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Past and Present Glaciological Responses to Climate in Eastern Baffin Island

J. T. ANDREWS,[1] R. G. BARRY,[2] R. S. BRADLEY,[2] G. H. MILLER[1] AND L. D. WILLIAMS[1]

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Much of Baffin Island is close to the modern glaciation limit and climatic changes within the last decade are already being reflected in snow cover extent. Statistical analysis of glacierized and ice-free corries indicates that changes in direct solar radiation due to astronomical factors are inadequate to account for glacierization of those at present ice-free. These and other sources of evidence demonstrate the need for augmented winter snowfall in order to increase the extent of glacierization. The pattern of glacial history in this area is for maximum ice extent during the early glacial phase (>68,000, <137,000 BP), followed by a reduction in ice volume during the cold pleniglacial (>24,000, <68,000 BP) and then a limited late glacial advance (the Cockburn Stade, ca. 8,000 BP) due to increased precipitation. The Barnes Ice Cap did not disappear in the Holocene as it did in the last interglacial. The area is highly suitable for long-term monitoring of climatic change and glacial response.

INTRODUCTION

> The point I wish chiefly to make is that the climatic conditions of Baffin Island and Labrador are wonderfully near those which produce glaciation.
>
> (Tarr, 1897, p. 320)

In determining when the present interglacial might end we must consider where and how the next glaciation could start. This paper summarizes the findings of our researchs in eastern Baffin Island (Fig. 1) since 1968, building on previous work in the eastern Canadian Arctic and sub-Arctic since the mid-1950s.

Ives (1957, 1958, 1960) showed that Flint's concept of initial mountain glaciation in Labrador and eastern Baffin Island, followed by westward transfer of ice mass leading to the growth of the Laurentide Ice Sheet (Flint, 1943, 1971, p. 482), is not supported by the field evidence. Instead, Ives proposed that the Laurentide ice developed on the upland plateaus of Labrador–Ungava by a lowering of the regional snowline. Of the three accumulation zones of the Laurentide Ice Sheet (Baffin Island, Labrador–Ungava and Keewatin), only Baffin Island is significantly glacierized at present. Elsewhere snowline is high and the growth of an ice sheet presents a climatological problem (Loewe, 1971; Brinkmann and Barry, 1972). The broad interior plateaus of Baffin Island, at elevations of about 600 m, and their dissected eastern rim which fronts Baffin Bay and Davis Strait (Fig. 2) lie close to, and in some areas above, the present glaciation limit (Andrews and Miller, 1972). About 300 y. a. large areas of Baffin Island were covered by thin perma-

[1,2] Institute of Arctic and Alpine Research and Departments of Geological Sciences[1] and Geography,[2] University of Colorado, Boulder, Colorado 80302.

