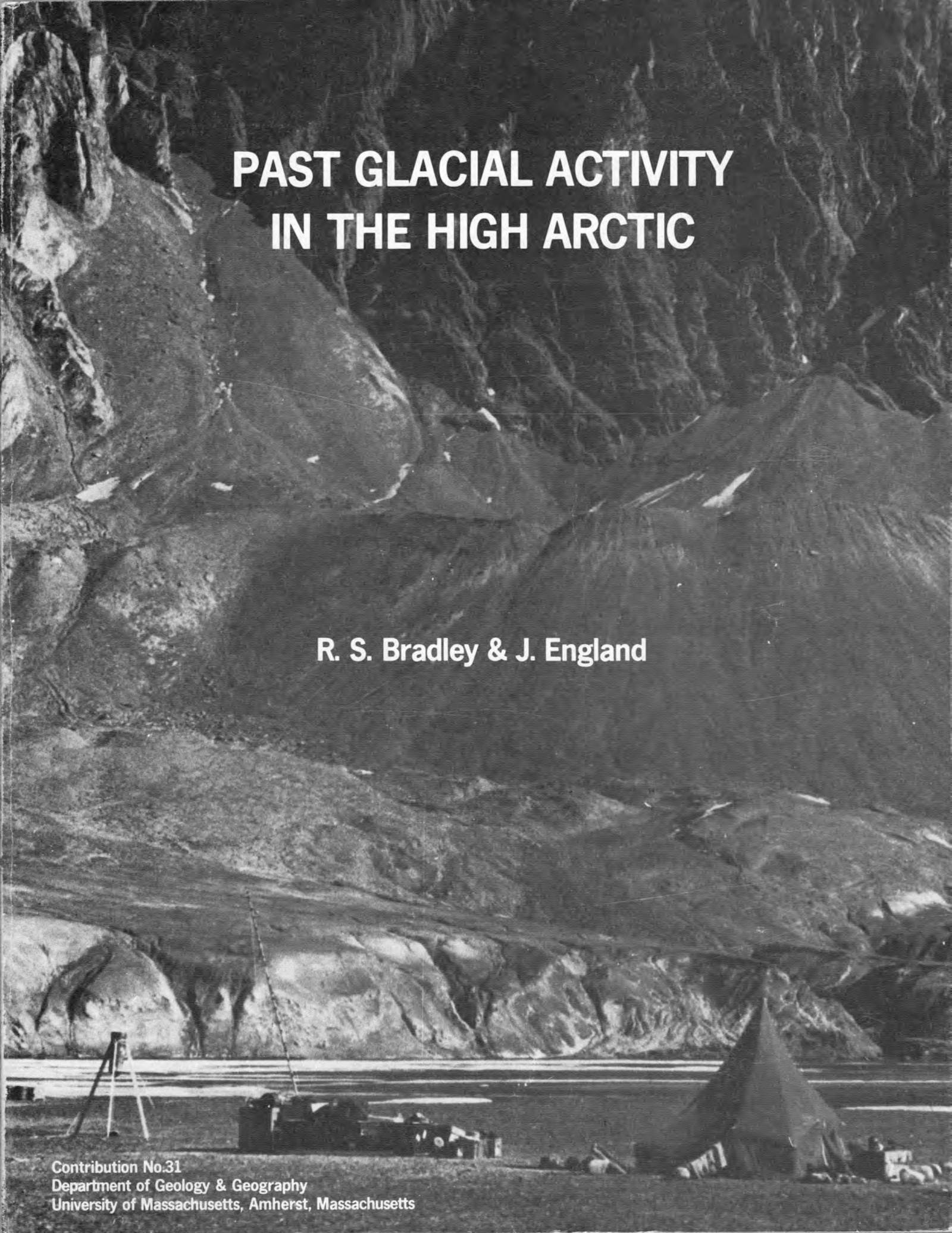

PAST GLACIAL ACTIVITY IN THE HIGH ARCTIC

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Contribution No.31
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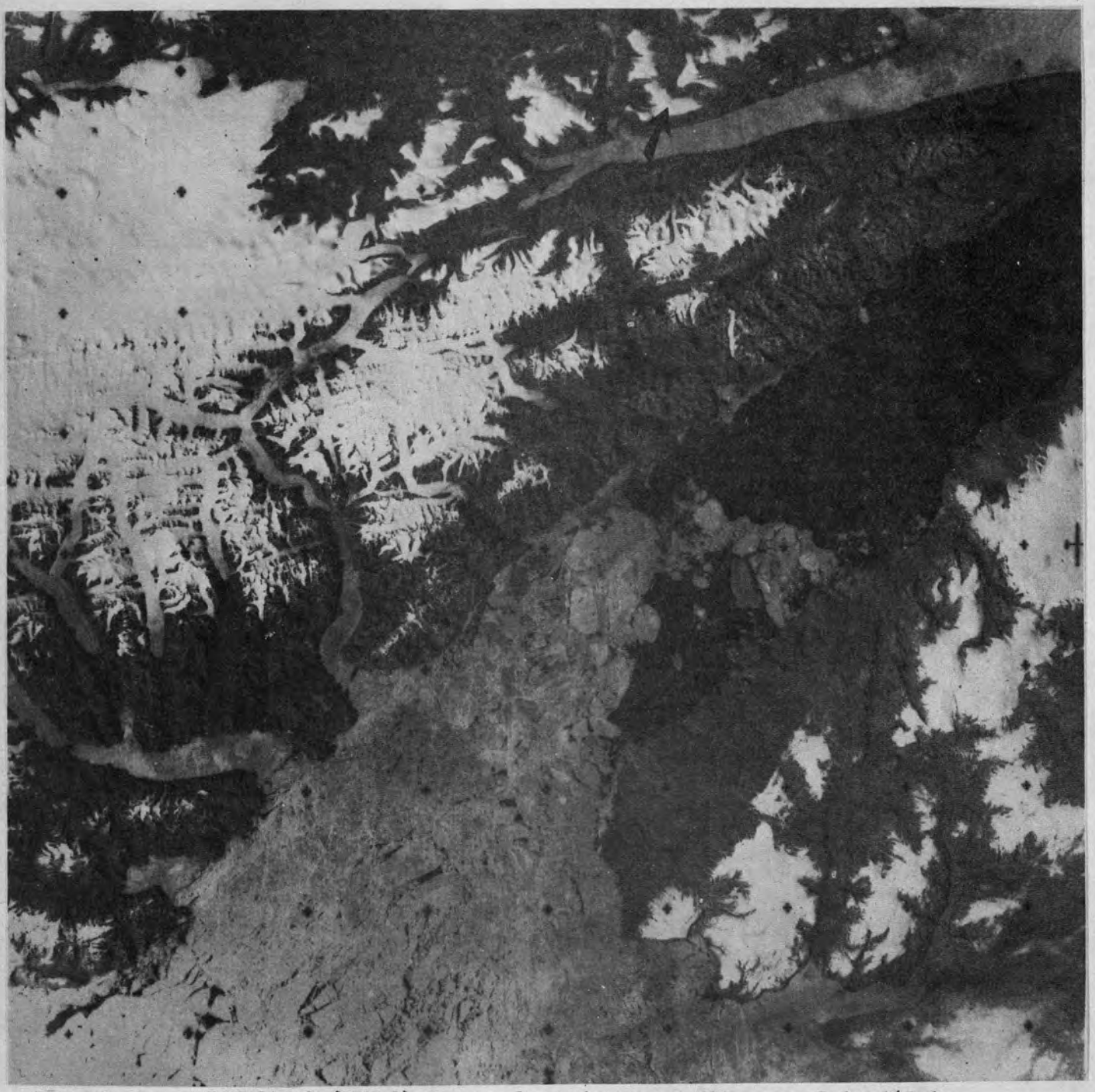

Frontispiece. LANDSAT 2 (RBV-2) image of northeastern Ellesmere Island(Judge Daly Promontory) and northwestern Greenland, taken on July 25,1976 from an altitude of 931 km. Loose pack-ice chokes Kennedy Channel to the south; land areas are generally snow-free and ice caps and glaciers are clearly delineated. The Mer de Glace Agassiz is seen at upper left. Simmonds Ice Cap is marked by an arrow. Center of image: 80°39'N,68°50'W. Scale,1:3,369,000. National Aeronautics and Space Administration image 8-2550-18474-2-01.

CONTENTS

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SUMMARY

Research has focused on two principal time scales:

A) Late Quaternary (>80,000-3,000 B.P.) and (B) Recent (>1750 to present).

A. LATE QUATERNARY EVENTS (Chapters 1 and 2)

1) The maximum extent of Greenland ice along easternmost Judge Daly Promontory and the Hazen Plateau is marked by a zone of crystalline erratics deposited >30,000 B.P. (based on ^{14}C dates) and possibly >80,000 B.P. (based on amino acid age estimates).

2) The maximum advance of the Greenland Ice Sheet extended only 100km beyond its present margin and several mountain summits on eastern Ellesmere Island remained ice-free at this time.

3) Subsequent to this, the outermost Ellesmere Island ice advance cross-cut the zone of Greenland erratics at lower elevations. This Ellesmere Island ice advance was characterized by thin, topographically-controlled ice lobes which formed ice shelves where they entered isostatically-depressed embayments along western Kennedy Channel.

4) Relative sea level at the time of ice shelf formation was ∿175 m a. s. l. Associated fossiliferous proglacial terraces have provided ^{14}C dates indicating initial ice recession ∿28,000-30,000 B.P. whereas amino acid age estimates on the same samples indicate ages >35,000 B.P.

5) Ice recession at 28,000-30,000 B.P. occurred at a time of low solar radiation receipts when the Laurentide Ice Sheet to the south was increasing in size. This ice sheet acted as a topographic barrier restricting the advection of moist air into the arctic archipelago and resulting in starvation of ice bodies to the north.

6) Subsequent to the outermost Ellesmere Island glaciation there was a limited advance of late Wisconsin ice marked by the Hazen Moraines formed ∿8100 B.P.

7) The N.W. Greenland Ice Sheet terminated in Hall Basin during the late Wisconsin and recession began ∿8400 B.P.

8) Between these late Wisconsin Greenland and Ellesmere Island ice margins there existed a ∿100 km wide ice-free corridor.

9) This ice-free corridor experienced synchronous postglacial emergence ∿8100-8400 B.P. and the pattern of displacement clearly indicates the glacio-isostatic dominance of the N.W. Greenland ice load over the adjacent N.E. Ellesmere Island coastline.

10) Following maximum postglacial ice recession there was a late Holocene readvance (possibly initiated ∿3000-4000 B.P.) which has resulted in present glacier margins reaching their maximum postglacial extent.

B. RECENT EVENTS (Chapters 3 and 4)

1) An abrupt change in the summer climate of the Canadian High Arctic and northwestern Greenland occurred around 1963/64. No evidence for a return to pre-1963 conditions is apparent.

2) The change in climate involved: a lowering of mean July freezing level heights of up to 500m; a decrease in mean July maximum temperatures (at the surface) of up to 2.7°C; a marked decrease in annual melting degree day totals (down to as low as 65% of pre-1963 values); a concomitant increase in mean annual precipitation of up to 140% of pre-1963 levels. Conditions after 1963 thus favored reduced net mass losses on glaciers in the region.

3) Glacier mass balance is strongly controlled by summer climatic conditions; in particular, annual melting degree day totals are highly correlated with long-term mass balance records.

4) Reconstruction of glacier mass balance to 1947/48 emphasizes the significance of the climatic change since 1963. On the NW Devon Ice Cap cumulative mass loss from 1947/48 to 1962/63 is estimated to be $\sim$3500 kgm m^{-2}. However, from 1963/64 to 1973/74 a total of <350 kgm m^{-2} have been lost.

5) Significant ice cap growth is presently limited by low amounts of precipitation with the result that even during a period of cold summers and predominantly positive net balance, an occasional warm summer may obliterate cumulative mass gains over many years.

6) Ice caps above 1000m on the Hazen Plateau have registered net mass gains in recent years and formerly snow-free summits above 900m have had continuous snow cover in recent years.

7) The post-1963 change in summer climate was related to the massive increase of volcanic dust in the upper atmosphere (primarily as a result of the eruption of Mt. Agung).

8) Diffuse radiation receipts at Resolute reached record levels in 1964 and declined thereafter to $\sim$1969. Diffuse radiation at Resolute is inversely related to annual melting degree day totals which are in turn highly important for glacier mass balance. High dust loading thus corresponds to reduced mass losses on High Arctic glaciers and ice caps.

9) Other periods of high volcanic dust loads in the atmosphere (e.g. 1750-1880) probably experienced low ablation season temperatures; consequently glacier mass balance was probably positive during these periods. Conversely, the relatively dust-free period 1920-1963 was probably characterised by predominantly warm summers with more negative mass balance conditions.

10) An objective classification of synoptic weather types has been developed for the Canadian High Arctic for the period 1946-1974. 96.5% of days were grouped into 22 basic types.

11) Stepwise multiple regression analysis indicated those types which were closely related to inter-annual variations of monthly mean maximum temperatures. Maximum explained variance with a minimum number of variables was achieved in the months April-August.

12) Stratification of precipitation data by synoptic type indicates a small number of types are generally responsible for most of the annual precipitation at Alert and Isachsen, though these are not the most 'efficient' types (in terms of precipitation amounts in relation to type frequency)

13) At Isachsen seven relatively infrequent types account for 23% of annual precipitation. These are all situations in which depressions dominate the region and it is suggested that many of these are North Atlantic depressions regenerated along the Siberian coastline.

14) In warmer periods, northward displacement of North Atlantic depressions would result in increased frequency of these types and heavier precipitation in the High Arctic. Associated temperatures may be cool even though increased advection of southerly air is involved.

SECTION A: LATE QUATERNARY EVENTS

CHAPTER I

PAST GLACIAL ACTIVITY IN THE HIGH ARCTIC

INTRODUCTION

Northeastern Ellesmere Island and northwestern Greenland are separated by only 20-40 km along the lengths of Kennedy and Robeson channels (Fig. 1.1). In this area the present day United States Range and Agassiz ice caps on Ellesmere Island are but 150 km from the margin of the Greenland Ice Sheet. The intervening landscape along both coastlines is characterized by dissected plateaus and mountains of low to moderate elevation (300 - 1200 m a.s.l.). The proximity of Ellesmere Island to Greenland, combined with their moderate topographies, provides an ideal location for investigating the past interactions of their respective ice sheets. Recent fieldwork between these ice sheets has provided new information on past glacial activity in the region which is directly relevant to both palaeoclimatic and chronological interpreations of high latitude ice cores (Dansgaard et al., 1969; Paterson et al., 1977).

Early physiographic analysis of northern Ellesmere Island led to the hypothesis that the Greenland Ice Sheet had once overridden this landmass (Taylor, 1956). Subsequent field investigations in the United States Range showed that Ellesmere Island erratics extended near to these summits, therefore, the complete inundation of this area by the Greenland Ice Sheet was rejected (Smith, 1959). More substantive evidence for a limited Greenland ice advance onto northeastern Ellesmere Island was later indicated by the presence of granite and gneiss erratics along the eastern edge of the Hazen Plateau and Judge Daly Promontory (Christie, 1967). However, the advance of the Greenland Ice Sheet onto this area, as suggested by the presence of these granite and gneiss erratics, was considered uncertain since both the provenance and complete distribution of these erratics was not firmly established. As a

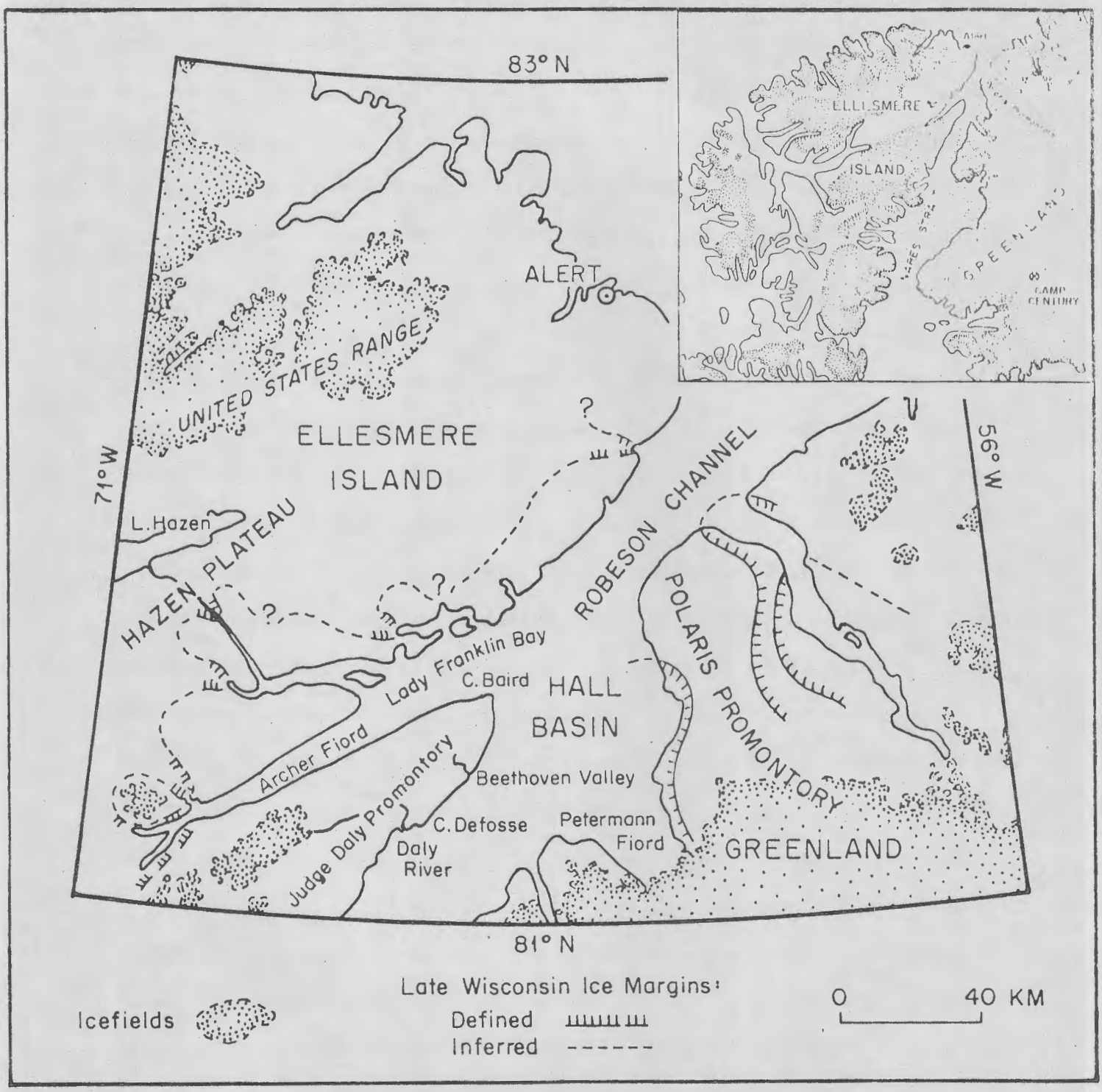

Figure 1.1 Location of study area and position of late Wisconsin ice margins.

result, it was suggested that a northern Ellesmere Island source be considered as a possible alternative to their deposition by the Greenland Ice Sheet (England, 1974a and b). It was concluded, however, that if the granite and gneiss erratics did originate on Greenland then the ice advance responsible for their deposition must predate the formation of the outermost Ellesmere Island moraines along western Kennedy Channel. These glacial features have not been disturbed by any subsequent ice advance and they are associated with an ice marginal terrace dated 27,950 ± 5400 B.P. (St 4325, England, 1974b).

In recent literature it has been generally assumed that the Greenland Ice Sheet was contiguous with an ice sheet over the Canadian Arctic islands during the last glaciation (Blake, 1970; Flint, 1971; CLIMAP Project Members, 1976). More specifically, it has been proposed that, from at least 59,000 B.P. to approximately 13,000 B.P., there was a substantial ice ridge over Nares Strait built up to a width of ca. 700-800 km between Knud Rasmussen Land (N.W. Greenland) and an ice sheet over the Queen Elizabeth Islands (Dansgaard et al., 1973; Fig. 1.1). The attitude of this ridge was estimated to be 2500 - 3000 m. Evidence in support of such an ice ridge is provided by the analysis of the total gas content from the Camp Century ice core which suggests that the northwestern Greenland Ice Sheet was ca. 1300 m thicker than today toward the <u>end</u> of the last glaciation (Raynaud and Laurius, 1973).

By contrast, however, several authors have cited stratigraphic evidence for a restricted ice cover over northwestern Greenland during the last glaciation (Davies et al., 1959, 1963; Bendix-Almgreen et al., 1967; Tedrow, 1970; Davies, 1972; Weidick, 1976). In general the outermost glacial deposits in this region are considered to predate the last glaciation based on associated 'old' radiometric dates, advanced rock weathering, and subdued moraine morphology (England, 1974b). On the other hand, the younger glacial deposits are considered to

occur closer to the present day ice margins. This is similar to conclusions reached on northeastern Ellesmere Island where a restricted late Wisconsin ice margin has been reported (England, 1974a and b). The results presented here relate directly to this question of late Wisconsin ice extent in the region and to the former existence of a Greenland/Ellesmere Island ice ridge.

MAXIMUM EXTENT OF NORTHWESTERN GREENLAND ICE SHEET

During 1975/76 the authors conducted fieldwork on Judge Daly Promontory, northeastern Ellesmere Island (Fig. 1.1). The area investigated occurs sixty km to the west of the Petermann Glacier which outlets from the Greenland Ice Sheet. Observations were designed to establish whether the Greenland Ice Sheet had advanced onto Ellesmere Island and, if so, to map the profile of its uppermost erratics and to date the oldest Ellesmere Island ice margin cross-cutting it.[1] The advantage of this field area is that the Ellesmere Island ice caps overlie, and hence transport, Phanerozoic sedimentary bedrock, whereas erratics from the Greenland Ice Sheet are derived, in part, from the crystalline basement of the interior Precambrian Shield.

A twenty km east to west transect was run from the western shore of Kennedy Channel into the interior of Judge Daly Promontory. Along this transect three mountain summits (ca. 1000 m a.s.l.) were ascended and the observed profile of uppermost crystalline erratics clearly confirms the extension of the Greenland Ice Sheet onto northeastern Ellesmere Island. Figure 1.2 shows the maximum extent and profile of Greenland erratics deposited across Judge Daly Promontory (England and Bradley, 1976, 1977a). This outermost zone of Greenland till is predominantly characterized by sparse granite, gneiss

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[1] It was assumed that the uppermost profile of the granite and gneiss erratics would reflect the direction of the former ice advance responsible for their deposition (i.e. a Greenland vs. Ellesmere Island source area).

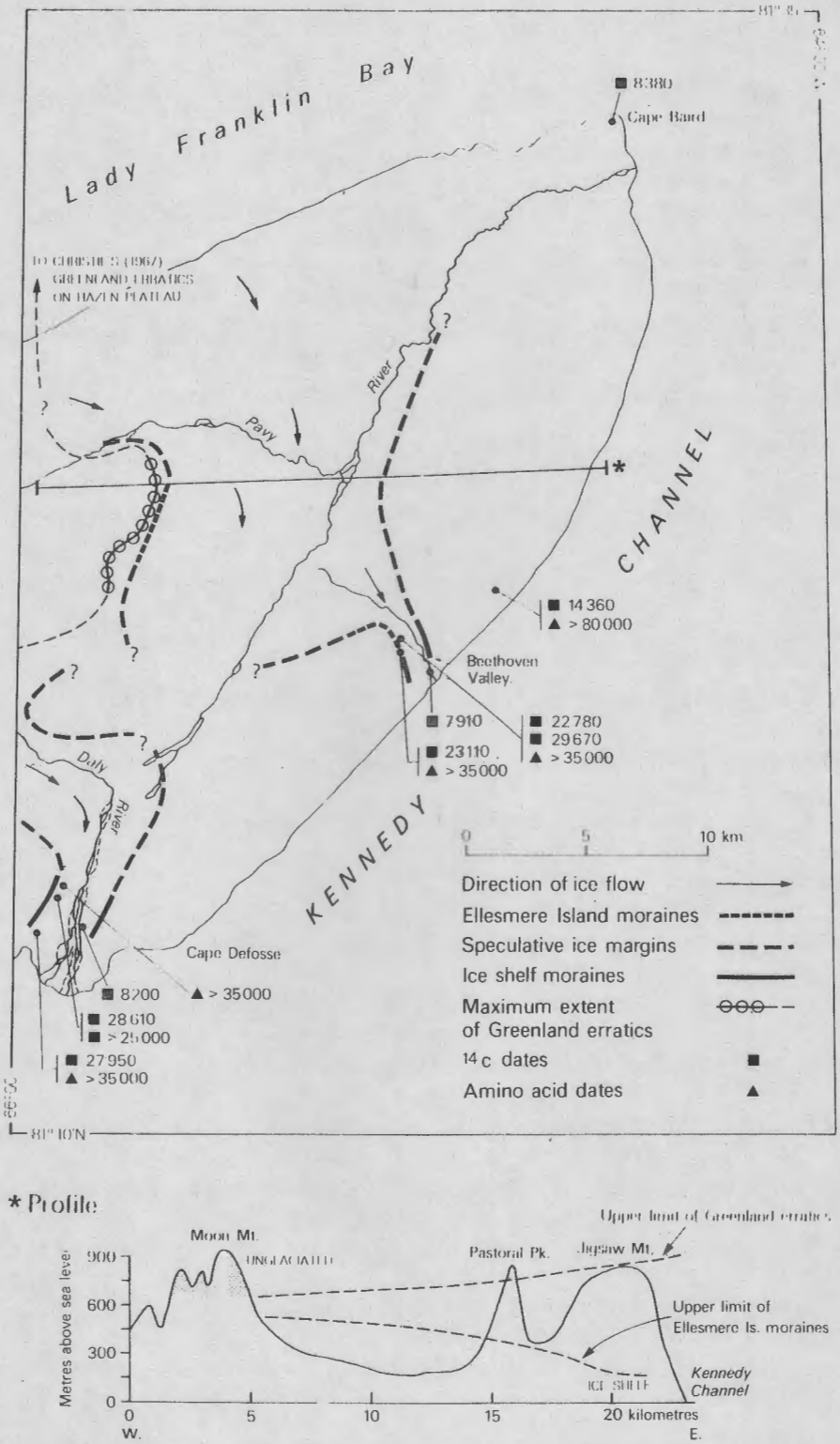

FIGURE 1.2 Judge Daly Promontory showing the maximum extent of Greenland till, outermost Ellesmere Island moraines and ice shelves, and location of ^{14}C and amino acid dates. Cross section shows profile of glacial deposits along transect marked by asterisk.

and quartzite erratics resting upon deeply weathered bedrock or embedded in its associated colluvium. The bedrock, predominantly Palaeozoic sandstones, is extensively oxidized and frost shattered to a depth of >1 m and tors of 1 to 3 m in height are abundant (Plates 1.1 and 1.2). Thick sheets of soliflucting colluvium, comprised of comminuted and oxidized bedrock chips, have engulfed many of the erratic blocks (Plate 1.3). In addition, on a mountain summit immediately above western Kennedy Channel, a mature felsenmeer (developed on sandstone bedrock) has entirely incorporated the sparse granite erratics which occur within the surface debris (Plate 1.4). Much of this bedrock weathering is considered to have occurred since the deposition of the Greenland erratics which, in turn, exhibit considerable frost shattering and granular disintegration (Plates 1.5 and 1.6). Such extensive weathering suggests that this former ice advance is of considerable antiquity and it parallels the advanced weathering noted on the outermost glacial deposits of Inglefield Land, northwestern Greenland, which were thought to correspond to the Greenland ice advance onto Ellesmere Island (Tedrow, 1970).

It is noteworthy that, within 70 km of the present day Petermann Glacier, the uppermost observable limit of the former Greenland Ice Sheet is only 600 m a.s.l. Taking into account the elevation of the adjacent valley bottom these uppermost erratics suggest a maximum Greenland ice thickness of 350 - 600 m in the interior of Judge Daly Promontory. On the mountain summits above these erratics (Fig. 1.2) periglacial rock weathering has progressed from bedrock through felsenmeer to coarse frost hummocks (Plate 1.7). It is concluded that this uppermost zone above the Greenland till has remained unglaciated, possibly throughout the Quaternary.[2]

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[2] Redeposition of the Greenland erratics by mass movement down to the elevation of the 600 m limit is unlikely due to its uniformity and the absence of erratics above this level, even in topographic depressions. Based on present observations there is no evidence that this upper zone has ever been glaciated.

Plate 1.1 Deeply oxidized and frost-shattered sandstone bedrock with soliflucting colluvium incorporating large granite erratic in foreground. Typical bedrock weathering in zone of Greenland erratics, interior Judge Daly Promontory. R.S. Bradley, in left center of photograph, provides scale.

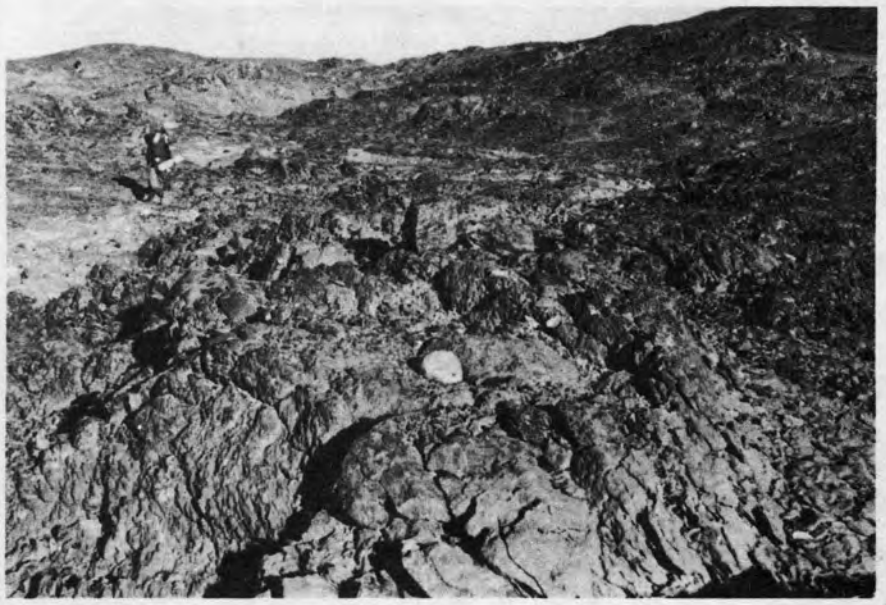

Plate 1.2 Similar area as Plate 1.1. Deeply weathered bedrock with sparse Greenland erratics. Granite boulder is apparent in central foreground, R.S. Bradley in left background for scale.

Plate 1.3 Many bedrock slopes in the zone of the Greenland erratics (Fig. 1.2) are presently mantled with such frost-shattered, oxidized and pitted bedrock chips.

Plate 1.4 Surface view of Jigsaw Mt. (Fig. 1.2) looking east across Kennedy Channel to the mouth of Petermann Fiord, N.W. Greenland. Granite erratics can be found on this summit beneath the surface of periglacially overturned felsenmeer. This weathering very likely occurred subsequent to the deposition of the granite erratics.

Plate 1.5 Massive granular exfoliation on granite erratic, central Judge Daly Promontory. Individual crystals and crystal aggregates could easily be removed by hand. Boulder appears as found.

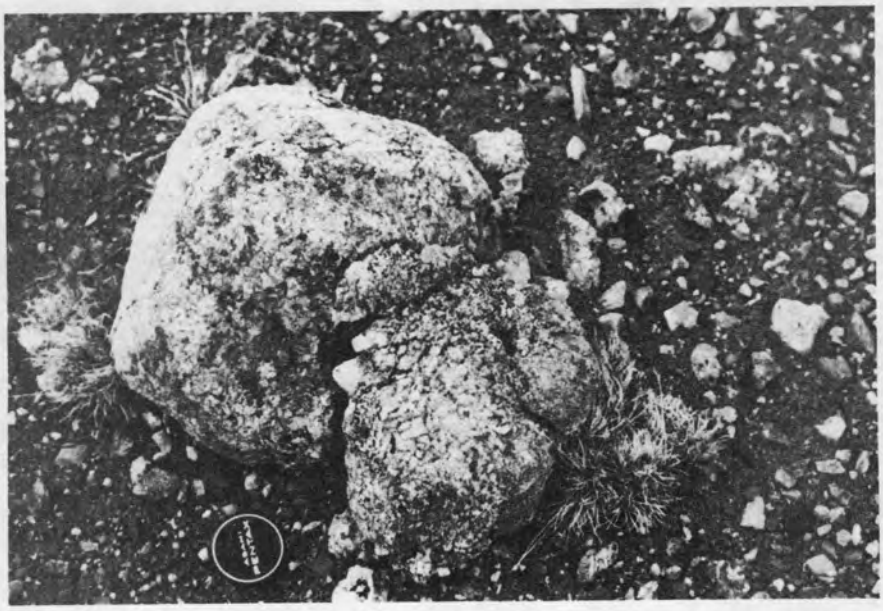

Plate 1.6 Frost shattered granite erratic near site of Plate 1.5. Approximately 55% of the granite erratics investigated fell into weathering categories exemplified by Plates 1.5 and 1.6. Only 25% were unweathered (fresh).

Plate 1.7 Coarse frost hummocks on summit of Pastoral Peak (Fig. 1.2) looking southwest along eastern coast of Judge Daly Promontory. No erratics were found in this periglacial surface material (elevation 815 ± 10 m a.s.l.).

Plate 1.8 Uppermost Ellesmere Island (ice shelf) moraines on either side of bedrock gully. Above them is (darker) weathered bedrock with sparse Greenland erratics (cf. Plates 1.1 and 1.2). Downslope is exposed section (∿50 m thick) comprised of marine till (upper half) overlying stratified sands. Site of organic sample ^{14}C dated >25,000 B.P. (DIC-584) is shown by dark, exposed area on lower right side of section. Site of sample DIC-550 (28,610 $^{+1710}_{-2180}$ B.P.) is shown by black arrow.

MAXIMUM EXTENT OF ELLESMERE ISLAND ICE SHEET AND TIMING OF THE GREENLAND ADVANCE

The absolute age of the maximum Greenland Ice Sheet advance is unknown. However, a minimum estimate is provided by the age of the subsequent and outermost Ellesmere Island ice advance which cross-cuts the Greenland till at lower elevations (Fig. 1.2). This latter Ellesmere Island glaciation is characterized by moraines composed mainly of sedimentary lithologies whose gradients reflect thin, topographically-controlled ice lobes extending across Judge Daly Promontory to Kennedy Channel (see profile, Fig. 1.2). The termini of two ice lobes were investigated; the first originated from the interior of Judge Daly Promontory and flowed southward to Cape Defosse whereas the second, 20 km to the northeast, was formed by southeastwardly flowing tributary ice from Lady Franklin Bay (Fig. 1.2). Both termini flowed into isostatically depressed embayments along western Kennedy Channel where they were forced to float, forming ice shelves (see Chapter 4). Morphologic evidence for ice shelves (c.f. Theil and Ostenso, 1961; Thomas, 1973) is provided (locally) by steeply descending lateral moraines which become abruptly horizontal for ca. 2 km in both valleys (England and Bradley, 1977b). The horizontal moraines and associated proglacial terraces are often fossiliferous downvalley from their apparent grounding lines. An outwash terrace formed in one of the valleys occupied by these ice shelves suggests a former relative sea level at 175 m a.s.l. This is consistent with the water depths required to float the estimated thicknesses of both glaciers.

An initial ^{14}C date on fragmented shells from a proglacial terrace adjacent to the moraines at Cape Defosse dated 27,950 ± 5400 B.P. (St 4325; England, 1974a and b). An amino-acid age estimate on this sample, and on additional shells from a nearby kame terrace, suggested dates >35,000 B.P. (England and Bradley, 1976). In 1975 a 50 m section was investigated three km up-valley from the proglacial terrace (site of St 4325) where marine till overlies

bedded sands (Plate 1.8). The till extends up to ∿100 m a.s.l. and it occurs immediately downslope from the local ice shelf moraine. It is fossiliferous and its deposition presumably occurred during the 175 m a.s.l. sea level stand associated with the ice shelf. Fragmented shells from this till dated $28,610 \begin{smallmatrix}+1710\\-2180\end{smallmatrix}$ B.P. (DIC-550). The underlying bedded sands in turn contain the locally extinct plant species Dryas octopetala (J. Packer, personal communication) and a sample of this dated >25,000 B.P. (DIC-584).

The second ice shelf moraine occurs twenty km to the northeast in the Beethoven Valley (Fig. 1.2) and immediately downslope, is associated with a massive, proglacial marine terrace (Plate 1.9). Two samples of fragmented shells collected from these moraines and terraces dated $23,110 \begin{smallmatrix}+660\\-720\end{smallmatrix}$ and $22,780 \begin{smallmatrix}+810\\-900\end{smallmatrix}$ B.P. (DIC-544 and 546, respectively). Both ^{14}C dates, however, are considered to be minimum estimates since the samples from which they were obtained were encrusted with calcite (50%) and silica (50%) as determined by X-ray analysis. These contaminants could not be entirely removed and they may date, in part, from the recrystallization of the shells following their initial deposition (I. Stehl, personal communication). Amino acid age estimates on both samples suggested ages >35,000 B.P. Because of the controversial nature of these dates the site of sample DIC-546 was revisited in 1976 where a larger, unencrusted shell sample was collected from the proglacial terrace. This 50g sample (subjected to 25% leaching) dated $29,670 \begin{smallmatrix}+830\\-930\end{smallmatrix}$ B.P. (DIC-738) and takes precedence over the previous date of $22,780 \begin{smallmatrix}+810\\-900\end{smallmatrix}$ B.P. (Fig. 1.2). In addition, a date of 28,100 ± 380 B.P. (GSC-1656) was previously obtained on organic debris collected from a marine limit delta along the southeastern edge of the Hazen Plateau, 55 km to the northeast of these former ice shelves. The similarity of this date to those previously discussed is apparent and it may reflect a corresponding, early

Plate 1.9 View looking south across the upper Beethoven Valley showing the horizontal ice shelf moraine (∿200 m a.s.l.) and fossiliferous, proglacial terraces (∿175 m a.s.l.) immediately downslope. Above the ice shelf moraine one enters weathered bedrock and sparse Greenland erratics.

Plate 1.10 Advanced pitting on sedimentary lithologies (impure limestone/sandstone) making-up outermost Ellesmere Island moraines. Rock chips on surrounding surface form an ubiquitous lag gravel over stoney/sand weathering profiles >40 cm in depth.

recession of the Ellesmere Island ice sheet from southern Robeson Channel. However, possible contamination of this sample (GSC-1656) by redeposited Tertiary material cannot be excluded (England, 1974a).

The close correspondence of these dates to those obtained along the ice shelf at Cape Defosse (27,950 ± 5400 and 28,610 $^{+1710}_{-2180}$ B.P., St 4325 and DIC-550, respectively) suggests that these finite dates are all minimum estimates on the outermost Ellesmere Island glaciation. These 28,000 - 30,000 B.P. dates are the first finite dates of pre-Holocene age reported along an ice margin in the eastern Canadian arctic. Stratigraphically they are minimum estimates on the age of the outermost Ellesmere Island ice advance; radiometrically, they may also be minimum estimates. However, the close correspondence of these dates (on both marine shells and organic detritus at three different locations) makes it unlikely that they are the product of contamination, and hence the dates are considered to be valid. Their similarity in age is logical given the fact that both ice shelf moraines occur at similar elevations (ca. 200 m a.s.l.) and represent similar ice thicknesses, indicating that they were formed in the same (contemporaneous) sea level. At present it is concluded that these proglacial marine terraces, formed ca. 28,000 - 30,000 B.P., represent initial recession from their respective ice margins whereas the establishment of the ice shelf moraines predates them by an unknown degree.[3] Advanced surface weathering on these outermost moraines and terraces (Plate 1.10) appears consistent with these early dates of deglaciation. On these moraines, more resistant erratics (such as quartzites) often exhibit thick accumulations of subsurface travertine as do the older tills on Inglefield Land, N.W. Greenland (Tedrow, 1970). These moraines, in turn, cross-cut a much more severely weathered zone containing erratics previously deposited by the Greenland Ice Sheet (Plates 1.1, 1.2, 1.4 and 1.5). During the recession

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[3] The date on marine till along the lower Daly River, however, suggests that the ice shelf may be of similar age (28,610 $^{+1710}_{-2180}$ B.P., DIC-550).

of the outermost Ellesmere Island ice margin the interior of northeastern Judge Daly Promontory was occupied by a large, proglacial lake ($\sim$50 km^2). This former lake is referred to as Glacial Lake Pavy and is marked by extensive outwash terraces graded to several elevations as the lake drained.

Five km to the northeast of the outermost Ellesmere Island moraines, an ice-pushed moraine occurs at 200 m a.s.l. immediately above the western shore of Kennedy Channel (Fig. 1.2). This moraine is characterized by Greenland erratics and it grades continuously into proglacial lacustrine sediments towards the interior of Judge Daly Promontory. Stratigraphically, the moraine represents the youngest glacial event within the zone of the Greenland erratics and fragmented shells, presumably scoured out of Kennedy Channel, have been incorporated into it. A sample of these shells was ^{14}C dated at 14,360 $^{+1120}_{-1300}$ B.P. (DIC-547, Fig. 1.2). However, this is probably a minimum and/or contaminated date as only 5 g were collected, no leaching was applied, and the porous nature of the shells made the removal of encrusted silica and calcite impossible (I. Stehli, personal communication). An amino acid age estimate on the same sample clearly distinguished it as being older than the shells incorporated in the outermost Ellesmere Island moraines and a tentative date of 80,000 to 160,000 B.P. was suggested (G. Miller, personal communication).

LATE WISCONSIN ICE EXTENT: NORTHWESTERN GREENLAND AND NORTHEASTERN ELLESMERE ISLAND

Opposite Judge Daly Promontory, a former ice advance which extended out of Petermann Fiord is marked by moraines that enter Hall Basin from the southwest margin of Polaris Promontory (Davies, 1972). Dated marine terraces related to this moraine system suggest that the ice advance is of Holocene age (<6100 B.P., W-816; Weidick, 1972). A minimum estimate on the extent of this ice margin would place the terminus of the Petermann Glacier in central Hall

Basin, within 20 km of Judge Daly Promontory and the mouth of Lady Franklin Bay (Fig. 1.1). Evidence in support of such a late Wisconsin advance is found on the Ellesmere Island side of Hall Basin where differential postglacial emergence is strongly dominated by the subsequent recession of the adjacent Greenland Ice Sheet (England, 1976a).

Additional evidence that the northwestern Greenland Ice Sheet occupied Hall Basin during the Holocene is provided by abundant, ice-rafted granite erratics deposited throughout Archer Fiord/Lady Franklin Bay on raised beaches up to the local marine limits. The frequency of these erratics suggest that Greenland ice was actively calving in Hall Basin and that Ellesmere Island glacier ice did not block the fiord. This is consistent with the restricted position of the late Wisconsin ice margin, delimited by the Hazen Moraines (Fig. 1.1; England, 1974a, 1976b). Finally, a marine terrace at Cape Baird, at the northernmost tip of Judge Daly Promontory, is capped by granite erratics and its emergence of 110 m compares closely with the marine limit (107 - 110 m) on central Polaris Promontory (Davies, 1963). The similarity of these marine limit elevations probably reflects similar amounts of glacio-isostatic unloading and hence a comparable distance from the Greenland Ice Sheet margin controlling the depression. The initial emergence of the Cape Baird terrace is indicated by a sample of <u>in situ</u> shells dated 8380 ± 150 B.P. (DIC-737; Fig. 1.2) and this probably reflects a synchronous recession of the bordering Greenland Ice Sheet. Although the Cape Baird terrace emerged ca. 8400 B.P. it is <u>not</u> considered to represent an earlier, late Wisconsin Ellesmere Island ice margin beyond the Hazen Moraines. On the contrary, the sedimentation responsible for the massive terrace (∿110 m thick) is considered to have taken place during the recession of the outermost Ellesmere Island ice margin (∿28,000 - 30,000 B.) whereas its emergence (∿8400 B.P.) is thought

to coincide with the recession of the late Wisconsin Greenland Ice Sheet from Hall Basin.[4]

It has been proposed that during the late Wisconsin glaciation the northwestern Greenland and northeastern Ellesmere Island ice sheets did not merge (England, 1976a and b). This is indicated by the separation of their respective Holocene moraine systems and by the synchronous emergence in the intervening ice free corridor, suggesting the decay of a marginal depression (Walcott, 1970). This synchronous emergence extends over a distance of 100 km and indicates initial glacio-isostatic unloading between the two ice margins at 7500 - 8100 B.P. (England, 1974a).[5] Additional evidence for synchronous emergence between the two ice margins is provided by raised marine deltas of Holocene age which occur on the distal sides of the ice shelf moraines and terraces dated 28,000 - 30,000 B.P. These latter valleys were clearly unoccupied by Holocene ice margins and consequently their respective Holocene deltas are the product of fluvial sedimentation along an ice-free coastline depressed between the separated Greenland and Ellesmere Island ice margins. The Holocene marine limit on the distal side of the lower Daly River ice shelf dated 8200 ± 260 B.P. (DIC-549) whereas a delta below the Beethoven Valley ice

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4 The Holocene shells (∿8400 B.P.) obtained from the Cape Baird terrace were collected from its uppermost topset beds. Shells collected from within the delta are presently being dated to determine whether the delta was formed during an earlier period.

