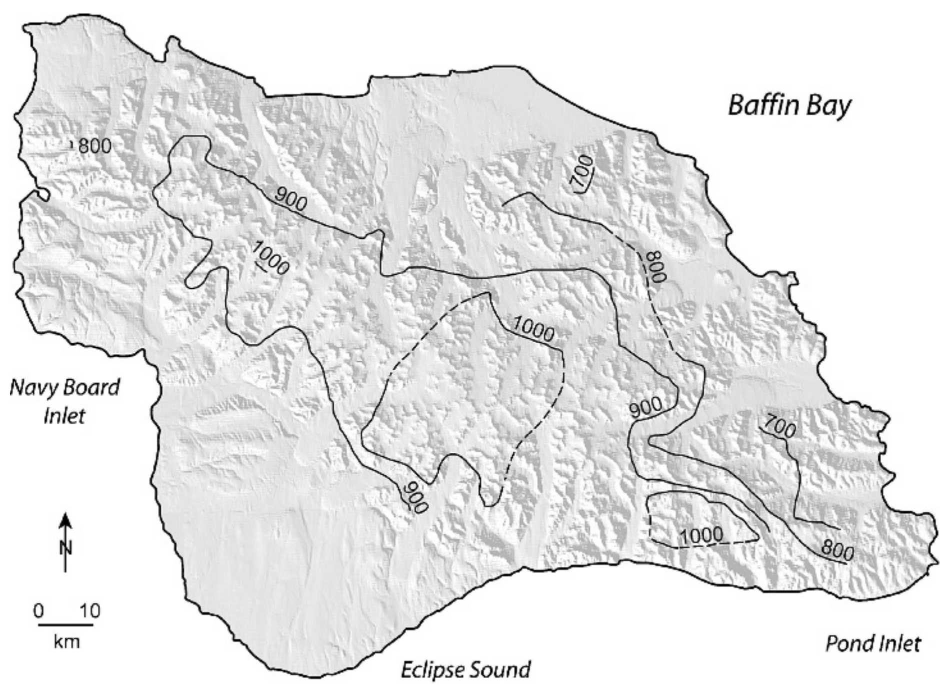


**FIGURE 4. Regional snowline elevation map (contours in meters). The 9 August 2001 Landsat imagery was used to identify the ice/snow boundary. Elevation data and the shaded relief map were derived from a DEM based on the 1958/1961 aerial photographs.**

1961 glacier outlines from the NTDB. These topographic maps, derived from aerial photography taken in June and July 1958, and July 1961, show the glacier outlines for the 1958–1961 period.

In order to obtain an accurate representation of the amount of change which has occurred between 1958/1961 and 2001, the data sets had to be made compatible. Because some areas of exposed bedrock near the center of the ice cap were omitted from the 1958/1961 data set, the outer perimeter of the ice cap was used as a measure of area. However, adjustments also had to be made in the evaluation of the perimeter ice area in order to accurately represent the post-1961 change. For example, isolated ice masses situated adjacent to the ice cap were not always included in the 1958/1961 database and were therefore excluded here. Other areas either contiguous in 1958/1961 or included in the 1958/1961 data set were added for comparative purposes. The effect of these adjustments is that changes in the perimeter ice area that follow are minimum estimates.

The area values resulting from our comparison of changing ice extent on Bylot Island determined from the 1958/1961 aerial photographs and the 2001 Landsat data are 5700 $km^2$ and 5585 $km^2$, respectively. This difference, of 115 $km^2$ or 2% of the 1958/1961 area as measured to its outer perimeter and thus including nunataks, shows that the ice cap as a whole has decreased in area.

Abdalati et al. (2004) used airborne laser altimetry to show that the pattern of thinning/thickening of the ice caps in the Canadian Arctic is highly variable, especially in mountainous terrain. Although there is a general inverse relationship between elevation and thinning, it is one that is difficult to extrapolate, even over relatively uncomplicated ice caps such as the Barnes Ice Cap to the south on Baffin Island. In the absence of a fine grid of surface-altimetric data on Bylot Island, monitoring the behavior of smaller ice bodies and exposed bedrock outcrops provides information on the nature of mass balance change.