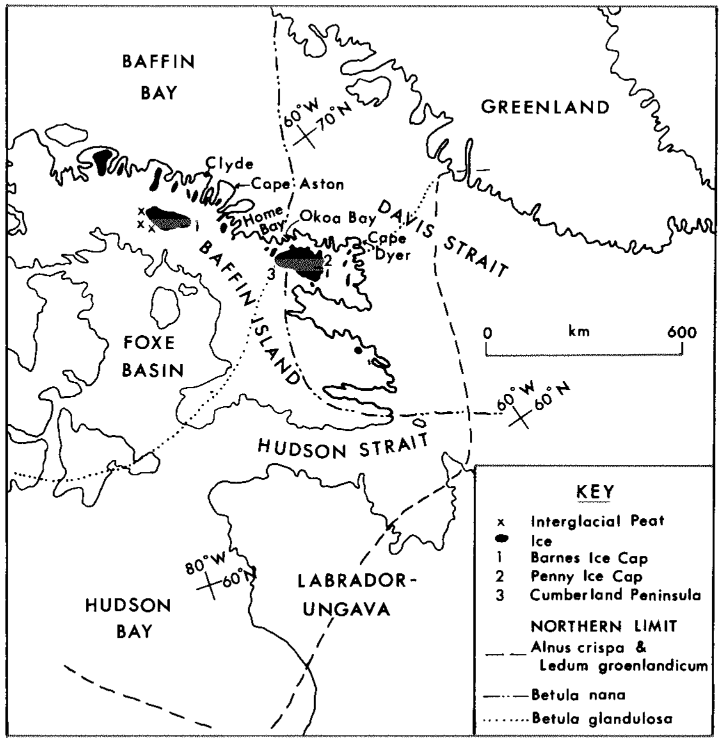

FIG. 1. Location map of Baffin Island showing areas mentioned in the text and the present northern limits of certain shrub/plant species found in the interglacial beds around the Barnes Ice Cap.

nent ice (Ives, 1962; Falconer, 1966). Baffin Island is thus a critical area in which to monitor glaciological and climatological changes. The processes that are involved may be taking the world toward the next full glaciation. Accordingly the glacial chronology and related climatic changes of the island over the last 120,000 yr are of global significance.

This paper summarizes: (1) the climate of the last interglacial; (2) the timing and extent of stades during the last glaciation [3]; (3) the characteristics of glacierized and ice-free corries on Cumberland Peninsula in relation to present and past snowlines and solar radiation; and (4) recent changes evidenced by an increase in the number of snowbeds during the last decade and by climatological data.

THE LAST INTERGLACIAL

Interglacial peats occur around and beneath the Barnes Ice Cap (Fig. 1). The main deposit in the Isortoq Valley was folded by ice moving westward. The presence of macrofossils of *Betula nana,* sensu lato, *Ledum groenlandicum,* and a local source for *Alnus* (probably *Alnus crispa*) pollen, were interpreted (Terasmae *et al.,* 1966, p. 316) to indicate a July temperature 1–4°C warmer than present, more precipitation, and a 20–25-day longer growing season. The ecology of the fossil materials suggest a modern analogy with conditions 400–600 km south of the Barnes Ice Cap, in southern Baffin Island or northern Labra-

[3] As the Barnes Ice Cap and Penny Ice Caps did not disappear during the Holocene it would appear that this area can be defined, technically, as still experiencing the Wisconsin Glaciation.

FIG. 2. Oblique air photograph (T220 L-20, Copyright, Govt. Canada) looking east over local icefields and glaciers toward Broughton Island (67°30′N and 64°00′W) off the east coast of Baffin Island. This illustrates the extent of ice during the early stade of the last glaciation (EG), the middle stade (MG), the late stade probably about 8000 BP (LG) and the Neoglacial moraines (NG). The broad massive hills (S) show the characteristic light tone denoting an absence of lichens indicating that these summits have carried a thin permanent ice/snow cover in the recent past. The 1500–2000-m mountains near Cape Dyer are visible at the extreme upper right. Corrie glaciers are evident in the middle foreground.

dor. The small amounts of *Pinus* and *Picea* pollen indicate that the area was north of the treeline. Some of the fossil plants are not found on Baffin Island today (Fig. 1), and they did not succeed in migrating there during the Holocene warm interval. The Barnes Ice Cap, and probably many of the mountain ice caps and glaciers, did not survive the last interglacial (the Flitaway). If similar conditions prevailed in other polar areas then world sea level should have been higher than present.

A date on these interglacial materials would have worldwide importance as they occur so close to one of the Laurentide Ice Sheet's main accumulation areas. ^{14}C dating

is not useful although dates of >40,000 BP have been obtained (Terasmae *et al.,* 1966). The possibility of dating the material by uranium series methods is being investigated.

THE LAST GLACIATION: CHRONOLOGY AND EXTENT

The concept of the complete inundation of the eastern Canadian Arctic by ice of the last glaciation has been much debated (e.g., Ives, 1963). Ives (1957, 1958) recognized three altitudinal zonations in weathering of the surficial materials in the Torngat Mountains but the ages of these deposits were unknown. In Baffin Island, Løken (1966) reported ^{14}C ages > 54,000 on marine shells from a high marine delta at Cape Aston (Fig. 1) at 80 m a.s.l. and suggested that extensive ice-free areas existed during the earliest Wisconsin. A bedrock knoll rising above the delta had weathering characteristics similar to the middle zone (Koroksoak Glaciation) of the Labrador coast (Ives, 1957; Løken, 1962) indicating the weathering was probably pre-Wisconsin in age.