5 The older dates (∿8100 B.P.) come from either catchment basins with high sedimentation rates (where the establishment of a marine limit is rapid) or from raised beaches dependent upon the initial marine transgression. Hence they are considered to provide the best estimate on the earliest emergence of this ice-free corridor. The younger dates (∿7500 B.P.) are characteristically found in deltas at the mouths of small catchment basins where lower (fluvial) sedimentation rates established deltas which probably lagged behind initial emergence.

shelf dated 7910 ± 145 B.P. (DIC-545; Fig. 1.2). Of the two samples the 8200 ± 260 B.P. date is considered to be the best estimate on both the initial timing and amount (90 m) of postglacial emergence in this locality since its marine limit was established along the lower Daly River where sedimentation rates substantially exceed those of the Beethoven Valley.[6]

The 8200 ± 260 B.P. date in the lower Daly River valley closely compares with the oldest date on initial emergence along the margin of the Hazen Moraines, 70 km to the northwest (8130 ± 200 B.P.; GSC-1775, England, 1974a), and with the initial emergence of the Cape Baird terrace bordering the Greenland Ice Sheet margin in Hall Basin (8380 ± 105 B.P.; DIC-737). This synchronous emergence between the Ellesmere Island and N.W. Greenland ice sheet margins is consistent with the glacio-isostatic dominance of the area by the Greenland Ice Sheet (England, 1976a). Decay of the marginal depression over a distance of >100 km suggests early Holocene ice recession ca. 8100 - 8400 B.P.; as yet there is no glacio-isostatic evidence for a N.W. Greenland ice advance <6100 B.P. (Weidick, 1972). Furthermore, that the Greenland Ice Sheet did not extend beyond Hall Basin during late Wisconsin time is demonstrated by the preservation of the ice shelf moraines along eastern Judge Daly Promontory and by the lack of ice-contact features on the adjacent coastline of Lady Franklin Bay. Independent estimates based on isotopic analyses of the Devon Island and Camp Century ice cores suggest that, during the late Wisconsin, the northwestern Greenland Ice Sheet was only ∿125 km beyond its present margin (Paterson, in press). However, this in turn may be a maximum estimate since it is possible that the present N.W. Greenland ice margin is the product of a late Holocene

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6 The 8200 ± 260 B.P. date (DIC-549) is given precedence over an earlier date associated with the marine limit in the lower Daly River (7500 ± 660 B.P., St 4092; England, 1974a).

readvance (Nichols, 1969) which has extended an unknown distance beyond the limit of maximum Holocene recession (from which the ∿125 km estimate should be applied).

DISCUSSION

Multiple ice sheet margins pre-dating the last glaciation, both by position and extent of rock weathering, have been reported along 3,000 km of the eastern Laurentide ice margin; from Newfoundland (Grant, 1977) and Labrador (Ives, 1958; Løken, 1962; Andrews, 1963) in the south to Baffin Island (Mercer, 1956; Løken, 1966; Pheasant and Andrews, 1973; Boyer and Pheasant, 1974; Ives, 1975) and Somerset Island (Dyke, 1976) in the north. Additional evidence of advanced weathering (on glacial deposits of presumably pre-late Wisconsin age) have been cited in the High Canadian and northwestern Greenland arctic (Boesch, 1963; Hattersley-Smith, 1969; Tedrow, 1970; Davies, 1972). Our results from northern Ellesmere Island reinforce these observations and suggest the presence of at least four such weathering zones (Figs. 1.1 and 1.2) delimited, from oldest to youngest, by (a) unglaciated mountain summits (b) the maximum extent of Greenland erratics (c) the outermost Ellesmere Island moraines and (d) the Hazen Moraines. The presence of these weathering zones reinforces earlier hypotheses which favor late Quaternary refugia over northeastern Ellesmere Island (Leech, 1966; Brassard, 1971).

It is apparent that the most recent advance of the Greenland Ice Sheet onto Judge Daly Promontory is >30,000 B.P. whereas the uppermost till(s) within this zone may be much older (Quaternary or Upper Tertiary?). On the basis of the known distribution of erratics the northwestern Greenland Ice Sheet extended 20 - 70 km onto the adjacent Ellesmere Island coast - a distance of only 100 km beyond its present ice margin. It is also of interest that deglaciation from the outermost Ellesmere Island ice margin may have begun

ca. 28,000 - 30,000 B.P. This is of particular relevance to the hypothesis that astronomical variations exert a strong control on glacial events in high latitudes (Milankovitch, 1941; Kukla, 1975; Hays et al., 1976). Recent calculations of circumpolar solar radiation receipts indicate a major trough at ∿33,000 - 25,000 B.P. which would have resulted in extreme cold at high latitudes (Berger, 1975). In fact, this is indicated by the δO^{18} profile from the Camp Century ice core (∿78°N) which shows the onset of extreme cold ∿31,000 B.P. (Dansgaard et al., 1972). However, although it is likely that these conditions would favor the expansion of the southern Laurentide Ice Sheet, in higher latitudes it is much more likely that lower temperatures would lead to greater aridity and hence glacial recession. Indeed paleoclimatic models support the concept of lower precipitation in high latitudes during the maximum extent of the late Wisconsin Laurentide Ice Sheet (Tanner, 1965; Lamb and Woodroffe, 1970; Williams et al., 1973). Such a topographic barrier would restrict the advection of moisture into the arctic archipelago and hence it would contribute to the starvation of ice bodies to the north, over the High Arctic (Andrews et al., 1974; England, 1976b). Similarly, Dansgaard et al., (1971) found a better correlation between the Camp Century ice core record and other independent chronologies when precipitation amounts were assumed to be <u>less</u> than present day amounts. Andrews et al. (1974) also pointed out the relationship between the paleoclimatic record in the Camp Century ice core and glacier ice extent on eastern Baffin Island and eastern Greenland. Our evidence indicates that periods of extreme cold lead to <u>diminishing</u> ice extent at high latitudes as a result of lower precipitation. We therefore do not support the notion of extensive late Wisconsin ice sheets over the Arctic Ocean (Mercer, 1970; Broecker, 1975) and adjacent lands of North America and Greenland (Blake, 1970, 1972; Dansgaard et al., 1973; Hughes et al., 1977).

SUMMARY

Field observations on northeastern Ellesmere Island indicate a maximum advance of the northwestern Greenland Ice Sheet of <100 km beyond its present margin. This occurred prior to the outermost Ellesmere Island ice advance which occurred >30,000 B.P. Recession from the Ellesmere Island ice margin began at least ca. 28,000 - 30,000 B.P. During this sequence of glacial events, significant land areas remained ice free. The late Wisconsin ice extent along both northeastern Ellesmere Island and northwestern Greenland was extremely limited leaving an ice-free corridor along Kennedy and Robeson channels. Recession from these ice margins is indicated by initial postglacial emergence ca. 8100 - 8400 B.P. The relatively minor extent of late Wisconsin ice in the High Arctic probably reflects a period of extreme aridity associated with the build up of the Laurentide Ice Sheet to the south.

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CHAPTER 2

FORMER ICE SHELVES IN THE CANADIAN HIGH ARCTIC

INTRODUCTION

Ice shelves in the Canadian and Greenland High Arctic are presently formed by either landfast sea ice or floating glacier margins. Ice shelves created by the accretion of landfast sea ice are well documented from northernmost Ellesmere Island (cf. the Ward Hunt Ice Shelf, Koenig et al. 1952; Hattersley-Smith et al. 1955; Crary, 1960; Lyons and Mielke, 1973). Radiometric dates on the youngest driftwood trapped behind the Ward Hunt Ice Shelf and on organic debris incorporated within it suggest initial formation ca. 3000 - 4000 B.P., hence, following the postglacial Climatic Optimum (Crary, 1960; Hattersley-Smith, 1969; Lyons and Mielke, 1973). The buildup of landfast sea ice is due to the freezing of low salinity sea water at its base and, to a lesser extent, to the periodic surface accumulation of iced firn (Marshall, 1955). The growth of such ice shelves is favoured by severe winter cold, low precipitation and limited summer melting (Hattersley-Smith, 1960). Depositional features along the landward margins of these ice shelves have been briefly described and are restricted to shattered boulders transported down ice ramps from the adjacent land (Hattersley-Smith et al. 1955) or to "debris-laden ice ridges" where the shelf is grounded (Lyons and Mielke, 1973, p. 315). At present morphological evidence for more extensive pre-Holocene ice shelves has not been cited either due to its absence or a lack of systematic investigation. It seems likely that such landfast sea ice was more extensive in the past, perhaps during the cold phase recorded in the Camp Century and Devon Island ice cores between 65,000 and 10,000 B.P. (Dansgaard et al., 1973; Paterson et al. 1977).

Ice shelves formed by floating glacier ice discharging from land-based ice sheets have been extensively reported from Antarctica (Swithenbank, 1957;

Crary et al., 1962; Swithenbank and Zumberge, 1965; Budd, 1966; Holdsworth, 1969; Thomas, 1973, 1976). In addition, the occurrence of present day, floating glacier termini in arctic Canada and Greenland is widely recognized (Koch, 1928; Sorge, 1933; Krinsley, 1961; Carbonnel and Bauer, 1968; Feazel and Kollmeyer, 1972; Løken et al. 1972). The dimensions of such ice shelves are generally limited by the rate of ice flow from the adjacent land, rates of melting and calving, submarine topography and additional forces such as the bending stresses at the hinge line (Holdsworth, 1969). Their principal morphologic distinction is a comparatively flat upper surface with a limited amount of freeboard (ratio of total ice thickness to front height is ca. <8.5; Budd, 1966; Reeh, 1968, 1969; Thomas, 1973).

Several authors have speculated on the presence of extensive ice shelves during former glaciations of the High Arctic (Hattersley-Smith, 1960; Mercer, 1970; Grosswald, 1972; Broecker, 1975; Hughes et al., 1977). Stratigraphic evidence has also been cited which suggests the presence of shelf ice bordering the Magdelen Islands, Gulf of St. Lawrence, during the Wisconsin Glaciation (Prest et al., 1976). Although submarine and near sea level moraines have been described from arctic Canada and Greenland (Crary, 1956; Løken, 1973; Ten Brink and Weidick, 1974; Blake, 1977) no documentation of former ice shelf moraines has been made.

EVIDENCE FOR FORMER ICE SHELVES

During 1975/76 studies were conducted on the surficial geology of Judge Daly Promontory, northeastern Ellesmere Island (Fig. 2.1). In this area moraines deposited by the outermost Ellesmere Island ice advance cross-cut an older and more extensive zone of Greenland till (England and Bradley, 1976). The distribution and gradients on the Ellesmere Island moraines indicate the presence of thin, topographically-controlled ice lobes draining southeastward across

the Promontory to sea level along western Kennedy Channel. The terminal of two ice lobes were investigated, one originated from the interior of Judge Daly Promontory and extended to Cape Defosse, whereas the second, 20 km to the northeast, represented tributary ice flowing southeastward out of Lady Franklin Bay into the lower Beethoven Valley (Fig. 2.1). Both ice lobes crossed an

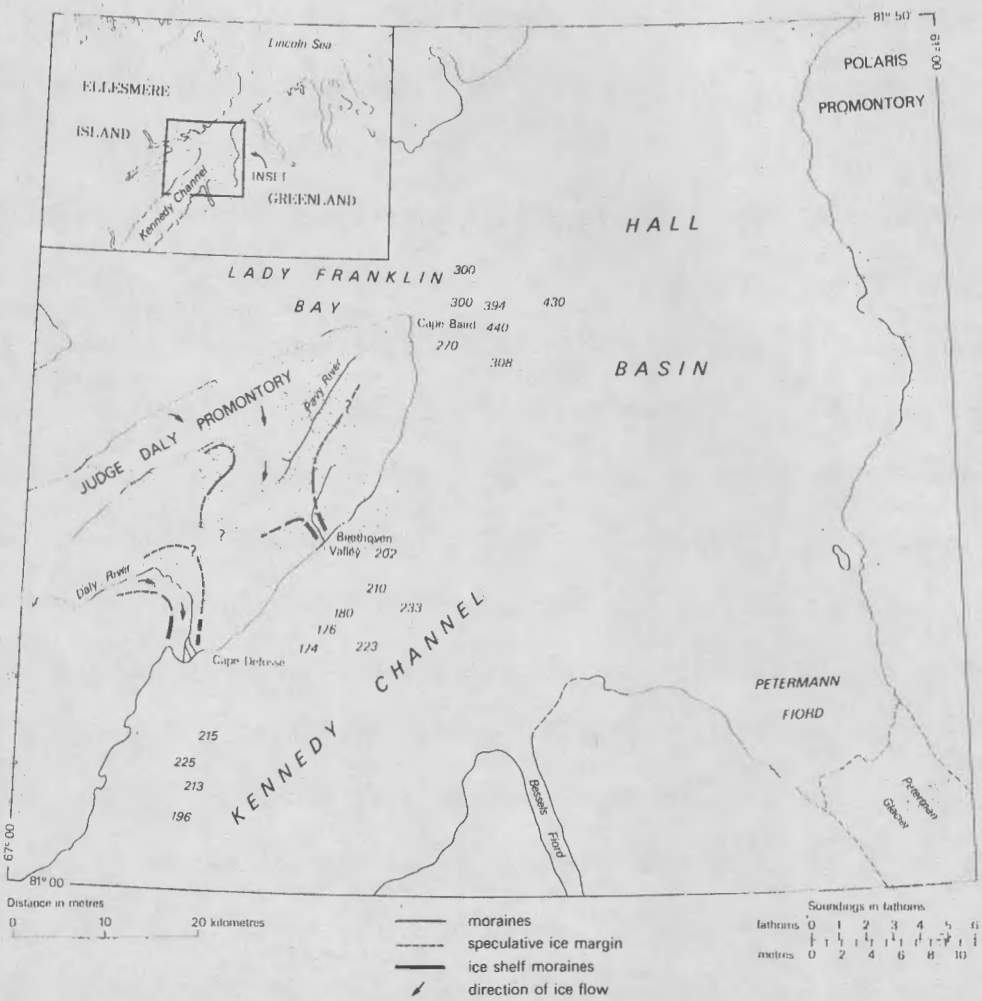

Figure 2.1

Map of Judge Daly Promontory, northeastern Ellesmere Island and adjacent Greenland coast. Outermost Ellesmere Island moraines, ice flow directions and the location of former ice shelves are indicated. Water depths are shown in fathoms.

interior lowland (ca. 200-300 m a.s.l.) before descending into narrow valleys, 2-3 km in width, which lead to Kennedy Channel. Relief in the valleys is >500 m and bathymetric soundings show water depths of >360 m 5 km offshore (Canadian Hydrographic Survey, 1973). Due to glacio-isostatic depression of these valleys both outlet glaciers were forced to float in the resulting embayments along western Kennedy Channel. Evidence in support of such ice shelves is based on morphology, stratigraphy and the relative sea level at the time of their formation. The chronology of these ice shelves is also discussed.

MORPHOLOGY

The uppermost Ellesmere Island moraines in the interior of Judge Daly Promontory occur at ca. 500 m a.s.l. and descend to ca. 260 m a.s.l. at the entrance to the lower Beethoven Valley (Fig. 2.1). Within half a km of this latter point a well-developed system of conical kames and lateral moraines descend steeply downvalley to an elevation of 200 m a.s.l. where they become abruptly horizontal for a distance of ca. 2 km. Immediately upslope from these horizontal lateral moraines one encounters a sharp break in weathering characterized by deeply oxidized bedrock, tors and a sparse distribution of crystalline erratics previously deposited by the Greenland Ice Sheet. The horizontal moraines are considered to represent the uppermost lateral margin of a floating outlet glacier whose grounding line was equivalent to the lowermost sector of steeply sloping lateral moraines up-valley. A vertical and ground level view of these moraines on the southwest side of Beethoven Valley are shown in Plates 2.1 and 2.2, respectively (see end of chapter). The slope of the moraines shown in plate 2.2 compares with observations made on the Ross Ice Shelf, Antarctica, whose profile is characterized by "(1) the abrupt increase in elevation as one goes from the ice shelf onto the continental ice sheet and (ii) the depression associated with the juncture of the ice shelf

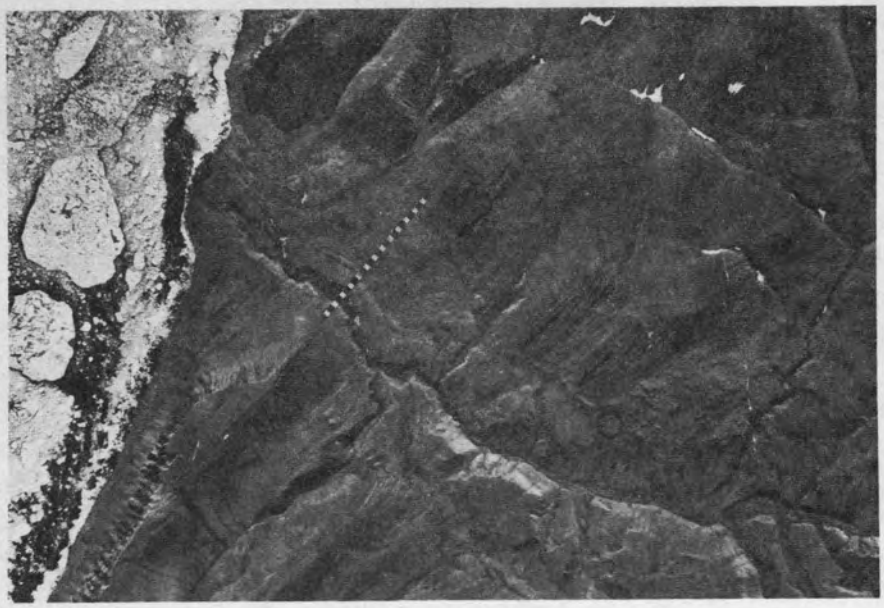

Plate 2.1 Air photograph of Beethoven Valley showing the horizontal ice shelf moraines (black arrows) and the approximate grounding line (black circle). Dotted line shows the approximate outer limit of this ice shelf based on morphologic evidence. Copyright Canadian Government, air photograph A-16680-107.

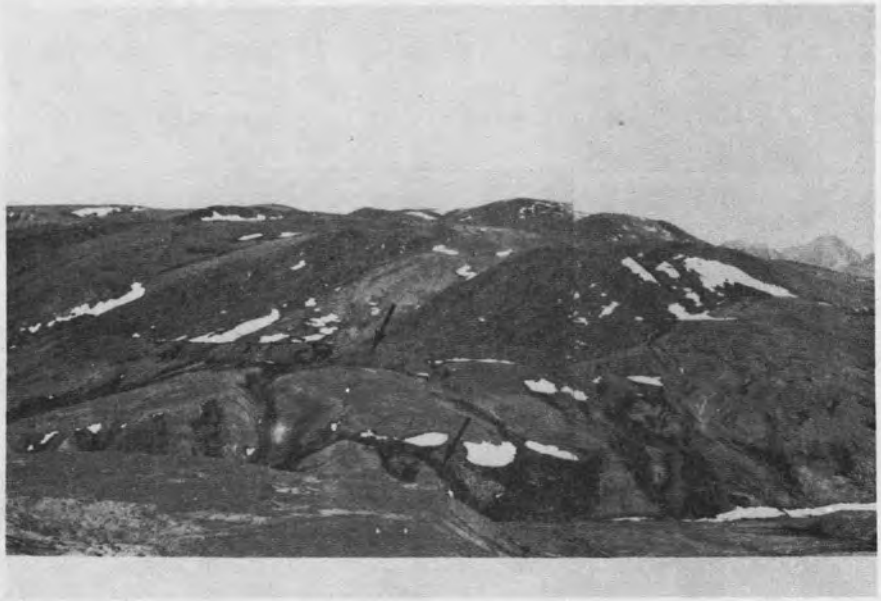

Plate 2.2 View looking southward across upper Beethoven Valley showing segment of horizontal ice shelf moraines (ca. 200 m a.s.l.) and the steeply sloping lateral moraines extending into the interior of Judge Daly Promontory (ca. 260 m a.s.l., right background). Note slight depression in the moraines at the contact with the former ice shelf. Associated proglacial, marine terraces occur downslope from ice shelf moraines. Locations of dated shell samples are shown by black arrows.

and ice sheet" (Theil and Ostenso, 1961, p. 825). Several altimeter transects, corrected for both temperature and pressure, were run along the horizontal sector of the Beethoven Valley moraines and an elevation difference >1 m was not detected. Similar, but less extensive, lateral moraines occur on the opposite side of the valley and suggest an ice shelf width of ca. 2 km.

Twenty km to the southwest of Beethoven Valley an outlet glacier from the interior of Judge Daly Promontory formerly reached Kennedy Channel via the lower Daly River valley (Fig. 2.1). Along the western slope of this valley another prominent, horizontal moraine system occurs at ca. 195 m a.s.l. and is bordered upslope by the same deeply weathered bedrock and sparse Greenland erratics. This moraine system and the morphology of its upper surface are shown in Plates 2.3 and 2.4, respectively. The surfaces of the horizontal moraines in both valleys show little relief (<.5 m), are ca. 5 m in width and covered by a highly frost shattered lag gravel over a stoney/sand weathering profile. These moraines appear to have formed in moats along the ice margins which received glacial meltwater together with rock debris derived by periglacial mass movement from the adjacent slopes. Hence the moraines formed passively in that glacier flow was probably not responsible for their deposition. On the basis of the valley size and the distribution of depositional features the ice shelf in the lower Daly River was not more than 2 km in length and width.

STRATIGRAPHY

In the Beethoven Valley the ice shelf moraines are occasionally fossiliferous, exhibiting sparse fragments of marine shells. That these shells have not been ice-transported across the interior of Judge Daly Promontory is clearly evidenced by their termination up-valley at a point coinciding with the apparent grounding line. In addition no shells were found in the interior of Judge Daly Promontory despite extensive traverses of this area. The manner

Plate 2.3 View looking southwestward across lower Daly River to ice shelf moraines ca. 195 m a.s.l. (black arrows). Downslope are unconsolidated deposits composed of marine till overlying bedded sands containing organic debris (open circle). Site of DIC-550, from fossiliferous till, is shown by black arrow.

Plate 2.4 View looking southward along the surface of the ice shelf moraine, west side of the lower Daly River. Black arrows point to break in slope where one enters weathered bedrock and sparse Greenland erratics.

by which these shells have been incorporated in the moraines is unclear; they may have been scoured-up by the advancing ice as it crossed its grounding line or, alternatively, they may have been gradually transferred to the surface by the accretion of freezing sea water at the base of the floating glacier. This latter process has been well documented from the 40 m thick Ward Hunt Ice Shelf where organic material (siliceous sponges, sea worms, pelecypods, remains of arctic cod) has been transported to the surface (Lyons and Mielke, 1973). Lyons and Mielke (1973, p. 315) also report a rich biota in both the ice shelf's debris ridge and in the ice moat between this ridge and the shore. As regards glacier flow as a mechanism for transporting these shells into the moraines it is of interest that particle trajectories through the Brunt Ice Shelf, Antarctica, do not reveal basal flow lines returning to the surface (Thomas, 1973).

Adjacent to the ice shelf moraines in the lower Beethoven Valley are massive, proglacial terraces graded to ca. 175 m a.s.l. (Plate 2.2). These terraces are capped with coarse till and/or ice-rafted debris overlying thickly bedded and poorly sorted outwash sands. The terraces occur at similar elevations on both sides of the valley and they are considered to represent rapid sedimentation along the retreating Ellesmere Island ice margin following the removal of the ice shelf. These terraces are fossiliferous throughout, though most shells are fragmented. Terraces up-valley from the former grounding line, however, are not fossiliferous.

Along the west side of the lower Daly River a high, terrace-like deposit occurs downslope from the ice shelf moraines (Plate 2.3). The truncated face of this 50 m thick deposit reveals marine till overlying bedded sands containing organic debris. The till is fossiliferous and its deposition is considered to have taken place during the formation of the ice shelf. The underlying fluvial sands stratigraphically predate the till and their preservation puts maximum

limits on the depth to which the floating ice shelf extended. Down-valley from this exposure both raised beaches and fossiliferous, proglacial terraces occur up to 105 m a.s.l. (England, 1974). These and other fossiliferous deposits from the Beethoven and Daly River valleys have been dated both by ^{14}C and the amino-acid method and are discussed under the section on chronology.

FORMER RELATIVE SEA LEVEL

Estimates can be made on the thickness of these former ice shelves and, hence, the water depths required to float them. In the Beethoven Valley a maximum estimate of ice thickness is based on the difference in elevation between the bedrock floor (ca. 90 m a.s.l.) and the horizontal moraines (200 m a.s.l.). This suggests a maximum thickness of <110 m for the ice shelf since it is assumed to be floating. As a result the associated water depth must also be somewhat less than .88 x 110 m (Reeh, 1969) or <97 m above bedrock. This results in a maximum relative sea level of <187 m a.s.l. As discussed under the section on Stratigraphy proglacial terraces ca. 175 m a.s.l. occur adjacent to these ice shelf moraines in the Beethoven Valley. The elevation of these graded terraces suggest water depths of ca. 85 m above bedrock which would be capable of floating an ice thickness of ca. 100 m. Such an ice thickness would extend from the horizontal moraines to within 10 m of the bedrock floor. It is suggested that these 175 m terraces, containing fragments of marine shells, represent the approximate relative sea level that existed during the formation and breakup of the associated ice shelf. The deposition of these terraces clearly necessitated the removal of this ice shelf from the valley.

Along the lower Daly River the estimated ice thickness between the preserved bedded sands underlying till (ca. 45 m a.s.l.) and the horizontal moraines (195 m a.s.l.) is 150 m. This would suggest a required water depth

of ca. 130 m above the bedded sands (ca. 45 m), hence a similar relative sea level of ca. 175 m at the time of ice shelf formation. The absence of terraces at this elevation in the valley may be due to the fact that 1) they never formed, 2) they have been removed by subsequent erosion or 3) the ice tongue stagnated in the lower valley, i.e. if the ice shelf remained in place during ca. 15-20 m of emergence it would have become grounded. Moraines on the valley sides at 150 m a.s.l. (below the horizontal moraines) may reflect such stagnation and grounding as the sea level dropped from the ice shelf stage.

CHRONOLOGY

In the lower Daly River valley fragmented shells collected from a proglacial terrace at 105 m a.s.l. dated 27,950 ± 5400 B.P. (St 4325, England, 1974). An amino acid age estimate on the same shell sample, and on additional shells collected from a nearby moraine, suggested ages >35,000 B.P. (England and Bradley, 1976). Three km up-valley from the proglacial terrace the Daly River has exposed a section of marine till overlying bedded sands containing organic remains. The marine till is fossiliferous and its elevation of ∿100 m a.s.l. is below both the ice shelf moraine and the former relative sea level at 175 m a.s.l. Shell fragments from this till dated $28,610 \begin{smallmatrix}+1710\\-2180\end{smallmatrix}$ B.P. (DIC-550). The underlying bedded sands in turn contain the locally extinct plant species *Dryas octopetala* a sample of which dated >25,000 B.P. (DIC-584, Plate 2.3).

Along the southwestern slope of Beethoven Valley two samples of fragmented shells were collected in 1975. The first sample, incorporated in the horizontal ice shelf moraines, dated $23,110 \begin{smallmatrix}+660\\-720\end{smallmatrix}$ B.P. (DIC-544) whereas the second, collected downslope and washing out of the 175 m terrace, dated $22,780 \begin{smallmatrix}+810\\-900\end{smallmatrix}$ B.P. (DIC-546). X-ray analysis of both shell samples, however, revealed that they were encrusted with 50% calcite and 50% silica. These contaminants could not be completely removed and may date from the recrystalli-

zation of the shells following their initial deposition. Hence, it was concluded that both dates were minimum estimates. Amino acid age estimates on the same samples indicated ages >35,000 B.P.

During 1976 the 175 m terraces were revisited and a second sample was collected. These shells occurred in the same location as sample DIC-546, however, they were unencrusted by contaminants and over 50 g were obtained. This sample dated 29,670 $^{+830}_{-930}$ B.P. (DIC-738) and it takes precedence over the first date of 22,780 $^{+810}_{-900}$ B.P. This most recent date closely coincides with the other finite ^{14}C dates along the ice margin at Cape Defosse (27,950 ± 5400 and 28,610 $^{+1710}_{-2180}$ B.P., St 4325 and DIC-550, respectively). It is concluded that these ca. 28,000 - 30,000 B.P. dates on proglacial terraces (St 4325 and DIC-738) represent initial recession from the ice margin which previously formed the ice shelves. However, the 175 m sea level appears to be consistent with the water depths required to float the calculated ice thicknesses in both valleys and, hence, the ice shelves may not be substantially older than the proglacial terraces as the date on the marine till suggests (28,610 $^{+1710}_{-2180}$ B.P., DIC-550).

DISCUSSION

During the maximum ice advance on northeastern Ellesmere Island outlet glaciers formed ice shelves along western Kennedy Channel when the relative sea level was ca. 175 m above present. Evidence in support of these ice shelves is principally morphologic and is based on the horizontality of two separate moraine systems which extend for 2 km beyond steeply descending moraines up valley. These ice shelves are useful stratigraphically in that they delimit the extent of former ice margins and, chronologically, because they formed in a marine environment which favours the deposition of dateable, fossiliferous units. In addition, these ice shelves provide estimates on the former relative sea level at the time of their formation since this can either

be observed (proglacial terraces) or calculated, given the local ice thickness.

Throughout the Canadian and Greenland arctic numerous outlet glaciers descend from upland icefields into prominent fiords and embayments. In addition, glacio-isostatic depression during former glaciations resulted in the inundation of many low coastal valleys that are presently above sea level. Therefore, during the advance of arctic glaciers in the past, many ice shelves similar to those described from eastern Judge Daly Promontory must have formed. Where such ice shelves were constrained between steep valley sides remnant, depositional features, such as horizontal moraines, should be preserved. Air photo analysis of the coastline south of Cape Defosse, Judge Daly Promontory, indicates the presence of additional ice shelf moraines. At present the extent of former ice shelves in the North American arctic is open to considerable speculation (Mercer, 1970; Broecker, 1975; Hughes et al., 1977) and hence the mapping, dating and analysis of their related deposits is pertinent to the understanding of high latitude Quaternary environments.

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SECTION B: RECENT EVENTS

CHAPTER 3

RECENT CLIMATIC FLUCTUATIONS OF THE CANADIAN HIGH ARCTIC AND THEIR SIGNIFICANCE FOR GLACIOLOGY

INTRODUCTION.

The Canadian High Arctic (north of Latitude 74°N) contains the greatest concentration of land-based snow and ice outside of Greenland and Antarctica (Figure 3.1). Glaciation levels vary from over 1200m. above sea level on north central Ellesmere Island to less than 300m. a.s.l. along the coast of north-western Ellesmere Island where extensive ice shelves are presently found in sheltered fiord mouths and embayments. (Miller et al., 1975). Prior to 1946 the climate of this area was virtually unknown with only scattered records available from early expeditions memoirs (e.g. Greely, 1888; Nares, 1878). The most complete records are those of Greely's ill-fated expedition to Fort Conger (Figure 3.1) where meticulous synoptic observations were kept continously for two years (August 1881 to July 1883) as part of the United States contribution to the First Polar Year. During this period daily minimum temperatures as low as -52.3°C were recorded and the daily maxima never rose above 11.7°C.

Although Greely's observations were a great contribution to polar meteorology, they were limited in duration and geographic extent. It was not until the end of World War II that a network of meteorological stations (known as 'JAWS'[1].) was established in the High Arctic under the cooperative sponsorship of the U.S. and Canadian Governments (Buss, 1971; Table 3.1). Unfortunately, these stations are few and far between (Figure 3.1) and they are all located close to sea level. Hence the climate of the mountainous interiors of the islands remains virtually unknown except for limited observations compiled by glaciological expeditions, primarily during the ablation season (c.f. Sagar, 1960; Lotz, 1961; Havens, 1964; Müller and Roskin-Sharlin, 1967). Although the primary purpose of the JAWS stations was to provide synoptic observations

1. Joint Arctic Weather Station

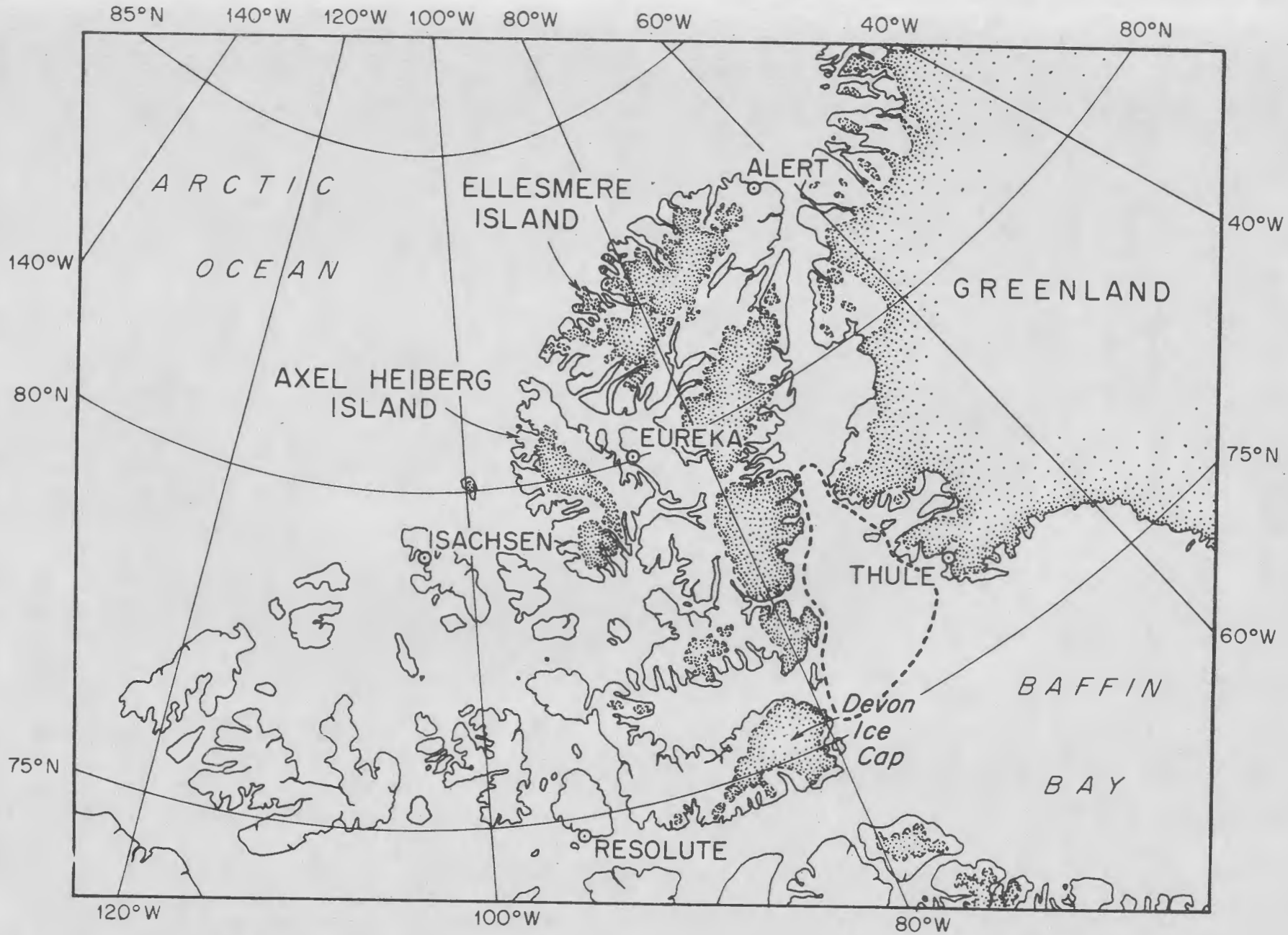

Figure 3.1 Location of principal weather stations. Ice caps are stippled. Dashed line is the average extent of the North Water in March (after Dunbar,1969).

TABLE 3.1

LONG-TERM HIGH ARCTIC WEATHER STATIONS

Station number[1].	Station	latitude	longitude	eleva. (m)	Record starts	Record ends[2].
2400300	Alert	82°30'	62°20'	63	June 1950	
2401200	Eureka	80°00'	85°56'	2	May 1947	Aug.1963
2401200	Eureka	80°00'	85°56'	10	Aug.1963	
2502600	Isachsen	78°47'	103°32'	25	May 1948	
2403500	Resolute	74°41'	94°55'	17	Oct.1947	Oct. 1953
2403500	Resolute A	74°43'	94°59'	64	Oct.1953	
17602-W	Thule	76°33'	68°49'	38	Oct. 1946	July 1952
17605-A	Thule	76°32'	68°45'	60	Oct. 1951	

1. Station numbers are Canadian Atmospheric Environment Service index numbers except for Thule which is a U.S. Weather Bureau Station (not part of the JAWS network).

2. Where station relocation occurred, otherwise station has operated uninterrupted at the same location to the present day.

TABLE 3.2

CHANGE IN MEAN JULY MAXIMUM TEMPERATURE (° C)

Station	Record length	a) Start of record to 1963	Standard deviation	b) 1964 to end of record	Standard deviation	Change (b-a)
Alert	1950 - 76	7.2	2.4	5.9	1.4	-1.3
Eureka	1947 - 76	8.9	1.4	7.8	1.2	-1.1
Isachsen	1948 - 76	6.3	2.1	4.8	1.6	-1.5
Thule	1947 - 74	8.3	1.2	5.6	1.4	-2.7
Resolute	1948 - 76	7.5	1.3	6.0	1.6	-1.5

(surface and upper air) for aviation purposes, their continuous operation for almost 30 years has provided a basis for looking at the broadscale climate and climatic fluctuations of the area[2] and the importance these fluctuations may have for the mass balance of snow and ice bodies in the region.

TEMPERATURE

THE ABLATION SEASON

In the High Arctic, where temperatures are well below freezing for most of the year, the character of the ablation season is of critical importance to glacier mass balance. A common index of ablation season conditions is the mean maximum temperature of the warmest month, July. Lotz and Sagar (1962) for example showed that ablation on the Gilman glacier (north central Ellesmere Island) was closely related to daily maximum temperatures particularly in July when 75% of ablation occurred (Sagar, 1960). Furthermore, Bradley (unpublished ms.) found that both mass balance and equilibrium line elevations on the White glacier, Axel Heiberg Island, are closely related to July maximum temperatures at Eureka and Isachsen. Figures 3.2 to 3.4 show mean July maximum temperatures (Tmax) at the stations listed in Table 3.1 Although year to year variability of temperature is high, careful examination of the records shows that temperatures fell markedly in the early 1960s, generally around 1963/1964. This is similar to the abrupt changes in July freezing level heights throughout the Archipelago (Bradley, 1973). Freezing levels averaged as much as 500m lower in the decade following 1963 as in the preceding decade. Table 3.2 shows that the actual changes in July Tmax at each station ranged from 1.1°C to 2.7°C, and that inter-annual variability was generally lower in the period after 1963. Further analysis of daily data shows that this change in mean July Tmax was strongly

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2. Although the stations are widely separated geographically, principal component analysis of mean monthly temperature and precipitation data from a large number of Canadian Arctic weather stations (Appendix 3) indicates that the High Arctic can be considered a distinct climatic region. Hence it is logical to look at these records collectively.

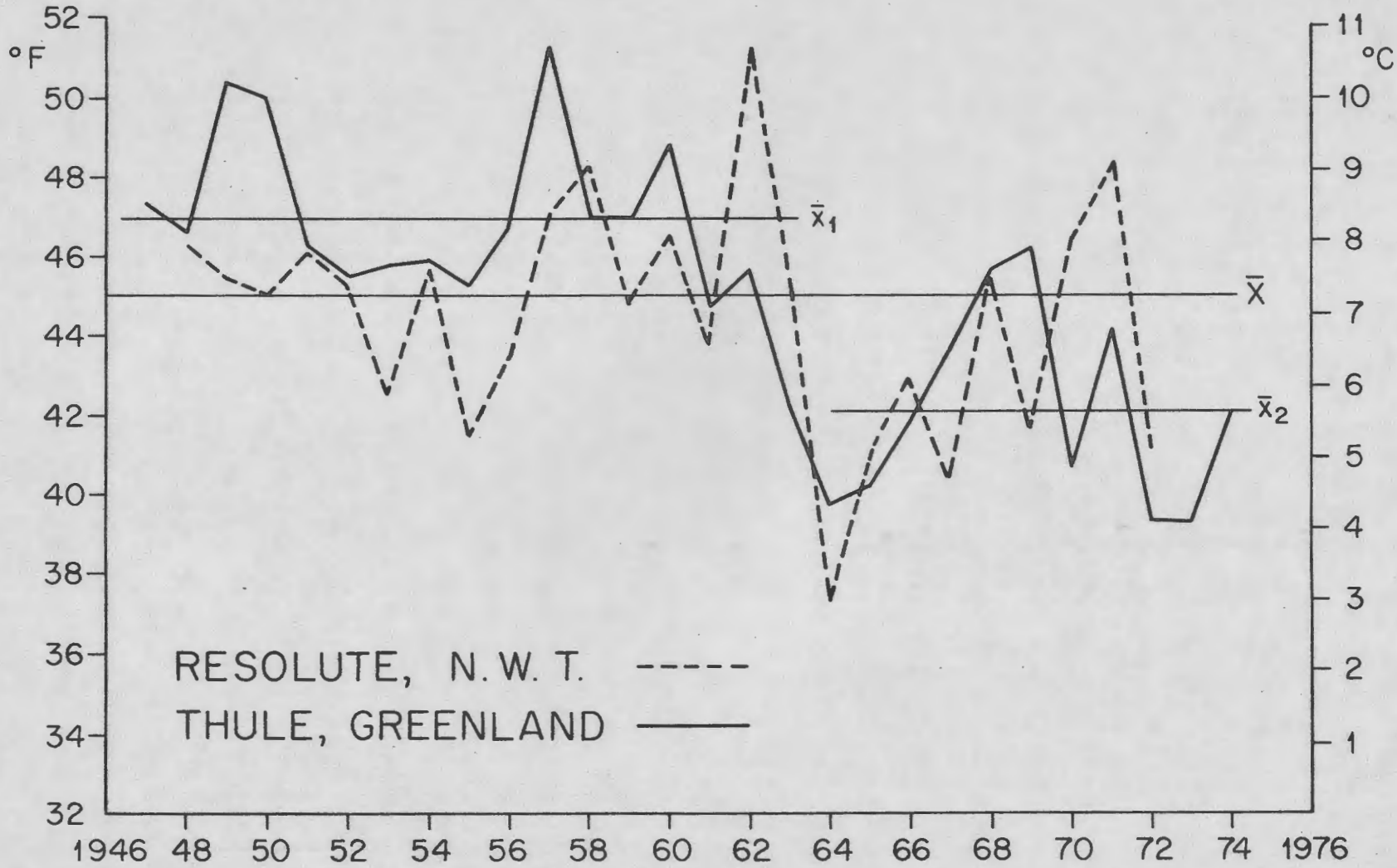


Figure 3.2 Mean July maximum temperatures at Thule and Resolute. Line $\bar{x}_1$ denotes average temperature at Thule up to 1963; $\bar{x}_2$ denotes average 1964 to 1974. $\bar{X}$ is overall mean.

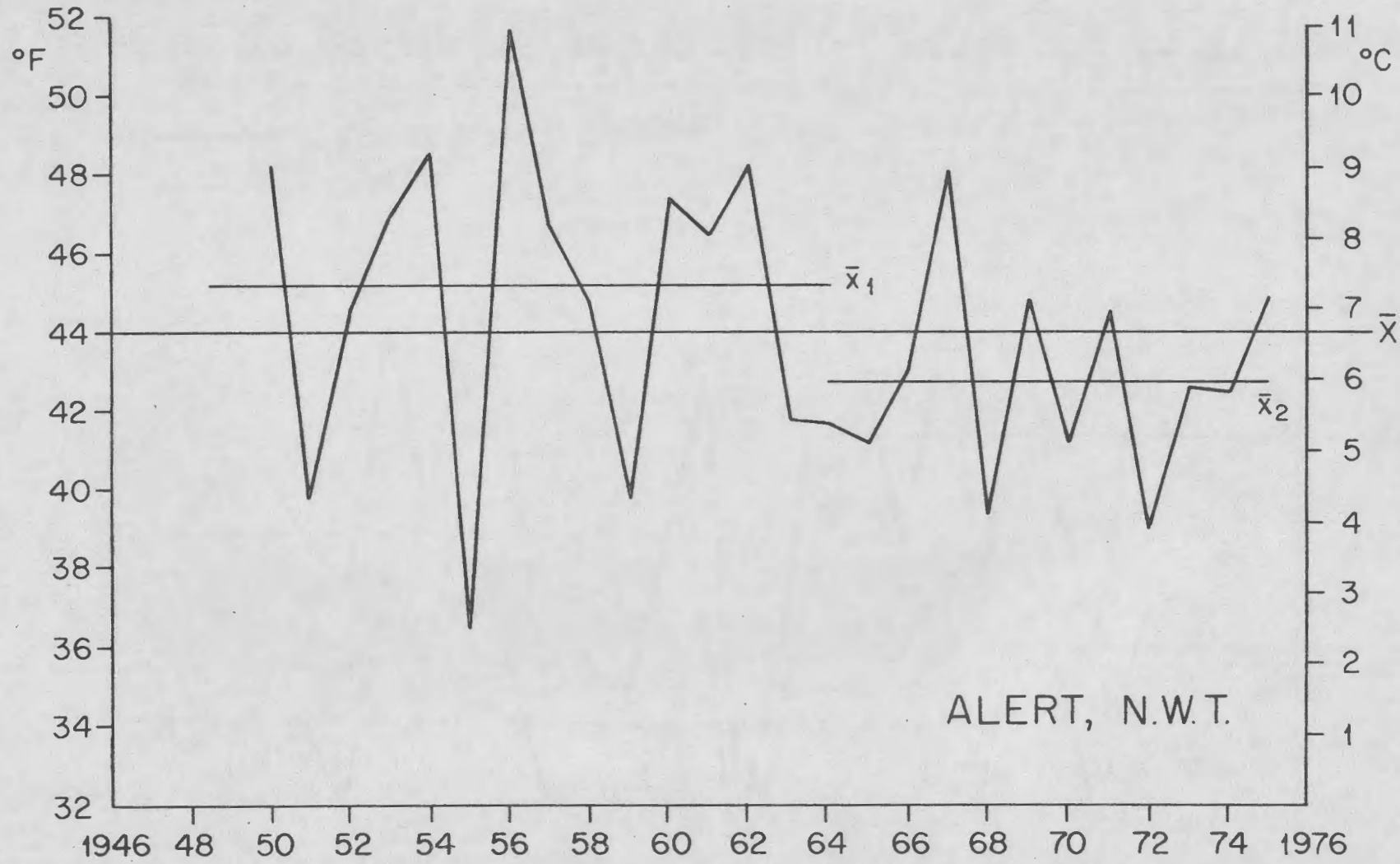


Figure 3.3 Mean July maximum temperatures at Alert. Line $\bar{x}_1$ denotes average at Alert up to 1963; $\bar{x}_2$ denotes average 1964 to 1974. $\bar{X}$ is overall mean.