Thus, if we consider the main ice cap alone, the amount of bedrock exposed at present is 15.3% (4734 $km^2$ ice and 855 $km^2$ exposed rock). The same figure for the generalized 1958/1961 data is 13.0% (4987 $km^2$ ice and 745 $km^2$ exposed rock). This represents an increase of 110 $km^2$ in the amount of bedrock exposed over the last 40 to 43 years. The difference in the amount of ice between the original Geomatics Canada 1958/1961 data and the present data shows a decrease of 253 $km^2$ or about 5% of the 1958/1961 total.

### *RETREAT OF INDIVIDUAL GLACIERS*

In order to quantify the rate of glacial retreat, four of the larger glaciers on Bylot Island have been examined using aerial photographs from 1958/1961 (Fig. 5). Aerial photographs along flight line A17040 were acquired on 23 July 1961 and those along flight line A16294 on 28 August 1958. The amount of retreat and the area lost from the snout have been derived by comparing the Landsat ETM+ panchromatic data and aerial photographs (Table 2). Measurements were taken using a line trending subparallel to the direction of ice flow, extending from the furthest present ice position to the 1958/1961 and Neoglacial moraine systems, thus yielding minimum retreat estimates. Co-registration errors were avoided by measuring areas and lengths within rather than between images.

All four glaciers shown in Figure 5 have been in retreat since the Neoglacial maximum. Glaciers C55, C79, and Kaparoqtalik (A17) have lost more than twice the area in their snout regions during the 40/43 years from 1958/1961 to 2001 than in the 77/80 years from the Neoglacial maximum to 1958/1961 (Figs. 5A, 5B, and 5D). This is not so for Sermilik Glacier (B37), which exhibits a relatively equal change in area throughout the interval from the Neoglacial maximum to 2001 (Fig. 5C). However, this may be because Sermilik Glacier ends in the sea and therefore loses mass by calving as well as surface melting. Aerial photographs show that calving was active in 1958. This may be extended back to 1948 through the observations of Falconer (1962), who indicated that there were no marked changes during the 10-year interval from 1948 to 1958. The discontinuous moraine pattern and proximity to the coastline suggests that calving was also likely to be occurring during the Neoglacial maximum (Fig. 5C).

The age of the Neoglacial maximum on Bylot Island is known only roughly due to the difficulty of absolute dating. Two radiocarbon dates have been obtained from Neoglacial moraines on the island. DiLabio and Shilts (1979) reported a peat sequence overlain by Neoglacial moraine dated at 450 $\pm$ 70 yr BP. A radiocarbon date of 120 $\pm$ 80 yr BP was obtained from twigs found within Neoglacial moraines at an elevation of 80 m from Glacier C79 (Klassen, 1993a). Lichenometric data have also been used to constrain Neoglacial age estimates farther south on Baffin Island (Fig. 1). Neoglacial moraines along the western Barnes Ice Cap and on Cumberland Peninsula were interpreted to be less than 100 years old (Andrews and Barnett, 1979; Davis, 1985). Although we cannot confirm the correlation between the more southerly Neoglacial moraines and those on Bylot Island, the radiocarbon date of 120 $\pm$ 80 yr BP and the lichenometric data of $<$100 yr are in approximate agreement. Radiocarbon ages from organic matter within moraines pre-date the period of glacial advance, whereas lichen growth post-dates it (Davis, 1985). An age of 120 years ago is therefore assumed here in further calculations involving the timing of retreat from Neoglacial terminal moraines.