Pheasant (1972) and Pheasant and Andrews (1972) studied the glacial and raised marine sequences in northern Cumberland Peninsula (Figs. 1 and 2). A radiometric date on marine molluscs, collected within permafrost from the highest marine unit overlain by till on the outer coast of Narpaing Fiord (68°07′N and 65°05′W), is 137,000 ± 10,000 BP (B. Szabo, U.S.G.S., Denver pers. comm., 1971).[4] The shells are thick aragonite specimens with no evidence of calcite by X-ray diffraction analysis. The $\delta^{13}C$ and $\delta^{18}O$ analyses of *Mya truncata* specimens gave consistent positive values, whereas samples from Holocene sediments had negative values. We attribute this to differences in salinity related to variations in the input of glacial meltwater. The impoverished fauna of the marine unit and the isotope results suggest a cold saline sea. The lateral and end moraines of this early, last glacial stade lie at the contact between a relatively unweathered till and the middle zone of weathered till. Relative sea level was 70–80 m a.s.l. (Fig. 3). The stratigraphic sequence is similar to that reported 300 km to the north by Løken (1966) and Feyling-Hanssen (1967) where a marine unit overlain by till has a radiocarbon age >50,000 BP and a $^{230}T/^{234}U$ age ⩾ 115,000 BP (Løken, pers. comm., 1971). The data add support to the chronology of Fig. 3 although further stratigraphic and dating control is required.

Deglaciation followed this early advance. All ^{14}C dates from associated marine deposits are > 29,000 BP. A high delta in mid-Quajon Fiord (67°45′N and 65°08′W) contains shells pushed up during a later readvance. The shells include warm water indicators such as *Chlamys islandicus* (Andrews, 1972) and $\delta^{13}C$ and $\delta^{18}O$ content of *Mya truncata* are comparable with postglacial values from the same area. A date of 68,000 ± 5000 BP has been obtained from the sample (B. Szabo, U.S.G.S., Denver, pers. comm., 1970).

Mid-Wisconsin readvances and/or periods of relative crustal stability are indicated by major delta and terrace levels on the outer coast at 25 m and 15 m. A date of 40,000 ± 1740 BP (GSC 796) has been reported on a probable equivalent of the higher terrace and the lower feature is dated at between 24,000 and 32,000 BP (England and Andrews, submitted).

No ^{14}C dates have been collected in eastern Baffin Island betwen 10,500 and 24,000 BP despite the presence of ice-free coasts. There is a remarkable increase in ^{14}C dates associated with a major moraine system and deltas dated between 8500 and 7500 BP (Andrews and Ives, 1972). The moraine system, the Cockburn Moraine (Falconer

[4] A detailed study of the dates on "old" marine shells is being prepared by Szabo, Hare and Andrews using uranium series, amino acid, radiocarbon and stratigraphic methods.