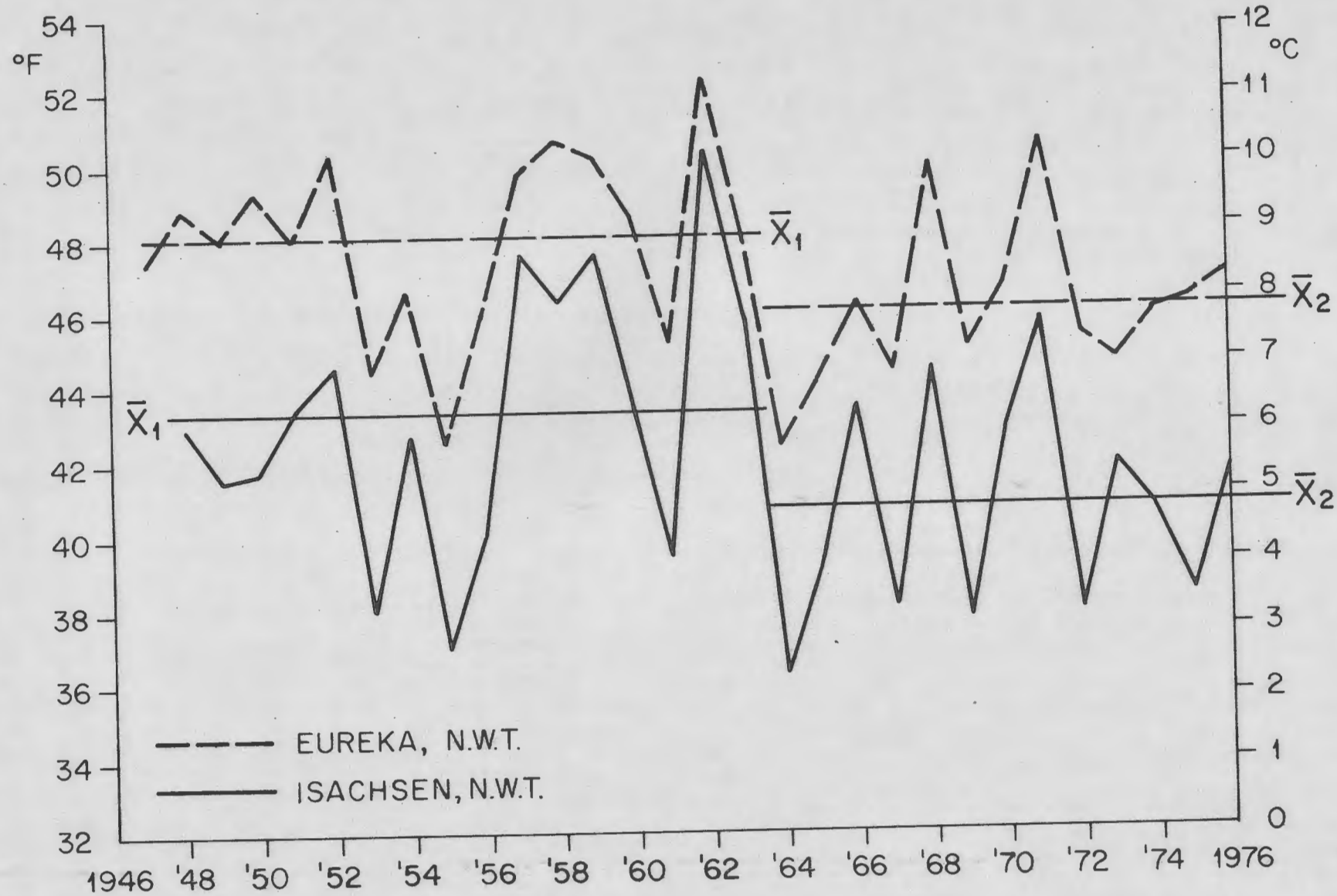


Figure 3.4. Mean July maximum temperatures at Eureka and Isachsen. Lines $\bar{x}_1$ denote average for period up to and including 1963; $\bar{x}_2$ denotes average from 1964 to end of record.

influenced by changes in the frequency of extremely warm summer days. At Alert, for example, there were 32 days with Tmax >15.5°C during the period 1950-1963 (an average 2.3 days per year) whereas in the period 1963 - 1976 there have been only 4 such days in total. Since 1963 average absolute monthly maxima at Alert have fallen by 1.8° and 2.4°C in June and July, respectively, while at Isachsen the corresponding changes are even greater (Table 3.3).

Although these data indicate a significant change in the temperature of the warmest month of the year, it should not be assumed that this aptly summarises the entire picture of ablation season conditions, as the total melt season duration may vary widely from year to year.

LENGTH OF THE MELT SEASON

Although temperatures >0°C may occasionally be recorded in mid-winter months during periods of extreme warm air advection (Thomas and Titus, 1958) daily records indicate that the melt season (when Tmax >0°C) is generally a fairly continuous period with few interruptions. To avoid those infrequent warm days in mid-winter (e.g. Feb. 26, 1965 when Tmax at Alert was +1.1°C) the 'melt season' was defined to be the length of time from the first two consecutive days with Tmax >0°C in the spring to the last such days in the fall.[3] The average duration of the melt season, so defined, is shown in Table 3.4 The shortest

3. Anomalies early and late in the year were avoided by specifying that there must be another occurrence of above freezing temperatures within one month (after the event in the Spring, before the event in the Fall) before it could be counted as either initiating or terminating the melt season. At Thule this one criterion was changed to 10 days because of the higher frequency of occasional isolated warm days in the early Spring and late Fall.

TABLE 3.3

CHANGE IN MEAN MONTHLY ABSOLUTE MAXIMUM TEMPERATURE (°C)

		a) Start of record to 1963	b) 1964 to end of record	Change (b - a)
Alert (1950 -76)	June	10.1	8.3	-1.8
	July	15.8	13.4	-2.4
Isachsen (1948-76)	June	8.6	6.5	-2.1
	July	13.7	11.2	-2.5
Resolute (1948 -76)	June	8.5	6.2	-2.3
	July	13.9	12.2	-1.7

TABLE 3.4

AVERAGE DURATION OF MELT SEASON[1]

Station	1st of 2 consecutive Tmax > 0°C	Stand. devn. (days)	Latter of 2 consecutive Tmax > 0°C	Stand. devn. (days)	Average length of melt season (days)	Stand. devn. (days)
Isachsen	June 7	6	Aug. 31	7	86	10
Alert	June 2	11	Sept. 1	9	92	16
Resolute	June 4	9	Sept. 7	9	96	13
Eureka	May 30	10	Sept. 6	8	100	12
Thule	May 21	12	Sept. 20	9	123[2]	13

Extremes	Longest Season (days)	Shortest Season (days)
Isachsen	101 (1957)	70 (1956, 1967, 1972)
Alert	120 (1968)	66 (1956)
Resolute	120 (1952)	69 (1956)
Eureka	126 (1955)	76 (1956)
Thule	147 (1952)	90 (1961)

1. Averages for period of record shown in Table 1.

2. An average of 5-6 additional days per year experienced T max > 0°C (ranging from 0 to 14 additional days per year).

melt season, on average, is experienced at Isachsen in the northwestern sector of the Queen Elizabeth archipelago, where mean summer temperatures are also lowest. The average daily temperature at Isachsen during the melt season (as defined above) is only 1.6°C. Although additional climatic data from this region are virtually non-existent it seems likely that the low glaciation levels along northern Axel Heiberg and northwestern Ellesmere Island are in part the result of these very brief, cool ablation seasons. (c.f. Arnold, 1965; Alt, 1975). By contrast, at the northern end of Baffin Bay, melt seasons average almost 50% longer than at Isachsen, with Thule having a melt season of approximately 4 months. In addition, above freezing temperatures have been recorded in every month of the year (averaging 5 to 6 such occurrences per year). Temperatures as high as 6.1°C have been recorded in February (e.g. 2/24/65). Such extremes are clearly related to Thule's position at the northern end of Baffin Bay where both warm air advection from the south and the presence of the North Water (Dunbar, 1969) ameliorate the mid-winter climate (Figure 3.1).

Of particular interest in Table 3.4 is the melt season duration at Eureka which averages 2 weeks longer than at Isachsen ∿380km to the south east, and 4 days longer than at Resolute over 600km to the south. It can indeed be claimed that Eureka is "The Garden Spot of the High Arctic" (Eureka Weather Service Office Motto)! This relatively long melt season is presumably due to its more continental location (Figure 3.1) away from cool maritime influences and their associated coastal fogs and low cloud which so frequently affect the northwestern margins of the archipelago (Alt, 1975).

It is clear from Table 3.4 that at all stations except Thule, the melt season closely approximates the months of June, July and August and hence it might be assumed that the mean temperature of these months would be a useful index of ablation season conditions. At Alert, for example, mean temperature of the melt season (1951-74) was +1.6°C whereas the June-August mean for the

same period was +1.3°C. However, Table 3.4 also shows that both the onset and termination of the melt season may vary considerably from year to year. Extremely cool summers (e.g. 1956, 1972) may reduce the duration of the melt season by ∿25%. Thus, at Alert in 1956 the melt season did not begin until June 15, a week before the summer solstice, and was over by August 19. In other years, the melt season length may be up to 30% longer than average; in 1968 for example the melt season was almost twice as long as in 1956. Yet in 1956 Alert had the warmest mean July Tmax on record and in 1968 one of the coldest (Figure 3.3). Hence neither July Tmax nor the mean temperature of the period June to August can be assumed to closely reflect ablation season temperature conditions from one year to the next and a more suitable index must be sought.

MELTING DEGREE DAYS

A more useful index of summer ablation may be given by the annual melting degree day total (MDD). A melting degree day is the difference between 0°C and the daily mean temperature when the latter is above 0°C. The index is commonly computed on the mean temperature $\frac{(Tmax + Tmin)}{2}$ but this has some limitations (Arnold and MacKay, 1968) and a more meaningful index is given by computing the index for Tmax and Tmin separately (Figure 3.5). The index takes into account both melt season length and the accumulated warmth of the season.

Table 3.5 gives long-term mean Tmax and Tmin MDD for the stations under consideration. Isachsen has the lowest total with only 404 MDD (Tmax + Tmin). Alert and Resolute have surprisingly similar MDD totals considering Alert is >900km further north (only 36 MDD (Tmax + Tmin) difference on average). Once again Eureka stands out as exceptionally warm in the summer - almost double the MDD total at Isachsen and almost equal to that at Thule. This high total is due not only to higher daily maxima but also to more frequent cases of minimum

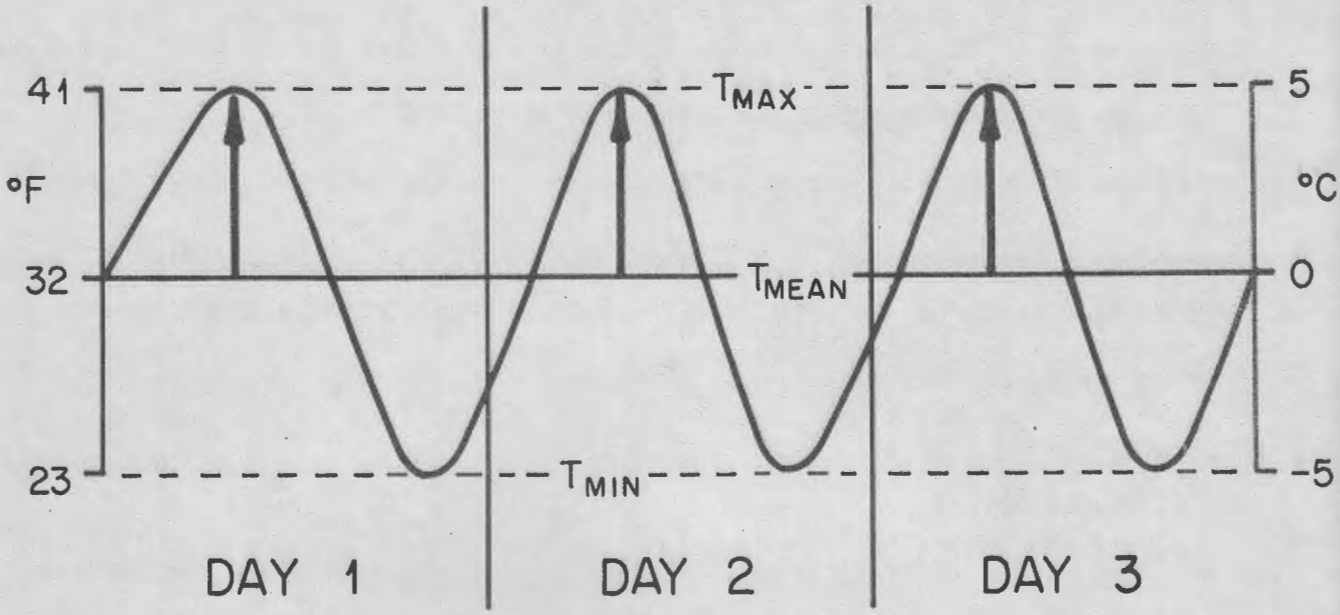


Figure 3.5 Schematic diagram illustrating the importance of computing melting degree day totals on T_{max} and T_{min} separately. If data were computed on T_{mean} in the period illustrated, zero MDD would be registered when in reality temperatures were >0°C for much of the time. ($\Sigma T_{max} = 15; \Sigma T_{min} = 0$)

TABLE 3.5

AVERAGE ANNUAL MELTING DEGREE DAY TOTALS (°C)

Station	Record length	Tmax > 0°C	Tmin > 0°C	ΣTmax + Tmin > 0°C
Isachsen	1948-76	347	58	404
Alert	1951-76	411	61	472
Resolute	1948-76	456	91	508
Eureka	1948-76	604	156	760
Thule	1947-74	640	167	807

TABLE 3.6

CHANGE IN AVERAGE ANNUAL MELTING DEGREE DAY TOTALS (Tmax + Tmin, °C)[1]

Station	1st complete annual record	Mean: Start of record to 1963	Mean: 1964-76	%[2]
Thule	1947	937	604[3]	65
Eureka	1948	808	702	87
Resolute	1948	616	462	75
Alert	1951	505	440	87
Isachsen	1948	458	339	74

1 Multiply by 1.8 for values in °F > 32°F

2 Post-1963 average as a % of pre-1964 average

3 1964-74 inclusive

temperatures remaining above the freezing point. At Eureka and Thule temperatures may remain continuously above 0°C for several weeks.

Of particular interest for mass balance studies in the area is the annual melting degree day total since records began (Figures 3.6a & 3.6b). Again these data indicate an abrupt change in the summer climate of the region occurred between 1963 and 1964. At all stations, inter-annual variability is high but MDD totals since 1963 have fallen significantly (Table 3.6). This is most apparent at Thule where mean Tmax MDD totals (1964-1974) were only 67% of the average from 1947 to 1963. Tmin MDD totals (1964-1974) were only 56% of 1947 to 1963 averages with the greatest changes occurring in the months of June and July. At Isachsen (Tmax + Tmin) MDD totals were 74% of 1948-63 values in 1964-75 and at Resolute, Alert and Eureka the corresponding figures were 75%, 87% and 87% respectively.

MELTING DEGREE DAYS AND GLACIER MASS BALANCE

It is clear from the above discussion that there was a significant change in summer temperatures in the High Arctic during the 1960s and early 1970s. Yet it has been argued that mass balance measurements from the north western sector of the Devon Ice Cap (taken since 1960, and comprising the longest such series of observations in the Canadian Arctic) show no evidence of a cooling trend (Koerner, 1977). Has the change in climate affected glacier mass balance in the region? Figure 3.7 shows the relationship between Devon Island mass balance since 1960/61 and average melting degree day indices at Thule and Resolute (∿400km to the east and ∿350km to the west of the Ice Cap, respectively). The series are highly correlated ($P<0.001$) indicating the strong influence summer temperature conditions exert on glacier mass balance. Using the regression equations, mass balance on the NW Devon Ice Cap can be reconstructed back to 1947-48, when instrumental observations were first made at both Thule and

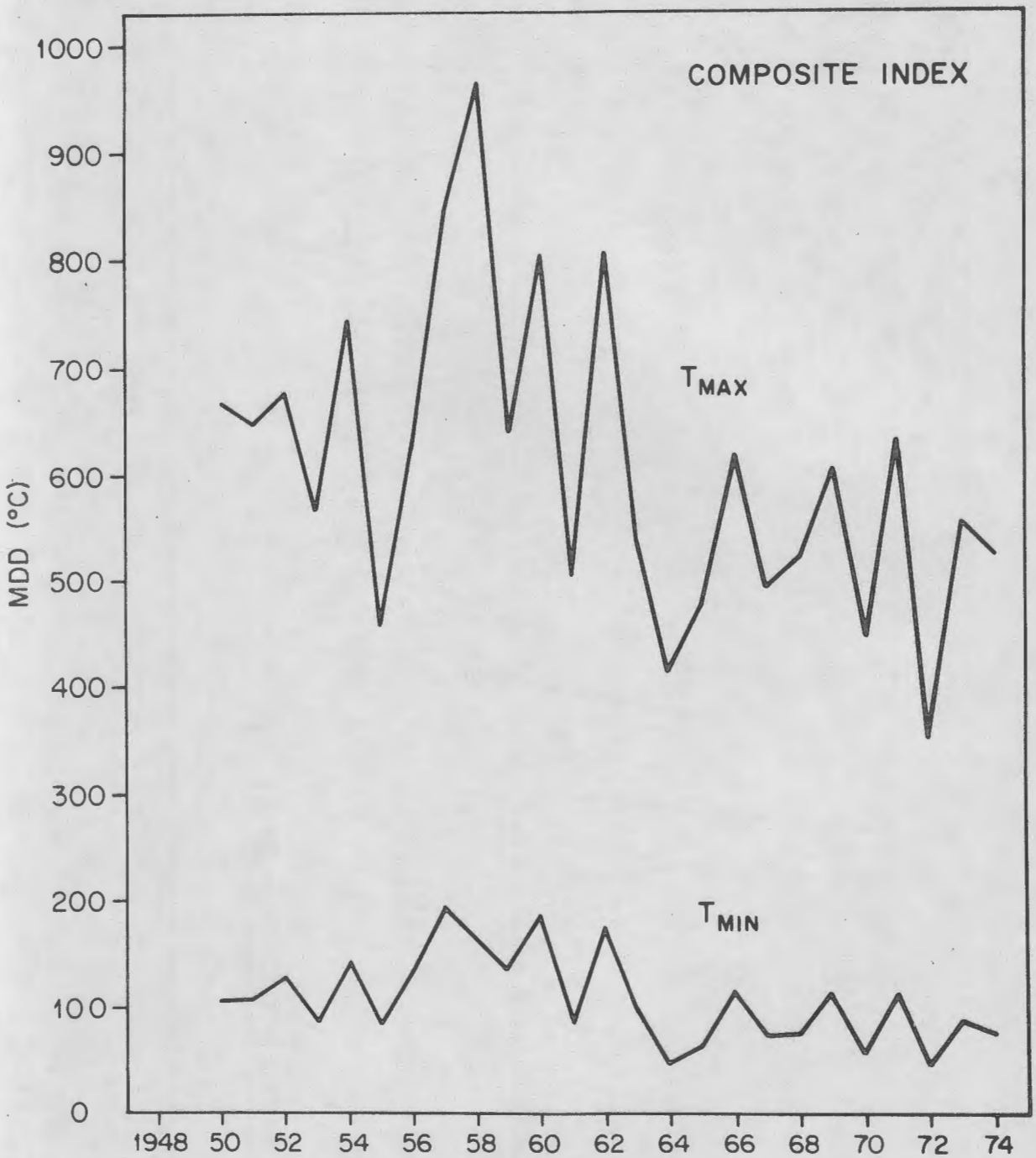


Figure 3.6a) T_{max} and T_{min} melting degree day totals per year averaged for Alert, Eureka, Isachsen, Resolute and Thule.

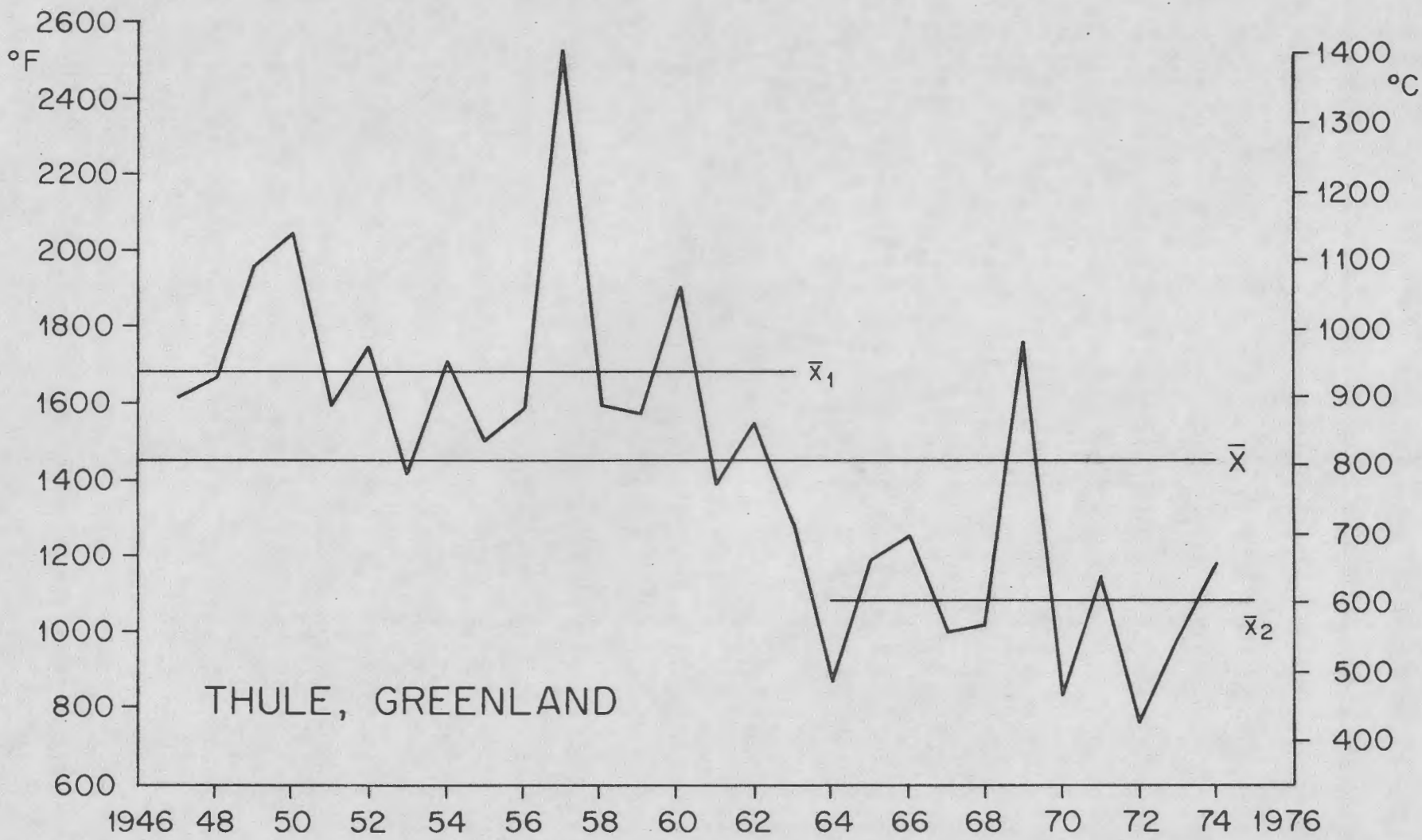
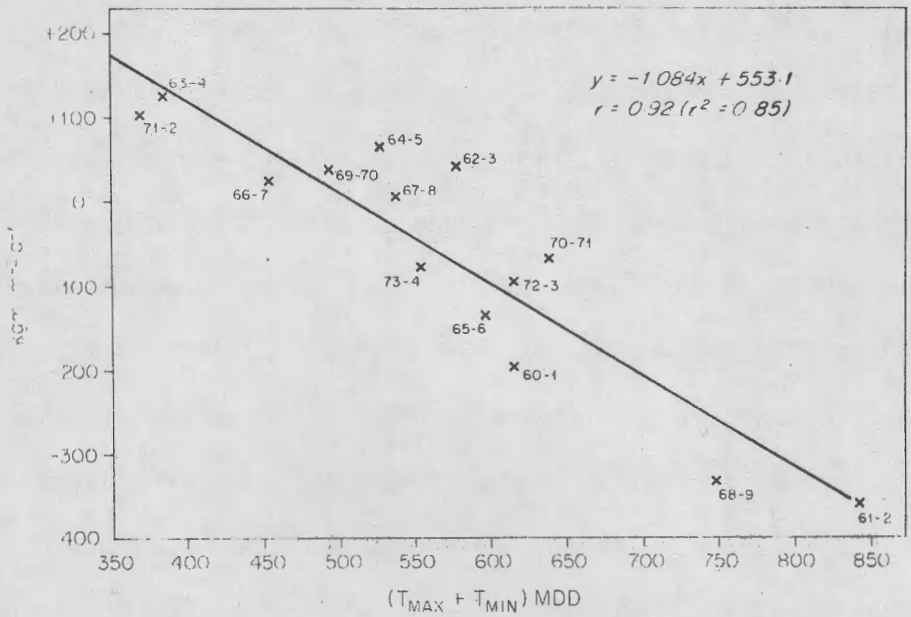


Figure 3.6b) Annual ($T_{max} + T_{min}$) melting degree day totals at Thule showing marked decline in totals after 1963.



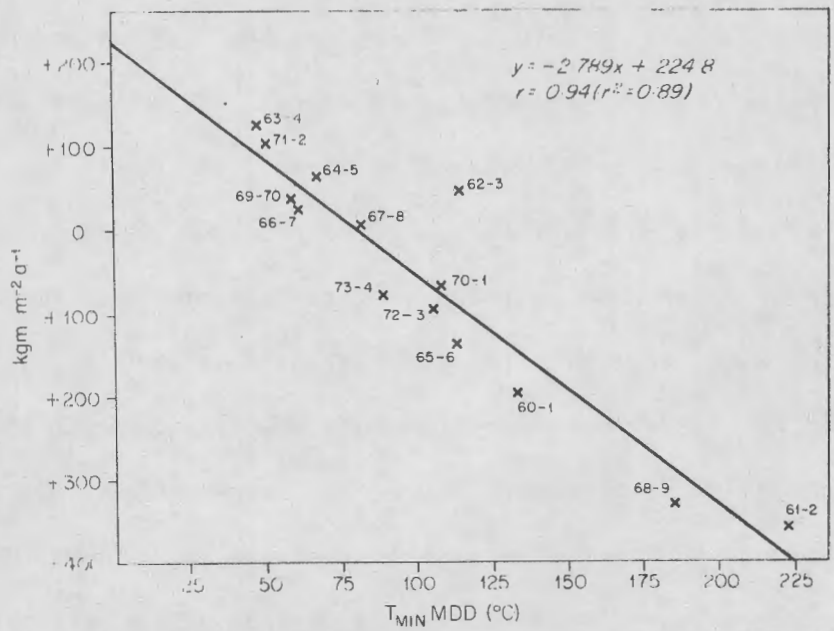


Figure 3.7 Regression of mass balance on the northwest sector of the Devon Ice Cap (Koerner,1977) and:(a) average of (T_{max} + T_{min}) melting degree day totals at Thule and Resolute (b) average of T_{min} melting degree day totals at Thule and Resolute.

Resolute (e.g. Figure 3.8). From this diagram the recent period can be placed in perspective and the post-1963 change is seen to be highly significant. Between 1947 and 1963 the ice cap continuously lost mass with greatest losses occurring in the late 1950s. In the last decade, positive balance years have outnumbered negative balance years though overall there has still been a mass loss since 1963. This is seen clearly in Figure 3.9 where cumulative mass losses since 1947 are shown. Between 1947/48 and 1963/64 it is estimated that the Devon Ice Cap lost 3500 kgm m^{-2} whereas since 1963/64 the net loss has been < 350 kgm m^{-2}. Similar studies using the only other long series of mass balance data in the High Arctic (from the White Glacier, Axel Heiberg Island) show these results are probably typical of a wide area of the North American High Arctic. Thus the change in climate since 1963 has indeed had a significant impact on snow and ice bodies of the region.

It is interesting to note that although positive balance years have occurred as frequently as negative balance years since 1963 an individual negative year (such as 1969) may obliterate the total mass gains of all the positive years together (Figure 3.8). However, the reconstruction shown in Figure 3.8 is based on a linear regression equation (Figure 3.7) derived from a limited data set. Studies with other climatic indices indicate that a curvilinear relationship may give a more appropriate model when greater extremes are considered, as shown schematically in figure 3.10. The form of this relationship suggests that mass balance is limited in a positive sense by accumulation whereas negative mass balance is relatively unlimited; or to take it to extremes, an ice cap may lose substantial amounts of snow, firn and ice each year whereas it can never gain more mass than it accumulates in any one balance year. Hence, with such skewed distribution to mass balance (where an 'average' negative year can remove the accumulated gains of many positive years) the critical control on ice cap growth must inevitable be precipitation. Only if accumulation on the Devon

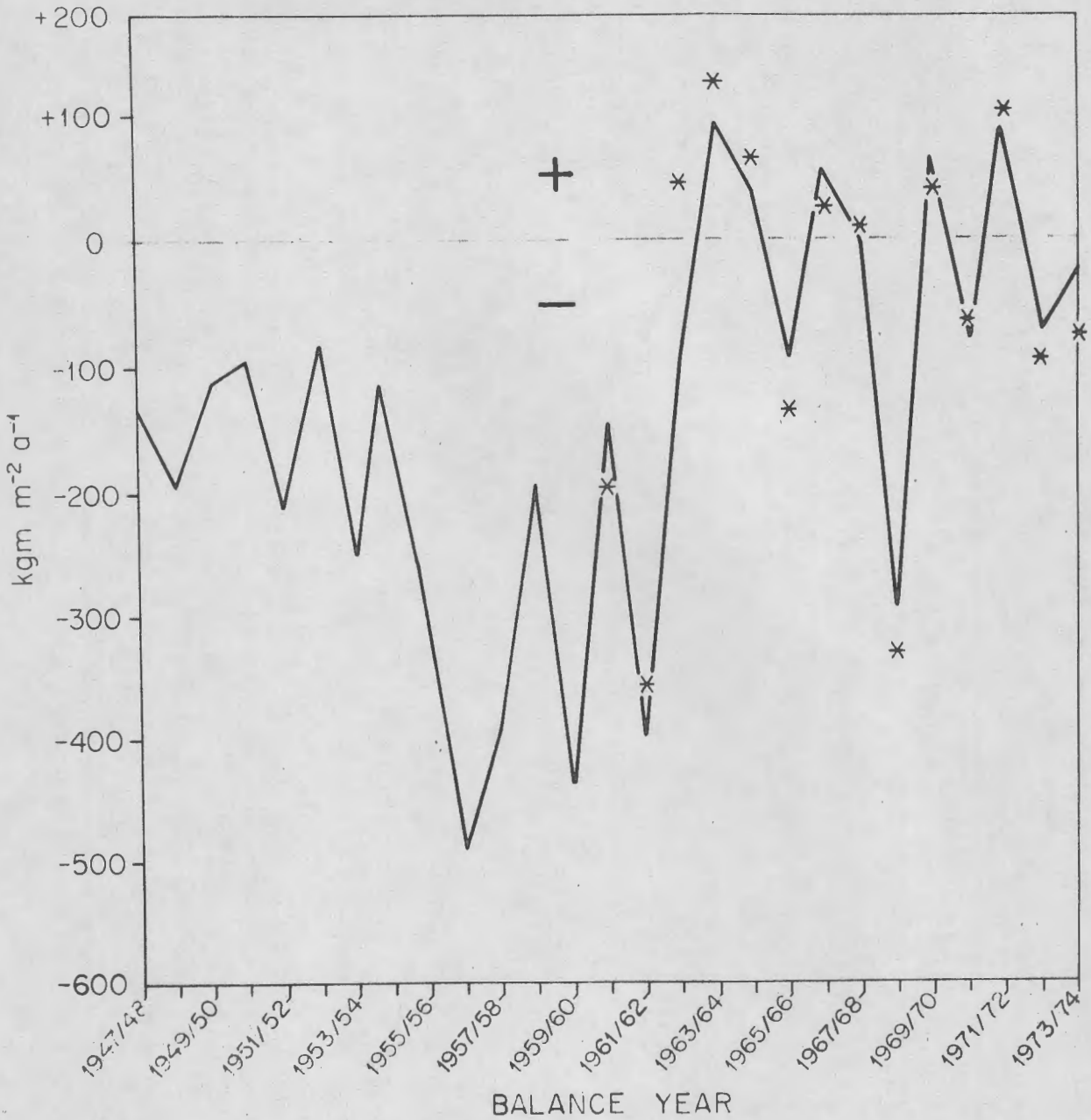


Figure 3.8 Reconstruction of mass balance on the northwest sector of the Devon Ice Cap based on the regression equation in Figure 3.7b). Asterisks denote measured mass balance values (Koerner,1977).

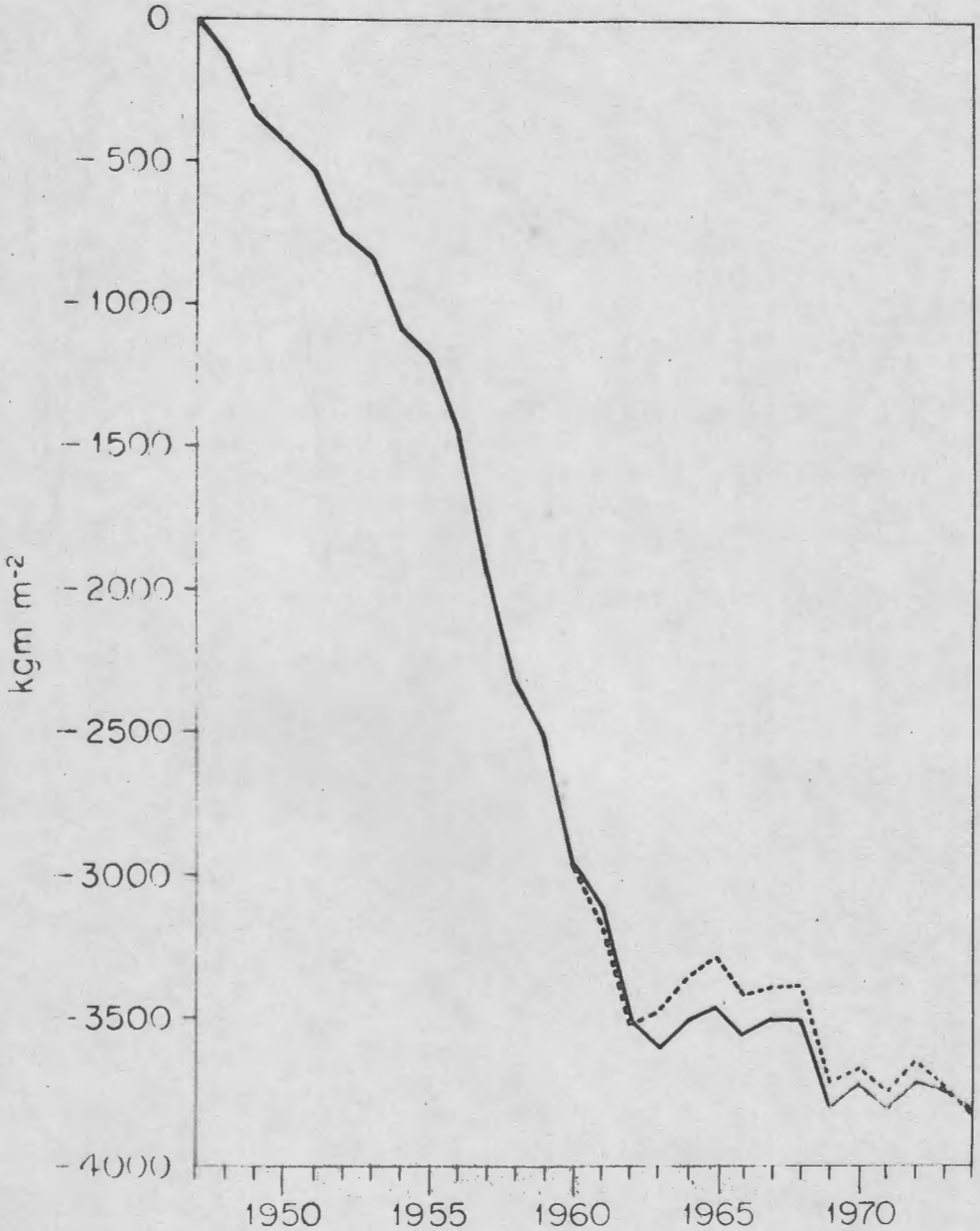


Figure 3.9 Reconstruction of cumulative mass losses on the northwest sector of the Devon Ice Cap since 1947. Dashed lines indicate cumulative values since 1961 if measured values (Koerner,1977) are used.

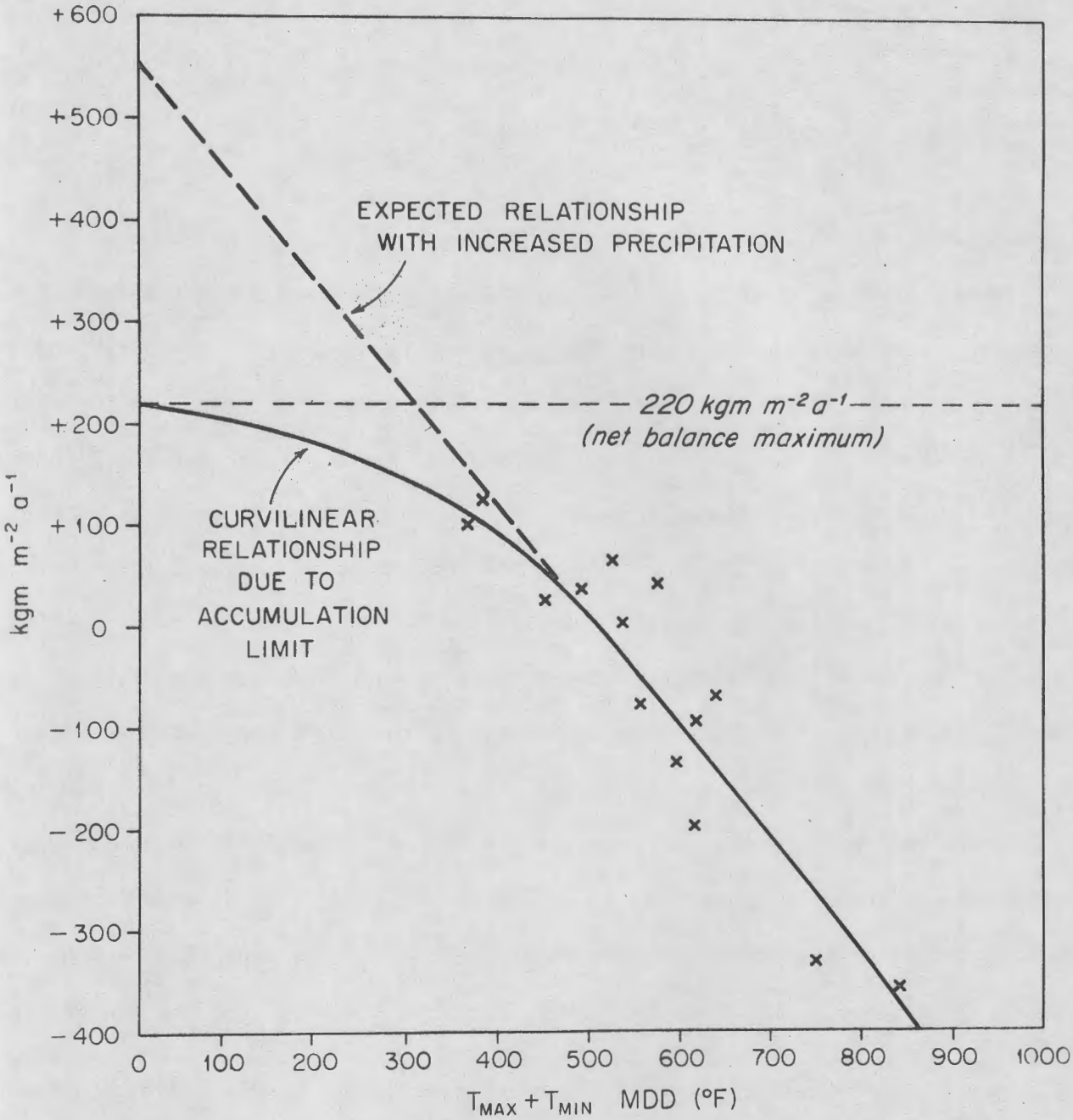


Figure 3.10 Schematic diagram illustrating the probable relationship between mass balance and melting degree day totals at extremely low MDD values under the accumulation conditions of recent years. For the relationship to remain approximately linear, where an'average' positive balance year would be approximately equal in magnitude to an 'average' negative balance year, precipitation amounts would have to be considerably higher.

Ice Cap increases can the curvilinear relationship shown in Figure 3.10 approach a linear relationship in which an 'average' positive year can balance an 'average' negative balance year. Significant growth of the ice sheet is thus unlikely without increased accumulation.

PRECIPITATION

MEASUREMENT PROBLEMS

Precipitation in arctic areas is difficult to measure accurately and it has been suggested that absolute ammounts of snowfall are greatly underestimated (Hare and Hay, 1971). Furthermore, in the early 1960s, Canadian precipitation measuring procedures were altered following the widespread introduction of 'type 3' Nipher shielded precipitation gauges (Potter, 1964). Prior to this change in instrumentation (which varied from station to station, Table 3.7 snowfall was measured every 6 hours and assumed to have a density of 0.1 (i.e. 10mm of snow = 1 mm of precipitation). After 1960 (or the date type 3 Nipher gauges were installed, if after 1960) snow was collected in the gauge and melted to obtain a water equivelant measurement.[4]

This change in recording procedure introduces a significant discontinuity into the precipitation record as indicated by an analysis of snow densities in the period after the procedural change (Table 3.8). Mean monthly snow densities are generally lower than 0.1, the figure formerly assumed. For the winter months,

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4. Monthly snow density analysis indicates recording procedures did not change on the dates indicated by Potter (1964) at Isachsen and not until 5/63 at Resolute. At Isachsen it appears that procedural changes were not initiated until 5/66. Furthermore, at all stations, the procedure does not appear to have been consistently adhered to; densities of 0.1 were commonly used for a run of months -or even years (eg. at Eureka form 10/68 to 8/70) and then a change to values $\neq$ 0.1 commonly occurred. In computing values for Table 3.8 all density values were used; hence it is likely that the densities in that table are maximum estimates.

TABLE 3.7

Dates on which Nipher shielded snow guages were installed at Canadian stations (from Potter, 1964)

Alert	July 1963
Isachsen	? 1962
Eureka	September 1963
Resolute	? 1952/53

TABLE 3.8

Monthly mean snow densities (to June 1975) after introduction of water-equivelant recording procedure[1].

	Period starts	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Alert	7/63	.092	.091	.096	.093	.070	.095	.104	.097	.079	.080	.096	.094
Isachsen	5/66	.101	.099	.095	.099	.089	.106	.098	.099	.093	.090	.099	.098
Eureka	9/63	.084	.083	.087	.090	.084	.091	.100	.096	.088	.087	.084	.085
Resolute	5/63	.093	.094	.094	.088	.082	.098	.104	.098	.091	.090	.097	.095

1. $\text{Density} = \frac{\text{(Total Precipitation - Rainfall)}}{\text{snowfall}}$

November-April, densities average ∿5% lower than assumed and in the heavy precipitation months of May, September and October actual densities average ∿15% less than 0.1. Snow densities are lowest overall at Eureka, the most continental locality. The significance of this is that prior to the recording of snowfall water equivelants, total precipitation amounts were overestimated relative to later measurements and in considering precipitation variations over time this factor must be taken into account.

A further problem with precipitation data concerns the frequent occurrence of 'Traces' in the records of Arctic weather stations. Jackson (1960) has pointed out that the practice of recording precipitation every 6 hours may lead to underestimation of daily total precipitation (ie: four 6-hourly Traces =1 (daily) Trace, rather than any finite total). 'Traces' are commonly recorded for the daily precipitation total, particularly in mid-winter months (Table 3.9a). If a trace is assumed to be half of the lowest amount normally recorded (ie: 0·005 inches, 0·127mm) annual precipitation totals increase by +8 to +26%(Table 3.9b).This is clearly an important difference and it seems likely that annual precipitation amounts in the High Arctic are being underestimated (at least in part) because of the high frequency of Traces. An adjustment based on this fact may account for some of the discrepancy noted by Hare and Hay (1971) between recorded annual precipitation and measured runoff.

PRECIPITATION VARIATIONS

Table 3.10 shows monthly precipitation as a percentage of annual totals. At all stations, the bulk of precipitation falls in the four months July-October (∿47 to 66% of annual totals) and a significant proportion of this falls in the form of snow during the melt season, increasing albedo and retarding ablation. In order to investigate precipitation fluctuations through time, snowfall amounts during the period when densities were assumed to be 0.1 were adjusted to the densities given in Table 3.8 The data were then combined into two seasonal precipitation totals:

TABLE 3.9

a.) Percentage of days per month with precipitation total recorded as a Trace

	Period	J	F	M	A	M	J	J	A	S	O	N	D
Alert	5/51-6/75	40	34	27	23	25	24	17	15	19	25	30	36
Eureka	5/47-6/75	46	46	42	30	25	23	21	20	30	35	44	48
Isachsen	5/48-6/75	48	50	41	40	36	42	30	29	34	40	44	54
Resolute	10/47-12/72	49	51	43	39	40	39	28	30	41	39	52	54
Thule	11/6/75	32	31	32	28	34	32	21	21	29	31	35	30

b.) Comparison of presently recorded annual precipitation and Annual precipitation assuming 'Traces' = 0.127mm

	Period	a) Traces=0.127mm	b) Traces excluded	a/bX100%
Alert	5/51-6/75	169.7	157.5	108
Eureka	5/47-6/75	76.2	60.4	126
Isachsen	5/48-6/75	124.8	105.2	119
Resolute	10/47-12/72	153.8	134.3	114
Thule	11/51-12/70	153.0	138.8	110

TABLE 3.10

Monthly Precipitation as a Percent of Annual Total

	Resolute (10/47-12/72)	Isachsen (5/48-6/75)	Eureka (5/47-6/75)	Alert (7/50-6/75)	Thule (11/51-12/70)
J	2.1	2.7	4.9	4.5	8.0
F	2.5	2.4	4.1	3.2	8.3
M	2.3	2.3	3.4	4.6	3.7
A	4.3	4.1	3.7	4.6	4.0
M	6.5	8.7	5.0	6.9	8.3
J	9.0	7.7	6.6	8.8	4.6
J	18.8	19.5	20.6	12.8	13.5
A	23.3	20.5	16.4	17.4	11.2
S	12.8	15.7	16.2	17.5	10.4
O	10.9	9.9	11.3	9.5	11.5
N	4.0	4.4	4.3	5.3	9.2
D	3.5	2.3	3.5	5.0	7.4
Mean Annual Precipitation					
(mm)	134.3	105.2	60.4	157.5	138.8
(inches)	5.3	4.1	2.4	6.2	5.5

July to October and November to June (Figures 3.11 to 3.15). Although abrupt changes in the precipitation record are not as apparent as in the temperature record (perhaps due to the greater variability of inter-annual precipitation amounts) the data have been divided into comparable periods (Table 3.11). At all stations, November - June precipitation has increased although overall amounts have remained quite low (generally <80 mm). In the summer and early winter months (July-October) precipitation amounts have also increased at Alert and Isachsen but no change was recorded at Resolute and at Eureka average precipitation actually declined. At all stations, however, annual precipitation totals have increased, with a maximum change of + ~ 50 mm at Alert. These increases alone are important for glacier mass balance in such an arid environment, but when the fall in summer temperature is also considered, it is clear that this recent change in the climate of the Canadian High Arctic has particular significance.