Linear retreat distances from the Neoglacial maximum varied from 0.9 to 1.8 km for the four glaciers. Again, the majority of retreat occurred from 1958/1961 onwards (Table 2). Kaparoqtalik Glacier showed the largest retreat distance of 1.8 km, 83% of which occurred since 1958. These values were 72, 69, and 66% for Glacier C55, Glacier C79, and Sermilik Glacier, respectively. The values are representative of the larger non-surging glaciers on the southern and southwestern coasts of Bylot Island. Other large glaciers in this area have retreated between 1 and 1.5 km. The average rate of retreat for the four glaciers shown in Figure 5 during the interval between the aerial photographic data and the 2001 Landsat imagery was 23 m $yr^{-1}$. Kaparoqtalik Glacier exhibited the highest rate, 34 m $yr^{-1}$. This contrasts with average retreat rates of about 4 m $yr^{-1}$ from the Neoglacial maximum to the time of the aerial photographic data and 11 m $yr^{-1}$ from the Neoglacial maximum to 2001. Overall, retreat from the Neoglacial maximum to present was approximately half that of the mid-20th century to today (Table 2).

## Discussion

Most glaciers on Bylot Island have been in retreat over the last 120 years or so, and overall ice extent has decreased by about 5% since 1958–1961. The general pattern of rising surface air temperatures in the Arctic therefore appears to be reflected in the data on changing ice extent presented here. The warming trend evident from the 1960s onward (McBean et al., 2005, fig. 2.6) coincides with our findings of substantially higher retreat rates from 1958/1961 to 2001 than from the Neoglacial maximum to 1958/1961 (Table 2). However, detailed local-scale correlations between temperature, mass balance, and ice extent must be treated