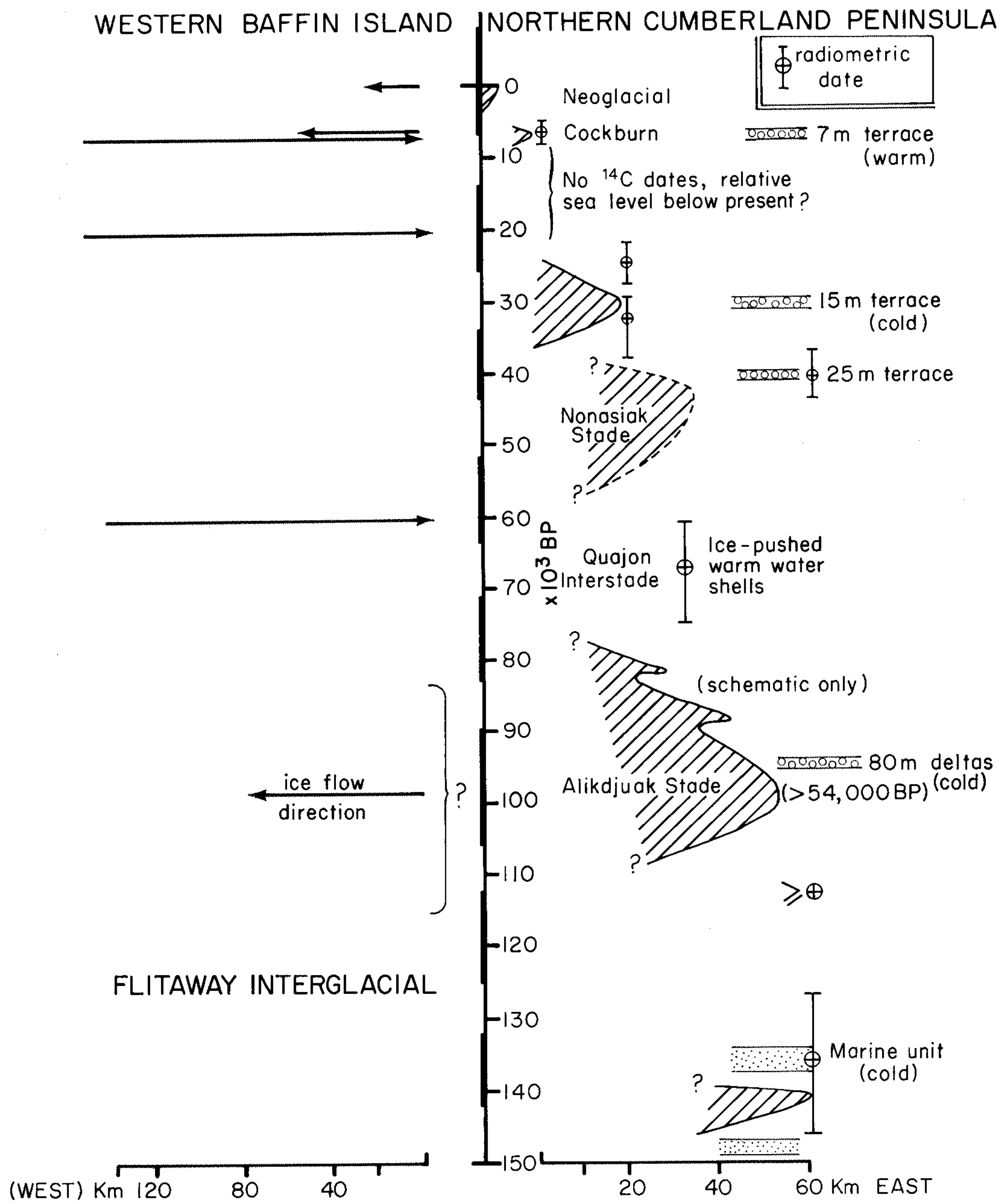

FIG. 3. Time/distance diagrams for eastern and western Baffin Island showing ice extent, flow direction, glacial stades and marine terraces of the last glaciation. The point of origin for the western section is the location of the Barnes Ice Cap.

et al., 1965), is correlated along 1200 km of coast by similar radiometric dates and by the pattern of isostatic uplift. A correlative event occurred in Greenland (Weidick, 1972; Ten Brink, 1972). In Baffin Island, the Cockburn Moraine marks the maximum

late glacial expansion of the northeastern Laurentide ice, and a similar argument may apply to the Greenland record. This readvance was probably associated with the opening of Baffin Bay and Davis Strait and the consequent increase in cyclogenesis causing increased solid precipitation in the early Holocene.

Deglaciation of fiord heads in Baffin Island was not complete until 5000 BP. The brief period of the "thermal maximum" is marked by the melting of ice-cored moraines of local glaciers, whereas the succeeding Neoglacial advances are marked by large ice-cored moraines, the oldest of which indicate an initial advance between 3000 and 4000 BP. The Penny Ice Cap is now very close to its size about 6000 BP.