RECENT CLIMATIC CHANGE AND VOLCANIC DUST

An important aspect of the recent change in the climate of the Canadian High Arctic is the relatively abrupt shift which occurred around 1963-64. This is particularly well illustrated in Figure 3.6b and it was noted in upper air data by Bradley (1973). Also of interest in this regard is the recent study of 1000-500 mb thickness (for the area shown in Figure 3.16a) by Dronia (1972). Although Dronia's observations were biased towards high latitudes (by using data from a uniform latitude-longitude grid) the results (Figure 3.16b) show a marked change in the climate of the northern hemisphere around 1963-64 with predominantly negative 1000-500 mb thickness departures (from the 1949-73 mean) after 1963.

It is suggested that these changes are related to a massive input of volcanic dust into the upper atmosphere as a result of the eruption of Mt. Agung (8°S, 115°E) in 1963. Lamb (1972) indicates that the total dust veil in the

TABLE 3.11

Seasonal Precipitation Totals

(snowfall, adjusted for density and rainfall) in mm.

July - October

Station	Period	% of $\bar{x}$ Annual Precip	a) Start of Record to 1963	s	b) 1964 to 1976	s	Change (b-a)	%[1.]
Alert	1951-76	57	74.9	28.8	96.4	26.8	+21.5	129
Isachsen	1948-76	66	65.8	26.3	75.3	35.9	+9.5	114
Eureka	1948-76	65	41.0	24.7	35.6	10.0	-5.4	87
Resolute	1948-76	66	86.0	22.6	86.3	32.2	+0.2	100
Thule [2]	1952-74	47	66.7	40.9	59.9	20.6	-6.8	90

November-June

Station	Period	% of $\bar{x}$ Annual Precip	a) Start of Record to 1962/3	s	b) 1963/4 to 1975/6	s	Change (b-a)	%[1.]
Alert	1950/1 -75/6	43	50.3	18.2	79.5	23.5	+29.2	158
Isachsen	1948/9 -75/6	34	28.0	14.0	47.8	16.8	+19.8	171
Eureka	1947/8 -75/6	35	17.6	10.0	24.9	5.2	+7.2	141
Resolute	1947/8 -75/6	34	42.9	13.6	46.8	16.5	+3.9	109
Thule [2]	1951/2 -74/5	53	65.5	38.1	79.5	31.5	+14.0	121

1. Period b as a % of period a.
2. Thule data not adjusted for density; rainfall is not recorded separately so for much of the year snowfall density can not be calculated.

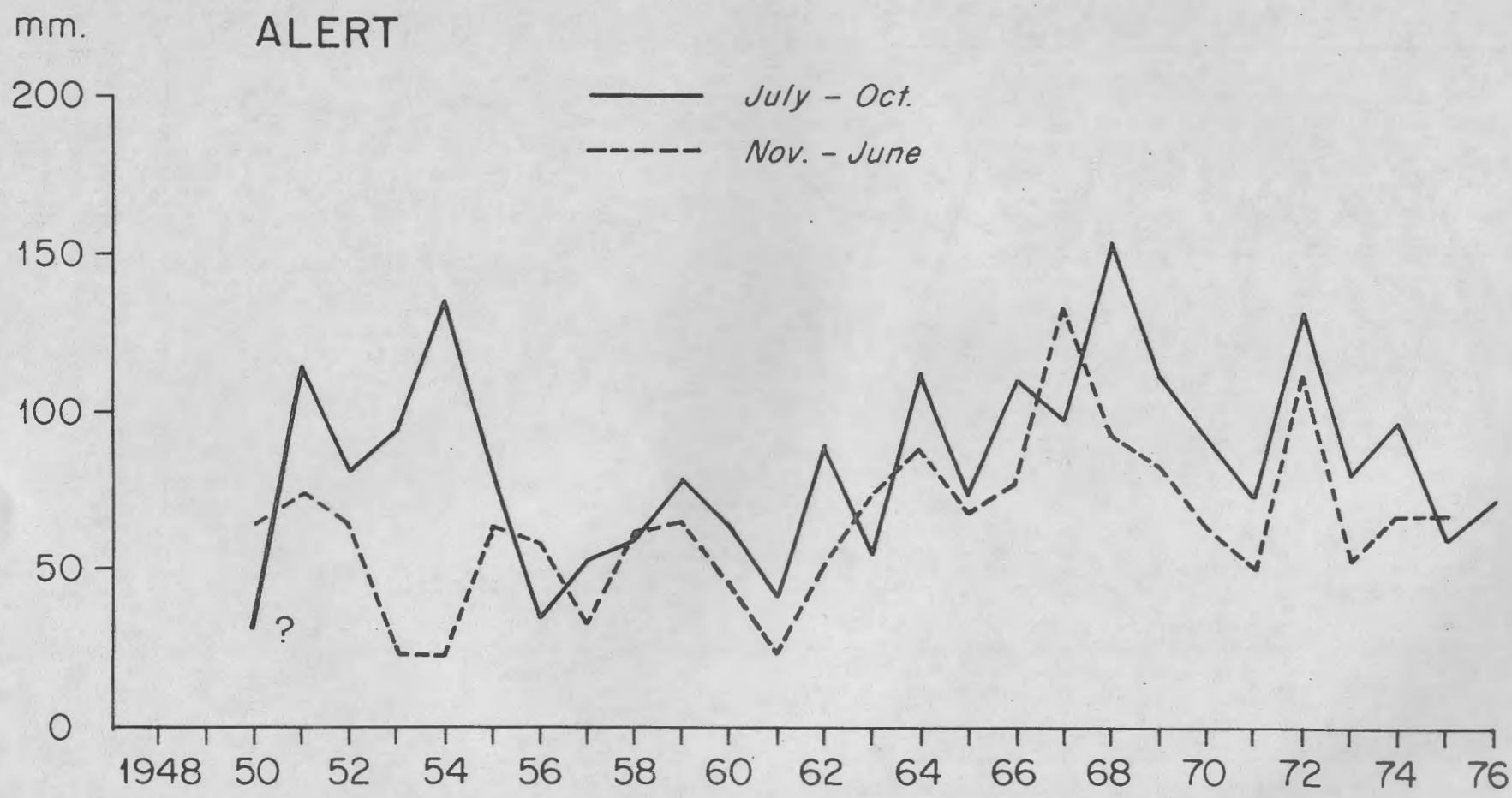

Figure 3.11 Seasonal precipitation totals at Alert adjusted for snow density before July 1963 as explained in the text.

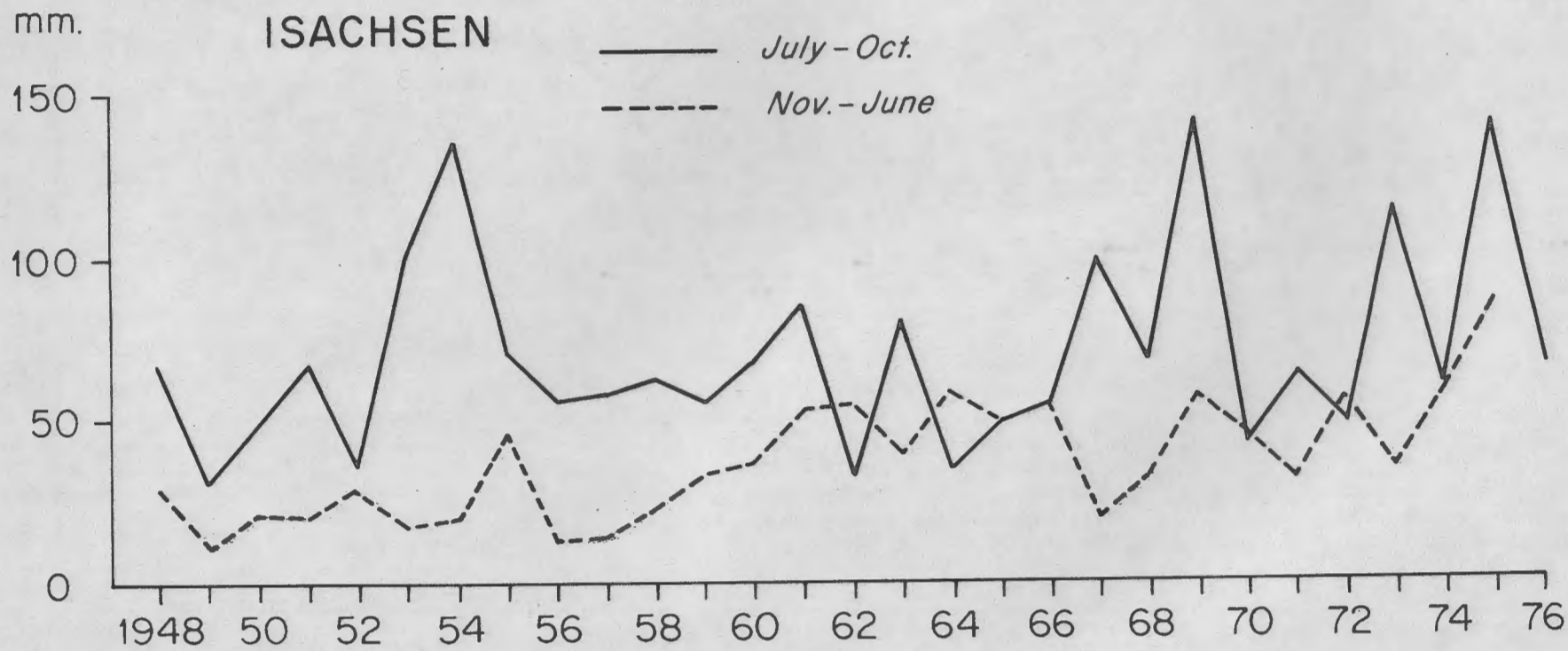

Figure 3.12 Seasonal precipitation totals at Isachsen adjusted for snow density before May 1966 as explained in the text.

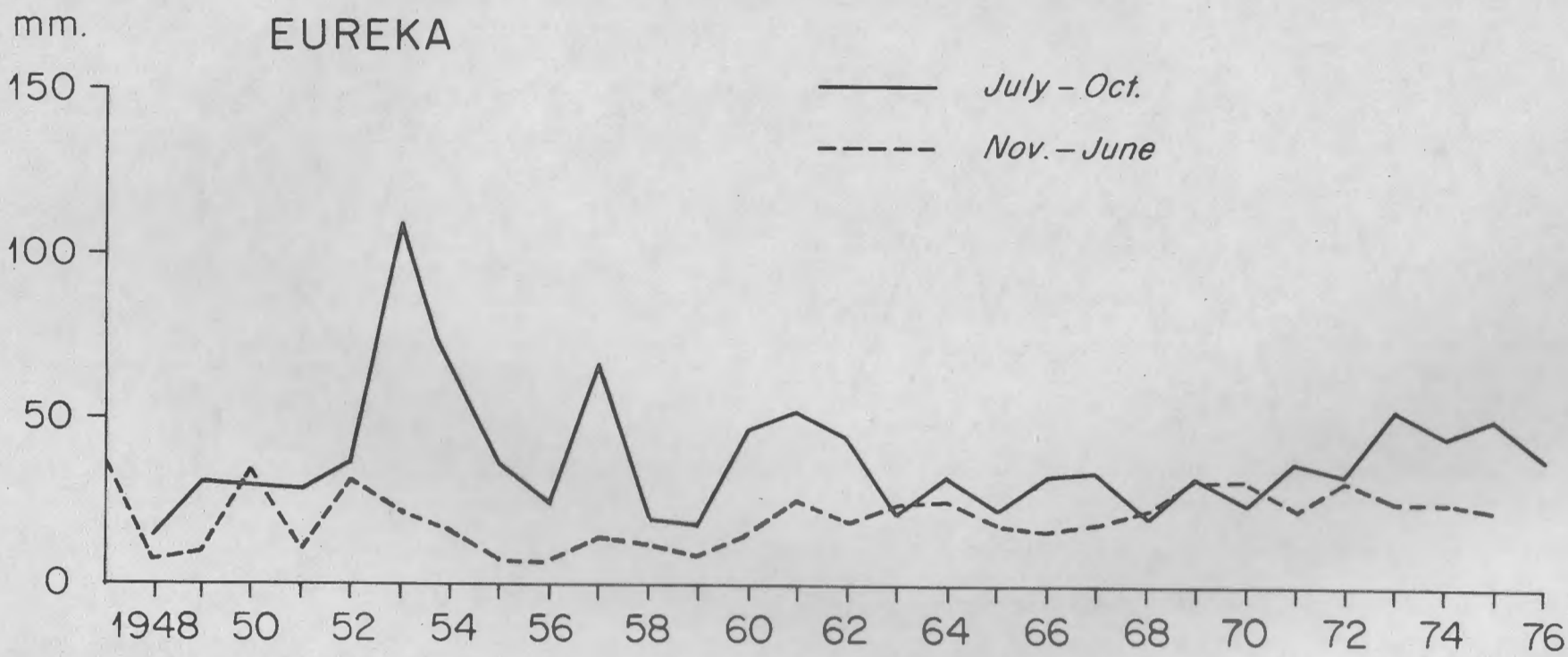

Figure 3.13 Seasonal precipitation totals at Eureka adjusted for snow density before September 1963 as explained in the text.

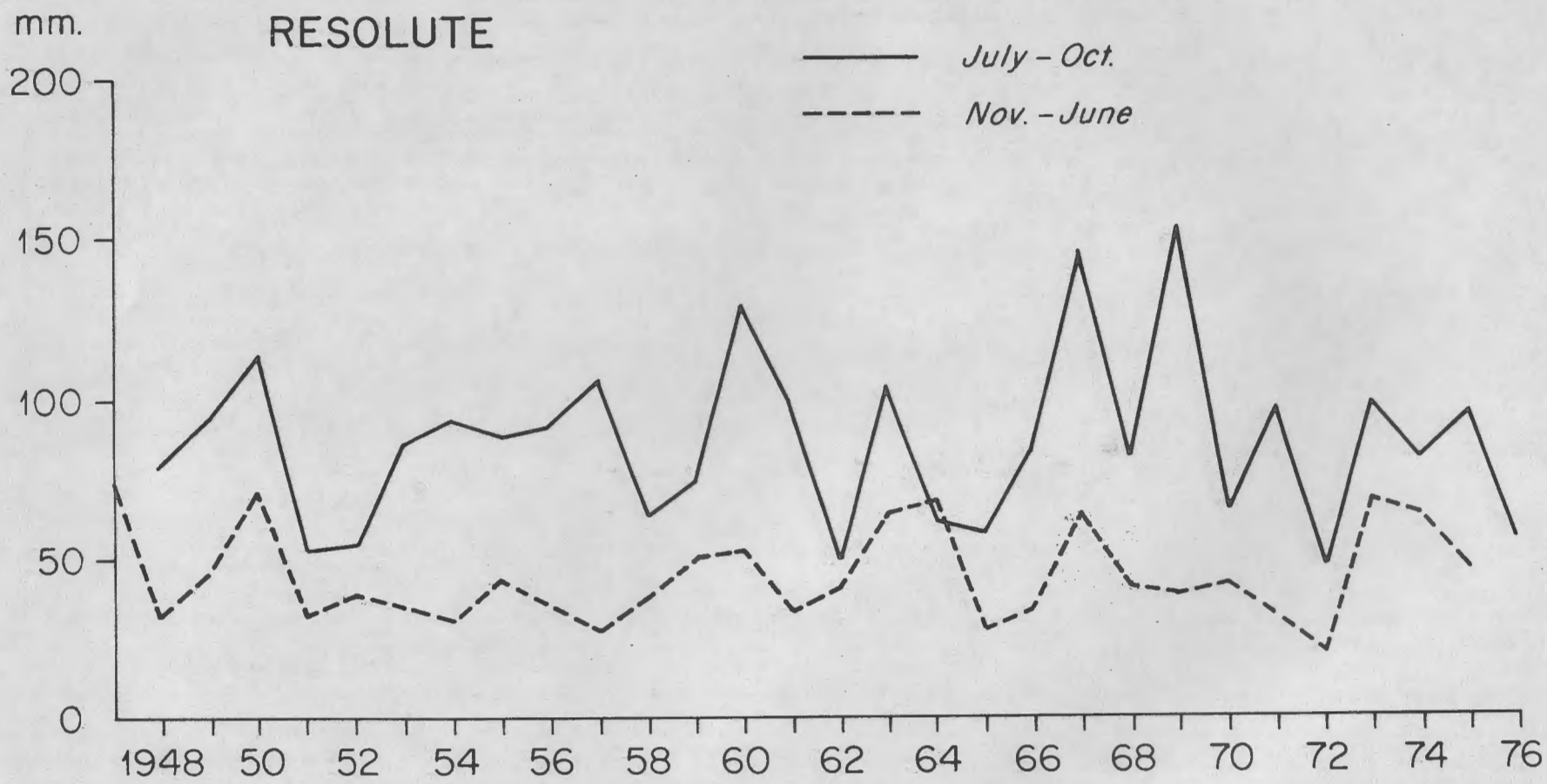

Figure 3.14 Seasonal precipitation totals at Resolute adjusted for snow density before May 1963 as explained in the text.

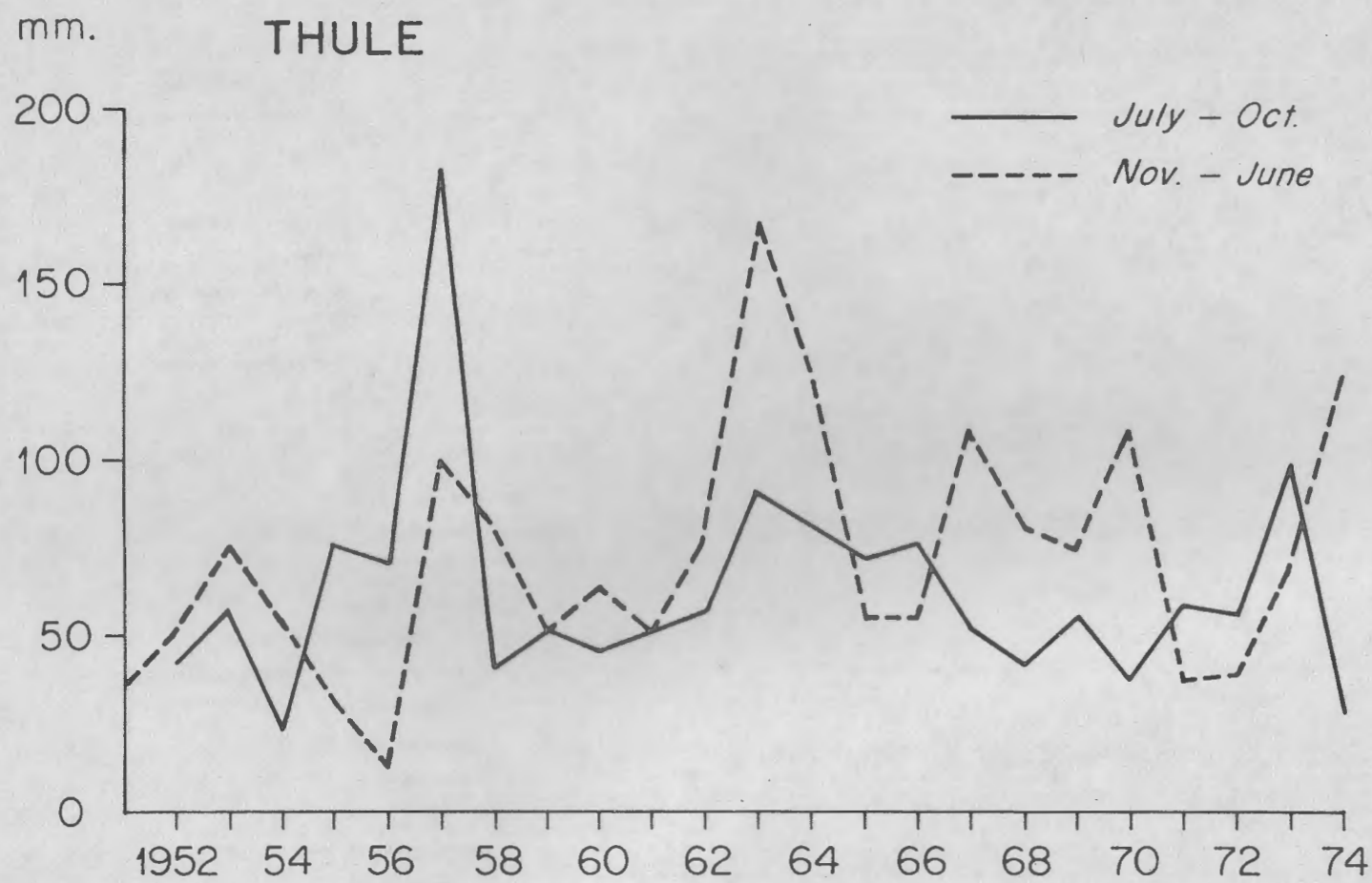

Figure 3.15 Seasonal precipitation totals at Thule (no snow density adjustments made).

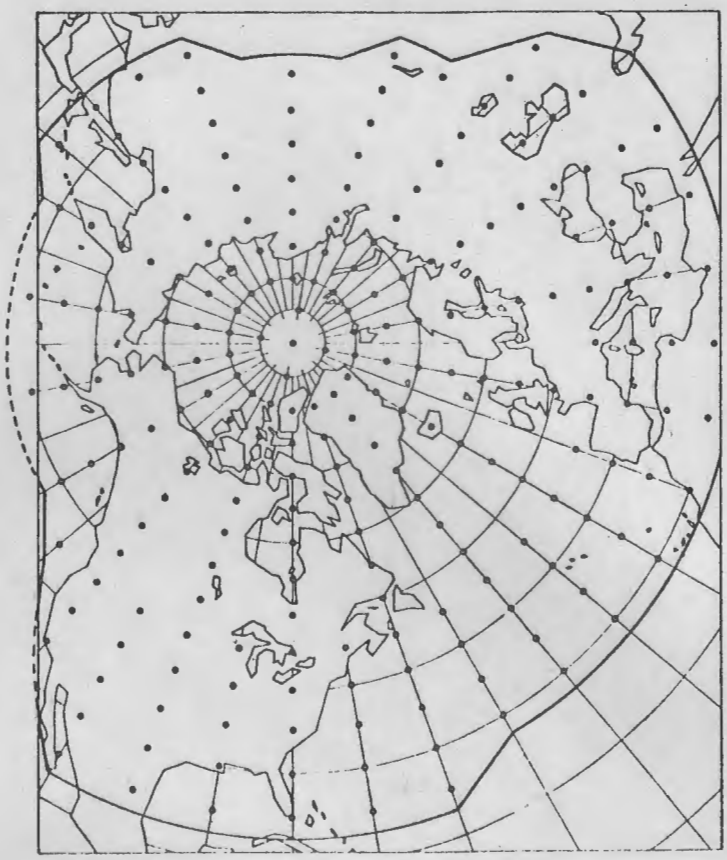

Figure 3.16a)Grid network of 1000-500 mb thickness values used in study by Dronia (1972)

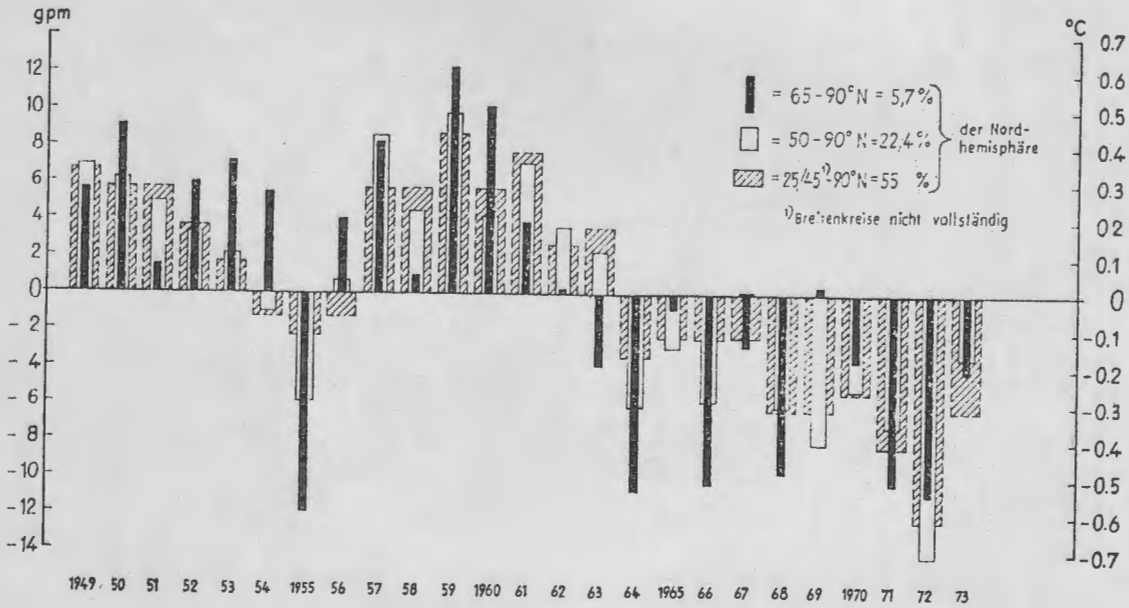

Figure 3.16b) Annual values of 1000-500 mb thickness over the grid network shown in Figure 3.16a) for the latitude zones indicated.

northern hemisphere 1963-68 was the greatest since the period 1883-1890 following the huge eruption of Krakatau (6°S, 105°E) in August, 1883 (a Dust Veil Index in the mid-1960s of 1100 compared to 1500 after Krakatau; Lamb, 1972). Recent work by Angell & Korshover (1977) & Yamamoto et al (1975) indicates that the greatest change in northern hemisphere surface temperatures in the last 25 years was related to the input of Mt. Agung dust into the stratosphere. In the "North extra-tropics" (30°-90°N) Angell & Korshover (1977) estimate that Agung dust may have caused a temperature decrease of 0.6°C, an amount greater than in any other zone examined, including the "South extra-tropics" (30°-90°S) where dust levels were generally higher.

Volcanic dust in the stratosphere would have the most significant climatological impact at high latitudes in summer when solar radiation passes through the greatest depth of atmosphere and the surface is illuminated continuously (Lamb, 1970). Furthermore, the residence time of volcanic dust is greatest at high latitudes and may remain in the upper atmosphere for a decade or more depending on particle size and initial injection height (Lamb, 1972). Dust from the Agung eruption affected solar radiation receipts at high latitudes of the USSR (71-81°N) by late 1963 (Dyer & Hicks, 1968) & the effect is clearly seen in solar radiation and temperature data for Resolute (Fig. 3.17). In the summer of 1964 diffuse radiation reached the highest level ever recorded & direct radiation fell to the lowest values on record. This increase in diffuse & decrease in direct radiation (often with no change in total radiation receipts is a typical 'volcanic dust signal' & is very similar to that recorded in Aspendale, Australia in the summer of 1963 when direct radiation was reduced (due to Agung dust in the stratosphere) by 24% but diffuse radiation was almost doubled (Dyer & Hicks, 1965). Unfortunately no solar radiation data are available for Resolute before 1961 so it is impossible to compare post-Agung values with any long-term pre-eruption value. How-

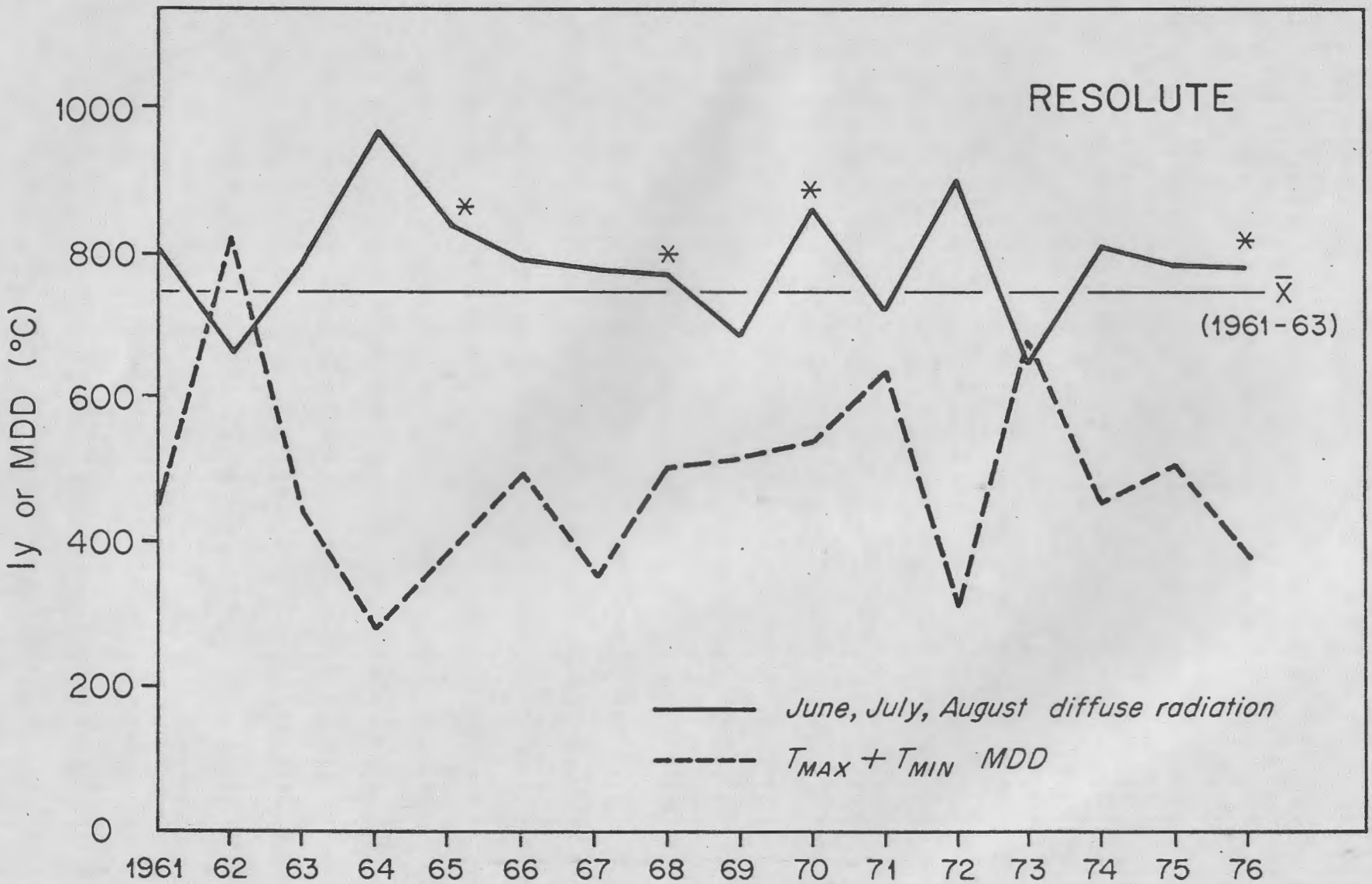

Figure 3.17 Solid line: diffuse solar radiation at Resolute (daily average for June, July and August); dashed line: (T_{max} + T_{min}) melting degree day totals at Resolute. Inverse relationship is significant at <1% level (r= -0.83)

ever, there is some indication in Figure 3.17 that summer diffuse radiation values decreased slowly from 1964 to 1969 while direct radiation values increased. This may reflect stratospheric dust gradually settling out following the eruption. There is evidence to suggest that Mt. Agung dust entering the Northern Hemisphere was relatively fine (0.1-1μ) & that the initial eruption injected dust to heights of 22-23 km (Dyer & Hicks , 1968, Volz, 1964). Theoretically, particles with a diameter of ∿0.5μ would take ∿7-8 years to fall through still air to a tropopause at 12 km and this appears to be consistent with the radiation effect observed at Resolute.

As seen in Figure 3.17 there is an inverse relationship between diffuse radiation (for June-August) & (Tmax + Tmin) MDD totals at Resolute. The correlation ($r=-0.83$) is statistically significant ($P<0.01$) & indicates that diffuse radiation totals are closely linked to total summer 'warmth' which in turn is a critical factor affecting glacier mass balance as discussed above. Hence in periods with large amounts of volcanic dust in the atmosphere diffuse radiation totals would be high, surface MDD totals would be low & glacier mass balance would be positive.

If the Agung eruption was responsible for the change in ablation season conditions during the 1960's, discussed above, then it is likely that other periods of frequent volcanic activity resulted in temperature changes in the High Arctic at least as large as those observed since 1963. Thus it is probable that in the period 1750-1880 (when there were at least 14 eruptions of a magnitude equal to or greater than that of Agung) ablation season temperatures in the High Arctic were extremely low. Consequently, glacier mass balance was almost certainly positive during this interval, as indicated by isotopic and stratigraphic studies of the Devon Ice Cap (Koerner, 1977). Conversely, the period 1920-1960 (when volcanic activity was exceptionally low) was probably characterized by predominantly warm summers with more negative mass balance conditions. Hence the warmer period seen in Figures 3.2 to 3.6 prior to 1964 was probably typical of summer conditions back to the 1920's and the climate of the post-Agung period may be more typical of conditions characteristic of the last century.

SUMMARY AND CONCLUSIONS

Analysis of climatic data for the last 25-30 years from the Canadian High Artic and northwestern Greenland indicates that a significant climatic change occurred in the area around 1963/64. Summer temperatures fell markedly and precipitation amounts generally increased; this resulted in much reduced net mass losses on glaciers in this region after 1963 than in the preceding period. No evidence for a return to pre-1963 conditions is apparent.

Regression equations relating mass balance on the Devon Ice Cap and annual melting degree totals indicate that mass balance is strongly controlled by summer temperature conditions. Winter precipitation at adjacent weather stations may vary by a factor of 3 but this appears to have little effect on the mass balance/melting degree day relationship. Reconstruction of Devon Ice Cap mass balance to 1947 indicates the climatic fluctuation of the early 1960s is outstanding and highly significant for mass balance. From 1947 to 1963 the cumulative mass loss on the Devon Ice Cap was estimated at $\sim$3500 kgm m^{-2}; since 1963 the mass loss has been < 350 kgm m^{-2}. However, although positive balance years since 1963 have occurred as frequently as negative balance years, mass losses during negative balance years are generally much larger than mass gains in positive balance years. It is suggested that this is due to low accumulation amounts on the Devon Ice Cap under present climatic conditions and that <u>significant</u> growth of the Ice Cap is unlikely without marked increases in accumulation.

The change in climate of the area was abrupt and related to the input of volcanic dust into the stratosphere after the eruption of Mt. Agung in 1963. There is global evidence of a cooling effect but the effect is likely to be maximised and persist longest at high latitudes. Solar radiation data from Resolute indicate that the dust affected direct and diffuse radiation receipts for at least 6 years. If Agung dust in the upper atmosphere was responsible for the

recent climatic change it seems likely that other periods following major volcanic eruptions may have experienced similar conditions favoring positive mass balance. Conversely, the climate of the period 1947-63 was probably typical of the entire period $\sim$1920-1963 when the atmosphere was relatively free of dust.

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CHAPTER 4

A SYNOPTIC CLIMATOLOGY OF THE CANADIAN HIGH ARCTIC

INTRODUCTION.

Over the past ∿30 years, synoptic meteorological observations have been made at a number of stations in the Canadian High Arctic and northwestern Greenland (Figure 4.1). This network is sparse by mid-latitude standards but relatively dense for such a high latitude region and provides a useful data set for studying climatic fluctuations and their relationship to the mass balance of snow and ice bodies in the region (c.f. Bradley, 1975; Chapter 3 of this report). Further insight into this question can be achieved by a synoptic climatological approach in which the data are stratified into sub-sets defined by the particular circulation pattern over the region at the time the observations were made. In this way the weather events in one locality can be examined in terms of the prevailing atmospheric circulation (Barry and Perry, 1973). Hence those circulation types associated with, for example, extreme cold, heavy precipitaion or strong ablation can be identified, and the type frequency over time may shed light on climatic fluctuations of the region (providing no 'within-type' changes have taken place). Furthermore, circulation patterns associated with one type of weather at one locality may be associated with quite different conditions elsewhere and these inter-regional variations may also be of significance.

CLASSIFICATION PROCEDURE

In arctic regions, synoptic classification schemes have previously been developed for Labrador-Ungava (Barry, 1960) and the Baffin Island area (Barry, 1972). The resulting catalogs of synoptic types have been examined in terms of those circulation patterns favoring either snow accumulation or ablation (Bradley, 1974; Barry et al, 1975). A similar but more local study of atmospheric circulation in relation to conditions on the Meighen Ice Cap has been undertaken by Alt (1975).

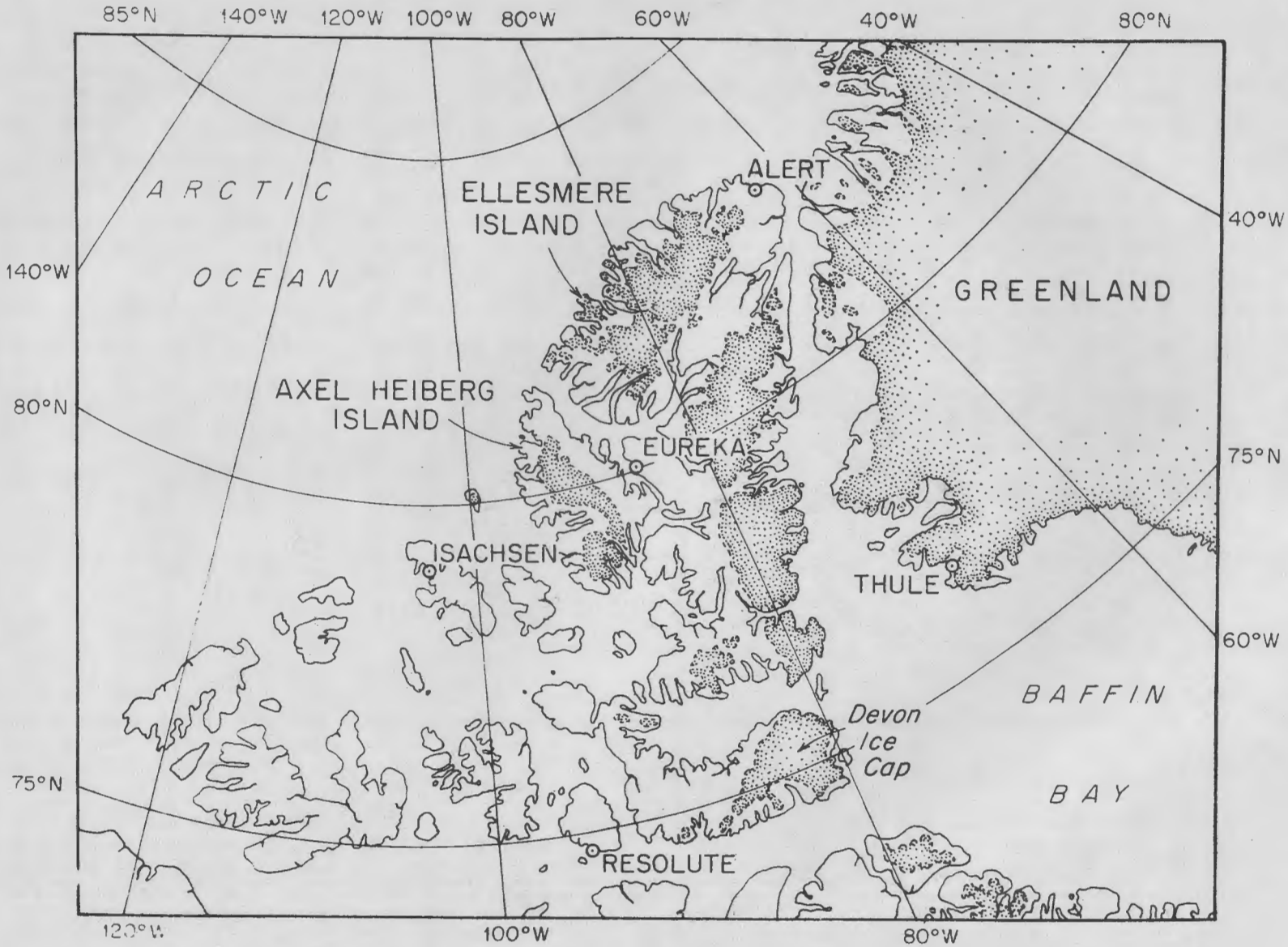

Figure 4.1 Long term weather stations in the Canadian Arctic islands & northwestern Greenland.

For the North Pacific/Chukostskiy/Alaska region, Putnins (1966) developed a classification of synoptic types, but this was not specifically applied to snow and ice conditions (Putnins, 1968). In all of these studies the initial classification of the synoptic types and the development of the synoptic catalog was subjective. In this study, the classification was as far as possible objective, based on the statistical properties of each circulation pattern. The methodology proposed by Kirchoffer (1973) was used and applied to a 30 point grid network of ∿1200 GMT mean sea-level pressure data for the area shown in Figure 4.2. Data used were from the Northern Hemisphere Historical Weather Map Series (Jenne, 1975). This Series contains data back to 1899 but it was felt that for high latitude regions many of the data are spurious as observations were virtually non-existent prior to the late 1940s. In this study the period January 1, 1946 to August 31, 1974 was selected; for most of the period both surface and upper air synoptic meteorological observations have been made at those stations shown on Figure 4.1 and on drifting ice platforms in the Arctic Ocean and Beaufort sea. Hence it is considered that the pressure data used were quite reliable. The classification procedure involves grouping similar circulation patterns on the basis of the sum of squares of the differences between data points on each map. The computed score, S, is thus:

$$S = \sum_{j=1}^{N} (Z_{aj} - Z_{bj})^2$$

where Z_{aj} = normalised grid values at point j on day a.

Z_{bj} = normalised grid values at point j on day b.

N = number of data points (30)

Normalised grid values are used to avoid two identical map patterns (but with different pressure values) being given a large score when the maps should in reality be considered as the same circulation type. This enables synoptic pressure maps from all times of the year to be considered in a single catalog (even though mean pressure may vary significantly from January through December). Seasonal differences are thus reflected in changes of type frequency. The normalisation procedure for each map is as follows:

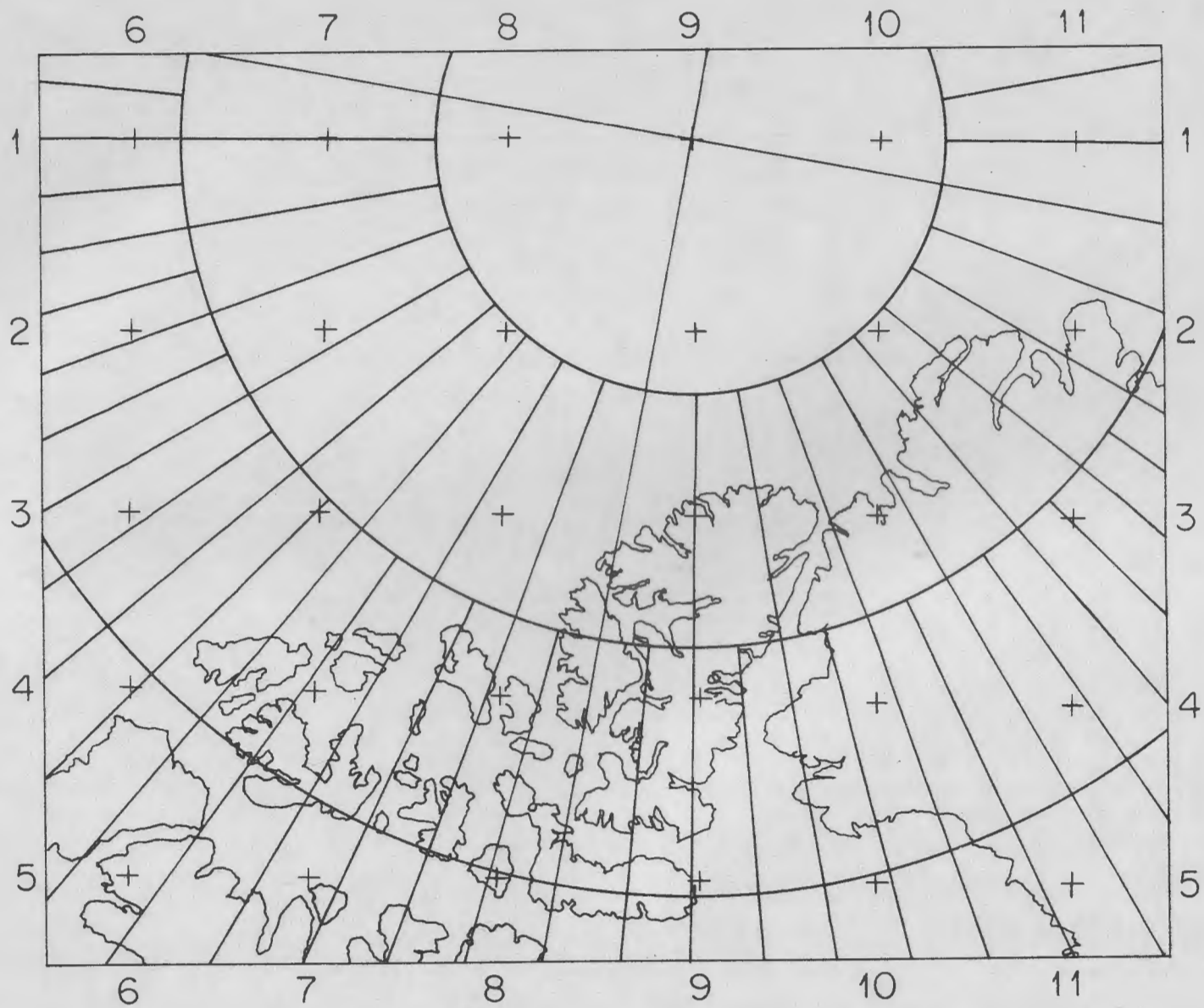

Figure 4.2 Grid network for synoptic classification scheme. Latitudinal zones 1-5 & meridional zones 6-11 are identified.

$$Z_i = \frac{(x_i - \bar{x})}{s}$$

where Z_i = normalised value of the ith grid point

x_i = data value at grid point i

$\bar{x}$ = mean of all 30 points

s = standard deviation of the 30-point grid

In addition to computing the sum of squares of the differences for all points on the maps, subset values were computed for latitudinal zones 1 to 5 and meridional zones 6 to 11 shown on Figure 4.2. These 11 "zone scores" (s_1 to s_{11}) were used in the procedure for assigning each map to a particular type as discussed below.