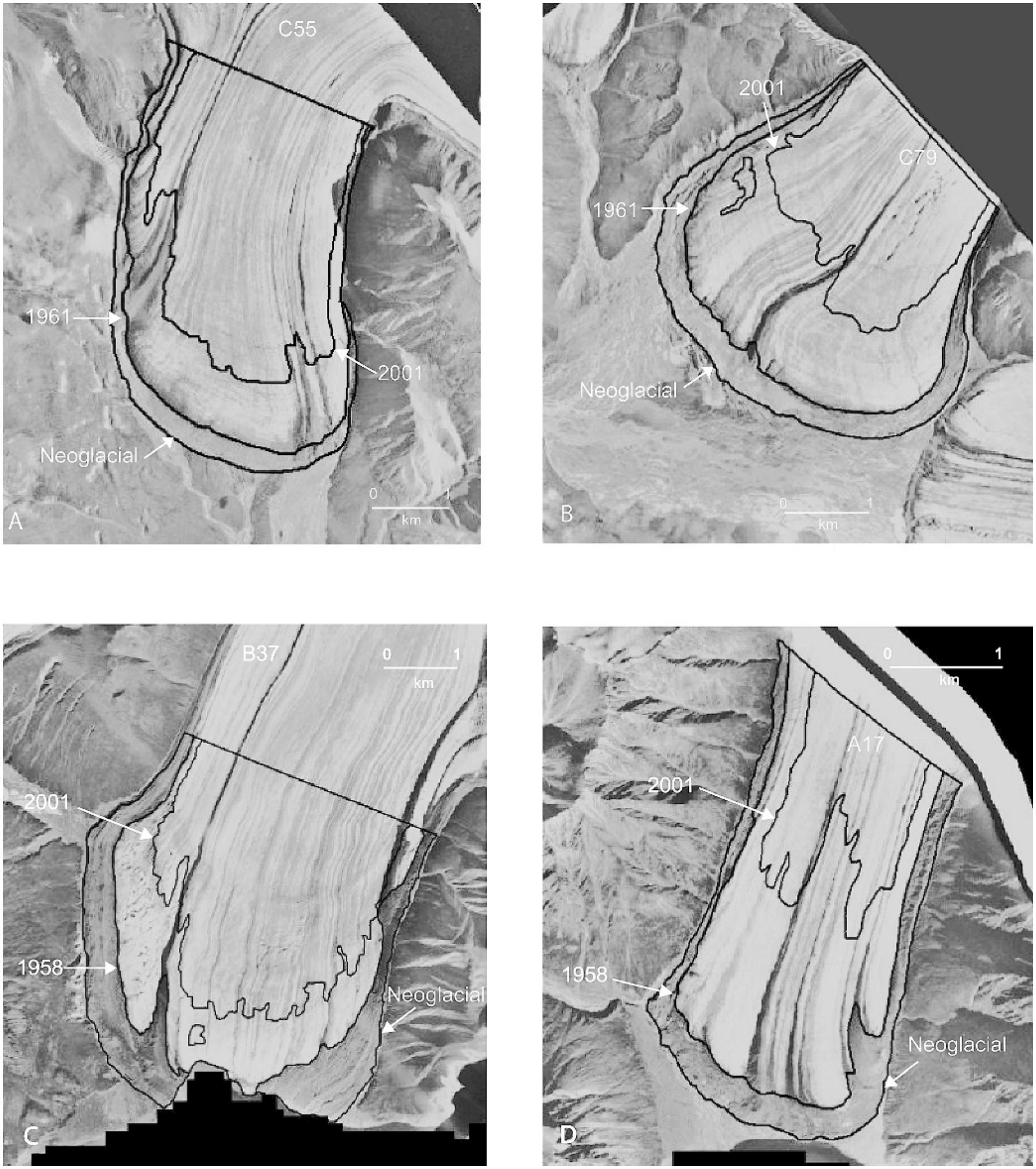


**FIGURE 5. Changes in glacier terminus positions since the Neoglacial maximum. End moraines are outlined for the 2001 snout area, the 1958/1961 margin and the Neoglacial maximum. (A) Glacier C55, reference aerial photograph A17040, no. 63. (B) Glacier C79, reference photograph A17040, no. 59. (C) Sermilik Glacier (B37), reference photograph A16294, no. 49. (D) Kaparoqtalik Glacier (A17), reference photograph A16294, no. 50. Glaciers located in Figure 1.**

with caution due to the widely spaced grid of the available climate data and the high interannual variability of surface temperatures in the Arctic (Kållberg et al., 2005).

The interpretation of changes in ice-covered area over the period since the Neoglacial maximum should include consideration of iceberg calving in addition to climate. This is because any changes in the length of tidewater calving fronts will produce an ice-dynamic effect on mass loss and ice extent that is not related directly to climate change. There is evidence that, relative to today, an increased number of calving glaciers were active during the Neoglacial. Sermilik Glacier in the south (B37; Fig. 5C) and two glaciers in the north (D181 and D119; Figs. 1 and 2A) exhibit incomplete Neoglacial terminal moraines indicative of past calving. Their Neoglacial calving fronts, reconstructed from

**TABLE 2**

**Decreases in glacier terminus from the Neoglacial maximum to the mid-20th century to 2001 (Fig. 5). The glaciers are located in Figure 1.**

| | | Glacier C55 | Glacier C79 | Sermilik Glacier (B37) | Kaparoqtalik Glacier (A17) |
|---|---|---|---|---|---|
| Area change ($km^2$) | Neoglacial max. to 1958/1961 | 1.3 | 2.2 | 4.5 | 1.6 |
| | 1958/1961 to 2001 | 4.0 | 5.1 | 4.8 | 3.7 |
| | Neoglacial max. to 2001 | 5.2 | 7.3 | 9.3 | 5.3 |
| Retreat length (m) | Neoglacial max. to 1958/1961 | 260 | 340 | 470 | 290 |
| | 1958/1961 to 2001 | 660 | 760 | 930 | 1460 |
| | Neoglacial max. to 2001 | 920 | 1100 | 1400 | 1750 |
| Retreat rate** (m $yr^{-1}$) | Neoglacial max.$^{+}$ to 1958/1961 | 3.3 | 4.3 | 6.1 | 3.8 |
| | 1958/1961 to 2001 | 16.5* | 19.0* | 21.6$^{++}$ | 34.0$^{++}$ |
| | Neoglacial max.$^{+}$ to 2001 | 7.7 | 9.2 | 11.7 | 14.6 |

$^{+}$ Retreat rate calculated over the last 120 years using 2001 as a baseline, thus using a 77 and 80 year interval for the 1958 and 1961 data, respectively.