The general pattern of events on west and east Baffin Island is illustrated in Fig. 3. The pattern of an early stade significantly more extensive than later stades is repeated in many Arctic glacial chronologies (for review see Andrews, *in press*). This observation suggests that the initial glaciation of arctic areas occurred during relatively warm periods possibly related to increased winter cyclonic activity (Bradley and Miller, 1972, and this paper). With increased climatic severity, precipitation would diminish in high latitudes and glaciers would be reduced in size. At the same time, over-all cooling would promote a southward migration of the main Laurentide accumulation centers. In our view, the glaciation of arctic areas must rely primarily on an increase in solid precipitation. In Baffin Island this could result from advection along the limb of the trough over Baffin Island due to an intensification of the meridional circulation. This would probably be associated with an overall decrease in the zonal index (cf. Barry, 1966; Brinkmann and Barry, 1972). At the present time approximately half of the autumn and winter snowfall in the Cumberland Peninsula area occurs with depressions located in Davis Strait–Baffin Bay and these account for most of the heavy snowfalls in autumn (Andrews *et al.*, 1970; Barry, 1972).

CORRIES AS INDICATORS OF CLIMATIC CHANGE

Whatever the cause of a change from interglacial to glacial climate, the sites which are favored for snow drifting and where the duration of snowmelt is limited, must be glacierized early in the glacial cycle. In Cumberland Peninsula, Baffin Island, such sites are provided by corries (Fig. 2). In the area between Okoa Bay and Cape Dyer 493 corries have been identified on aerial photographs. For each corrie, clear-sky direct solar radiation incident upon the base of the backwall on a day well into the ablation season was computed (Williams *et al.*, 1972) using the method of Garnier and Ohmura (1968). Analysis of the distribution of corries permits an assessment of topoclimatic conditions (Table 1) related to corrie glacidrews, 1972) and $\delta^{13}C$ and $\delta^{18}O$ contents of ation (Williams, 1972).

Figure 4 shows sections for the area (hereinafter referred to as the Cape Dyer area) of the Cape Dyer and Padloping Is-

TABLE 1

MEAN VALUES FOR ELEVATION OF CORRIE BACKWALLS (METERS) AND DIRECT RADIATION (cal cm^{-2} dy^{-1}) FOR AUGUST 15TH FALLING ON THIS POINT

	Cape Dyer/Padloping map sheets		
	Glacierized	Partly glacierized	Empty
Elevation (m)	964	870	652
Direct radiation	144	190	240
Number of corries	177	45	65
	Okoa Bay map sheet		
Elevation (m)	1014	839	773
Direct radiation	122	171	240
Number of corries	64	36	96