In order to reduce computational time to within reasonable limits an initial classification was developed on a random sample of ∿20% of days from the entire period 1946-1974. This procedure provided a representative sample of 2128 days from all months of the year (an average of 5 to 7 days per month) and from all years of the period (from 14 to 24% of days in each year). The data were normalised and the sum of squares of the differences scores (S and s_1 to s_{11}) were computed for all pairs of map patterns. A pair of maps were considered similar if (i) the overall score (S) was $\leq$30 (i.e: 1.0 X N, the number of grid points) <u>and</u> (ii) the latitudinal and meridional zone scores (s_1 to s_{11}) were $\leq$ 1.8N (where for latitudinal zones, N=5, and for meridional zones N=6). The value of 1.8 was determined empirically and based on earlier work with the classification by Kirchoffer (1973) and Barry et al (1977).[5.]

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1. The determination of threshold values for the overall and zone scores is the only subjective aspect of this classification procedure. Altering the threshold changes the number and internal consistency of the types. It is equivelant to altering the correlation threshold in classification procedures such as those used by Lund (1963) and Hartranft et al, (1970).

This procedure was designed to ensure that not only were the types similar overall but that each sector of the map met stringent requirements of similarity.

At this stage, each map had been assigned 2,127 scores (overall and zonal) corresponding to the other days of the random sample. The map which had the largest number of scores below the designated thresholds ("key-day 1") was then removed along with all the qualifying similar types. The procedure was repeated for the second most 'typical' type ("key-day 2") and so on until all days were grouped into clusters of 5 days or more. In this way 22 major types were identified, accounting for 97.5% of all days in the sample. The remaining days were considered to be unclassifiable by this procedure.

Because many days may have scores below the threshold for two or more types they could be misclassified if placed in the first type-group removed from the total data-set. Thus once the principal types were identified, the score comparison was repeated, this time assigning each map pattern to the key day type with which it had the lowest overall score (below the threshold value).

It was then assumed that these 22 types, derived from a random sample of days, were representative of the range of circulation patterns experienced in the entire 29 year period. Hence the remaining ∿8,000 maps were normalised and compared with the 22 types, following the procedure outlined above.[2.] 96.5% of days were thus classified into the initial 22 synoptic types.[3.] The complete synoptic catalog is listed in Appendix 4.

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2. It can be readily appreciated that to perform on all ∿10,000 days computations carried out on the sample would require enormous computer storage (and prohibitive costs); by using an initial random sample this problem was circumvented without, it is felt, materially affecting the synoptic catalog.

3. Careful examination of the unclassified types suggests that in many cases non-classification was due to one or more erroneous data points in the data files.

THE SYNOPTIC TYPES

Table 4.1 shows the frequency and mean scores of the 22 synoptic types for the period January 1946-August 1974. It should be noted that the type number does not reflect its frequency ranking in the final catalog; frequencies changed from the random sample where the type numbers were assigned. Type 1 is most common, accounting for ∿23% of all days on an annual basis. However the occurrence of this type varies according to the season, with mid-winter frequencies generally three times the mid-summer level (see Figure 4.7 and discussion below). The most common 10 types account for over 76% of all days classified. Overall mean scores (S) range from 10.9 to 20.2 with scores generally inversely related to frequency, indicating greater internal diversity in the less frequent types (c.f. type 1 and type 20). The synoptic types, represented by the 'key days' for each type, are shown in Figures 4.3 to 4.6. Key days are listed in Table 4.2 together with the predominant meridional component of airflow over most of the archipelago. The types are approximately equally divided between those with southerly and those with a northerly flow component, but in terms of overall frequency there is an overwhelming predominance of 'northerly' types (outnumbering 'southerly' types by more than 3 to 1).

Type frequencies by month are shown in Figures 4.7 and 4.8 and are summarised in Table 4.3. As one might expect, the types with a seasonal maxima in winter have predominantly northerly flow whereas summer types generally have southerly airflow.

CLIMATIC CHARACTERISTICS OF THE SYNOPTIC TYPES

Monthly climatic data from each meteorological station in the High Arctic were stratified by synoptic type to determine the climatic characteristics of each circulation pattern. Although these data are still being analysed some preliminary observations can be made.

TABLE 4.1

SUMMARY OF SYNOPTIC CLASSIFICATION (January 1, 1946 to August 31, 1974)

Type	%	Mean Score(s)	Standard Deviation
1	23.4	10.9	4.8
2	9.3	13.4	5.3
3	7.1	12.3	5.0
4	12.0	13.1	5.4
5	3.9	14.1	4.3
6	5.0	13.9	4.6
7	4.4	14.9	4.9
8	2.3	15.9	5.6
9	2.3	16.5	5.2
10	1.2	17.5	5.3
11	2.6	15.7	5.3
12	3.1	16.1	4.2
13	3.5	13.6	4.7
14	1.0	20.2	4.0
15	4.1	13.8	4.5
16	4.0	12.9	4.6
17	1.1	17.4	5.2
18	1.5	16.8	4.8
19	1.1	17.3	5.1
20	0.8	18.9	4.5
21	1.7	15.4	4.6
22	1.2	17.4	4.9
Missing Data	0.5	-	-
Unclassified	3.0	-	-

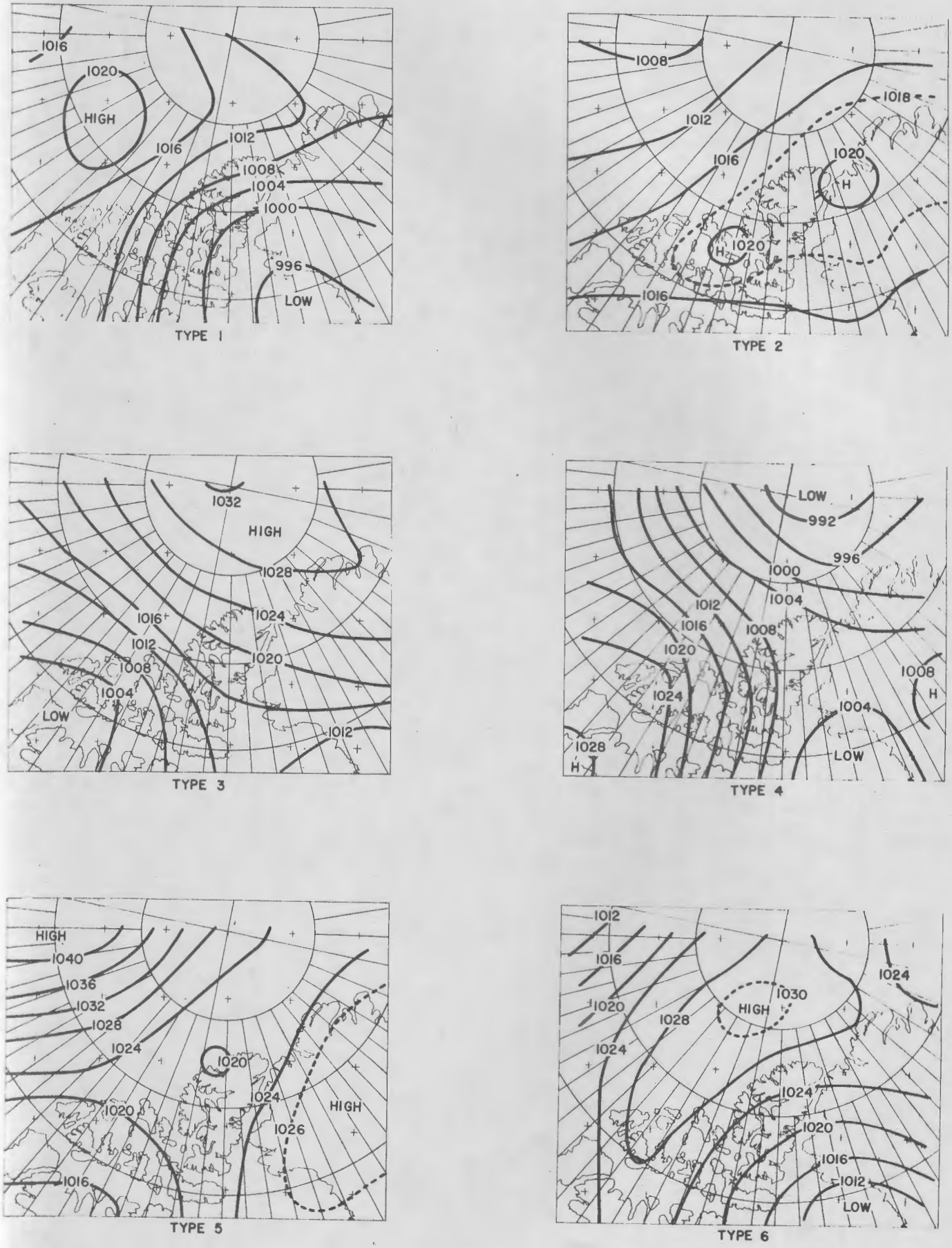


Figure 4.3 Sea-level pressure distribution on type days for synoptic types 1 to 6.

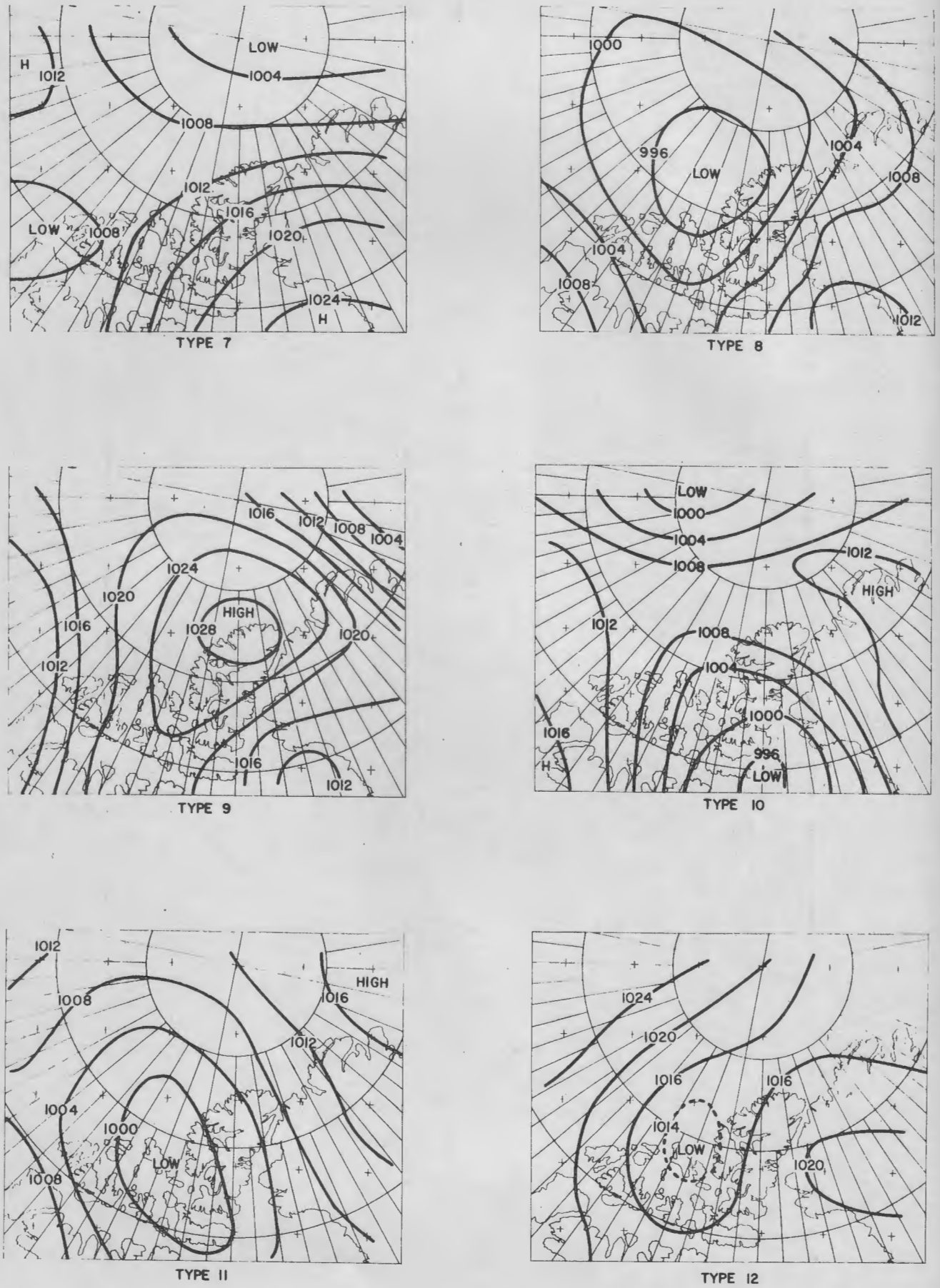
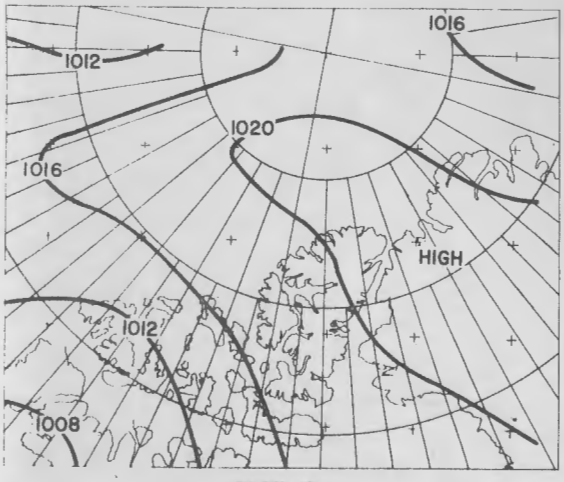
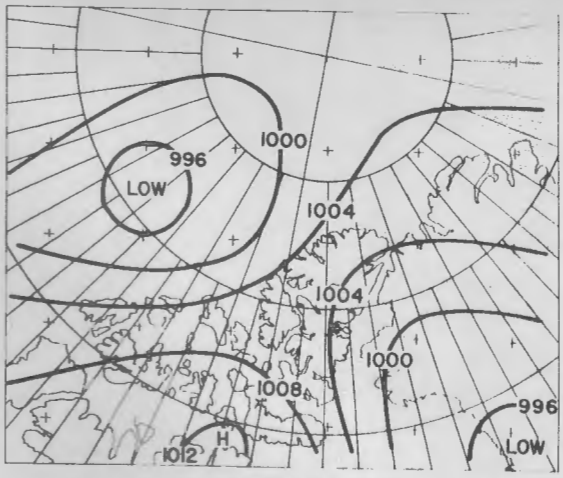


Figure 4.4 Sea-level pressure distribution on type days for synoptic types 7 to 12.



TYPE 13



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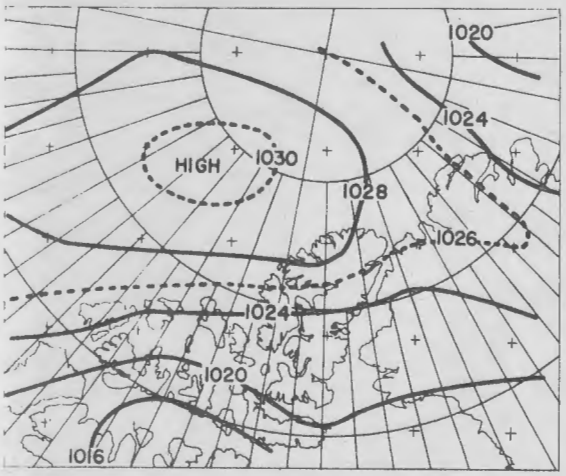
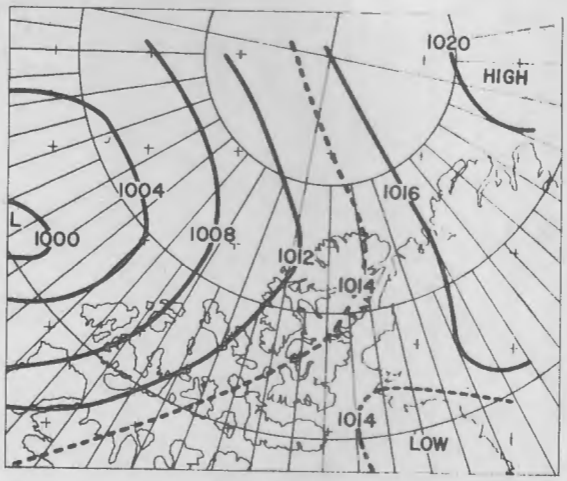
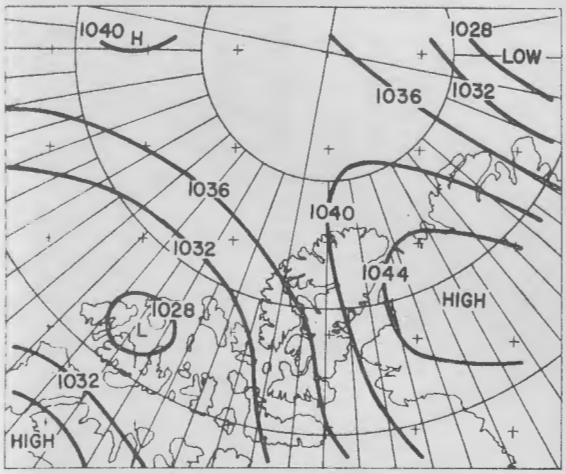


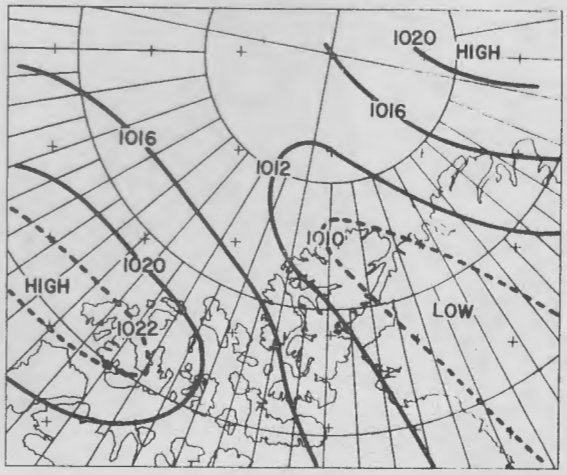
TYPE 15



TYPE 16



TYPE 17



TYPE 18

Figure 4.5 Sea-level pressure distribution on type days for synoptic types 13 to 18.

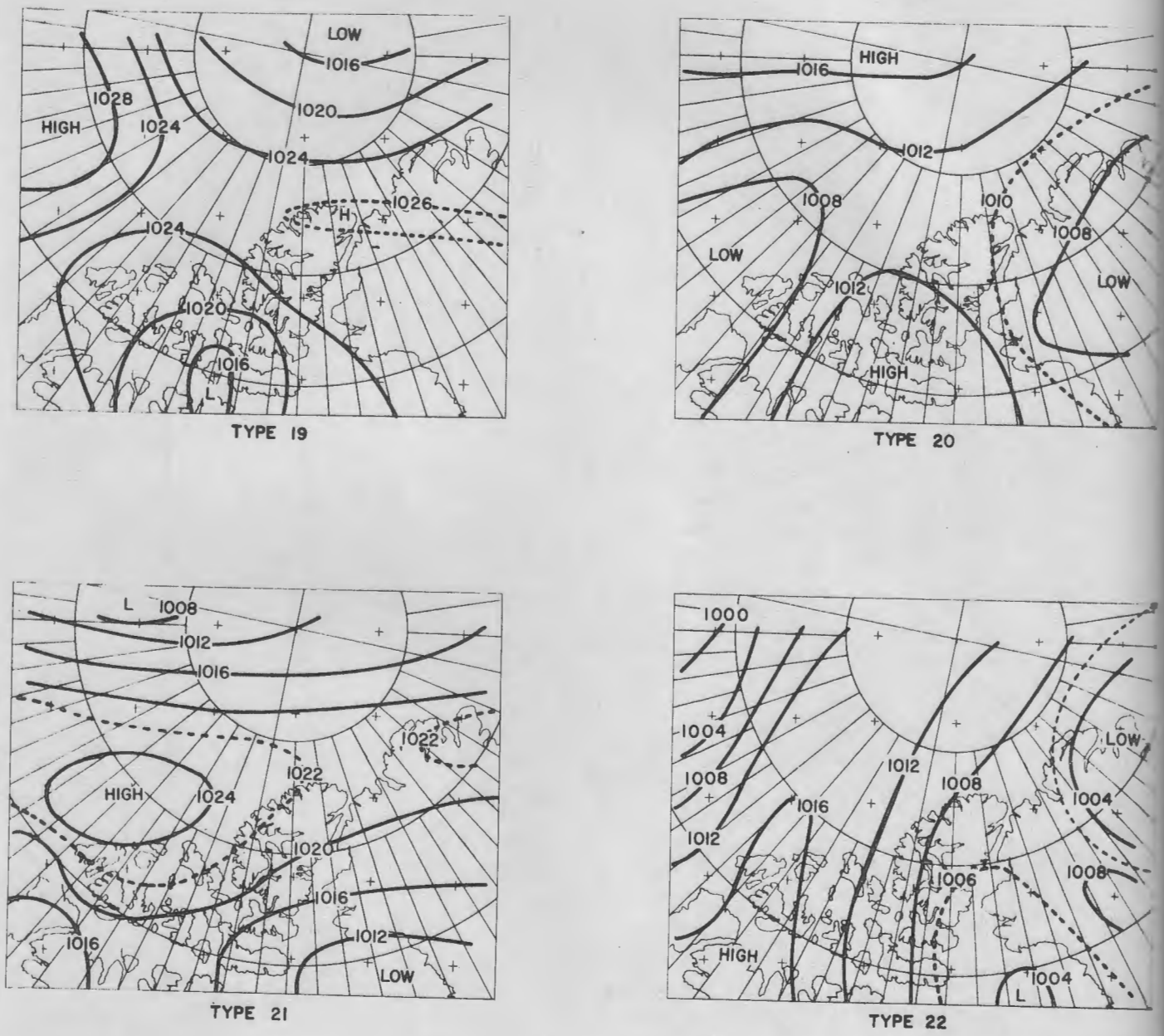


Figure 4.6 Sea-level pressure distribution on type days for synoptic types 19 to 22.

19 to 22.

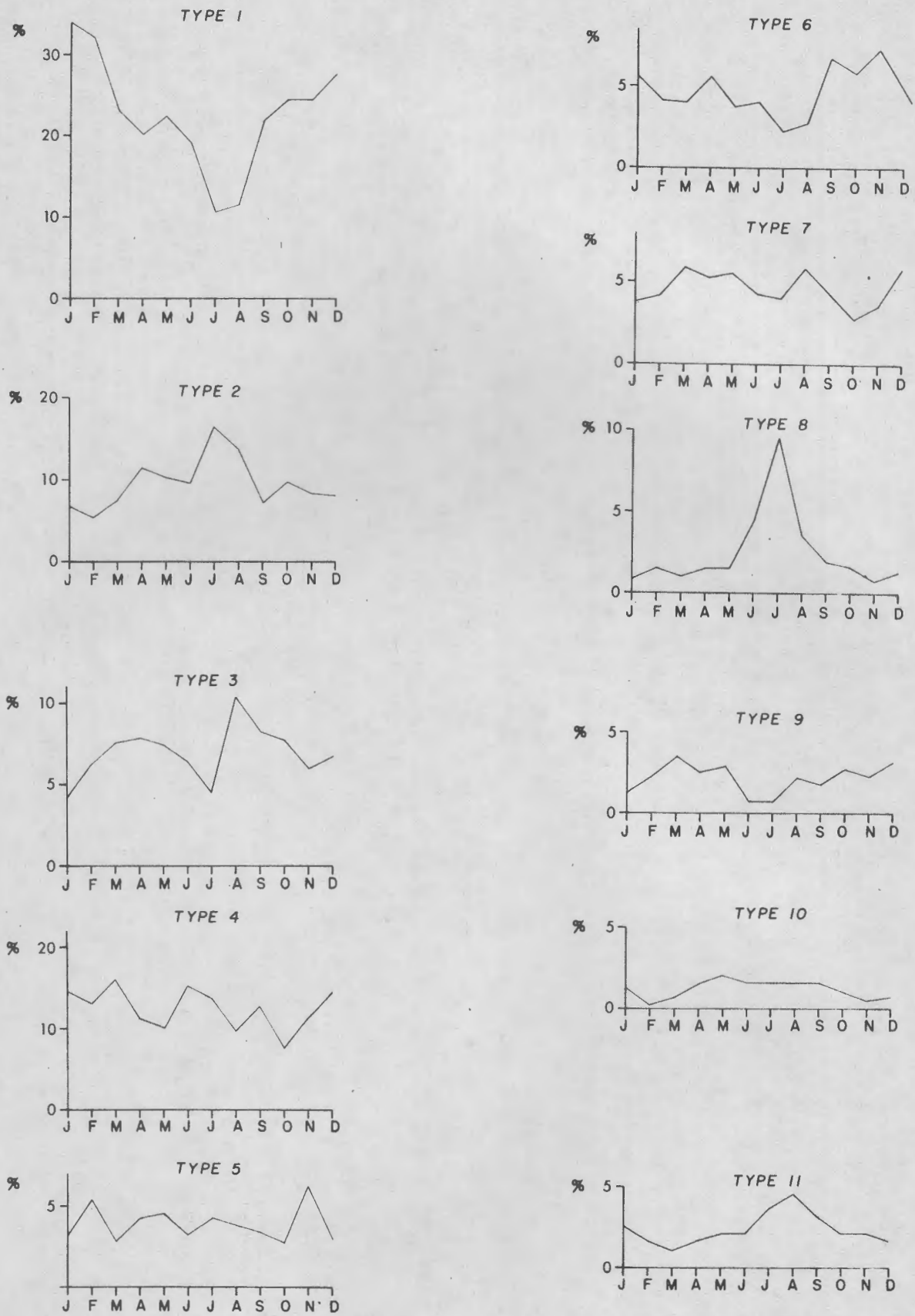


Figure 4.7 Mean monthly frequencies of synoptic types 1 to 11 (% of days per month).

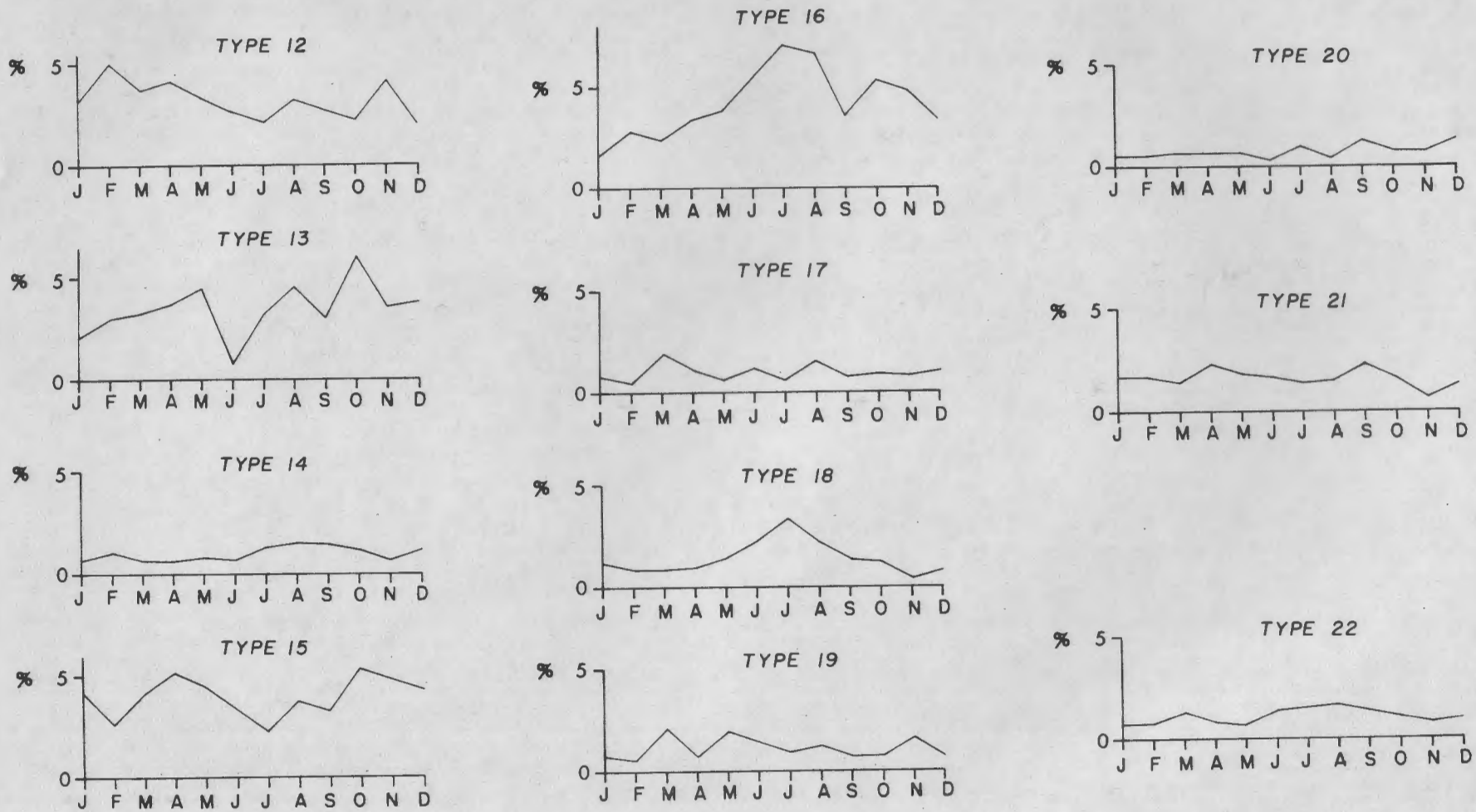


Figure 4.8 Mean monthly frequencies of synoptic types 12 to 22 (% of days per month).

Table 4.2

Key days for High Arctic Synoptic Types

Type	Predominant Airflow	Key Day	Type	Predominant Airflow	Key Day
1	N	August 23, 1972	12	N(W) S(E)	May 20, 1974
2	?	April 25, 1963	13	S	June 25, 1954
3	N	November 7, 1964	14	S	August 11, 1953
4	N	March 25, 1973	15	N	June 9, 1957
5	N(W) S(E)	March 26, 1972	16	S	August 27, 1946
6	N	November 4, 1954	17	S	February 7, 1947
7	S	July 16, 1971	18	N	June 30, 1947
8	N(W) S(E)	July 19, 1960	19	N(W) S(E)	May 10, 1948
9	S(W) N(E)	October 11, 1953	20	S(W) N(E)	July 20, 1948
10	N	October 5, 1972	21	N	September 24, 1960
11	N(W) S(E)	July 3, 1950	22	N	September 6, 1961

TABLE 4.3

SUMMARY OF TYPE FREQUENCY BY MONTH

Type	Relative Seasonal Maxima	Type	Relative Seasonal Maxima
1	Mid-winter	12	Late Winter
2	Mid-summer	13	Spring & Fall
3	Spring & Late Summer/Fall	14	Late Summer/Fall
4	none	15	Spring & Fall
5	none	16	Late Summer/Early Winter
6	Fall/early winter	17	none
7	none	18	Summer
8	Mid-Summer	19	Spring
9	Winter	20	Early winter
10	Spring/Summer	21	Spring & Fall
11	Late Summer	22	Summer

Temperature: For each month the types were ranked in order of increasing temperature (Tmax and Tmin). Tables 4.4 and 4.5 show the results of this analysis for Alert and Isachsen respectively. In both tables the extremely warm or extremely cold types commonly maintain their relative ranking in all months. At Alert, for example (Table 4.4) types 8, 16, 11, 7 and 13 (Figures 4.3 - 4.6) rank amongst the warmest types in all months. These types are all characterised by low pressure to the west or southwest of Alert with relatively high pressure over Greenland. The resultant flow pattern leads to warmer air from the south being advected northward at all times of the year. By contrast the four coldest types at Alert (types 1, 6, 15, and 21) are all characterised by low pressure to the south in Baffin Bay and/or high pressure to the west or northwest of Alert (Figures 4.3 to 4.6). This leads to cold northerly or northwesterly airflow form the Arctic Ocean over the Alert area, hence the associated low temperatures. In winter months, mean temperatures at Alert may vary by up to 17°C during different synoptic situations; in summer, mean differences are <8°C.

At Isachsen there is less consistency in the coldest and warmest types from month to month; in fact, type 9 is the warmest in June, July and August whereas at other times of year it is generally one of the coldest types (Table 4.5). In type 9 situations a high pressure center over northwestern Ellesmere Island brings easterly and southeasterly airflow over Isachsen. It is suggested that in summer months the relatively warm land mass of Ellesmere Island results in warm air advection over the Isachsen area whereas in winter this regional source of energy is absent hence type 9 is relatively cold. Overall the warmest synoptic situations at Isachsen are those with low pressure to the west or northwest and/or a high pressure cell to the east or northeast (types 13, 16, 2, 17 and 7) resulting in the advection of warm air from the south. The coldest synoptic types have either a low pressure center over or to the east of Isachsen (e.g. type 12) or a high pressure cell to the west bringing cold northerly air from the Beaufort

Table 4.4

Mean Tmax (°C) at Alert during synoptic type occurrence (ranked by temperature): July 1950-1975

JAN.			FEB.			MARCH			APRIL			MAY			JUNE		
Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax
16	1.9	-17.8	8	1.5	-20.1	11	1.1	-18.4	8	0.3	-12.6	8	1.7	-1.6	17	1.3	5.6
8	0.9	-20.2	11	1.6	-21.3	18	0.5	-20.4	16	3.3	-13.1	11	2.7	-4.1	8	4.0	5.4
17	0.8	-20.4	16	2.8	-24.1	16	2.6	-24.3	13	4.0	-15.1	16	3.8	-5.0	16	4.7	5.1
13	2.3	-20.7	17	0.6	-24.6	8	0.9	-24.5	7	5.3	-15.8	7	5.8	-5.5	9	0.7	4.7
11	2.2	-21.6	13	3.2	-24.7	13	3.5	-24.9	2	11.8	-17.7	17	0.7	-5.8	7	4.7	4.2
7	4.2	-24.0	3	6.6	-26.5	7	5.8	-26.2	11	1.5	-17.8	13	4.6	-6.5	13	1.8	4.2
5	3.5	-25.6	2	5.7	-26.8	2	7.9	-26.8	21	1.9	-18.5	4	10.5	-6.5	2	10.4	3.4
14	0.5	-26.8	7	4.3	-27.1	19	2.4	-27.2	10	1.5	-18.7	14	0.7	-6.9	11	2.4	3.4
9	1.3	-27.1	5	5.6	-27.1	17	1.9	-28.1	17	1.3	-18.7	18	0.9	-7.0	20	0.3	3.1
12	3.2	-27.2	12	4.1	-28.6	5	2.7	-28.2	14	0.7	-19.4	2	11.0	-7.1	12	2.5	2.4
2	7.0	-27.5	22	0.4	-29.6	12	3.8	-28.3	4	11.0	-19.8	20	0.5	-8.2	10	1.9	1.9
3	4.2	-27.9	20	0.6	-29.7	21	1.5	-28.4	3	8.1	-20.7	12	3.5	-8.4	3	5.1	1.9
10	1.2	-28.2	19	0.6	-30.0	20	0.7	-28.9	18	0.8	-20.9	5	5.0	-8.5	19	1.4	1.5
4	15.1	-28.6	15	2.9	-30.1	3	7.7	-29.0	9	1.9	-21.5	9	2.4	-8.8	5	3.2	1.5
15	4.6	-29.4	10	0.3	-30.3	4	16.1	-29.0	12	3.9	-21.9	3	6.7	-9.0	18	1.9	1.4
1	33.3	30.2	4	13.0	-31.2	9	3.2	-29.6	6	5.0	-22.0	19	2.3	-9.7	14	0.7	0.8
21	1.6	-30.7	14	1.0	-31.3	14	0.8	-30.4	19	0.7	-22.6	22	0.7	-9.7	4	15.7	0.7
6	5.4	-30.9	9	1.8	-31.9	1	23.0	-31.1	22	0.4	-22.6	21	1.7	-10.3	6	4.0	0.4
22	0.5	-31.5	1	31.4	-32.1	15	4.6	-31.2	5	4.4	-23.2	1	22.7	-10.9	21	1.9	0.2
19	0.9	-31.8	21	1.8	-32.3	22	1.1	-31.3	1	21.3	-24.5	15	3.9	-11.0	15	3.2	-0.1
18	1.5	-32.1	6	4.4	-32.7	10	0.7	-31.8	15	5.6	-25.5	10	1.9	-11.3	22	1.5	-0.2
20	0.4	-34.8	18	1.0	-34.1	6	4.2	-32.4	20	0.7	-26.1	6	0.7	-12.9	1	26.8	-0.2

(Table 4.4 continued)

JULY			AUG.			SEPT.			OCT.			NOV.			DEC.		
Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax
8	10.1	+10.7	8	2.8	+7.5	8	2.1	-1.3	8	1.7	-6.5	13	3.7	-15.0	8	1.4	-18.9
16	5.9	9.6	11	4.0	7.0	11	2.8	-3.0	7	3.0	-9.1	11	2.3	-16.3	7	5.9	-22.3
2	17.4	8.6	7	5.8	6.5	2	7.2	-3.4	19	0.8	-10.6	16	4.9	-17.3	22	0.6	-22.9
11	3.9	8.6	16	5.8	6.0	5	3.3	-4.0	17	1.0	-11.2	22	0.9	-18.6	13	3.5	-23.4
12	2.5	8.1	2	14.2	5.2	12	2.4	-4.7	16	5.2	-12.0	8	0.8	-19.0	11	1.9	-23.7
7	3.6	7.5	13	4.6	4.9	7	4.4	-4.9	13	6.3	-13.2	7	3.9	-19.1	16	3.6	-24.9
3	4.5	7.5	3	10.2	4.9	17	0.7	-5.6	11	2.2	-14.2	20	0.9	-19.3	2	7.6	-24.9
19	1.0	6.6	10	1.8	3.6	18	1.6	-5.8	12	2.3	-14.6	12	4.5	-20.0	17	1.0	-24.9
10	1.7	6.5	17	1.7	3.6	4	13.3	-6.0	4	8.3	-15.4	2	7.9	-20.1	4	15.7	-25.1
14	1.4	6.4	14	1.5	3.5	10	1.7	-6.5	3	7.7	-15.6	5	6.4	-21.2	5	3.2	-25.8
5	4.1	6.3	18	2.3	2.4	16	3.5	-6.9	2	9.2	-15.7	17	0.9	-21.2	10	0.5	-26.0
17	0.8	5.7	4	9.8	2.2	22	1.5	-7.0	20	0.8	-15.9	10	0.5	-21.4	3	6.3	-26.3
15	2.3	5.4	9	2.3	1.9	13	3.2	-7.9	5	2.8	-16.4	4	11.3	-23.2	19	0.5	-26.4
13	3.2	5.1	12	3.2	1.6	20	1.1	-7.9	9	2.7	-16.5	18	0.5	-23.5	14	1.4	-27.2
21	1.3	5.1	5	4.0	1.6	14	1.5	-8.4	15	4.3	-17.8	19	1.3	-23.7	12	2.1	-27.5
9	0.6	4.9	20	0.5	1.0	1	22.5	-8.6	1	24.6	-17.8	3	5.6	-24.1	9	3.0	-27.6
4	14.1	4.7	22	1.8	0.8	15	3.3	-8.6	18	1.3	-18.3	9	2.4	-24.2	1	27.9	-27.8
18	3.0	4.4	15	3.9	0.4	3	8.5	-8.7	22	1.0	-18.4	1	24.8	-24.7	21	1.5	-28.0
22	0.9	3.9	21	1.8	0.6	6	7.1	-10.0	14	1.0	-18.6	15	4.8	-25.1	20	0.8	-28.2
6	2.5	3.9	6	3.1	0.6	9	1.6	-10.1	6	6.2	-18.8	14	0.7	-25.2	15	1.9	-28.2
20	0.8	3.5	1	11.2	-0.3	21	2.9	-10.5	10	1.0	-19.4	6	6.5	-25.4	6	4.1	-29.1
1	11.2	2.5	19	1.2	-0.4	19	0.7	-12.3	21	1.7	-20.1	21	0.5	-29.2	18	0.8	-31.1

Table 4.5

Mean Tmax (°C) at Isachsen during synoptic type occurrence (ranked by temperature)

[1]May 1948 to Dec 1974

JAN.			FEB.			MARCH			APRIL			MAY			JUNE		
Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax
13	2.2	-25.3	13	3.0	-26.9	11	0.1	-23.7	16	3.3	-15.6	14	0.6	-4.0	9	0.7	+4.6
17	0.9	-27.1	16	0.8	-29.4	13	3.3	-24.8	13	3.7	-16.3	17	0.7	-5.1	20	0.3	4.4
16	1.8	-27.3	10	0.2	-30.0	3	7.5	-27.3	8	1.5	-16.9	8	1.5	-5.4	13	1.9	3.4
15	4.3	-29.0	5	5.3	-30.8	20	0.7	-27.3	2	11.5	-19.5	11	2.3	-5.5	7	4.4	2.5
7	3.9	-30.1	15	2.7	-31.1	16	2.3	-28.5	3	7.8	-19.7	13	4.6	-6.6	17	1.2	2.5
5	3.2	-30.1	3	6.1	-31.2	2	7.6	-29.5	21	2.3	-20.3	16	3.7	-6.7	10	1.7	2.5
2	6.9	-30.8	8	1.5	-31.3	18	0.7	-29.6	7	5.2	-20.5	3	7.4	-7.3	2	9.7	2.3
21	1.6	-31.1	17	0.5	-31.8	17	1.9	-30.1	14	0.6	-21.0	7	5.5	-7.3	16	5.3	2.2
14	0.6	-31.3	11	1.9	-32.3	6	4.0	-30.2	10	1.5	-21.4	18	1.3	-7.3	5	3.2	2.0
3	4.2	-31.5	6	4.2	-32.8	15	4.2	-30.5	6	5.6	-21.5	22	0.6	-7.3	6	4.0	2.0
9	1.3	-32.0	2	5.4	-32.8	7	5.8	-30.6	4	11.1	-21.7	4	10.1	-7.6	15	3.4	1.9
22	0.8	-32.2	21	1.6	-33.3	9	3.6	-30.7	9	2.5	-21.9	2	10.1	-8.1	14	0.6	1.8
1	33.6	-32.2	7	4.2	-33.6	8	0.8	-30.7	5	4.2	-23.8	19	2.1	-8.8	3	6.4	1.7
8	7.8	-32.3	1	31.7	-33.8	19	2.2	-30.8	18	0.9	-23.8	20	0.6	-8.9	19	1.3	1.6
12	3.2	-32.6	9	2.3	-34.2	10	0.7	-30.8	17	1.2	-23.9	12	3.3	-9.9	8	4.5	1.3
4	14.2	-32.6	22	0.8	-34.7	21	1.4	-31.1	11	1.6	-24.5	9	2.8	-10.1	12	2.7	1.2
10	1.3	-32.7	12	5.0	-34.7	5	2.7	-31.3	12	4.2	-24.7	5	4.5	-10.2	18	2.2	1.1
6	5.5	-33.3	20	0.5	-35.4	1	22.9	-31.6	1	20.2	-24.9	21	1.9	-10.2	22	1.4	1.1
11	2.6	-33.5	4	13.0	-36.0	14	0.7	-31.7	15	5.2	-24.9	1	22.1	-10.7	1	19.0	0.5
18	1.3	-34.7	14	1.0	-37.2	22	1.4	-33.0	19	0.7	-25.7	15	4.5	-11.2	11	2.3	0.5
19	0.9	-36.0	19	0.5	-37.5	4	16.3	-33.1	22	0.7	-26.0	6	3.8	-11.2	4	15.3	0.3
20	0.5	-36.5	18	0.9	-37.5	12	3.7	-34.4	20	0.6	-27.2	10	2.0	-11.4	21	1.7	-0.2

[1]Frequencies in %; missing data and untyped days account for remainder of days (to 100%)

Table 4.5(continued)

JULY			AUGUST			SEPTEMBER			OCTOBER			NOVEMBER			DECEMBER		
Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax	Type	Freq.	Tmax
9	0.7	+10.5	9	2.2	+6.0	8	1.9	-1.7	7	2.7	- 9.0	13	3.5	-17.3	13	3.8	-22.9
13	3.1	9.1	3	10.3	5.7	2	7.1	-3.2	16	5.3	-10.0	8	0.7	-19.8	8	1.3	-24.3
3	4.5	8.6	13	4.5	5.4	16	3.5	-3.4	8	1.7	-11.4	16	4.8	-20.3	20	1.4	-24.8
15	2.2	8.4	15	3.8	5.0	11	3.3	-3.6	13	6.0	-11.6	11	2.2	-20.8	3	6.8	-26.3
2	16.9	7.9	2	13.7	4.2	13	3.2	-4.0	17	0.9	-12.6	3	5.9	-21.3	11	1.7	-26.5
19	0.9	7.4	17	1.5	4.2	17	0.8	-4.3	3	7.7	-13.0	2	7.6	-22.5	17	1.0	-27.4
6	2.2	7.1	7	5.9	4.0	10	1.6	-4.8	19	0.7	-13.8	22	0.8	-22.5	7	5.8	-27.4
7	4.0	7.0	16	5.7	4.0	18	1.4	-4.9	11	2.1	-13.8	20	0.8	-23.1	2	7.0	-27.8
16	6.0	6.8	5	3.8	3.9	7	4.3	-5.1	2	9.5	-15.4	19	1.6	-23.9	5	3.5	-27.8
10	1.6	6.4	20	0.4	3.3	3	8.1	-5.2	14	1.1	-16.0	15	4.9	-24.7	15	4.4	-28.4
5	4.4	6.0	21	1.6	3.3	14	1.4	-5.5	18	1.1	-16.2	17	0.8	-25.0	12	2.1	-28.7
17	0.7	5.8	22	1.6	3.1	5	3.4	-5.6	15	4.5	-16.7	1	24.9	-25.1	16	3.3	-29.2
21	1.3	5.8	18	2.1	2.6	4	12.9	-5.9	10	1.0	-16.7	7	3.5	-25.2	14	1.3	-29.3
22	1.5	4.9	6	2.9	2.6	12	2.9	-6.3	5	2.7	-16.8	12	4.2	-25.2	1	27.7	-29.4
14	1.3	4.8	14	1.4	2.2	9	1.9	-6.5	20	0.7	-17.0	5	6.1	-25.5	22	0.9	-30.0
11	3.9	4.5	11	4.5	2.2	22	1.4	-6.7	4	7.6	-17.3	6	7.2	-25.5	4	14.5	-30.7
20	0.9	4.3	8	3.3	1.7	1	21.7	-7.0	1	24.4	-17.4	14	0.6	-25.8	21	1.4	-30.8
1	10.8	4.2	19	1.1	1.7	20	1.3	-7.4	9	2.8	-17.6	4	11.1	-25.9	6	4.1	-31.0
4	13.8	3.9	4	9.6	1.6	6	6.6	-7.5	21	1.7	-17.9	9	2.4	-27.4	10	0.6	-31.8
8	9.5	3.3	1	11.4	1.3	15	3.4	-7.6	6	5.9	-18.1	21	0.7	-27.7	19	0.6	-32.2
18	3.2	3.2	10	1.6	1.3	19	0.6	-8.9	12	2.3	-18.6	10	0.4	-29.3	9	3.1	-32.3
12	2.2	2.5	12	3.2	0.7	21	2.8	-9.6	22	1.0	-20.4	18	0.4	-29.9	18	0.7	-36.8

Sea and Arctic Ocean over the region (types 1, 4, 18, 21).[4] These 'warmest' and 'coldest' types are not always the same as at Alert but the general situations are clearly similar - northerly airflow from high pressure areas to the west in cold types and southerly airflow towards low pressure areas to the west in warm types.