* Retreat rate calculated over the 40 year interval from 1961 to 2001.

$^{++}$ Retreat rate calculated over the 43 year period from 1958 to 2001.

** A measurement error of one pixel would yield an error in calculated mean retreat of 0.08 m $yr^{-1}$ for the Neoglacial to 1958/1961 period, and of 0.25 m $yr^{-1}$ for 1958/1961 to 2001.

moraine ridges, together measure 10.3 km in width. This figure may be increased if the historical accounts of Falconer (1962) are correct. Falconer (1962) cited written descriptions and photographs to suggest that Narsarsuk Glacier (A32; Fig. 1) reached the sea in 1909 and terminated on land by 1928. Similarly, Falconer stated that a smaller glacier to the west was observed to reach tidewater in 1910, remaining so until some time between 1948 and 1958. Kaparoqtalik Glacier (A17; Fig. 5D) also appears to have had a calving front as described by F. L. M'Clintock during a voyage in 1858 (M'Clintock, 1860, *in* Falconer, 1962). The terminal moraine of Kaparoqtalik Glacier reached the sea between 1921 and 1924 (Mathiassen, 1933) and the glacier had receded from the shore by 1948 (Falconer, 1962). Kaparoqtalik Glacier has a relatively well-defined Neoglacial moraine at the shoreline. Thus, the greater length of glaciers that reached tidewater in the early 20th century and during the Little Ice Age, relative to the last half century or so, would have resulted in mass loss through iceberg calving as well as by surface melting. Given that glacier retreat appears to have been greater since 1958–1961 than in the period from the Neoglacial maximum (Table 2), this also implies that the rate of melt-driven retreat has increased over the last half century or so relative to that between the Neoglacial and 1958–1961.

We have also reconstructed the snowline elevation for a single snapshot close to the end of the 2000–2001 balance year (Fig. 4). Mass balance data from the Devon Ice Cap acquired since 1961 show the 2000–2001 balance year to be unusually negative, with net mass balance outside the data set's standard deviation for the strongly negative years from 1998 to 2001 (R. M. Koerner, personal communication, 2006). Studies over the last 40 years or so in the Canadian High Arctic also show that precipitation has relatively low interannual variability (Koerner, 1979). Thus, the mass balance is driven mainly by summer melting. However, mean summer temperatures from Pond Inlet (Fig. 1), the nearest weather station to Bylot Island, do not show 2001 to be significantly warmer than either the interval from 1922 to 2005, for which we have complete summer temperature data from only 50 of the 84 years, or from the 1998 to 2001 interval during which there were high values of negative mass balance from the northwest Devon Island Ice Cap. This further illustrates the difficulties in extrapolating temperature and/or mass balance records over even relatively small geographical areas and emphasizes the need for a finer spatial coverage of data to be collected and archived so that more reliable interpretations can be made in the future.

## Conclusions

- In 2001, ice covered 4783 $km^2$ or 43% of Bylot Island, located at 73°N in the Canadian Arctic archipelago (Fig. 1). The glaciers lost 5% or 253 $km^2$ of their area over the period from 1958/1961 to 2001.
- Ten glaciers on Bylot Island, located in Figure 1, are identified to be of possible surge-type, based primarily on deformation structures observed on satellite imagery.
- The regional snowline on Bylot Island ranged from over 1000 m to under 700 m just before the end of the balance year in 2001 (Fig. 4). The lowest elevations occurred along the east-northeastern coast, probably reflecting the north-easterly moisture source of Baffin Bay.
- The majority of glaciers on Bylot Island show evidence of retreat from their Neoglacial maximum positions approximately 120 years ago (Fig. 5). More than twice as much area was lost from the mid-20th century to 2001 than over the interval from the Neoglacial maximum to the mid-20th century for the non-calving glaciers measured (Table 2). Retreat rates were also highest from the mid-20th century to 2001, varying from roughly three to nine times that of the earlier period.
- The measured amount and rate of deglaciation on Bylot Island is consistent with the observed increase in climate warming in many parts of the Canadian Arctic since the 1960s in particular.

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