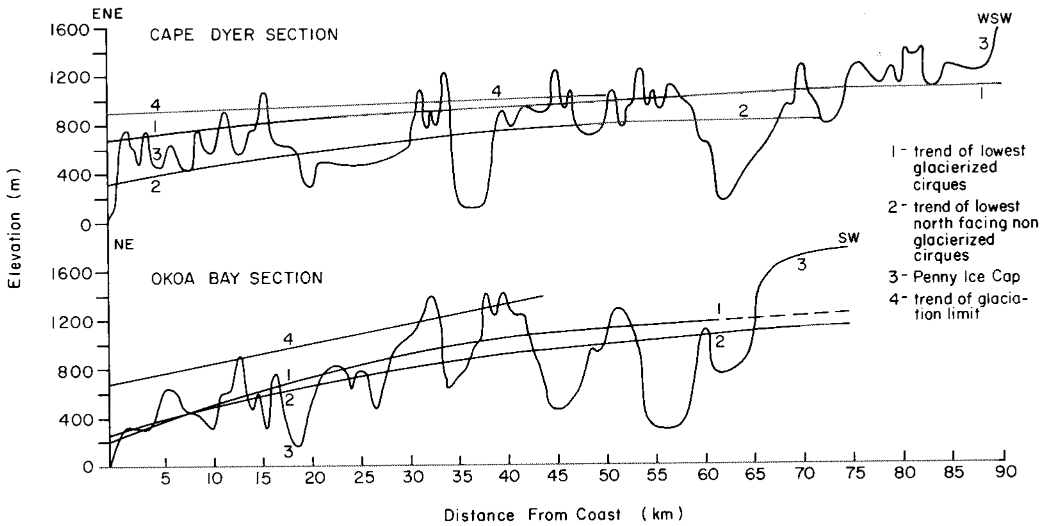

FIG. 4. Cross sections normal to the coast for the Cape Dyer region and Okoa Bay region. Each section shows (1) trend of the lowest presently glacerized corries; (2) trend surface of the lowest nonglacierized corries with same orientation range as (1); (3) Penny Ice Cap; and (4) Glaciation Limit (from Andrews and Miller, 1972).

land maps and for the area of the Okoa Bay map.

Trend surfaces of corrie floor elevations have been used before to estimate the paleosnowline (e.g., Robinson *et al.,* 1971). In accord with Flint (1971, p. 68) only the lowest corries of generally northern aspect were used for the trends. With the exception of the Cape Dyer glacierized corries, the trend surfaces fit the data very well. Coefficients of determination are (with number of corries in parentheses): Cape Dyer glacierized (85) 0.37, Okoa Bay glacierized (38) 0.65, Cape Dyer nonglacierized (23) 0.83, and Okoa Bay nonglacierized (27) 0.83.

In both areas the trend surfaces of modern and Pleistocene snowlines lie close together (Fig. 4) especially when compared with other areas. Flint (1971, p. 71) for example, cites differences ranging from 650 m to 1500 m whereas the differences in trend surfaces are 200–300 m in the Cape Dyer area and 0–200 m in the Okoa Bay area. In the much more heavily glacierized Cape Dyer area, maximum corrie glacierization would be attained by a uniform lowering of the snowline. In the Okoa Bay area, however, modern and paleosnowlines are virtually coincident (the accuracy of the trend surfaces is reliably estimated as ± 50 m). This means that at a given location there is a very narrow range of elevation within which north-facing corries are ordinarily ice-free today. In contrast, there are many south-facing corries with a wide-range of elevation which do not support glaciers. Optimum corrie glacierization in the Okoa Bay area must be visualized, therefore, in terms of conditions which would allow ice to exist in south-facing corries, with little lowering of the snowline. This requires a decrease in the relative influence of direct solar radiation upon glacierization, which cannot be accomplished by lower temperatures alone (Williams, 1972, p. 83); increased snowfall would be more crucial.

It is also necessary to consider the degree of glacierization produced by a decrease in incoming solar radiation. The ideas of Mi-

lankovitch (1969), that glaciation would be facilitated by the reduction in solar radiation receipts at different latitudes due to changes in the earth-orbital parameters, have been much discussed. Recent computations of the effects of such changes (e.g., Shaw and Donn, 1968; Sellers, 1970) indicate that the change in temperature is too small to account for glacial ages. However, in a region such as the Cumberland Peninsula, which is balanced on the threshold of optimum corrie glacierization, the effect of changes in solar radiation alone might have a marked influence on corrie glacierization. The greatest *decreases* in incident solar radiation at 65°N which might be related to the glaciation of Narpaing Fiord (dated between 68,000 ± 5000 BP and 137,000 ± 10,000 BP, in this paper) are those at 72,000 and 116,000 BP (Vernekar, 1972, p. 19).

Summer solstice direct radiation was computed for the Okoa Bay cirques at 0, 72,000, and 116,000 BP.[5] The corries were classified as fully glacierized, partly glacierized, or empty, and on the basis of corrie elevation and present-day summer solstice direct radiation, discriminant functions were computed to give the best predicted classifications into these three groups (see Dixon, 1970, p. 214a). The corries were then classified by these discriminant functions using the values of summer solstice direct radiation for 72,000 and 116,000 BP (Table 2). The changes in predicted glacierization were similar for both times and the amount of induced glacierization was minor; of 91/132 corries correctly classified with respect to present conditions only 15% were predicted to change either from nonglacierized to partly glacierized, or from partly to fully glacierized at 116,000 BP. Considering the nonglacierized and partly glacierized cirques in a single category, 118 of the 132 would be correctly classified by the discriminant functions today, and of these only three would be predicted to have been fully glacierized at 116,000 BP from the change in direct radiation alone. Comparable minor shifts were also calculated for deglacierization at the radiation maxima.