In order to evaluate the relative importance of each type to the monthly fluctuations of temperature over time, a stepwise multiple regression analysis was undertaken with the mean maximum temperatures for each month as the dependent variable and the synoptic type frequencies in each month as the independent variables. For example, July maximum temperatures at Alert were analysed with the frequency of all 22 synoptic types in July. Synoptic type 1 was most highly correlated with Alert July Tmax accounting for 53% of the variance. As discussed earlier, type 1 is a characteristically cold type, hence the relationship is inverse with mean July temperatures higher in years with low type 1 frequency (Figure 4.9). The next synoptic type entering the regression was type 3 (a warm type with average maximum temperatures 5°C higher at Alert than during type 1 situations). The addition of type 3 increases the total variance explained to ∿63%.[5] In this example more than half of the variance of Tmax was explained by one variable (synoptic type 1 frequency); this is exceptional as most months require at least two variables to explain >50% of the variance. Similar analyses of Eureka and Isachsen monthly Tmax data (Tables 4.6 to 4.8) indicate that Tmax in the months of April to August (excluding June) are dependent on a small number of synoptic types. Generally >45% of explained variance in these months can be obtained with 2 independent variables. In other months (particularly

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4. It is of interest that the coldest temperature ever recorded in the Canadian Arctic Islands (-53.9C [-65°F]) was registered at Isachsen during a type 1 situation.

5. $y = -0.78x_1 + 0.84x_2 + 44.1$ where y = July Tmax (°C) and x_1 and x_2 are the monthly frequencies of synoptic types 1 and 3 respectively.

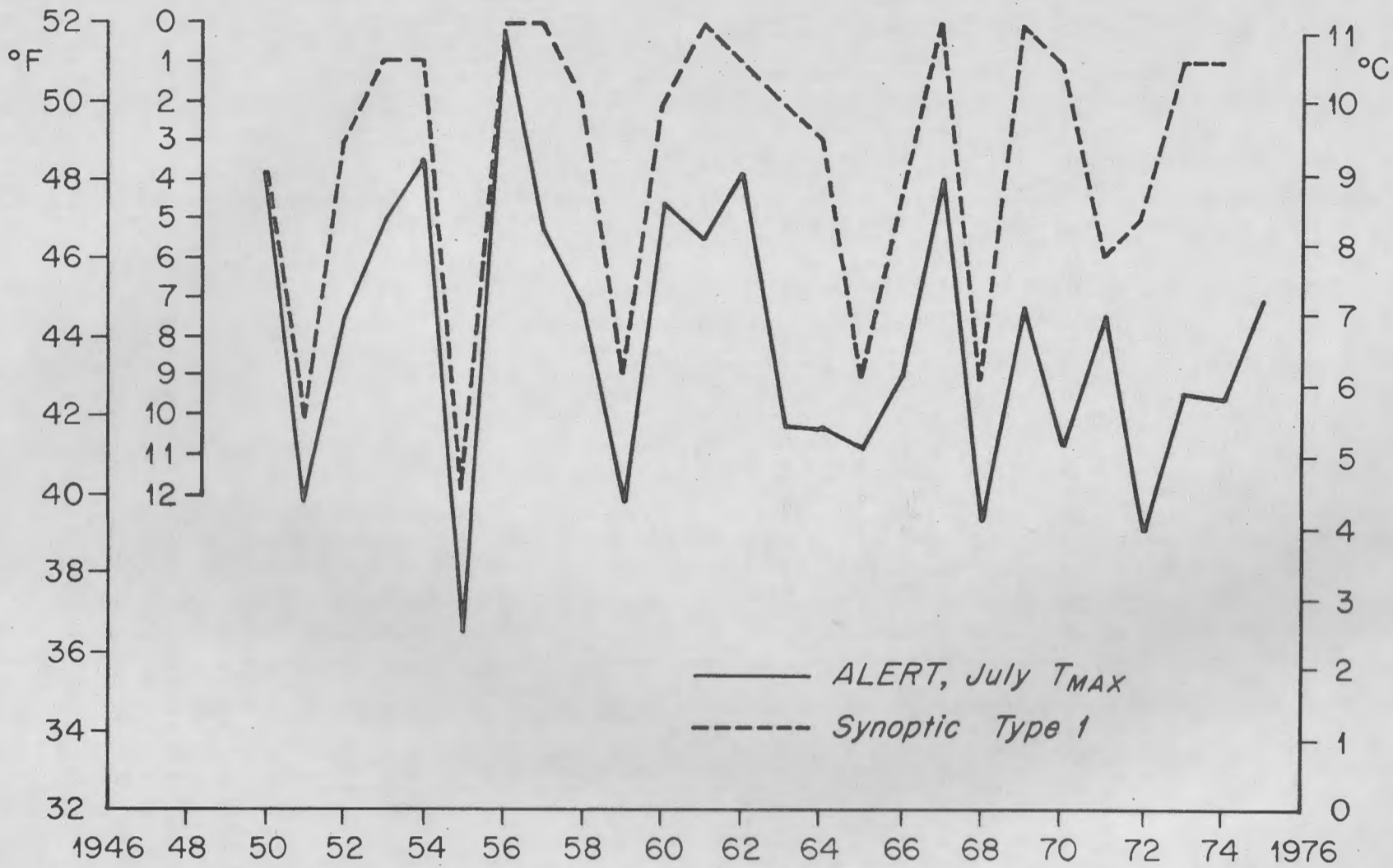

Figure 4.9 Alert July mean maximum temperatures and frequencies of synoptic type 1 in July (note: synoptic type 1 frequency scale is inverted)

Principal synoptic types accounting for variance of the monthly maximum temperature record

Table 4.6

Alert

	Primary Type	%[1]	Correlation[2]	Secondary Type	%[1]	Correlation[2]	Σ%[3]
Jan.	16	21	+	6	14	-	35
Feb.	18	33	-	3	21	+	54
Mar.	21	25	+	11	20	+	45
Apr.	1	48	-	13	29	+	77
May	11	36	+	7	25	+	61
Jun.	22	20	-	8	15	+	35
Jly.	1	53	-	3	10	+	63
Aug.	1	23	-	17	14	+	37
Sep.	1	33	-	18	14	+	47
Oct.	1	22	-	19	15	+	37
Nov.	13	44	+	16	19	+	63
Dec.	12	22	-	7	16	+	38

Table 4.7

Eureka

Jan.	17	20	+	19	15	-	35
Feb.	14	34	-	1	16	-	50
Mar.	21	19	+	20	18	+	37
Apr.	16	35	+	1	12	-	47
May	11	27	+	1	11	-	38
Jun.	5	15	+	9	14	+	29
Jly.	14	32	-	4	15	-	47
Aug.	15	41	+	3	22	+	63
Sep.	17	25	+	8	18	+	43
Oct.	19	24	+	1	24	-	48
Nov.	1	20	-	18	10	+	30
Dec.	12	21	-	7	20	+	41

1 % Explanation of variance

2 Correlation with temperature record (+ or -)

3 Σ% explanation of variance with 2 best independent variables.

Principal synoptic types accounting for variance of the monthly maximum temperature record

Table 4.8

Isachsen

	Primary Type	%[1]	Correlation[2]	Secondary Type	%[1]	Correlation[2]	Σ%[3]
Jan.	4	23	+	15	14	+	36
Feb.	21	23	+	6	18	+	41
Mar.	9	30	+	13	13	+	43
Apr.	16	31	+	2	19	+	50
May	1	30	-	21	11	-	51
Jun.	15	13	+	9	12	+	25
Jly.	18	33	-	14	18	-	51
Aug.	15	36	+	3	19	+	55
Sep.	8	27	+	7	18	+	45
Oct.	13	33	+	22	13	-	46
Nov.	13	31	+	5	11	-	42
Dec.	7	23	+	20	13	+	36

1 % Explanation of variance

2 Correlation with temperature record (+ or -)

3 Σ% explanation of variance with 2 best independent variables.

December, January and June) temperature fluctuations are dependent on a larger number of types and at least 4 synoptic type variables would be needed to account for 45% of the total variance. The reasons for these differences are not clear. It would seem likely that persistence of a particular synoptic pattern in certain months would greatly influence the temperature record. However, analysis of type persistence indicates this explanation is inadequate because type durations are commonly longer in mid-winter than in mid-summer. It is possible that frequent disturbance of the surface temperature inversion in winter months (on a local scale) results in surface temperatures showing little correlation with the regional flow pattern, but this explantion is unlikely in June. Further work is needed to clarify this question.

In the ablation season, two synoptic patterns are particularly important - types 1 (at Alert) and 15 (at Isachsen and Eureka). These are similar synoptic situations with a high pressure center northwest of Ellesmere Island and northerly flow over Alert, northeasterly flow over Isachsen and Eureka. Type 1 is very cold at Alert in all months whereas type 15 results in warm conditions at Eureka and Isachsen, particularly in August when the Ellesmere Island land mass to the east is relatively warm. Other types of importance in summer months are types 18 (very cold at Isachsen, averaging only 3.2°C in July) and type 14 (also cold, at Eureka). These types will be considered again in the following section.

Precipitation: Daily precipitation totals at Isachsen and Alert have been stratified by synoptic type to identify those types important to annual accumulation. In this study, all 'Traces' were assigned a value of 0.127 mm (0.005 inches) in order to take into account the large number of traces which occur, particularly in winter months (see Table 3.10, this report and accompanying discussion).

Table 4.9 shows the main synoptic types and their frequency for the two stations. At Alert, types 1 and 4 are of overwhelming importance to annual precipitation, accounting for over 50% of all precipitation recorded yet occurring on only 36% of days. These types are also the most important at Isachsen but provide less precipitation - ∿23% of annual totals. Although at each locality a small

Table 4.9

Synoptic Types Important to Annual Precipitation Totals

ALERT (50/07 to 74/12)			ISACHSEN (48/05 to 74/12)		
Type	% of Ann. Precip.	% Frequency	Type	% of Ann. Precip.	% Frequency
4	26.8	12.8	1	11.9	22.5
1	24.6	22.8	4	11.4	12.5
2	6.6	9.8	2	9.8	9.5
7	5.5	4.7	3	8.0	7.0
15	4.5	4.0	8	7.9	2.5
6	4.3	4.6	15	7.6	4.0
			7	6.7	4.7
	72.3	58.7	13	5.3	3.6
				68.6	66.3

number of types accounts for most of the annual precipitation, this partly reflects the frequency with which the types occur. Nevertheless, certain types are distinctly seasonal in occurence and they may be important 'precipitation - bearing' situations at certain times of year. For example, type 8 (low pressure center north of Isachsen, Figure 4.4) reaches a maximum frequency of ∿10% in July (Figure 4.7). July is one of the wettest months at Isachsen with ∿20% of annual precipitation (Table 3.10, this report); type 8 situations account for 24% of the monthly total yet they occur, on only 3 days in the month on average. Type 8 synoptic types are thus very important to summer precipiation but over the year as a whole other types result in more precipitation. Type 8 situations in July are amongst the coldest at this time of year (average Tmax = 3.3°C, Tmean only 1.4°C) so the frequency of this type is of particular significance to ablation in the area. Other very wet synoptic situations at Isachsen in summer months are types 2, 4 and 16. Table 4.10a & b shows average temperature conditions in relation to the amount of precipitation received during the occurrence of 'wet' synoptic situations at Isachsen and Alert respectively.

SYNOPTIC TYPES IN THE ABLATION SEASON

In order to assess the significance of each synoptic situation to summer ablation in the Isachsen and Alert areas, the contribution of each type to monthly precipitation totals (June-August) was plotted against the average temperature of the type as illustrated in Figure 4.10. In this way 4 groups can be recognized - types which are (1.) cool and wet, (2.) cool and dry, (3.) warm and wet and (4.) warm and dry - and the relative importance of each type during the ablation season can be assessed. (Table 4.10a)

At Isachsen, types 4, 8 and 11 are 'cool and wet' throughout the summer. All three types are characterised by high pressure to the southwest of Isachsen resulting in westerly airflow over the region. Types 8 and 11 are dominated by

Table 4.10

General climatic characteristics of synoptic types in summer months (June - August)

a.) Isachsen

		3 months	2 months
cool & wet	Types:	4, 8, 11	
cool & dry		1,12,18,21,22	20
warm & wet		2, 16	3,5
warm & dry		9,15,17	6,7,10,13,19

b.) Alert

	3 months	2 months
cool & wet	1,4	
cool & dry	5,6,18,19,21,22	9,14,15,20
warm & wet	2,7	
warm & dry	11,16	3,8,10,12,13,17

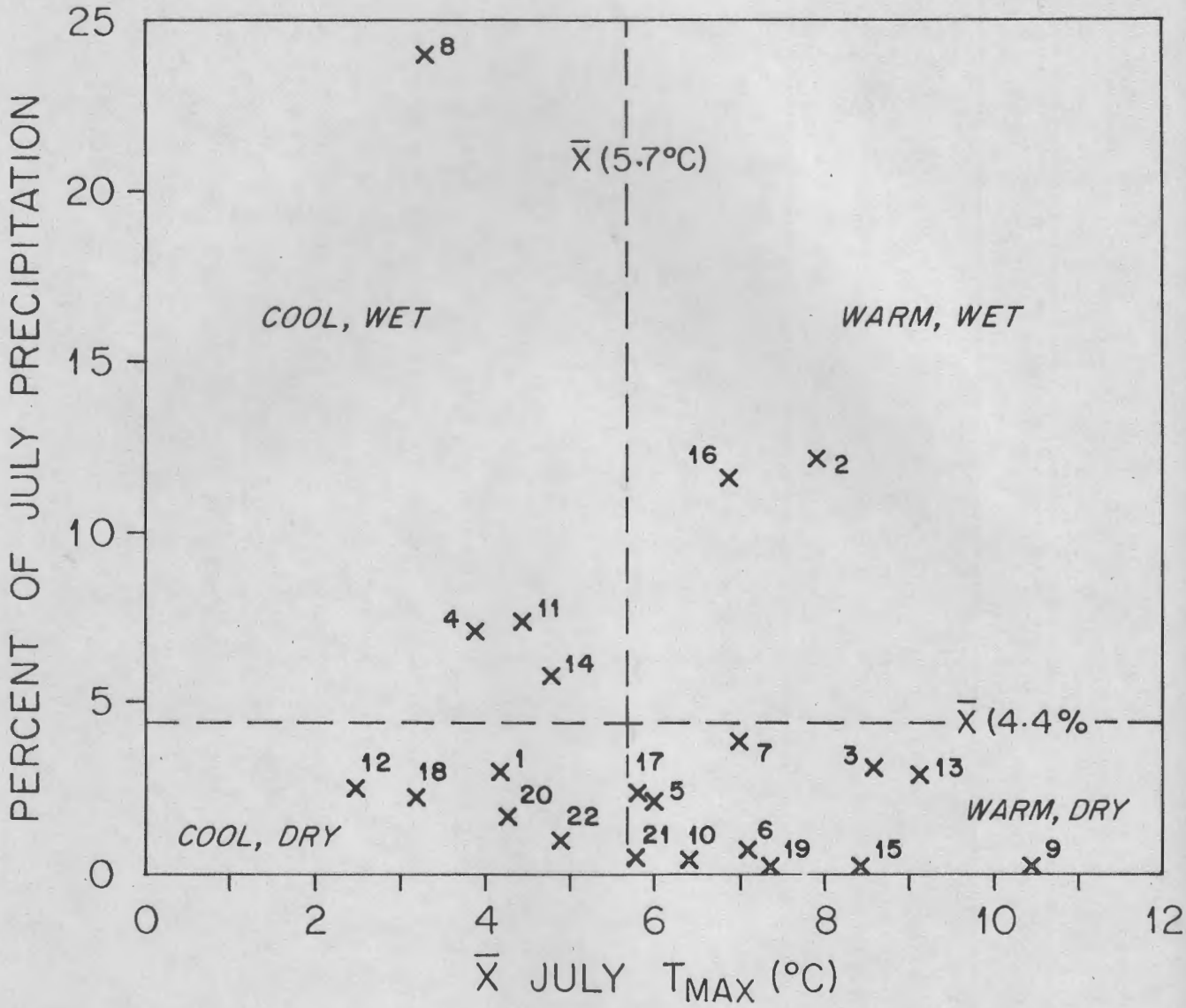

Figure 4.10 Plot of mean maximum temperature conditions at Isachsen in July during synoptic type episodes and the contribution each type makes to the monthly precipitation total.

a major low pressure area centered just to the east or southeast of Isachsen. In 'warm and dry' types (9, 15 and 17) Isachsen is either under the influence of an anticyclone or ridge (e.g. types 9, 15, 6) or low pressure to the south or south west results in warm advection from the southeast (types 17, 13, 7, 19). Average daily maximum temperature at Isachsen during 'warm, dry' types is 2.8°C greater than during cool, wet types (June-August). 'Warm, dry' types occur on 1.4% of all days and result in only 1.2% of annual precipitation whereas 'cool, wet' types account for 13.2% of annual precipitation and occur on only 5.6% of days per year. An increase in the frequency of 'cool, wet' types at the expense of 'warm dry' type frequency may thus result in significantly different summer conditions.

In view of the recent change in summer climate of the Canadian High Arctic (Bradley, 1973; Barry et al, 1975: Chapter 3, this report) it is of interest to examine synoptic type frequencies over time. This work is in a preliminary stage but some interesting results are apparent. Figure 4.11 shows the summer (June - August) frequency of 'cold, wet' and 'warm, dry' types at Isachsen. Although inter-annual variability is high, particularly in the earlier part of the record, 'cool, wet' types have increased in frequency over the last 15 years whilst 'warm, dry' types have decreased in frequency. The change is particularly marked after 1963; 'cold, dry' types averaged ∿24 days per summer after 1963 whereas the 1946-63 average was ∿18 days. 'Warm, dry' types averaged ∿9 days per summer after 1963 and ∿12 days from 1946-63.

A similar analysis was conducted on Alert summer climatic data and the results are summarised in Table 4.10b. Like Isachsen, type 4 situations are wet and cold (mean daily Tmax=2.5°C); ∿31% of June-August precipitation results form this synoptic type (on 13% of summer days). In fact, during the three summer months type 4 days account for 12% of annual precipitation. Also important 'cold, wet' types at Alert are type 1 situations in which airflow is northerly, from the

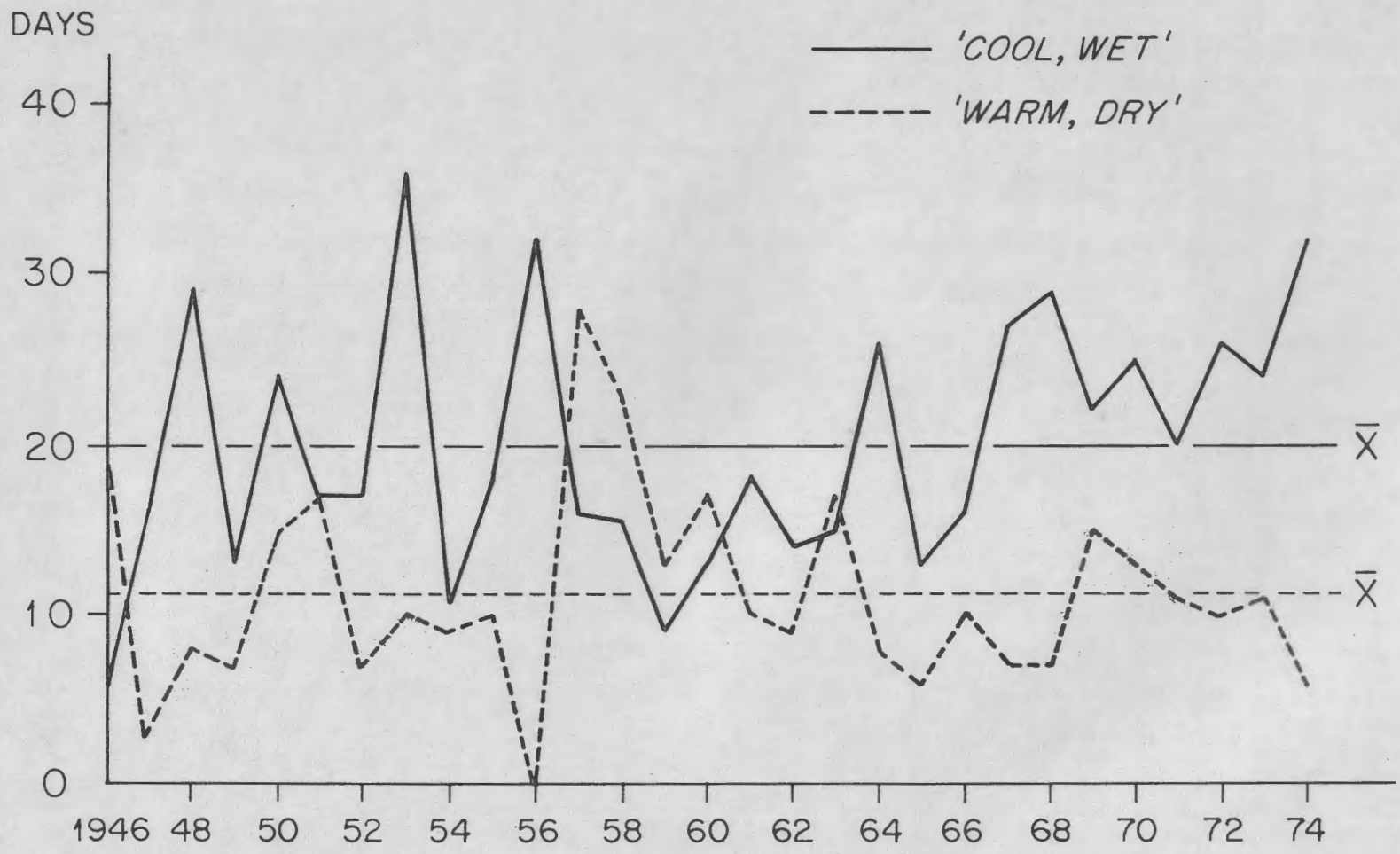

Figure 4.11 Frequency of 'cool, wet' and 'warm, dry' types at Isachsen in July to September of each year.

Arctic Ocean. However, as these types occur on ~14% of summer days and provide ~14.5% of summer precipitation their importance for precipitation totals is simply a function of their relatively high frequency.

'Warm, dry' conditions at Alert are associated with synoptic types 11 and 16. Type 16 was also warm at Isachsen but resulted in more precipitation at that station. Both patterns involve low pressure centers west of Alert but in the type 11 situations the center of the Low is close to but slightly east of Isachsen. Thus at Alert, type 11 situations are warm and dry (average Tmax = 6.8°C; and mean daily precipitation = 0.05 mm) due to warm air advection from Baffin Bay whereas at Isachsen they are cold and wet (average Tmax = 2.7°C; mean daily precipitation = 1 mm). A similar situation occurs with synoptic type 8 where a low pressure center between Alert and Isachsen places them in airflow from opposite directions, resulting in warm and generally dry conditions at Alert and cold, wet conditions at Isachsen.

The frequency of 'cold wet' types (1 and 4) has increased since ~1957 with consistently higher frequencies since 1963. These types occurred an average of 24 days per summer, 1946-1963 and ~28 days per summer, 1964-1974. Warm, dry types (11 and 16) have decreased in frequency from 9.5 to 7.4 days per summer in the same periods.

PRECIPITATION 'EFFICIENCY' OF SYNOPTIC TYPES

Throughout the previous discussion of precipitation resulting from different synoptic types, the actual frequency of each type greatly affected its contribution to annual precipitation totals. In fact, a type may be 'dry' by virtue of its low frequency but still result in relatively large amounts of precipitation per day of occurrence. In order to investigate the 'efficiency' of a type in bringing precipitation to a region the absolute frequency must be taken into account. By doing this, those types which may not (under the present climate) occur with great frequency but which are very 'efficient' at bringing precipitation to high latitudes can be identified. It is then possible to hypothesise what conditions may result from a decrease in

the frequency of 'less efficient' types and an increase in the frequency of 'more efficient' types.

To standardise the data for type frequency a 'raininess' index is used where

$$R_{ij} = \frac{P_{ij}\ N_j}{N_{ij}\ P_j} \times 100\%$$

P_{ij} = precipitation from type i in period j;

N_{ij} = frequency of type i in period j;

N_j = total number of days in period j;

P_j = total precipitation in period j.

A type which occurs 10% of the time and results in 10% of precipitation would thus score an R value of 100. As type frequency increases and the resulting precipitation decreases, $R \rightarrow 0$.

Preliminary studies of Isachsen monthly precipitation data (for July - September, when 56% of annual precipitation occurs) indicate that types 17, 16, 8, 11, 12, 7 and 14 are extremely 'efficient' precipitation bearing synoptic situations (monthly R values of up to 390) even though under the present climate their infrequent occurrence may cause them to be thought of as 'dry' types (see discussion above). All types are dominated by a low pressure center in the vicinity of Isachsen centered to the west, northwest or north of the station. In such situations warm[6] relatively moist air will be drawn into the

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[6]Types 7, 16 and 17 are relatively warm at Isachsen in June-August; types 8, 11, 12 and 14 are relatively cold (Table 4.10). However, at present these 'warm' cyclonic types occur twice as often as the cold cyclonic types. In September all types are relatively warm at Isachsen but Tmax is by that time < 0°C.

depression center from the south.

Although individual depression trajectories have not yet been examined, earlier work suggests that in most of these synoptic situations, depressions have moved into the Isachsen area from the Arctic Ocean and northern Beaufort Sea. Namias (1958) and Reed and Kunkel (1960) note that many depressions entering the Beaufort Sea in summer originate along the Arctic front which closely parallels the Siberian and Alaskan coastlines where thermal contrasts are strongest at this time of year. Similar observations were made by Klein (1957) and Wilson (1967). In relatively warm periods when depression tracks in the North Atlantic are displaced northward, regeneration of cyclones along the Siberian coast is likely to increase the frequency of these depressions crossing the Arctic Ocean and Beaufort Sea, with a concurrent increase in precipitation in the Isachsen region. Conversely, in cold periods when depression tracks are further south the frequency of these storm systems entering the Arctic Ocean Basin will be reduced and resultant precipitation amounts will be lower (in effect this is mirrored by the seasonal variation of these synoptic situations which nearly all reach maximum frequencies in summer months, Figures 4.7 and 4.8). Collectively these 7 cyclonic types occur on 19% of days per summer (June-September) but result in 40% of precipitation at Isachsen during these months; this is 23% of annual precipitation. An increase in the frequency of these types by only 2 or 3 days per summer month (at the expense of 'less efficient' types) would increase annual precipitation by at least 10%. It is thus conceivable that generally warmer 'North Atlantic' conditions would lead to increased cyclonic activity in the Beaufort Sea area with a concomitant increase in moist air being drawn into the region. Associated temperatures would depend on the particular

types which predominate (see footnote 6) but it is certainly possible that associated temperature could be quite low in spite of the advection of southerly air.

SUMMARY

An objective classification of synoptic type 5 has been developed for the Canadian High Arctic for the period 1946-1974. Certain types have distinct seasonal variations. Monthly mean temperature characteristics of the different synoptic types were determined for Alert and Isachsen and the types were ranked, warmest to coldest. Stepwise multiple regression analysis of monthly synoptic type frequency and mean Tmax temperatures at Alert, Eureka, and Isachsen indicated those synoptic types which were closely related to inter-annual variations of temperature. Although the main types varied from station to station generally maximum variance explanation with a minimum number of independent variables was achieved in the months April-August. Stratification of precipitation data by synoptic type indicated those types accounting for most of the annual precipitation at Alert and Isachsen. Generally, a small number of types account for the bulk of annual precipitation though this is really a function of type frequency. Ablation season temperatures and precipitation data for Alert and Isachsen were used to identify those types associated with 'cool, wet' or 'warm, dry' conditions. Generally, 'cool, wet' types have increased in frequency over the last ~15 years while 'warm, dry' types have been less frequent. This is true at both Alert and Isachsen even though the synoptic types are not the same in each case.

'Precipitation efficiency' was investigated for the wettest months of the year. Certain synoptic types which are relatively infrequent under present

climatic conditions are actually very efficient 'precipitation-bearing' situations. At Isachsen seven relatively infrequent cyclonic types account for 23% of annual precipitation. It is suggested that many of the depressions which dominate circulation over the Isachsen area in these situations originate from the regeneration of North Atlantic depressions as they pass along the Siberian coastline. It is thus likely that in warmer periods, northward displacement of Atlantic depressions would increase the frequency of storms entering the Arctic Ocean Basin and hence result in heavier precipitation in the High Arctic. However, the associated temperatures at Isachsen are not necessarily warmer, even though increased advection of southerly air is involved.

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APPENDICES

APPENDIX 1

SUMMARY OF OPERATIONS

During 1975 the party of J. England and R.S. Bradley established a camp on Judge Daly Promontory, northeastern Ellesmere Island (at 81°24'N, 65°20'W). Thirty eight days were spent in this field area where over 200 km of terrain were investigated, three mountains ascended and numerous collections of both organic and mineral samples obtained from glacial and marine deposits. A weather station was also kept at the base camp (see Appendix 7). Towards the end of the season (July 28) the party attempted a camp move to the Simmonds Bay ice caps at the head of Archer Fiord via Twin Otter aircraft. Since no landing site was feasible the party was evacuated to Alert Weather Station, northeastern Ellesmere Island, where additional reconnaissance studies were conducted. The party then departed on August 3 from Alert to Thule, Greenland, then on to Trenton Air Base, Ontario, via a Canadian Forces flight.

During 1976 two separate trips were made up to the field area on northeastern Ellesmere Island. On the first trip in from Resolute Bay, Cornwallis Island (May 26), the party chartered Bradley Air Services' DC-3 which was useful in transporting the larger equipment (komatik sled, freight canoe) which could not be carried the previous summer via Twin Otter. All equipment was consolidated at a base camp in Ella Bay, south head of Archer Fiord. From this location the party conducted a wide variety of field work including lake coring, Quaternary geology and establishing a mass balance stake network on the Simmonds Bay ice cap 30 km to the northeast of Ella Bay base camp. The party returned south, via Alert Weather Station, on June 23.

The second trip north during the summer of 1976 focused on returning to Judge Daly Promontory. The purpose of the return was to collect additional samples of both marine deposits and peat which were critical to the understanding

of information collected during the summer of 1975. Some of these earlier samples (collected in 1975) provided controversial results during the intervening winter which required additional testing.

The party set up camp in central Judge Daly Promontory on July 30 and about two weeks later hiked 25 km down the Pavy River to Cape Baird where additional studies were conducted on the Quaternary geology. On August 16th Bradley Air Services' Twin Otter took the party to Ella Bay where the base camp was secured for winter, then evacuated the party to Alert Weather Station for a Canadian Forces flight south. The calendar below summarizes the main events of the two summer seasons (1975/76).

1975

June 21	Party flies from Montreal to Resolute Bay
June 21-24	Prepare food and equipment cache, and arrange aircraft charter in Resolute Bay
June 25	Fly from Resolute Bay to field area via Eureka, western Ellesmere Island
June 26	Base camp established in central Judge Daly Promontory. Weather station also erected.
June 27-July 13	Extensive transects on foot surveying extent of Greenland erratics, climbing Moon Mt. (970 m a.s.l., see profile Fig. 1.2) and investigating Beethoven Valley. July 4 - July 5 was noteworthy in that a heavy storm with high winds destroyed the wall tent and the party lived in the remnant, three ft. high "cave" for the rest of the summer!
July 14	Leave base camp on foot for temporary "fly camp" 10 km to the S.E. Climb Jigsaw Mt. (∿865 m a.s.l.) to determine uppermost profile of Greenland erratics bordering Cape Cracroft, western Kennedy Channel. General reconnaissance of this area.
July 17	Climb Pastoral Pk. (∿815 m a.s.l.) along transect to determine uppermost limit of Greenland erratics (profile, Fig. 1.2).
July 20	Leave base camp on foot for temporary "fly camp" 20 km S.S.W. of base camp in order to reach lower Daly River valley.
July 21-23	Reconnaissance and sampling of glacial and marine units along lower Daly River.

July 24	Return to base camp
July 25-27	Further investigations around base camp and preparation for departure to Simmonds Bay ice caps inner Archer Fiord, for studies on recent climatic change.
July 28	Twin Otter arrives to remove party. Fly to Simmonds Bay ice caps. No landing possible so party is evacuated to Alert Weather Station.
July 29-30	Reconnaissance north of Alert Weather Station. Glacial and raised marine deposits investigated around Kirk Lake and Colan Bay.
August 3	Party leaves Alert Weather Station for Trenton air base, Ontario, via Canadian Forces flight. Equipment stored at Alert. End of 1975 field season.

1976

May 25	Party flies from Montreal to Resolute Bay.
May 26-27	Party organizes air charter and equipment for field work.
May 28	DC-3 takes party to field area from Resolute Bay. Equipment from previous year collected at both Eureka and Alert Weather Stations. Base camp established at head of Ella Bay, Archer Fiord.
May 30-June 3	Core Christianson Lake 3 km S.W. of base camp. Additional reconnaissance on surrounding glacial geology.
June 6	Party leaves base camp by skidoo and sled. Travels to Simmonds Bay, Archer Fiord, 25 km to N.E. en route to Simmonds Bay ice caps.
June 7	Party transported from sea level to ice caps (∿1100 m a.s.l.) via Defence Research Board's Single Beaver. Camp established on ice cap. Skidoo and sled left in Simmonds Bay.
June 7-14	Accumulation/ablation network (18 stakes) set up on ∿18 km^2 ice cap. Survey of snow cover above ice surface conducted.
June 14/15	Party returns to Simmonds Bay on foot via Murray Lake valley where additional investigations on raised marine deposits were made along the way.
June 15-18	Reconnaissance of glacial and marine deposits in Simmonds Bay and around Bulleys Lump during return to base camp in Ella Bay (via skidoo and sled).
June 19	Bradley returns briefly to Simmonds Bay ice cap via Parks Canada helicopter to collect remaining equipment. England continues reconnaissance on glacial deposits near base camp.

June 23	Party evacuated to Alert Weather Station for Canadian Forces flight south to Trenton Air Base, June 25.

Return Trip 1976

July 28	Party flies from Montreal to Resolute Bay.
July 30	Party charters Twin Otter from Resolute Bay to Judge Daly Promontory via base camp in Ella Bay.
July 31-August 11	Additional collections made on glacial and marine deposits associated with Greenland ice advance onto Judge Daly Promontory and also from Beethoven valley glacio-marine deposits. Further reconnaissance work in this area carried out as well.
August 12/13	Party travels on foot from central Judge Daly Promontory to Cape Baird (20 km N.E.) via lower Pavy River valley.
August 13-15	Sampling of glacial and marine deposits around the mouth of the Pavy River and the Cape Baird terrace.
August 16	Party is picked up by Twin Otter which transported field equipment to base camp in Ella Bay where it was stored for the winter. Then party was evaculated to Alert Weather Station for Canadian Forces flight to Trenton Air Base. End of 1976 field season.

APPENDIX 2

RADIOCARBON DATES AND AMINO ACID AGE ESTIMATES PERTAINING TO 1975/76 FIELD WORK

The following dated samples were collected during the field seasons of 1975 and 1976 on northeastern Ellesmere Island. The ^{14}C dates were provided by DICAR Radioisotopes Laboratory under the direction of I.C. Stehli. Amino acid age estimates on five samples were provided by Dr. G.H. Miller, INSTAAR, University of Colorado.

RADIOCARBON DATES

DIC-544 $23,110 \begin{smallmatrix} +660 \\ -720 \end{smallmatrix}$

Fragmented shells on surface of ice shelf moraine located on southwest side of Beethoven Valley, eastern Judge Daly Promontory ($81^{\circ}21'$N Lat, $60^{\circ}05'$W Long) at alt ∿200 m a.s.l. Coll. 1975 by J. England and R.S. Bradley. Comment (J.E.): The manner by which these shells have been incorporated in the ice shelf moraine is unclear: they may have been scoured-up by the glacier as it crossed its grounding line or, more likely, they may have been transferred to the surface by the accretion of freezing sea water at the base of the floating glacier. The shells were encrusted with deposits composed of 50% silica and 50% calcite. The shells were cleaned as much as possible with a dentist drill but all contaminants could not be removed. These contaminants may be the product of recrystallization following the original emplacement of the shells in the till, hence the date is likely a minimum estimate (I. Stehli, personal communication). This is also indicated by the date on DIC-738 (this list).

DIC-545 7910 ± 145

Complete bivalves of Hiatella arctica (30 g) from Holocene delta in lower Beethoven Valley, eastern Judge Daly Promontory (81°21'N Lat, 64°55'W Long) at alt ∿61 m a.s.l. Coll. 1975 by J. England and R.S. Bradley. Comment (J.E.): These shells occur in a delta on the distal side of the older ice shelf moraine and proglacial terraces up-valley (see DIC-544, 546 and 578, this list). There is no evidence of glacier ice in this drainage basin during the Holocene, hence, this delta is likely the product of fluvial sedimentation in the zone of the marginal depression maintained between the separated, late Wisconsin, Greenland and Ellesmere Island ice sheets. Due to low sedimentation rates in the Beethoven Valley, the 61 m delta is not considered to represent the relative sea level at ∿7900 B.P. In addition, the fact that this 61 m marine limit is younger than dated shorelines both to the north and south along this coastline (see DIC-747 and 549, respectively) may reflect the time lag in establishing the marine limit in the Beethoven Valley due to lower sedimentation rates.

DIC-546 $22,780 \begin{smallmatrix}+810\\-900\end{smallmatrix}$

Fragmented shells (∿30g) from ice-contact, glacio-marine terrace below ice shelf moraine on southwest side of Beethoven Valley, eastern Judge Daly Promontory (81°21'N Lat, 65°05'W Long). Coll. 1975 by J. England and R.S. Bradley. Comment (J.E.): This shell sample was encrusted with similar contaminants discussed under sample DIC-544. Hence it is also considered to be a minimum date and is superseded by DIC-738 which was collected

from the same site in 1976. Both of these shell samples are washing out of a marine terrace at 175 m a.s.l. which marks the relative sea level in the valley during the break-up of the ice shelf. Hence the outermost Ellesmere Island ice margin is older than DIC-546 and 738 (in this locality). Radiometrically both DIC-546 and 738 may be minimum estimates on the initial recession of this ice margin. An amino acid age estimate on sample DIC-546 indicated an age of >35,000 B.P. (G.H. Miller, personal communication).

DIC-547 $14,360 \begin{smallmatrix} +1120 \\ -1310 \end{smallmatrix}$

Fragmented shells incorporated in moraine deposited by Greenland Ice Sheet on easternmost Judge Daly Promontory, immediately above western Kennedy Channel (81°22'N Lat, 64°44'W Long). Coll. 1975 by J. England and R.S. Bradley. Comment (J.E.): Stratigraphically the moraine is the youngest glacial event within the Greenland erratic zone on Judge Daly Promontory. This zone is cross-cut by the outermost Ellesmere Island ice advance which is older than ∿28,000 - 30,000 B.P. (DIC-550 and 738). Hence, an age of ∿14,000 B.P. on sample DIC-547 is very likely too young. This shell sample was unfortunately small (5g), no leaching was applied and cleaning by hand made the complete removal of contaminants impossible. An amino acid age estimate on the same sample suggests a date of >80,000 B.P. (G.H. Miller, personal communication).

DIC-548 $8590 \begin{smallmatrix} +550 \\ -590 \end{smallmatrix}$

Fragmented marine shells from raised beach 4 km west of Cape Defosse, eastern Judge Daly Promontory (81°14'N Lat,

65°42'W Long) at alt ∿40 m a.s.l. Coll. by J. England and R.S. Bradley. Comment (J.E.): An age of ∿8500 B.P. for this 40 m beach is difficult to interpret since younger shells nearby date a relative sea level at ∿90 m a.s.l. (DIC-549). Fragmented condition of shells and the fact that this dated elevation is not consistent with the sequence of local Holocene emergence suggests that sample DIC-548 is contaminated. In addition, the sample was small (6.6g), partially encrusted and no leaching was applied.

DIC-549 8200 ± 260

Whole shells of *Hiatella arctica* collected *in situ* from marine silts underlying local marine limit (∿90 m a.s.l.) along lower, east side of Daly River, eastern Judge Daly Promontory (81°15'N Lat, 65°45'W Long). Coll. 1975 by J. England and R.S. Bradley. Comment (J.E.): Sample dates initial Holocene emergence along this coastline. However, this marine limit occurs on the distal side of an older ice shelf moraine in the same valley (DIC-550 and 584). Since this ice shelf moraine (∿200 m a.s.l.) has not been overridden it is concluded that late Wisconsin ice did not occupy the lower Daly River valley. Hence sample DIC-549 dates initial emergence beyond the late Wisconsin ice margin--hence the initial decay of an ice marginal depression. Due to small sample size (10g) no leaching was applied, however, it appeared clean under 90 x magnification (I. Stehli, personal communication).

DIC-550 $28,610 \begin{smallmatrix}+1710\\-2180\end{smallmatrix}$

Fragmented shells from marine till overlying bedded sands along lower, west side of Daly River, eastern Judge Daly Promontory (81°15'N Lat, 65°48'W Long). Coll. 1975 by J. England and R.S. Bradley.

Comment (J.E.): The shells have been incorporated in marine till deposited beneath an ice shelf which occupied the lower Daly River. They occur at ∿100 m a.s.l., hence well below the relative sea level of ∿175 m a.s.l. at the time of ice shelf formation. This sample provides a minimum estimate on the formation of the overlying ice shelf and the date is consistent with others collected in the area from similar stratigraphic positions (27,950 ± 5400, St 4325; also DIC-738, this list).

DIC-552 $3650 \begin{smallmatrix}+80\\-70\end{smallmatrix}$

Driftwood log embedded in slope debris along west side of Colan Bay, N.E. Ellesmere Island (82°30'N Lat, 62°55'W Long) at alt of 10 m a.s.l. Coll. 1975 by J. England and R.S. Bradley.

Comment (J.E.): The sample is the first ∿3600 B.P. date on driftwood collected around the Alert/Robeson Channel area (including Archer Fiord/Lady Franklin Bay). The deposition of the driftwood implies relatively open water during the summer months at this time. This is also suggested by the relative abundance of wood in this elevation range (∿6-10 m a.s.l.). This driftwood provides a maximum date on the 10 m shoreline since it occurs on a steep slope and, although well embedded, redeposition from a higher elevation cannot be excluded. However, this age appears quite reasonable for this elevation when plotted on a local uplift curve

(England, 1976a). Hence, redeposition (if it occurred) probably did not amount to more than a few meters.

DIC-553 5520 ± 95

Marine shells collected from silts along west side of Colan Bay, N.E. Ellesmere Island (82°30'N Lat, 62°55'W Long) at alt of 14 m a.s.l. Coll. 1975 by J. England and R.S. Bradley. Comment (J.E.): This shell sample was collected on the distal side of several ice-pushed ridges approaching Colan Bay from Hilgard Bay (to the west) via a low valley. It is not clear whether the ice-pushed ridges are the result of sea ice or glacier ice. Since local postglacial emergence inland of this site began ∿10,000 B.P. it seems more likely that these low ridges (∿2 m in height) are the product of sea ice rather than glacier ice. Such sea ice-pushed ridges could have been formed during the postglacial emergence of this through valley. The silts rise to 34 m a.s.l. which, in turn, is a minimum estimate on the relative sea level ∿5500 B.P.

DIC-584 >25,000

Sample of organic material (*Dryas octopetala*) collected from bedded sands underlying marine till along lower, west side of Daly River, eastern Judge Daly Promontory (81°15'N Lat, 65°48'W Long). Coll. 1975 by J. England and R.S. Bradley. Comment (J.E.): This sample was really too small for dating except as an indicator. Sample is probably greater than 25,000 B.P. (i.e. the I sigma value was enormous, hence a definite date was considered unrealistic, I. Stehli, personal communication). However, this date is not contradicted by

the age of the overlying marine till dated 28,610 $^{+1710}_{-2180}$ B.P. (DIC-550). Whether the organic material (Dryas octopetala) was growing locally prior to the ice advance or whether it is redeposited Tertiary material is not known. Further sampling is required.

DIC-737 8380 ± 105

Marine shells (Hiatella arctica) collected from topset beds of Cape Baird terrace, northernmost tip of Judge Daly Promontory (81°33'N Lat, 64°25'W Long) at alt of ∿110 m a.s.l. Coll. 1976 by J. England and R.S. Bradley. Comment (J.E.): These shells were collected in situ from the uppermost section of the Cape Baird terrace and provide a date on the initial emergence of this 110 m relative sea level. The terrace itself appears to be an ice-contact feature formed along the outermost northeastern Ellesmere Island ice margin which began to recede ∿28,000 - 30,000 B.P. (DIC-550 and 738). Hence, it is likely that the sedimentation responsible for the formation of the terrace is older than ∿8400 B.P. However, the emergence of the terrace ∿8400 B.P. is significant in that it records the initial recession of the late Wisconsin, N.W. Greenland Ice Sheet from Hall Basin to the east. It has been shown that the N.W. Greenland Ice Sheet isostatically-dominated the postglacial emergence over northeastern Ellesmere Island (England, 1976a) and the timing of this emergence ∿8400 B.P. is similar to the initial emergence near Cape Defosse, forty km to the southwest, dated at ∿8200 B.P. (DIC-549).

DIC-738 $29,670 \begin{smallmatrix}+830\\-930\end{smallmatrix}$

Fragmented and whole shells from a 175 m glacio-marine terrace below ice shelf moraines, southwest side of Beethoven Valley, eastern Judge Daly Promontory (81°21'N Lat, 65°05'W Long). Coll. 1976 by J. England and R.S. Bradley. Comment (J.E.): This shell sample takes precedence over DIC-544 which was collected from the same site and encrusted with contaminants. DIC-738 was an unencrusted sample, weighed ∿50g and was subjected to 25% leaching. This date, although finite, may be a minimum estimate on the recession of the ice shelf in this valley. The terrace (175 m a.s.l.) is consistent with the water depth required to float the estimated glacier thickness in this valley and it must have formed subsequent to the removal of the ice shelf. This date compares closely with others collected along the outermost, northeastern Ellesmere Island ice margin (St 4325, England, 1974; DIC-550, this list).

AMINO ACID AGE ESTIMATES

	Allo: Iso Free	Allo: Iso Hyd.
JHE-3 (*Mya truncata* fragment)	0.23	0.04

This sample was collected in 1972 at elevation of ∿105 m a.s.l. from a proglacial terrace along the lower Daly River, Judge Daly Promontory (81°14'N Lat, 65°48'W Long). Part of same shell sample ^{14}C dated 27,950 ± 5400 (St 4325; England, 1974). Tentative amino-acid age for this sample is >35,000 B.P.

	Allo: Iso Free	Allo: Iso Hyd.
JHE-3 (*Mya truncata* umbone)	0.25	0.05 0.054
From same sample as above, tentative age >35,000 B.P.		
JDS-11 (*Hiatella arctica*)	0.18	0.064
Shell fragments collected in 1975 from proglacial terrace where sample JHE-3 was obtained. Again tentative age is >35,000 B.P.		
JDS-10 (*Hiatella arctica*)	0.20	0.037
Shell fragments from kame terrace up-valley from aforementioned proglacial terrace. Both samples occur along lower west side of Daly River. Elevation of shells JDS-10 is ∿105 m a.s.l. Tentative age is >35,000 B.P.		
JDS-3 (*Hiatella arctica*)		
Shell fragments collected from upper surface (∿200 m a.s.l.) of ice shelf moraine along west side of Beethoven Valley. Part of same shell sample dated 23,110 $^{+660}_{-720}$ B.P. (DIC-544), however, this sample appears to have undergone recrystallization and hence it is likely a minimum estimate (see DIC-738). Tentative amino acid age estimate is >35,000 B.P.	0.28	0.048
JDS-6 (*Hiatella arctica*)	0.43 0.48	0.125 0.129
Fragmented shells collected from Greenland Ice Sheet moraine on easternmost Judge Daly Promontory at elevation of ∿200 m a.s.l. This is stratigraphi-		

cally the youngest glacial deposit within the zone of Greenland erratics on Judge Daly Promontory. A ^{14}C date on part of the same shell sample was 14,360 $^{+1120}_{-1310}$ B.P. (DIC-547), however, only 5g were used, no leaching was applied and the porous nature of the shells made the complete removal of contaminants impossible. These shells are considered to be at least twice as old as samples JHE-3, JDS-3, 10 and 11 (G.H. Miller, personal communication). This is consistent with the stratigraphic position of JDS-6 which occurs in deposits which predate those containing the aforementioned samples. Tentative age of sample JDS-6 is 80,000 - 160,000 B.P.

APPENDIX 3.

CLIMATIC REGIONS OF THE CANADIAN ARCTIC ISLANDS

Principal component analysis of mean monthly temperature and monthly precipitation data for 1960-1969 from 15 stations throughout the Canadian Arctic archipelago indicates 4 distinct groups of stations can be recognized on the basis of the first two principal components (Figures A3.1). Component 1 is primarily a precipitation factor, with winter temperatures also important. Component 2 reflects summer and early winter temperatures (June-October). The two components account for 79% of the total variance. The four station-groups delimited comprise discrete geographical regions (Figure A3.2). Region A encompasses the low Arctic stations from Holman Island to Frobisher Bay and Nottingham Island. This group is basically separated from the other stations on the basis of the 'temperature component' and this can be considered a latitudinal effect. Region D includes only Cape Dyer which is clearly isolated from other stations on the basis of its high precipitation receipts. Region C includes the eastern Baffin coastal stations and Dewar Lakes where both temperatures and precipitation characteristics distinguish the group. Region B comprises the High Arctic stations where low temperatures and low precipitation amounts are common characteristics. The boundaries of each group are not fixed and are indicated in Figures A3.1 and A3.2 as a general guide only; clearly additional data would enable the boundaries to be fixed more precisely.

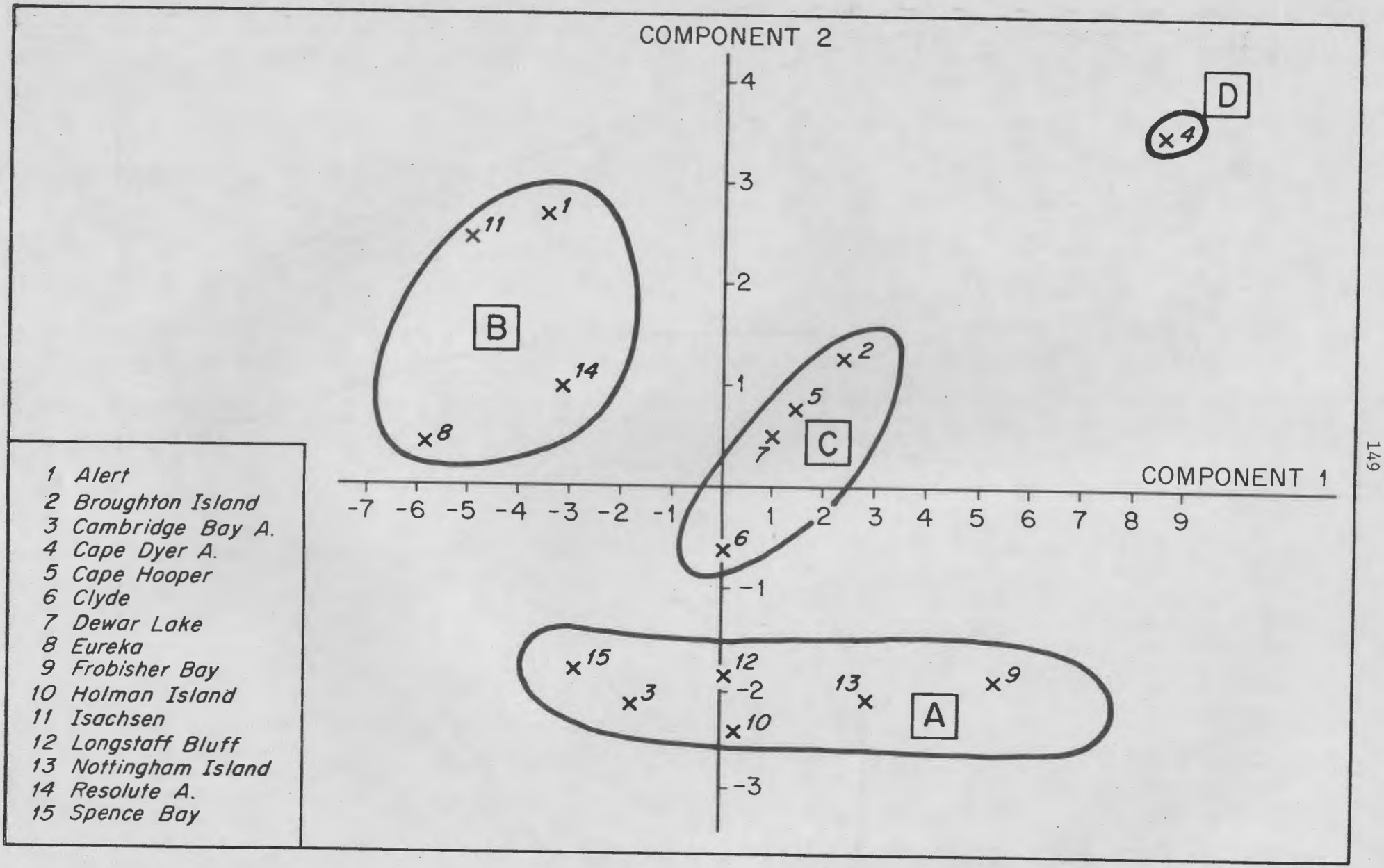

Figure A.3.1 Plot of first two principal components; suggested clusters A to D are indicated.

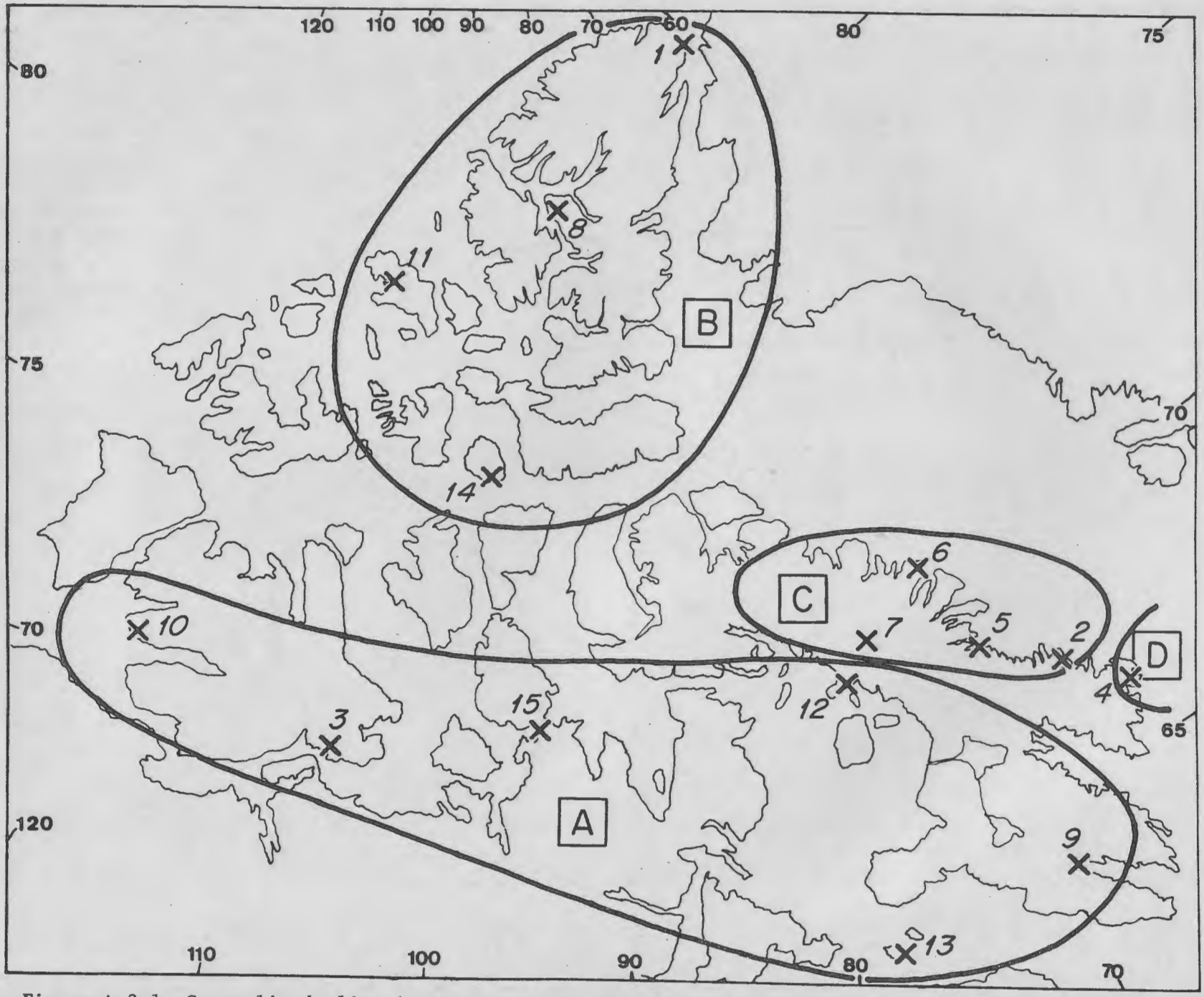

Figure A.3.1 Generalised climatic regions of the Canadian Arctic islands based on principal components in Figure A.3.1. Boundaries are approximate.

APPENDIX 4

SYNOPTIC TYPE CATALOG: JANUARY 1,1946 TO DECEMBER 31,1974.

Grid network is shown in Figure 4.2. In the following Tables synoptic types are listed across the page, day 1 to 16 on the first line, day 17 to the end of the month on the second line for each month. A value of 0 indicates an untyped day; -1 indicates missing data for the day. Key days for each type are shown in Figures 4.3 to 4.6.

1946

JAN	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1	1
	1	1	15	0	1	1	1	1	1	15	1	1	1	1	1	
FEB	1	15	1	3	3	1	1	1	1	1	1	1	1	6	6	6
	1	1	6	6	1	1	11	1	1	3	3	3				
MAR	3	1	3	3	11	1	15	1	1	3	15	6	6	13	13	2
	16	6	15	1	1	15	6	1	1	1	1	1	4	22	3	
APR	3	11	1	1	15	15	1	2	15	15	13	13	19	1	1	1
	1	1	3	3	1	13	15	2	6	6	9	3	3	6		
MAY	6	4	22	6	3	13	11	2	17	0	21	16	1	11	1	1
	9	15	6	1	1	19	10	1	3	21	21	6	1	9	15	
JUN	1	1	1	1	1	1	1	1	3	3	3	6	1	6	6	3
	6	6	3	15	1	1	1	1	6	15	1	1	1	15		
JUL	1	1	3	1	1	1	1	1	18	18	22	16	16	3	6	21
	6	3	15	1	1	1	1	3	11	11	1	18	3	13	9	
AUG	15	6	16	16	16	0	0	2	16	2	2	16	2	2	2	2
	2	6	14	11	16	3	3	6	0	16	16	8	11	1	6	
SEP	2	16	7	10	10	3	11	6	11	11	5	1	1	1	1	22
	0	3	1	1	21	0	0	13	17	9	17	9	15	21		
OCT	21	13	2	6	6	20	0	11	11	2	21	6	1	1	1	1
	0	2	6	3	6	1	6	9	6	2	6	16	16	3	3	
NOV	1	4	4	1	1	1	1	9	6	6	6	3	3	1	6	6
	2	2	6	11	13	6	9	16	3	3	0	0	4	4		
DEC	4	0	16	11	14	1	1	6	16	3	3	7	6	1	1	1
	1	3	3	3	20	20	15	1	1	1	1	1	1	1	1	

1947

JAN	22	9	1	1	3	6	3	18	1	11	0	18	18	1	11	6
	1	1	1	11	1	6	6	3	11	8	17	20	7	17	9	
FEB	12	4	10	3	16	16	17	5	1	5	5	1	1	1	5	11
	1	1	7	2	2	2	16	9	9	6	1	11				
MAR	1	13	6	16	16	16	0	1	6	1	6	6	0	9	5	1
	1	0	5	2	3	13	4	1	18	2	6	10	11	1	1	
APR	1	1	1	1	1	1	1	1	10	4	1	1	1	1	1	0
	0	4	1	1	1	1	1	1	1	22	1	7	13	6		
MAY	10	0	2	2	4	18	3	11	1	1	1	4	1	1	1	1
	1	1	1	1	1	1	1	0	2	2	7	0	4	1	1	
JUN	1	12	5	1	1	1	1	1	1	18	1	5	3	3	5	7
	13	2	3	18	4	1	1	1	1	1	1	18	18	18		
JUL	18	4	1	12	12	7	4	4	4	12	4	18	18	1	1	18
	18	18	4	1	4	12	7	3	5	5	11	1	11	18	11	
AUG	5	5	12	4	2	14	5	3	3	3	11	3	0	5	6	20
	3	11	4	10	1	10	10	22	1	1	1	4	2	2	13	
SEP	13	1	1	11	18	1	1	1	6	9	13	6	1	6	0	14
	0	1	15	1	10	1	10	4	4	4	4	4	0	15		
OCT	2	6	0	21	2	21	4	1	1	4	4	21	13	17	7	13
	16	13	16	13	8	2	16	0	21	22	14	22	13	2	2	
NOV	2	21	6	1	11	1	1	15	15	3	3	5	7	7	9	13
	7	12	1	1	1	1	3	15	1	15	1	1	3	15		
DEC	17	6	6	6	1	6	20	9	15	15	15	15	15	1	1	6
	1	0	13	0	0	16	3	15	6	1	18	1	4	2	2	

1948

JAN	13	2	13	3	3	5	5	15	15	1	1	1	1	1	1	1
	1	2	2	6	0	1	1	1	22	6	0	16	16	1	1	
FEB	1	6	1	1	4	1	4	1	15	22	1	1	1	1	1	1
	1	12	0	3	5	1	1	4	1	1	1	1	1			
MAR	1	4	0	15	4	0	4	4	2	2	15	15	3	1	1	4
	1	1	1	12	4	1	1	1	1	4	9	6	0	4	4	
APR	4	9	2	2	6	6	11	11	5	15	3	21	2	0	3	15
	15	6	0	0	0	1	3	1	22	17	16	17	7	17		
MAY	5	1	1	1	4	15	3	12	4	19	4	1	1	6	2	6
	20	17	12	0	6	21	4	15	1	18	16	18	3	3	1	
JUN	22	16	3	13	2	2	2	16	8	8	7	12	12	4	4	15
	5	11	15	15	15	4	4	4	18	1	12	19	8	8		
JUL	8	8	7	16	21	2	2	2	2	0	18	22	22	2	16	11
	18	22	22	20	5	5	4	4	1	18	22	9	7	2	13	
AUG	8	2	4	2	7	7	12	4	1	4	1	1	0	11	3	11
	0	11	5	0	4	19	13	3	11	3	11	11	8	11	8	
SEP	16	11	0	22	2	2	2	9	9	13	16	16	20	5	11	20
	5	15	17	5	11	12	4	9	3	11	11	12	12	6		
OCT	1	1	15	15	1	21	0	3	3	15	15	1	1	1	1	1
	5	1	1	12	12	0	9	13	16	2	16	13	16	7	11	
NOV	0	19	19	15	15	3	13	3	16	11	6	6	6	3	1	1
	1	4	1	4	19	4	21	6	1	4	1	6	2	2		
DEC	13	13	15	15	15	1	22	22	9	9	13	3	3	3	3	6
	1	15	17	0	1	1	1	1	6	6	3	12	5	5	19	

1949

JAN	4	10	6	2	2	13	2	6	22	17	1	1	1	19	21	4
	6	1	6	16	1	22	22	2	11	12	1	9	2	6	11	
FEB	11	12	4	14	6	1	1	4	1	12	1	1	12	5	12	4
	4	1	1	11	1	12	12	12	1	12	9	9		5		
MAR	9	11	1	12	4	21	6	1	22	1	22	2	2	22	10	4
	4	18	1	3	18	9	17	17	5	1	4	7	2	13	7	
APR	7	21	6	6	9	6	6	2	2	16	2	4	18	12	22	7
	12	6	4	7	22	21	21	9	3	1	4	4	9	9		
MAY	21	16	13	13	6	6	10	1	1	1	10	2	9	15	6	1
	6	3	16	3	3	1	15	15	2	3	3	13	3	16	3	
JUN	3	5	3	2	2	3	2	3	16	0	16	0	16	1	18	18
	1	6	3	1	5	12	8	8	0	0	0	20	3	2		
JUL	3	18	0	16	3	20	5	11	1	4	10	4	4	7	7	7
	7	4	4	-1	1	15	1	3	5	5	11	16	16	2	22	
AUG	2	2	2	15	3	3	3	7	7	16	16	16	3	3	7	8
	0	5	16	6	8	4	1	1	1	1	1	1	12	8	13	
SEP	2	7	14	0	20	15	12	1	1	12	1	0	7	13	17	3
	11	12	4	4	0	9	1	21	4	1	4	15	1	1		
OCT	1	1	21	2	2	14	2	2	2	2	16	3	9	0	0	15
	0	0	14	3	22	10	8	2	8	16	2	1	1	6	6	
NOV	6	1	1	1	9	15	1	1	4	1	1	0	5	5	15	1
	21	2	6	6	6	6	3	1	1	3	3	0	16	9		
DEC	20	1	22	7	7	7	13	13	10	1	1	1	1	1	1	1
	1	12	1	20	20	3	5	3	3	5	5	15	20	20	20	

1950

JAN	20	1	1	3	1	1	11	3	1	1	1	12	17	3	1	1
	7	1	1	1	1	1	4	14	10	15	1	1	1	11	11	
FEB	1	1	1	1	1	1	9	10	16	9	9	7	2	4	4	1
	22	22	4	22	7	8	12	4	1	1	1	1				
MAR	1	22	9	12	4	4	1	1	1	5	3	3	3	1	1	1
	6	20	7	7	4	4	1	4	9	9	9	4	4	4	1	
APR	1	1	4	6	2	16	11	22	6	2	17	3	5	15	1	12
	12	11	10	9	12	19	4	4	9	4	21	1	6	3		
MAY	15	15	1	1	1	1	15	15	9	5	6	9	9	9	3	7
	13	0	7	7	13	10	10	0	2	21	4	4	2	4	6	
JUN	9	7	3	11	8	16	17	3	0	3	0	15	18	4	4	4
	4	4	4	6	3	13	13	16	3	6	16	6	6	16		
JUL	11	11	11	11	1	1	11	5	0	2	4	1	1	19	15	15
	3	3	3	7	3	11	11	3	11	3	3	17	6	5	4	
AUG	1	1	18	18	3	22	2	2	18	0	14	11	12	1	1	11
	11	6	11	3	2	2	2	13	6	6	6	3	3	3	3	
SEP	11	11	1	1	12	4	1	16	16	3	3	3	3	1	1	1
	1	1	10	11	14	9	3	3	16	1	18	6	14	14		
OCT	18	1	1	1	1	1	4	1	15	15	3	1	22	2	6	1
	4	15	1	0	9	3	1	1	9	2	2	2	6	14	1	
NOV	15	11	15	11	11	16	4	15	8	2	6	20	21	3	5	0
	3	13	6	9	6	11	0	6	0	17	16	5	8	16		
DEC	7	17	21	15	1	1	1	4	9	3	9	9	7	2	3	15
	1	1	1	1	1	15	16	3	1	1	3	3	6	15	15	

1951

JAN	15	15	1	6	6	6	6	20	3	1	6	3	16	0	19	10
	4	21	1	21	6	1	1	4	1	4	9	1	1	1	1	
FEB	12	1	1	12	5	1	1	16	3	1	11	16	13	3	11	11
	1	7	7	13	12	22	6	4	4	4	9	9	-9	-9	-9	
MAR	12	4	4	4	4	2	21	6	1	19	1	9	15	3	3	19
	1	1	12	1	15	3	3	3	3	3	6	9	12	13	7	
APR	15	12	15	15	13	15	1	1	1	15	1	4	4	4	2	2
	2	22	6	5	1	1	5	3	3	3	16	16	13	7	-9	
MAY	7	2	2	3	3	3	6	11	1	1	1	1	1	1	1	12
	1	1	4	4	1	3	3	3	3	18	18	1	4	4	4	
JUN	4	4	0	17	5	15	4	15	15	15	3	3	5	13	13	7
	7	0	4	4	6	8	16	11	0	19	4	4	1	1	-9	
JUL	3	3	13	13	3	3	1	1	16	1	1	5	1	1	1	1
	3	15	3	2	16	3	3	11	18	20	11	5	1	1	22	
AUG	14	16	3	5	2	14	6	1	21	2	7	7	7	7	4	4
	4	4	4	6	6	3	15	15	5	1	4	17	1	16	16	
SEP	2	8	8	1	6	3	3	3	9	3	3	3	15	2	9	12
	4	4	1	4	1	1	1	5	1	1	2	16	16	6	-9	
OCT	6	2	16	7	7	15	1	6	3	4	4	4	1	1	12	4
	2	8	12	12	1	4	9	9	13	13	3	15	1	1	1	
NOV	6	6	16	7	2	1	11	5	12	1	1	15	3	16	16	16
	4	7	19	15	21	6	6	1	1	1	1	2	1	15	-9	
DEC	6	2	9	2	2	2	2	2	21	1	1	1	1	1	1	4
	6	1	1	6	1	1	1	1	1	22	3	3	3	3	3	

1952

JAN	3	3	1	1	1	20	1	12	1	13	1	22	18	11	0	9
	9	4	1	1	1	21	21	15	15	15	1	1	1	1	1	
FEB	5	1	1	3	1	7	3	6	7	3	3	1	1	13	4	1
	4	1	1	13	6	17	5	1	1	13	0	9	19	-9	-9	
MAR	4	15	15	3	17	3	6	13	17	17	1	1	1	6	22	9
	15	1	1	1	1	3	3	3	7	3	3	9	9	1	1	
APR	1	9	21	21	6	1	5	16	3	7	5	3	3	3	3	3
	3	5	4	4	2	2	5	5	2	16	16	3	16	13	-9	
MAY	2	2	13	13	16	16	16	2	16	13	13	13	13	3	15	15
	11	3	5	13	15	1	10	4	4	4	19	15	17	7	7	
JUN	13	3	3	3	3	1	1	12	1	1	1	17	3	7	11	3
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-9	
JUL	1	1	4	4	4	2	2	21	10	2	2	2	2	2	2	4
	4	8	4	12	12	12	5	5	5	11	5	1	11	13	13	
AUG	0	2	2	16	13	2	7	7	7	4	2	7	4	12	15	15
	1	1	1	12	19	19	4	4	4	4	12	12	19	10	11	
SEP	5	5	12	5	4	4	0	1	0	16	17	12	4	7	7	19
	4	2	21	4	1	1	4	1	15	1	3	1	1	12	-9	
OCT	1	1	1	4	2	3	6	2	19	0	4	4	1	4	2	16
	16	2	14	21	15	15	15	1	1	1	1	1	1	1	1	
NOV	1	1	12	1	4	12	15	1	7	7	7	6	15	17	19	0
	5	5	4	4	7	15	1	4	1	1	15	15	1	1	-9	
DEC	10	7	7	7	7	13	13	13	13	13	3	3	3	3	5	1
	1	1	1	1	5	5	1	1	1	0	6	1	5	7	3	

1953

JAN	1	1	1	4	4	1	1	4	4	1	1	1	1	1	1	4
	4	7	7	9	1	1	1	1	1	1	5	5	12	4	1	
FEB	1	0	7	11	8	16	14	4	0	7	2	21	21	4	6	4
	0	4	1	1	5	4	4	1	4	4	4	4	-9	-9	-9	
MAR	0	1	1	1	4	4	4	4	4	2	16	7	2	2	7	2
	7	4	21	21	1	15	15	9	15	6	21	2	7	7	16	
APR	7	2	16	13	2	2	13	10	-1	4	4	4	4	4	4	4
	6	21	2	2	2	7	2	2	16	16	8	4	4	1	-9	
MAY	1	1	1	1	1	1	12	5	1	16	7	16	7	4	4	4
	4	4	4	7	0	5	1	19	4	4	4	4	4	4	4	
JUN	4	4	4	0	4	4	8	9	12	10	6	15	1	1	1	4
	4	8	8	8	0	16	11	17	2	16	17	5	5	7	-9	
JUL	17	8	7	2	2	2	8	8	9	9	9	18	12	18	4	14
	1	12	4	2	2	2	2	4	4	4	4	4	6	4	4	
AUG	14	7	7	8	7	2	4	21	18	14	14	2	4	7	2	13
	10	10	4	21	21	21	13	13	13	11	18	9	17	16	2	
SEP	2	2	2	4	4	4	15	4	4	4	4	4	4	7	4	4
	4	4	21	6	2	2	4	4	4	21	6	21	21	2	-9	
OCT	15	4	4	16	14	4	4	0	0	4	9	13	3	15	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	12	11	20	
NOV	20	16	16	16	3	11	0	6	9	7	4	4	4	0	0	0
	9	4	1	1	1	5	12	8	0	7	3	12	12	12	-9	
DEC	1	4	4	4	4	4	4	4	4	4	4	4	4	21	1	4
	4	4	4	4	4	4	4	4	1	1	1	1	5	1	12	

1954

JAN	9	6	4	4	4	4	4	2	6	14	18	1	1	1	4	4
	3	1	4	9	16	1	1	1	1	1	8	11	16	3	1	
FEB	7	7	7	2	2	2	1	1	1	1	1	1	5	5	5	0
	1	20	16	16	16	0	22	7	2	2	16	2	-9	-9	-9	
MAR	4	2	16	2	2	8	2	2	2	4	4	9	3	1	6	6
	2	14	4	2	2	2	2	4	4	4	4	0	1	1	4	
APR	1	1	1	1	1	1	1	12	4	1	4	4	4	7	2	2
	2	2	2	10	10	1	1	21	4	4	4	2	2	6	-9	
MAY	2	2	2	5	7	0	2	2	13	3	1	4	18	7	2	16
	8	11	16	5	11	11	1	1	0	6	4	9	0	6	21	
JUN	1	1	1	1	1	5	12	1	10	15	9	10	5	15	1	1
	1	1	6	0	16	16	15	0	13	13	3	0	2	21	-9	
JUL	18	7	2	8	7	2	6	16	2	7	2	7	4	4	4	14
	4	1	20	3	8	4	4	21	2	2	2	2	2	2	2	
AUG	2	16	2	2	2	2	2	2	2	4	2	0	2	22	22	1
	1	4	6	2	2	2	2	7	2	0	2	16	5	12	1	
SEP	1	1	6	6	16	16	2	2	2	2	16	8	4	18	22	6
	16	16	17	15	5	13	13	9	7	4	4	4	4	2	-9	
OCT	5	1	1	11	3	5	1	1	1	20	5	20	17	13	7	10
	1	1	18	0	19	10	4	4	4	1	1	1	1	1	1	
NOV	6	15	1	6	6	1	14	1	1	1	1	1	1	1	1	1
	1	4	4	18	7	16	2	4	16	16	2	16	8	12	-9	
DEC	14	0	2	2	2	2	11	20	11	1	1	4	11	8	16	16
	16	2	8	2	9	9	1	1	1	1	4	0	16	16	16	

1955

JAN	2	2	16	2	2	2	7	0	2	4	2	7	4	9	2	2
	4	4	4	4	4	4	0	1	1	1	1	1	1	5	7	
FEB	2	3	1	1	1	1	1	1	5	7	2	2	2	16	2	13
	11	8	13	11	1	4	1	12	1	2	3	1	-9	-9	-9	
MAR	1	12	0	1	12	20	12	9	4	4	6	9	15	12	17	15
	15	15	15	15	15	1	1	1	1	3	5	5	15	15	1	
APR	1	1	12	1	1	4	2	2	2	2	2	2	2	2	2	16
	4	7	7	7	7	13	13	16	6	1	12	1	1	5	-9	
MAY	5	5	5	12	1	4	15	15	11	12	9	13	3	3	3	3
	3	13	3	3	15	1	1	1	5	5	5	4	4	12	2	
JUN	2	2	7	15	3	13	16	6	1	1	1	1	1	21	2	16
	3	3	7	16	0	0	4	4	1	6	1	1	15	1	-9	
JUL	1	5	1	1	1	1	4	4	4	20	1	20	15	1	1	1
	2	6	2	2	2	12	1	1	18	4	14	4	4	4	1	
AUG	12	1	1	4	10	10	3	3	3	20	17	10	4	4	4	2
	7	6	6	3	16	3	10	10	3	13	2	13	13	10	10	
SEP	4	22	1	1	1	1	1	15	1	18	10	1	6	2	16	16
	2	13	3	11	18	14	21	2	2	2	21	1	22	22	-9	
OCT	6	6	2	16	7	2	13	13	13	4	4	3	13	3	3	12
	7	19	21	1	1	1	1	3	3	3	0	2	15	1	1	
NOV	0	3	15	5	5	5	17	3	0	3	17	8	4	4	4	4
	1	1	6	1	4	2	2	14	0	2	2	2	6	1	-9	
DEC	1	1	4	4	15	15	13	13	15	3	3	11	11	1	5	1
	15	15	6	2	2	2	7	4	2	16	16	16	1	1	1	

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JAN	4	4	4	1	4	7	2	13	13	2	2	6	6	4	4	5
	3	3	13	13	3	10	21	13	8	4	18	1	1	4	0	
FEB	11	8	4	4	16	3	5	12	8	9	15	9	7	2	13	3
	3	5	12	4	14	2	0	6	3	3	3	1	1	-9	-9	
MAR	1	4	1	4	7	4	14	0	0	17	7	8	8	12	12	1
	4	2	2	7	2	2	2	2	2	1	4	1	1	1	5	
APR	15	13	15	3	3	15	15	3	3	3	16	13	3	16	16	2
	18	6	17	8	8	0	1	1	6	6	2	4	4	4	-9	
MAY	1	1	1	1	4	4	4	1	19	1	4	1	1	1	3	6
	1	1	1	1	1	1	1	1	1	1	1	4	12	1	5	
JUN	5	1	4	4	4	7	7	4	4	12	4	8	8	4	4	7
	2	7	7	8	7	16	8	7	2	2	7	4	2	4	-9	
JUL	4	14	7	2	2	2	2	2	2	8	18	9	2	8	2	8
	8	16	8	11	12	18	4	18	4	2	2	2	2	2	2	
AUG	2	2	2	16	2	16	2	2	16	11	16	3	3	5	1	4
	4	4	4	22	5	5	5	12	5	5	12	12	4	4	4	
SEP	4	4	1	1	1	1	1	1	1	21	21	2	2	0	21	0
	0	7	13	13	13	3	3	15	15	21	4	6	2	6	-9	
OCT	16	16	16	2	2	2	2	10	1	1	1	15	6	15	1	1
	1	1	1	1	1	12	12	6	18	22	9	9	13	2	-1	
NOV	2	13	13	3	1	1	1	4	4	4	1	1	4	1	7	5
	1	12	12	5	4	6	1	4	2	2	6	3	1	1	-9	
DEC	1	1	1	4	3	15	1	1	1	1	1	5	1	1	15	1
	1	1	1	1	1	4	7	2	16	16	4	4	4	9	14	

1957

JAN.	-1	4	4	1	1	12	12	1	1	15	6	6	12	4	7	19
	7	0	4	4	4	4	10	6	6	1	1	1	1	1	1	
FEB	5	5	5	11	5	3	1	1	5	3	3	3	7	13	13	13
	16	11	12	1	1	0	15	15	5	3	3	20	-9	-9	-9	
MAR	3	15	0	22	0	22	15	3	3	3	3	3	11	7	16	13
	5	3	3	1	5	4	4	4	4	4	4	4	4	4	21	
APR	6	3	2	14	4	6	2	2	2	2	6	6	6	2	2	18
	14	1	1	1	1	1	3	1	1	12	0	15	15	4	-9	
MAY	4	13	10	21	6	1	6	15	1	1	1	15	1	1	21	4
	9	9	9	15	15	15	15	1	1	1	12	9	4	4	4	
JUN	10	4	6	8	11	5	15	15	15	15	15	15	3	3	3	16
	6	2	8	8	7	7	7	2	16	16	0	6	6	6	-9	
JUL	6	15	15	0	6	2	3	3	3	13	0	0	22	21	2	10
	4	10	8	8	8	8	7	0	2	2	2	2	2	8	0	
AUG	0	10	2	2	2	13	13	3	22	14	21	2	2	4	4	4
	10	18	18	21	6	18	18	18	2	4	2	7	2	2	2	
SEP	7	2	6	15	16	0	15	15	15	15	5	11	3	3	3	11
	3	11	7	7	3	11	11	1	22	6	0	3	3	3	-9	
OCT	17	17	12	12	1	6	16	11	16	16	6	9	9	3	3	5
	1	1	1	22	2	4	1	6	11	1	1	1	12	1	5	
NOV	20	5	1	1	1	1	1	1	5	5	5	12	10	7	4	9
	15	1	1	5	5	5	5	1	5	1	1	1	1	1	-9	
DEC	1	15	1	1	15	11	11	6	1	1	3	3	1	1	1	12
	12	1	1	15	15	13	1	18	4	4	6	6	13	13	16	

1958

JAN	7	4	1	4	4	1	1	5	1	1	1	1	1	1	4	7
	7	7	7	13	17	17	3	16	13	13	16	11	1	1	-1	
FEB	1	3	16	2	2	2	1	1	15	1	1	4	1	4	12	15
	1	4	8	1	1	1	5	5	1	5	1	1	-9	-5	-9	
MAR	1	1	18	19	7	7	13	2	6	13	13	16	11	1	1	5
	1	12	4	2	2	13	17	19	1	1	1	4	4	0	10	
APR	10	4	12	5	15	1	1	1	1	1	1	15	3	13	11	1
	19	7	7	2	18	4	2	3	10	1	6	11	3	5	-9	
MAY	3	5	11	7	13	13	3	3	3	3	3	11	4	21	13	13
	16	2	2	4	1	10	2	0	0	11	1	1	4	4	1	
JUN	1	0	0	0	6	6	3	15	4	1	1	4	2	2	4	4
	4	4	18	18	8	2	2	18	3	11	10	0	2	2	-9	
JUL	7	16	16	13	17	15	1	1	15	19	4	19	10	10	16	11
	8	8	8	2	2	2	6	6	6	13	13	13	2	13	13	
AUG	13	3	3	3	9	13	21	4	15	9	9	2	2	2	7	7
	7	19	4	2	9	21	7	2	13	7	2	16	16	16	2	
SEP	2	2	2	2	2	2	2	2	7	7	4	4	9	14	3	17
	7	14	0	0	20	0	7	0	0	5	1	1	1	1	-9	
OCT	1	21	1	1	21	2	6	14	2	2	2	2	16	16	16	16
	3	0	13	19	0	13	8	4	2	4	21	1	4	4	4	
NOV	1	1	21	6	6	3	1	1	1	1	12	12	4	4	4	4
	7	4	1	1	1	1	1	3	15	1	6	6	6	1	-9	
DEC	1	1	12	21	4	4	15	15	15	4	1	1	1	1	15	1
	9	1	1	1	3	3	6	9	6	1	1	1	0	4	4	

1959

JAN	4	6	4	15	3	15	15	15	6	1	21	4	1	6	21	2
	2	13	1	15	1	15	1	1	1	1	1	1	4	4	1	
FEB	1	1	1	1	1	1	1	1	1	1	9	21	1	4	4	4
	4	4	7	7	2	1	4	19	4	4	4	7	-9	-9	-9	
MAR	7	4	4	4	4	9	2	1	1	1	1	1	4	4	4	4
	7	4	4	4	7	21	7	7	4	1	1	4	1	1	1	
APR	1	22	20	15	4	4	1	1	20	16	11	3	3	3	9	9
	15	15	15	1	1	1	1	21	13	13	2	6	10	10	-9	
MAY	4	2	2	6	6	1	1	5	5	7	7	2	2	2	7	2
	2	16	14	1	4	1	1	1	1	1	5	5	1	1	1	
JUN	1	19	21	21	21	21	21	2	2	2	16	14	7	15	0	7
	7	4	4	4	1	1	12	4	2	2	2	21	4	4	-9	
JUL	2	2	16	16	16	16	16	2	22	2	15	16	3	3	3	1
	1	1	1	1	1	4	22	16	13	3	3	15	1	1	1	
AUG	1	5	5	15	6	7	2	2	3	5	11	13	15	15	15	15
	3	1	3	3	15	15	1	1	15	22	22	6	8	0	0	
SEP	12	1	5	5	15	1	15	15	1	1	1	1	22	8	5	3
	11	1	1	1	1	1	3	3	11	11	1	1	1	1	-9	
OCT	15	1	1	1	1	1	18	4	1	1	1	1	1	20	13	2
	2	3	1	1	6	2	2	2	6	1	5	1	1	1	-1	
NOV	12	12	1	1	1	4	4	4	10	4	4	15	15	1	5	1
	9	13	3	16	16	16	13	2	7	1	1	1	1	1	-9	
DEC	1	1	1	11	11	16	16	16	2	16	13	4	4	7	9	4
	4	4	2	7	10	2	16	13	2	4	0	4	1	1	1	

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JAN	1	1	1	5	1	3	3	1	11	3	16	2	2	2	2	13
	16	13	6	4	4	4	1	1	5	5	15	15	15	3	-1	
FEB	1	1	1	1	1	1	1	22	15	3	17	12	7	15	6	6
	6	6	15	13	3	13	13	6	2	16	13	2	2	-9	-9	
MAR	2	2	15	16	3	12	15	1	1	12	17	17	16	17	16	6
	3	3	6	1	1	6	1	1	1	1	1	1	11	0	0	
APR	7	17	13	15	15	4	1	1	1	1	1	1	1	1	1	0
	5	20	12	7	4	1	3	16	3	3	16	2	2	1	-9	
MAY	1	6	1	1	1	1	11	8	2	16	2	2	7	7	0	0
	1	1	15	17	4	4	4	4	1	1	11	8	2	2	2	
JUN	16	2	11	1	1	1	1	5	3	3	3	16	10	16	0	3
	11	1	22	4	4	20	2	2	2	2	2	2	9	9	-9	
JUL	6	1	1	5	3	13	17	2	2	4	8	10	10	4	2	16
	8	8	8	12	5	5	11	11	9	5	15	5	5	5	3	
AUG	3	3	17	13	16	13	3	3	11	11	1	1	5	5	15	15
	5	3	3	3	3	3	9	15	15	15	15	5	15	5	5	
SEP	1	5	5	1	1	1	1	1	16	1	1	12	12	5	1	1
	4	7	21	15	19	6	21	21	21	21	6	6	2	13	-9	
OCT	13	3	3	3	3	3	16	2	9	19	1	1	1	15	15	1
	2	21	9	6	6	6	1	15	5	15	15	1	1	1	1	
NOV	1	1	1	1	1	4	4	4	1	5	15	15	15	1	1	5
	5	5	5	5	7	7	16	11	6	6	6	6	6	3	-9	
DEC	3	1	1	1	1	21	21	4	4	6	6	21	1	14	1	4
	4	4	1	4	4	15	1	1	1	1	1	1	1	1	1	

		1961														
JAN	1	16	3	3	15	15	1	1	1	1	1	12	11	1	1	1
	4	4	4	1	1	6	2	14	1	1	1	1	1	1	4	
FEB	2	7	6	3	1	4	21	9	20	1	1	1	1	1	4	12
	12	1	1	1	1	1	5	12	7	0	21	4	-9	-9	-9	
MAR	1	1	1	4	4	1	1	1	4	4	4	6	22	1	1	3
	15	1	1	1	1	1	1	1	1	1	12	4	12	12	15	
APR	15	15	5	5	12	5	15	15	5	15	15	3	5	5	17	9
	13	17	13	3	15	3	3	11	6	2	2	4	1	1	-9	
MAY	1	22	6	3	15	21	14	11	15	6	6	1	1	4	1	6
	13	6	1	2	16	2	7	2	19	4	6	2	16	8	4	
JUN	2	0	0	1	4	4	1	2	6	2	2	14	14	1	4	1
	4	4	0	7	4	4	4	1	1	1	1	12	12	12	-9	
JUL	11	16	16	16	16	2	2	2	8	8	10	14	7	8	8	8
	16	8	13	16	1	16	2	2	2	14	4	18	18	6	16	
AUG	3	3	3	3	5	1	1	1	1	1	1	11	13	3	13	13
	13	6	0	5	12	1	15	1	1	1	1	1	1	1	1	
SEP	1	1	16	3	1	22	22	9	1	4	1	20	1	1	3	3
	1	1	1	1	12	15	1	1	1	21	21	6	6	21	-9	
OCT	2	11	1	1	5	11	5	5	1	1	1	14	20	12	4	21
	21	1	4	22	6	6	6	0	1	0	9	13	7	13	3	
NOV	15	15	1	1	1	18	18	3	3	3	16	2	16	2	2	7
	13	12	10	6	2	16	2	13	2	2	6	2	2	7	-9	
DEC	7	13	13	3	3	8	4	4	14	4	6	14	16	5	12	1
	12	7	13	3	7	7	7	2	2	15	17	17	7	15	1	
		1962														
JAN	1	1	1	6	6	21	4	4	1	6	1	1	6	2	2	10
	2	4	4	12	4	11	11	1	1	1	1	1	1	1	1	
FEB	1	1	1	1	1	1	1	1	1	15	6	4	4	1	1	4
	1	1	1	6	4	7	5	7	2	2	7	2	-9	-9	-9	
MAR	2	2	2	9	2	13	13	13	3	3	3	15	5	20	15	1
	1	1	15	5	5	5	5	5	9	3	16	16	16	2	11	
APR	5	12	1	1	1	6	2	16	16	2	7	7	0	2	2	5
	19	1	1	1	1	1	1	1	6	6	6	6	4	14	-9	
MAY	2	2	10	1	10	1	5	15	12	19	15	11	5	3	1	1
	0	1	6	6	1	1	9	15	1	4	2	13	2	14	4	
JUN	21	2	16	2	2	16	16	7	2	18	1	1	1	6	6	2
	2	8	18	20	5	1	1	1	1	6	1	1	1	1	-9	
JUL	1	0	16	16	3	15	2	2	2	2	2	2	7	2	2	2
	2	2	4	9	2	2	2	2	2	4	4	2	2	8	8	
AUG	10	2	9	6	3	3	6	11	18	2	18	4	1	4	4	8
	12	1	1	1	4	4	17	3	21	2	19	3	3	16	11	
SEP	10	0	2	13	11	12	5	11	11	11	16	0	2	13	3	1
	4	4	4	4	4	7	4	4	4	0	15	19	19	21	-9	
OCT	1	1	1	1	1	1	1	15	5	-1	1	15	1	1	1	1
	2	6	13	13	15	21	2	21	2	6	17	17	1	0	1	
NOV	6	14	1	1	1	1	1	4	14	20	7	4	4	15	15	4
	12	3	20	16	1	12	5	11	4	7	2	2	2	2	-9	
DEC	13	13	11	6	9	3	3	18	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	7	2	11	11	5	15	17	17	