[5] The tables of Milankovitch (1969, p. 258) have been used in these calculations. The revised tabulations of Vernekar (1972) only became available after completion of this work. While the extremes are slightly greater than those of Milankovitch, the differences will not significantly change our conclusions.

GLACIATION LIMIT AND CLIMATIC TRENDS

The sensitivity of Baffin Island to small climatic fluctuations is readily apparent. Ives (1962) showed that whereas 2% of the north-central plateau region is presently glacierized, ca. 70% of the land surface was under thin permanent ice or snow in the recent past. Lichen trimlines are found throughout Baffin Island showing that the

TABLE 2

MEAN VALUES OF ELEVATION OF BASES OF CORRIE BACKWALLS (METERS) AND SUMMER SOLSTICE DIRECT RADIATION (cal cm^{-2} dy^{-1}) FALLING ON THESE POINTS TODAY, AND AT 116,000 BP

	Glacierized	Partly glacierized	Empty
Cape Dyer map sheet			
Elevation (m)	964	870	652
Direct radiation today	266	316	364
Direct radiation 116,000 BP	244	292	340
Number of corries	177	45	75
Okoa Bay map sheet			
Elevation (m)	1014	839	773
Direct radiation today	259	306	372
Direct radiation 116,000 BP	235	281	346
Number of corries	64	36	96

climatic deterioration of the 16th–19th centuries had pronounced effects on the dimensions of the ice bodies (see Fig. 2).

In the absence of an adequate number of climatic recording stations, the best possible means for estimating regional snowline and its relationship to the land surface, is by an analysis of the regional glaciation limit (Østrem, 1966; Weidick, 1968; Andrews and Miller, 1972). Such maps do not, necessarily, represent present climatic conditions, due to the lag response of glaciers to climate. If the limit is determined from large ice bodies, a climate of 50–200 yr previous is represented, whereas the limit based on small ice caps may reflect more recent climatic conditions.

Over north-central Baffin Island determinations of the glaciation limit are based exclusively on small ice bodies mantling locally high hill summits. The region is a rolling upland plateau with an elevation range of 400–700 m a.s.l., and a present glaciation limit of 700–900 m a.s.l. Lowering the glaciation limit by 200–300 m would put a significant portion of the land surface *above* the regional snowline, leading to significantly increased glacierization.

Climatic data show that wide fluctuations in seasonal mean temperatures and total precipitation amounts have occurred over the period of instrumental record (50–60 yr). One of the most remarkable features is the climatic fluctuation which began at the end of the 1950s (see Fig. 5). Mean summer temperatures have declined throughout the 1960s to a level cooler than for approximately 40 yr. An analysis of airflow types for July and August, using a catalog of synoptic types for the area (Barry, 1972), indicates that the recent summer cooling is related to a higher frequency of easterly and northeasterly airflow types and a concurrent decrease in the frequency of westerly and southwesterly airflow types. At the same time winter temperatures have risen, accompanied by markedly increased precipitation

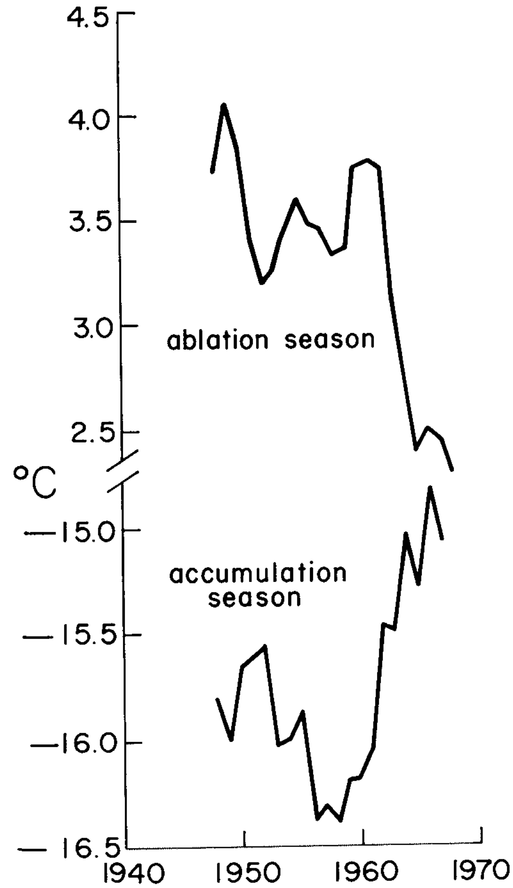

FIG. 5. Five year weighted binomial running mean temperatures from Clyde (Fig. 1), Baffin Island for accumulation season (September to May) and ablation season (June to August) for 1946–1970.

(Bradley and Miller, 1972). On a regional basis, winter precipitation has increased by more than 30% over the last 10 yr. Both the winter-warming trend and the increased precipitation are presumably related to a change in the frequency of southerly airflow types advecting warm moist air into the region. The net effect has been for heavier falls of snow in winter with lower summer temperatures and therefore less melting (Jacobs *et al.*, 1972), resulting in notably increased glacierization.

Recent field observations and comparisons

with aerial photographs taken late in the ablation seasons of 1949 and 1960 provide verification of a recent climatic deterioration. Snowbanks decreased from 1949 to 1960 and expanded during the next 10 yr. In one case, a permanent snowbed overlay 25 mm thalli of the lichen *Alectoria minuscula* which indicates a seasonally snowfree surface for the previous 40 ± 10 years. Additionally, at least two corries snowfree in 1960, are presently occupied by incipient glaciers.

These results suggest that for a large build-up of snow and ice to occur in the area, and in the high Arctic in general, the mean annual (and particularly mean winter temperatures) must be relatively warm, not cold as has been suggested by a number of workers (Dansgaard *et al.,* 1971; Von Klebelsberg, 1948; Loewe, 1971).

DISCUSSIONS AND CONCLUSIONS

Our findings reaffirm Tarr's (1897) assessment of the proximity of Baffin Island to full-scale glaciation. The modern glaciation limit is close to much of the land surface. The evidence strongly suggests that glaciation of Baffin Island will herald the next glaciation in North America although the timing of such a development is unknown. The climatic glacial mode may develop rapidly, but there is a lag of the order of 10^4 years in the subsequent build-up of a continental ice sheet (see Weertman, 1964; Barry, 1966; Bryson and Wendland, 1967; Barry *et al.,* 1971). The recent climatic fluctuations in the area are on too short a timescale to be viewed with alarm. The main control on glacierization in eastern Baffin Island is snowfall, not temperature. Moreover, changes in direct solar radiation due to astronomical factors are inadequate to explain the changes in corrie glaciation. The analytical methods employed here present a test of the Milankovitch ideas at a critical latitude with field data.

Baffin Island, particularly the eastern coast, reacts to climatic change during a glacial phase by (1) developing a first ice center, (2) reducing ice volume as the world enters a full glacial mode with consequent reduction in temperature and hence precipitation, and (3) showing a late glacial ice advance (such as the Cockburn Stade at 8000 BP) due to increased precipitation probably associated with more open water in the Davis Strait area and an increased tendency for northward movement of depressions. The present Neoglacial ice is nearly as extensive as the late glacial stade (Figs. 2 and 3). During the last interglacial the Barnes Ice Cap disappeared, which it has not done during the Holocene. Sea level should have been higher than present if conditions were similar in other polar regions. Based on a comparison of the crustal deflection at the margin of the ice load during late and early glacial time, it seems that the Alikdjuak Stade, early last glaciation, occurred when world sea level was close to present.

The results of our investigations show that Baffin Island is highly suitable for longterm climatic monitoring and continued intensive study as a guide to past, present and future environmental changes. The value of a multifaceted interdisciplinary research program in problems of palaeoclimatology and Quaternary studies is amply demonstrated.

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