1963

JAN	7	13	13	1	4	2	10	10	1	4	6	1	1	1	1	1
	4	7	21	6	1	1	1	1	1	1	1	7	17	1	12	
FEB	4	2	2	13	16	2	2	13	0	13	4	4	4	4	1	1
	1	6	1	1	6	6	21	1	1	4	4	21	-9	-9	-9	
MAR	1	-1	1	4	1	1	2	7	7	19	4	21	10	10	3	16
	16	7	2	2	2	6	1	1	4	1	3	1	1	1	-1	
APR	5	17	3	0	17	7	7	7	2	2	2	4	13	3	4	9
	9	9	21	21	0	2	2	21	2	4	4	1	6	6	-9	
MAY	1	1	4	10	10	6	16	3	3	3	1	1	1	1	1	18
	16	2	22	22	2	12	1	1	1	1	1	1	0	16	3	
JUN	1	4	4	6	6	6	16	16	16	0	20	3	3	1	1	-1
	18	11	3	1	1	22	16	16	6	1	1	0	9	0	-9	
JUL	21	21	2	13	16	16	8	7	4	4	6	6	1	15	15	1
	0	13	15	7	2	7	13	16	9	2	2	16	6	16	16	
AUG	17	3	3	3	3	11	16	16	16	16	8	11	2	16	16	16
	3	11	3	11	4	4	22	17	12	1	1	1	1	4	1	
SEP	4	1	1	1	1	1	15	1	1	1	1	1	1	18	10	1
	1	14	10	4	7	12	4	4	21	6	6	0	16	16	-9	
OCT	16	6	1	3	11	12	1	4	1	1	6	13	3	3	1	3
	11	11	1	1	5	12	5	5	5	10	0	20	3	5	4	
NOV	7	5	1	7	13	3	13	0	13	2	0	22	2	3	3	11
	18	1	1	15	1	1	1	4	4	4	4	7	4	2	-9	
DEC	2	6	1	6	2	6	2	2	2	16	12	4	2	0	4	1
	4	4	4	22	6	1	1	1	19	4	1	1	4	7	5	

1964

JAN	1	1	10	1	1	1	1	1	0	2	12	17	1	12	2	6
	1	11	12	0	7	3	11	7	13	15	1	18	1	1	12	
FEB	4	9	13	13	4	4	4	1	2	6	1	1	1	1	1	4
	12	4	4	4	4	1	1	1	1	1	1	5	15	-9	-9	
MAR	1	5	3	1	12	1	1	19	5	-1	4	4	2	13	11	4
	4	4	7	4	4	4	14	2	3	1	12	10	21	15	5	
APR	3	20	13	10	4	1	4	1	-1	3	1	1	1	1	3	1
	3	3	11	16	7	7	7	7	13	7	7	2	-1	8	-9	
MAY	4	6	0	21	6	3	5	1	1	1	2	2	7	16	13	2
	4	2	2	16	2	2	21	2	2	2	2	2	2	4	18	
JUN	22	3	11	8	2	2	2	8	11	11	11	6	18	18	1	1
	1	1	1	1	1	4	-1	1	1	5	17	7	5	17	-9	
JUL	5	12	7	8	8	16	8	8	4	15	5	12	1	18	18	4
	4	4	0	4	4	4	14	4	8	4	22	4	1	1	12	
AUG	12	4	4	1	1	1	18	7	2	2	2	2	2	13	13	7
	16	16	16	3	3	3	11	11	3	3	3	16	16	6	6	
SEP	13	13	3	13	1	1	1	4	6	3	15	1	1	1	3	13
	3	13	13	13	11	11	22	4	1	1	1	4	1	0	-9	
OCT	0	4	22	4	4	18	6	16	16	3	15	3	1	1	0	14
	1	1	9	9	1	4	1	4	4	4	4	7	2	21	2	
NOV	0	7	13	0	13	3	3	3	3	5	20	19	1	1	15	1
	1	6	6	3	0	1	1	1	1	10	1	1	4	4	-9	
DEC	4	7	8	1	21	3	10	21	13	17	5	12	1	1	1	1
	1	1	1	1	5	7	7	2	2	15	1	1	4	0	3	

	1965															
JAN	15	1	4	4	1	1	12	19	15	1	1	6	5	7	4	4
	4	4	4	1	1	1	1	3	1	13	4	4	4	1	1	
FEB	1	1	1	1	1	9	1	1	1	12	3	15	1	1	5	5
	5	12	7	19	1	7	21	15	3	3	3	11	-6	-9	-9	
MAR	7	7	13	13	8	7	4	4	21	6	14	0	12	4	19	19
	19	4	2	16	1	5	6	2	4	4	20	12	4	7	7	
APR	2	4	21	2	2	21	9	0	5	4	9	15	1	6	22	3
	20	15	1	1	4	4	4	1	2	2	6	4	2	2	-4	
MAY	2	16	16	3	13	7	9	3	15	15	1	10	15	15	19	5
	1	1	1	3	3	1	10	21	2	7	13	17	1	-1	19	
JUN	5	1	1	1	1	4	4	1	4	19	19	13	13	7	21	10
	1	15	5	5	5	1	1	1	4	1	1	1	6	1	-9	
JUL	1	3	3	0	13	7	-1	4	4	1	1	4	1	11	1	1
	20	5	18	0	2	7	7	4	5	12	12	1	1	12	1	
AUG	7	13	3	3	1	1	5	1	12	3	3	3	10	2	18	1
	1	22	4	2	2	14	22	2	2	2	2	4	2	2	11	
SEP	5	5	5	5	3	3	3	1	3	1	1	18	4	4	4	20
	5	1	1	1	1	1	1	1	1	3	1	1	5	1	-9	
OCT	1	0	1	5	4	2	0	16	16	10	16	16	16	2	2	2
	16	13	11	6	-1	14	6	6	6	1	1	1	1	1	1	
NOV	1	1	1	1	4	4	22	13	6	0	6	6	16	13	13	13
	2	2	2	13	2	2	13	2	2	9	16	16	6	6	-9	
DEC	6	6	3	3	3	3	1	1	20	3	8	14	20	0	4	20
	15	5	7	7	2	2	4	4	4	2	4	17	13	8	-1	

	1966															
JAN	16	2	2	4	1	1	1	13	11	11	16	8	7	7	7	7
	16	16	1	4	10	4	4	2	2	2	2	2	2	15	3	
FEB	16	3	3	3	3	3	3	3	0	3	11	1	12	1	1	1
	6	6	6	6	1	1	3	16	16	13	13	15	-9	-9	-9	
MAR	1	1	1	1	4	22	1	1	-1	5	13	13	13	9	1	1
	1	1	1	1	1	9	6	1	1	0	13	13	13	3	3	
APR	3	3	3	3	11	1	1	1	5	5	2	5	1	1	12	12
	1	12	13	3	3	1	1	4	4	4	2	14	21	21	-9	
MAY	4	4	2	7	7	9	9	9	7	8	4	21	6	1	0	0
	2	2	2	13	7	0	7	7	13	2	7	7	13	7	4	
JUN	4	21	1	1	6	0	12	4	4	22	2	2	8	12	4	2
	2	2	2	2	2	16	8	16	16	16	16	8	0	8	-9	
JUL	4	18	4	4	4	21	18	4	2	6	16	2	8	22	0	1
	1	1	12	12	4	7	7	1	1	5	5	3	3	3	13	
AUG	13	2	3	3	11	5	5	15	3	5	17	7	7	2	3	17
	19	7	7	2	2	13	3	1	1	15	15	3	5	3	5	
SEP	12	4	4	4	1	15	6	10	14	9	15	10	0	13	4	4
	2	16	1	17	1	1	4	2	0	1	2	3	6	3	-9	
OCT	-1	-1	2	-1	10	2	2	-1	1	-1	1	6	-1	-1	22	6
	6	2	13	13	2	2	3	1	15	1	1	21	18	1	4	
NOV	4	4	4	4	1	1	1	15	15	1	12	1	1	1	22	2
	6	16	17	2	1	1	1	1	12	5	11	6	0	2	-9	
DEC	8	1	1	1	5	20	1	4	14	16	3	20	16	16	3	3
	4	2	13	2	2	2	7	2	18	4	1	4	4	16	16	

1967

JAN	16	16	10	2	2	2	3	13	7	2	6	1	4	1	4	4
	4	6	6	2	2	21	16	15	3	11	11	11	8	17	1	
FEB	1	1	1	1	5	1	1	1	1	1	1	4	4	4	18	4
	4	18	6	6	4	4	4	4	21	6	14	12	-9	-9	-9	
MAR	12	12	1	1	1	1	1	1	1	1	1	2	2	4	4	14
	4	0	4	1	17	10	17	17	7	11	11	17	7	3	1	
APR	1	1	11	3	1	12	19	8	8	4	1	4	9	2	2	2
	2	2	2	7	2	2	8	4	4	4	2	7	7	7	-9	
MAY	7	7	7	16	16	8	2	2	8	8	13	20	5	5	5	3
	3	11	11	16	3	3	14	8	3	3	3	11	2	2	22	
JUN	6	1	1	1	1	1	18	4	1	1	2	2	2	2	18	4
	4	4	1	4	4	22	3	3	5	3	5	5	1	12	-9	
JUL	4	12	10	12	5	11	8	8	8	8	8	4	4	11	10	2
	2	2	16	16	6	8	0	19	0	17	9	8	7	2	2	
AUG	13	2	2	2	4	12	5	11	11	3	3	5	15	12	4	4
	14	22	2	8	13	13	16	7	1	0	6	0	0	12	11	
SEP	1	4	4	4	4	4	4	4	4	4	4	1	1	15	15	1
	1	1	6	1	1	1	4	7	10	2	2	4	18	18	-9	
OCT	6	18	4	4	4	4	2	2	7	9	8	7	4	4	4	12
	12	15	5	1	4	4	4	4	2	2	13	13	2	2	13	
NOV	16	8	6	5	1	15	1	1	1	12	1	2	16	16	1	1
	19	0	12	4	4	21	0	22	0	4	4	4	4	1	-9	
DEC	4	4	7	7	2	2	13	10	3	3	3	8	0	3	13	5
	12	1	22	4	1	1	1	1	4	4	19	1	1	2	2	

1968

JAN	7	2	2	8	10	4	2	6	6	6	10	21	18	1	5	1
	1	1	1	22	4	4	21	1	4	18	6	1	17	6	15	
FEB	1	4	4	6	10	8	2	9	17	7	9	6	1	1	1	1
	1	1	1	1	0	0	3	4	4	18	6	1	6	-9	-9	
MAR	0	4	4	22	6	1	12	4	4	4	4	4	8	1	4	4
	4	4	4	4	21	6	7	3	3	3	1	0	6	2	6	
APR	6	11	5	7	3	15	1	1	4	4	10	1	15	7	11	8
	4	7	6	1	1	1	1	1	1	19	17	3	1	1	-9	
MAY	7	9	9	17	1	1	1	1	1	2	2	13	13	13	16	16
	7	13	19	17	12	10	20	5	5	2	4	4	2	2	14	
JUN	2	2	4	2	2	4	7	4	4	4	4	1	4	1	1	19
	19	19	17	2	17	7	1	1	5	5	1	22	1	1	-9	
JUL	5	1	4	4	7	2	2	2	21	10	4	4	4	4	2	18
	11	11	1	1	6	1	5	16	1	4	4	1	1	1	1	
AUG	1	1	1	1	1	4	4	22	12	0	4	15	2	21	4	4
	4	4	4	21	2	16	0	2	2	2	13	8	4	4	4	
SEP	15	2	2	2	16	3	7	7	2	2	2	2	2	13	13	3
	3	6	1	4	22	14	0	0	7	7	8	7	4	7	-9	
OCT	2	2	2	16	16	7	3	16	16	13	1	1	0	13	13	6
	13	13	3	3	3	6	3	13	0	22	22	2	2	2	0	
NOV	0	11	5	5	5	1	1	1	15	7	7	5	1	1	1	1
	1	1	1	1	1	1	1	5	5	5	3	1	-1	0	-9	
DEC	22	14	21	1	1	18	18	15	10	2	4	14	2	4	2	2
	2	7	2	4	4	1	6	3	5	10	6	6	2	4	1	

	1969															
JAN	4	2	2	13	11	15	5	5	5	15	1	1	1	6	6	6
	3	15	3	2	2	6	6	1	22	14	0	22	4	7	4	
FEB	4	1	12	7	7	7	13	15	15	1	15	5	3	5	5	5
	0	17	5	1	4	0	2	2	2	13	10	6	-9	-9	-9	
MAR	0	6	6	3	3	3	3	6	16	0	4	4	1	1	1	4
	4	8	16	13	3	10	12	4	4	1	1	1	1	22	6	
APR	6	6	6	0	7	7	1	1	1	1	6	1	1	1	0	16
	11	0	0	10	4	21	21	4	4	4	6	6	6	0	-9	
MAY	7	13	3	13	13	13	4	4	4	12	1	1	1	1	1	12
	1	1	1	1	1	1	1	5	5	5	11	11	8	8	2	
JUN	0	3	3	3	0	4	4	4	1	6	2	14	2	4	18	4
	4	4	4	7	4	1	1	15	15	1	1	1	1	1	-9	
JUL	10	14	14	8	8	8	8	0	18	18	0	0	0	13	4	0
	8	11	8	18	20	3	11	8	7	13	16	8	8	2	2	
AUG	2	2	2	2	16	16	8	7	3	3	3	3	7	17	9	9
	13	17	16	13	13	5	1	1	14	14	2	6	2	0	6	
SEP	22	6	2	2	4	4	12	1	1	10	10	4	4	6	6	6
	1	1	1	4	4	4	4	4	4	4	7	7	7	7	-9	
OCT	13	13	13	13	13	11	0	2	0	7	4	9	21	1	1	1
	1	1	1	1	18	4	4	6	1	9	3	15	1	1	15	
NOV	15	15	1	1	1	1	1	9	13	5	12	4	4	4	4	4
	1	4	19	7	15	12	5	0	7	7	2	2	13	0	-9	
DEC	7	9	7	4	4	4	5	17	12	4	4	7	4	21	3	1
	5	4	4	4	1	5	1	1	1	1	12	8	16	2	7	
	1970															
JAN	7	17	0	1	4	4	4	1	11	1	5	1	1	12	4	4
	4	4	4	1	1	1	5	19	3	1	5	5	1	5	15	
FEB	1	1	5	5	15	1	5	1	1	1	1	1	21	1	1	1
	15	1	1	5	1	1	4	21	6	1	1	4	-9	-9	-9	
MAR	19	3	17	20	3	9	4	6	2	2	2	4	15	15	1	5
	11	5	13	1	1	1	4	4	7	4	2	7	7	19	1	
APR	1	1	1	15	15	15	1	1	18	7	7	2	2	8	4	4
	1	1	1	1	1	5	3	6	1	4	2	18	4	4	-9	
MAY	1	1	1	12	19	1	12	5	0	7	9	21	21	4	4	1
	1	1	1	4	4	4	4	22	9	9	21	14	2	8	8	
JUN	17	12	12	4	4	4	1	1	0	0	0	19	10	1	4	4
	19	10	1	10	4	4	4	2	2	0	0	4	4	4	-9	
JUL	4	4	19	4	8	16	2	7	2	2	14	2	2	4	4	1
	4	6	13	15	15	19	19	19	4	0	5	8	2	2	6	
AUG	6	20	5	12	1	1	6	9	0	0	15	15	1	1	1	1
	1	4	4	2	2	2	7	2	2	7	2	2	16	8	7	
SEP	12	4	4	4	7	7	7	8	4	18	4	4	6	7	7	6
	6	3	20	0	16	7	0	6	6	3	3	1	20	20	-9	
OCT	5	3	3	3	11	11	14	3	5	12	17	0	4	13	0	2
	8	7	7	1	1	9	9	7	7	4	7	4	2	16	8	
NOV	0	11	1	1	1	6	1	1	1	6	2	6	13	15	15	21
	2	2	13	11	11	7	7	2	1	4	7	11	1	1	-9	
DEC	1	1	1	4	4	4	4	12	4	7	7	7	13	19	1	1
	1	1	0	5	0	6	1	4	0	7	13	13	10	0	9	

	1971															
JAN	9	7	7	4	1	15	18	1	1	1	3	15	1	6	2	4
	4	4	9	15	1	1	5	3	20	1	4	7	10	19	1	
FEB	1	1	18	4	7	7	9	15	12	1	1	14	0	20	12	14
	14	6	1	12	0	8	11	16	0	1	4	21	-9	-9	-9	
MAR	3	3	17	7	7	7	7	7	9	6	16	3	13	13	2	3
	7	21	6	6	1	10	1	1	15	15	1	12	17	0	19	
APR	4	0	4	13	5	1	4	4	12	12	1	1	5	0	5	1
	13	13	16	13	13	16	7	2	7	6	17	12	12	4	-9	
MAY	0	9	10	10	10	10	10	10	12	12	1	12	19	15	1	1
	1	1	9	4	7	5	5	12	4	4	1	4	2	3	6	
JUN	2	0	16	5	4	4	4	11	13	13	13	7	2	7	9	4
	1	10	1	1	22	10	10	4	12	12	15	21	1	1	-9	
JUL	1	1	1	1	4	4	4	1	1	4	9	5	5	5	5	7
	7	7	10	2	6	22	6	6	2	2	2	8	3	16	16	
AUG	16	18	13	9	6	8	5	12	12	4	12	5	1	0	18	4
	4	9	2	2	0	7	7	7	7	4	4	18	3	5	1	
SEP	1	1	1	1	1	1	1	12	7	13	13	16	16	14	14	10
	1	12	4	2	17	12	4	7	2	2	8	2	8	16	-9	
OCT	8	8	7	5	2	4	2	7	9	2	7	7	7	4	2	2
	13	13	13	2	3	11	3	6	3	15	1	6	3	3	3	
NOV	5	5	1	5	1	1	19	1	1	4	4	4	1	1	5	2
	2	14	2	16	11	4	6	15	1	4	4	9	0	7	-9	
DEC	4	1	1	15	17	12	1	1	1	0	2	14	2	14	4	9
	3	3	5	1	1	1	1	-1	11	3	1	12	7	7	7	
	1972															
JAN	3	5	15	1	5	1	1	1	5	1	4	14	1	1	1	18
	1	1	1	5	1	1	4	1	1	12	1	1	4	4	7	
FEB	1	1	1	6	1	1	6	18	1	1	12	1	4	4	0	1
	17	19	1	1	1	1	12	12	1	1	5	1	1	-9	-9	
MAR	1	18	5	1	1	1	1	1	18	18	7	7	7	15	1	1
	1	1	4	1	20	5	5	5	5	5	13	2	3	13	12	
APR	19	4	4	7	2	2	2	2	5	0	15	1	13	13	3	1
	15	1	15	7	5	10	1	0	3	15	1	1	1	1	-9	
MAY	7	3	1	1	10	1	1	1	5	15	2	2	3	5	15	0
	12	1	20	20	1	4	1	15	15	21	4	1	1	1	1	
JUN	1	3	3	11	1	1	0	22	6	6	15	1	22	16	5	1
	1	1	1	1	1	18	0	1	22	1	6	6	0	6	-9	
JUL	21	21	4	4	4	4	19	19	0	3	11	11	11	8	2	7
	4	4	4	4	4	4	4	4	4	1	1	1	1	1	4	
AUG	4	4	10	9	2	16	16	16	8	8	2	8	8	18	6	20
	20	1	1	1	1	1	1	1	1	15	15	1	1	6	22	
SEP	12	7	4	4	7	0	5	11	5	5	3	5	1	1	3	3
	1	4	1	1	4	10	6	6	21	6	6	0	15	5	-9	
OCT	9	1	17	19	10	10	10	10	2	6	6	6	1	4	4	4
	4	2	16	11	5	6	3	1	1	1	11	11	3	3	8	
NOV	2	2	6	22	1	5	5	12	11	16	13	13	19	12	12	1
	5	5	6	0	1	1	1	1	12	12	12	15	1	5	-9	
DEC	5	5	1	1	1	22	6	6	1	1	1	6	5	5	1	1
	21	18	1	4	4	12	4	4	4	4	4	4	0	9	4	

1973

JAN	-1	-1	-1	-1	-1	-1	-1	10	1	1	12	4	1	-1	1	1
	1	1	1	10	0	-1	-1	3	0	4	2	2	16	13	8	
FEB	1	1	1	4	4	7	4	-1	1	1	12	1	4	4	0	1
	-1	-1	-1	-1	-1	-1	-1	4	4	4	1	1	-9	-9	-9	
MAR	12	7	7	3	6	9	7	15	1	12	7	7	19	-1	4	4
	4	4	7	19	19	4	1	4	4	4	4	4	7	4	4	
APR	14	4	4	1	12	12	0	9	9	1	19	1	1	1	5	5
	7	-1	1	1	1	12	12	7	7	9	9	13	3	3	-9	
MAY	7	5	1	1	1	1	9	2	2	2	2	16	13	4	19	5
	17	17	0	1	7	7	-1	7	19	9	2	2	7	16	12	
JUN	4	4	4	4	4	4	7	7	7	2	2	7	4	4	4	-1
	4	10	21	2	2	16	3	17	7	19	4	1	1	1	-9	
JUL	1	0	-1	17	2	2	10	0	8	8	8	8	8	2	2	2
	2	16	16	16	16	11	0	4	14	6	2	2	2	6	16	
AUG	2	2	2	2	2	9	17	12	4	9	17	11	11	12	19	19
	4	4	7	10	10	7	16	7	-1	21	13	13	16	16	16	
SEP	7	2	11	10	6	8	7	13	7	1	1	6	1	20	1	1
	6	6	6	6	6	3	16	-1	6	13	3	6	1	1	-9	
OCT	1	1	19	15	13	13	3	16	7	13	8	0	13	15	0	2
	16	3	3	5	1	1	6	6	6	2	16	13	17	1	12	
NOV	4	2	2	2	4	4	22	6	4	2	16	16	7	12	0	9
	15	17	12	19	4	9	9	17	17	3	3	3	3	1	-9	
DEC	1	1	5	1	3	1	1	1	1	4	4	4	7	0	9	16
	7	7	2	15	9	9	13	11	4	4	1	6	6	2	2	

1974

JAN	2	10	12	1	6	3	1	1	1	5	5	1	1	1	1	1
	1	1	12	1	12	4	4	8	0	1	1	1	5	3	1	
FEB	5	7	6	1	14	16	3	15	5	19	1	1	1	3	3	3
	0	1	4	2	2	4	4	18	1	4	4	2	-9	-9	-9	
MAR	2	16	22	-1	2	4	8	-1	2	14	-1	6	6	1	1	1
	1	1	1	1	1	1	1	1	1	4	4	10	19	10	1	
APR	4	10	-1	1	12	17	13	19	19	1	10	4	1	12	12	1
	5	1	17	16	17	11	5	-1	12	1	12	1	1	-1	-9	
MAY	1	3	3	13	16	-1	2	2	7	13	7	2	0	2	0	1
	1	1	12	12	12	19	10	12	13	4	7	11	1	1	12	
JUN	11	11	3	8	2	2	16	7	11	-1	4	7	0	2	2	8
	0	21	2	2	4	12	12	13	13	0	16	2	11	8	-9	
JUL	8	7	17	16	13	13	8	4	10	21	2	2	4	10	8	4
	8	4	8	2	11	11	1	4	4	2	2	2	2	2	2	
AUG	2	7	7	2	7	4	4	14	8	4	7	11	11	11	11	0
	3	3	3	7	11	21	22	9	9	1	1	1	1	6	4	
SEP	-1	2	11	10	6	8	7	17	7	1	1	6	1	20	1	1
	6	6	6	6	6	3	16	-1	6	13	3	6	1	1	-9	
OCT	1	1	15	15	13	13	3	16	7	13	8	0	13	15	0	2
	16	3	3	5	1	1	6	6	6	2	16	13	17	1	12	
NOV	4	2	2	2	4	4	22	6	4	2	16	16	7	12	0	9
	15	17	12	19	4	9	9	17	13	3	3	3	3	1	-9	
DEC	1	1	5	1	3	1	1	1	1	4	4	4	7	0	9	16
	7	7	2	15	9	9	13	11	4	4	1	6	6	2	2	

APPENDIX 5

HIGH FREQUENCY PROXY DATA SERIES: ICE, ORGANIC MATERIAL AND LAKE SEDIMENTS.

In the High Arctic there are three principal materials from which high frequency proxy climatic data may be obtained. These are 1.) ice and firn 2.) organic deposits (peat) and 3.) lake sediments.

Ice and firn: The Polar Continental Shelf Project (Ottawa) has embarked on a project to obtain an ice core from the Mer de Glace Agassiz. One of the major outlet glaciers from this ice cap drains into the valley behind Ella Bay (Plate A.5.1) our independent assessments of past glacial and climatic fluctuations are thus pertinent to their work. We will continue to collaborate with PCSP on this project.

Organic Material: Organic accumulations are rare in the Archer Fiord area, in our experience. However, on Judge Daly Promontory a glacial spillway in the valley to north of the Beethoven valley (Figure 1.) was found to contain a lush flora growing in very wet conditions where peat had accumulated. In several localities in this valley palsa-like features were observed in which apparently older, dry peat had been lifted above the general level of the ground by the growth of a thick ice lense ∿15cm beneath the surface. In 1975 a 27cm section of peat (10-12cm) and organic-rich mud (∿15cm) was exhumed; no more material could be obtained as the permafrost had been reached and drilling equipment was not available. In 1976 we returned to the same site, equipped with Sipre corer and ice auger. Although some progress through the organic rich mud was made, repeated efforts were unable to penetrate below 68 cm where a hard inorganic layer was reached. It is believed that this valley may profitably repay further efforts at coring (despite the logistical problems involved in reaching the site). The valley lies outside the ">30,000 B.P." Ellesmere Island ice margin and has probably not been glaciated since the

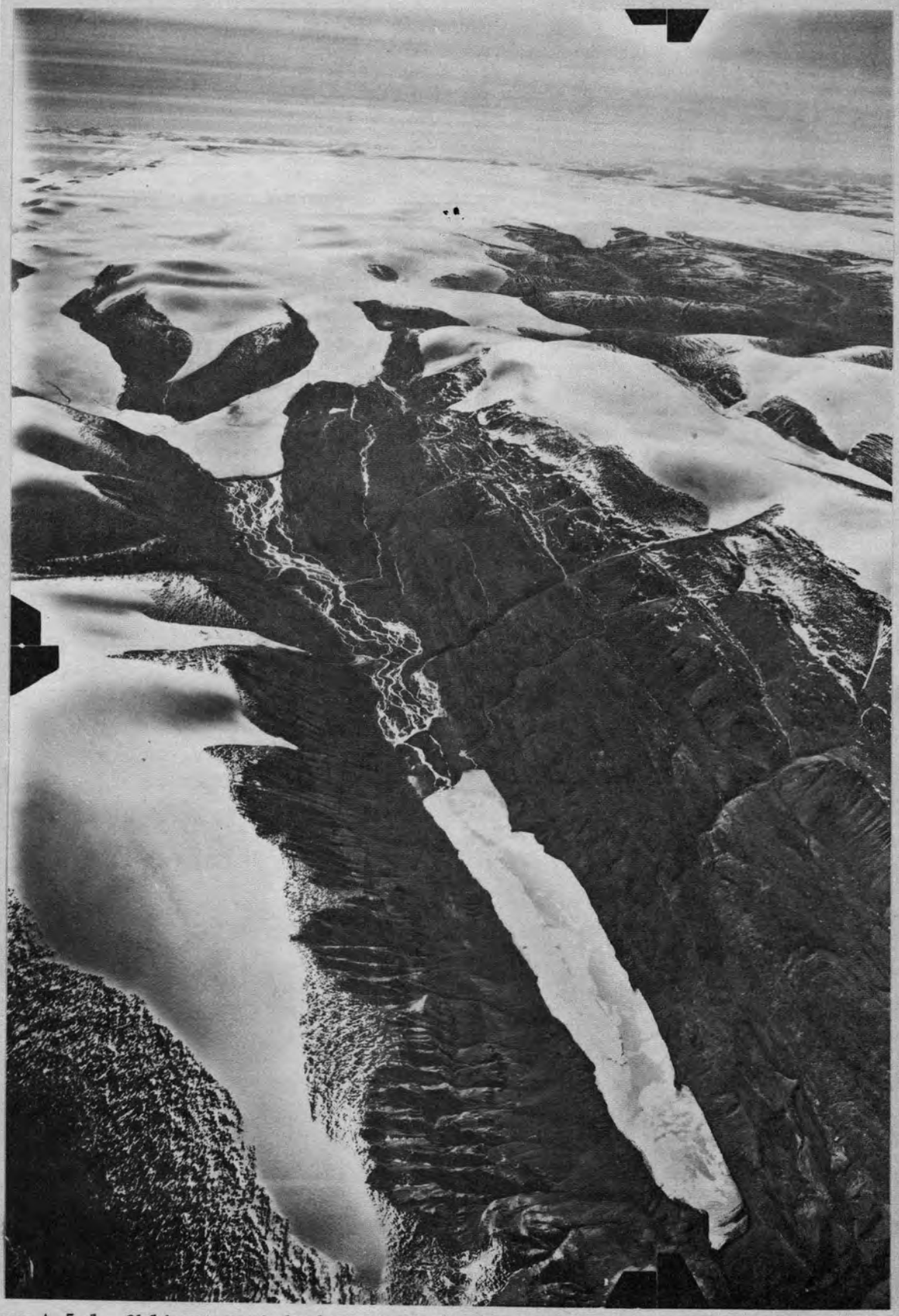

Figure A.5.1 Oblique aerial photograph looking towards the Mer de Glace Agassiz. Christiansen Lake, from which sediment cores were obtained, is seen in foreground. Ella Bay is off photograph at bottom right.

Greenland ice advance onto northern Ellesmere Island (>80,000 B.P.). It is possible that a very old sequence of inorganic and organic layers may be present with inorganic material periodically overriding the organic material as a result of solifluction or other mass wasting processes.

Organic material collected form the site has not yet been dated or examined for pollen owing to a lack of funds. J. Matthews (Geological Survey of Canada) kindly examined one section for insects (principally beetles) but none were found. It is hoped that this work can be pursued at a later date.

Lake sediments: as explained in our original proposal, it is probable that the reconstruction of past glacial and climatic conditions in the High Arctic will be greatly improved with careful analysis of lake sediments (for pollen, diatom and foraminiferal content, sediment characteristics and palaeomagnetic properties).

Very long sedimentary records can probably be obtained from selected lake basins in the outer coastal areas, beyond the late Wisconsin ice margin. In coastal locations, sediments deposited during periods of both ice advance and ice retreat may be preserved in sites which have been periodically isostatically depressed below sea level and then uplifted as regional ice loads diminished. In an exploratory study, two short cores were obtained from Christiansen Lake (Plate A.5) (81°2'N, 70°10'W), a ∿6 km long lake between the present margin of Lockwood Glacier (draining from the Mer de Glace Agassiz) and Ella Bay at the head of Archer Fiord. The lake is 14m above sea level and was formerly an arm of the sea; uplift isolated the lake ∿2500 B.P. and as the lake is over 28 m deep it is possible that old sea water remains trapped at the bottom of the lake (as found by Hattersley-Smith et al, 1972, in a number of other northern Ellesmere Island lakes. Driftwood in marine silts at the outlet of the lake dated 6000$\pm$ 150 B.P. (GSC-1775) and this provides a minimum date on deglaciation of the lower valley (England, 1977). Other material collected up-valley (not yet dated) will enable the rate of deglaciation of the valley to be estimated.

Ice thickness on May 30, 1976 was 1.88 m and sample holes were drilled with difficulty, even using a power ice auger. Two sites were sampled; water depth at site 1 was 9.8 m and at site 2, 28.5 m. Temperature profiles are shown in Figure A5.1 . Four short sediment cores (27 cm to 65 cm in length) were obtained using a WILDCO Davis-Doyle piston corer with 25lb. weight and 1 meter core tube. Owing to logistical problems the cores could not be kept intact and, when frozen, they were cut into 1 cm sample 'discs' to facilitate their transportation. Most of the sediment was extremely fine silt or clay, with a high carbonate content. Several coarser layers of sand-sized material were identified at similar levels in different cores. At present laboratory analysis of these sediments has not been undertaken except for preliminary palynological studies of core CL-4 by Dr. S. Short (INSTAAR, University of Colorado, Boulder). Results of this work to date are summarised by Dr. Short in the following section.

Pollen Analyses of Christiansen Lake cores: Sixteen samples from a 65-cm core from Christiansen Lake, Ellesmere Island have been processed. The matrix is a very inorganic lake sediment, and the many problems characteristic of arctic palynological preparations (Nichols 1975, 1975) are still being worked out. "Absolute" values are calculated using Stockmarr (1971) exotic additive methods. Samples are treated with hydrochloric acid, caustic soda, acetolysis, and hydrofluroic acid. Additional hydrofluoric acid treatments and several sieving steps have also proven necessary. The chemically processed samples were difficult to count because of the residual inorganic materials on the slides. Pollen grains were sparse and generally in poor condition (torn, lacking surface texture, etc.)

Two sets of samples have been processed: eight from the top of the core (1-2 cm, 3-4 cm, 5-6 cm, 7-8 cm, 9-10 cm, 11-12 cm, 13-14 cm, 15-16 cm) and eight from the base (50-51 cm, 52-53 cm, 54-55 cm, 56-57 cm, 58-59 cm, 60-61 cm, 62-63 cm, 64-65 cm); the latter set has not, however been completely

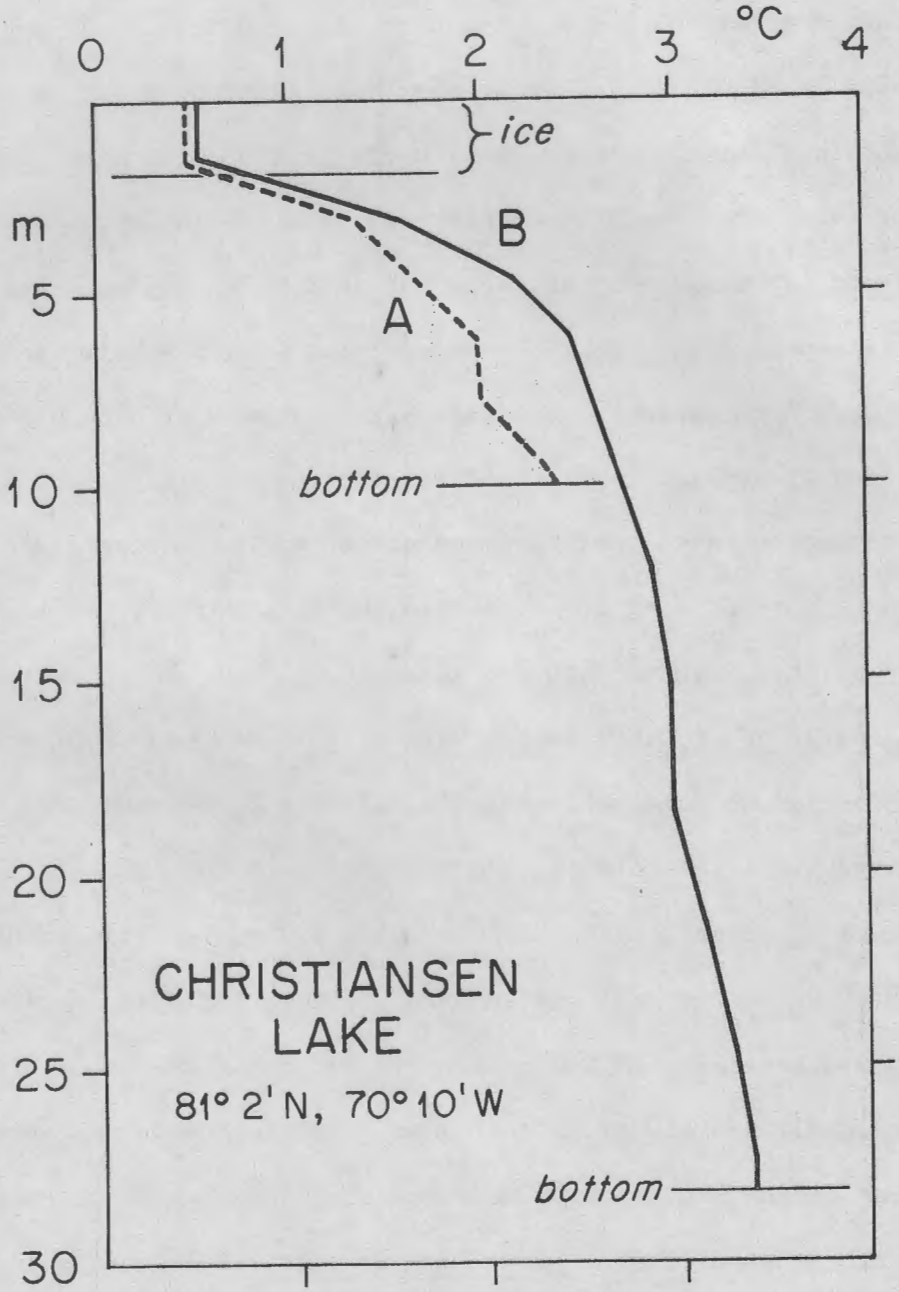

Figure A.5.1. Lake water temperatures; Christiansen Lake, May 30, 1976.

counted. Preliminary results suggest that slides counted from the upper levels contain more pollen grains, of both local and exotic types. These, however, are interim comments, and apply only to the relative percentage counts at present, because "absolute" pollen values based on dry-weight techniques are still incomplete. Local taxa represented include willow (Salix), pinks (Caryophyllaceae), the mustard family (Cruciferae), the sunflower family (Compositae), grasses (Gramineae), ferns (Filicales), clubmoss (Lycopodium), sedges (Cyperaceae), heaths (Ericaceae), and moss (Sphagnum). Exotic taxa, windblown from the forest over 2000 km distant, are alder (Alnus), birch (Betula), spruce (Picea) and pine (Pinus).

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APPENDIX 6

SNOWBANK SURVEY, JUDGE DALY PROMONTORY AND SIMMONDS ICE CAP STUDIES, HAZEN PLATEAU.

JUDGE DALY PROMONTORY

In view of previous work on Baffin Island (Bradley & Miller, 1972) in which the recent change in climate of the Canadian Arctic was related to snow bank growth, a survey of snowbanks on Judge Daly Promontory was undertaken in July of 1975 and again in July and early August of 1976. Aerial photographs of the area, taken in early July 1959, were used for comparison with contemporary conditions. Fourteen photo stations were established for future monitoring purposes.

In nearly all cases examined no significant differences between snowbank extent in 1959 and 1975/76 could determined. Snowbanks are strongly dependent on microclimate which is strongly controlled by topography, particularly at high latitudes where the solar angle is so low. Once a snowbank expands beyond its immediate niche the microclimate at its margin changes dramatically, ablation increases rapidly and the snowbank melts back to an 'equilibrium' situation. Climatic deterioration is unlikely to lead to extensive snowbank growth except in situations where former snowbanks have melted out in periods of extreme warmth, as may have been the case on Baffin Island in the period 1930-1955.

HAZEN PLATEAU

A more significant change in snow and ice cover during a climatic deterioration is likely to occur at higher elevations on plateau surfaces close to the glaciation limit where snow may remain throughout the year during low ablation summers. Such a situation is well illustrated on the Hazen Plateau (Plate A.6.1) where broad, flat hill summits reach elevations of >2500 ft (762m) (Figure A.6.1). Higher elevations of this

Plate A.6.1 Oblique aerial photograph looking across the Hazen Plateau in the direction of arrow on Figure A.6.1. Note extensive snow cover on upland surfaces suggesting susceptibility of this region to rapid glacierization.(Copyright Canadian Government, air photograph T 401 L-113).

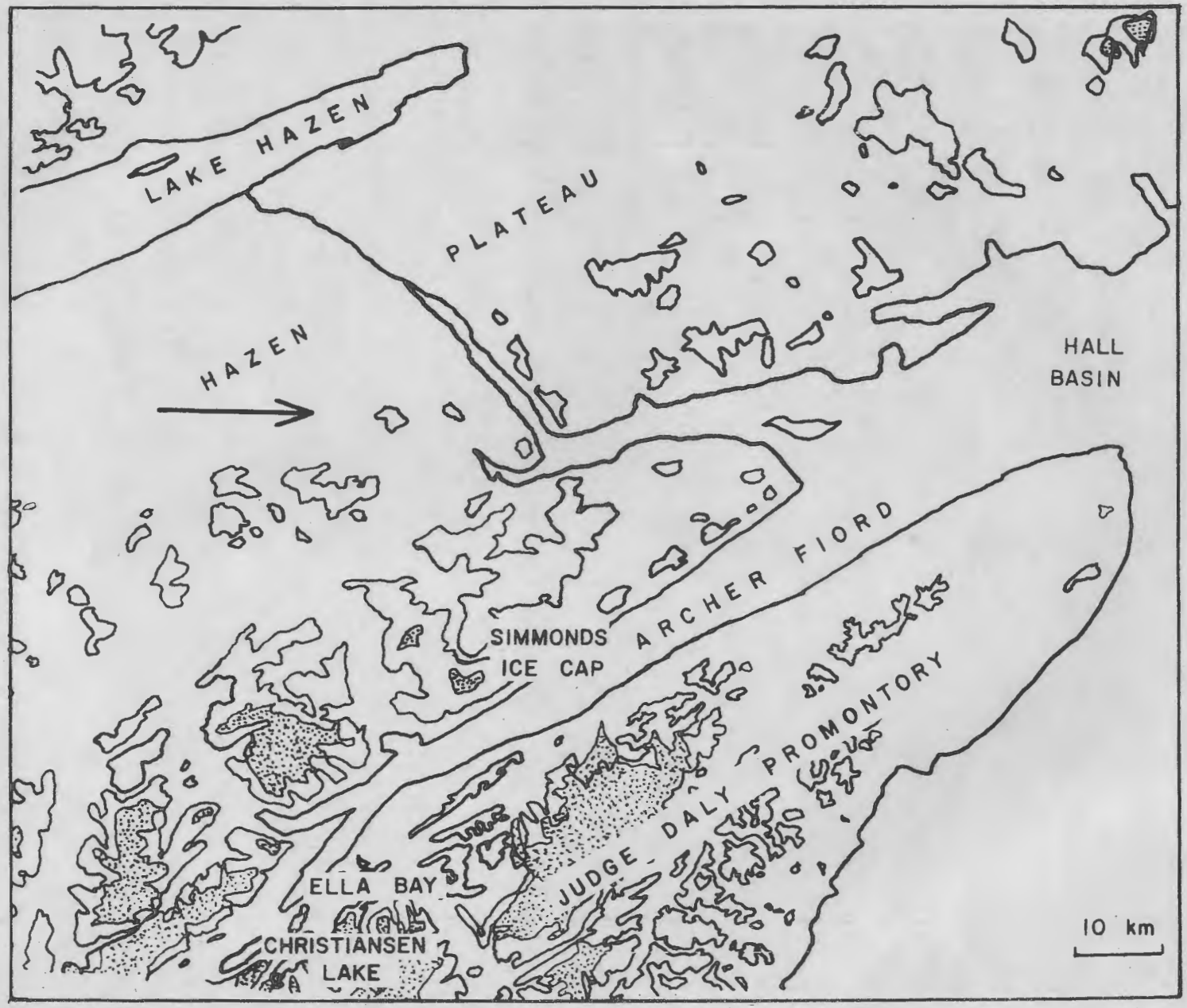

Figure A.6.1. Location map of Hazen Plateau/Archer Fiord/Judge Daly Promontory area showing extent of permanent ice caps (dotted) and areas above 2500 ft (762m)(contour lines). Note extensive upland plateau surfaces on Hazen plateau margins (c.f. the Frontispiece which includes the southern edge of the Hazen Plateau).

plateau may be occupied by small ice caps such as the Simmonds Ice Cap (central north shore of Archer Fiord) and the ice caps north of Hall Basin (Figure A.6.1) previously reported on by Hattersley-Smith and Serson (1973). However, it is of interest that in these two localities the hill summits on which the ice caps lie are very similar in elevation to other nearby hill summits, ie: the ice caps may be 'relict' features which, as a result of higher albedo, slightly higher elevations at the summit, more extreme microclimate etc, assist in their own preservation. They are thus most sensitive to prolonged climatic fluctuations and monitoring of these ice caps is of particular relevance to studies of arctic glacierization.

Aerial photographic survey

On August 5, 1975, a photogrammetric survey of the Simmonds ice cap and surrounding area was carried out by K. C. Arnold and D. Terroux of the Glaciology Division, Environment Canada, Ottawa. This was the first photographic survey of the ice caps since 1959. Unfortunately, the survey followed a period of bad weather which left considerable snow cover on the plateau. As a result, comparison with snow and ice extent on 1959 photographs is difficult, particularly on the formerly unglacierized hill summits.

Although a detailed analysis of the 1975 photographs was precluded due to lack of funds, preliminary studies suggest that the plateau area southwest of Simmonds Ice Cap had more extensive firn cover in 1975 than in 1959. Similarly, in 1975 more extensive snow/firn was visible on the southern side of Murray ice cap than in 1959. However, two small nunataks near the eastern edge of Simmonds Ice Cap were visible in 1975 but were not apparent in 1959. It would be of interest to visit these locations

to collect any surficial organic material which may have been exposed by the downwasting of the ice cap in this area. Further study of the 1975 and 1959 photographs, perhaps using color enhancement techniques, is needed to provide a quantitative assessment of glacierization in the area. In this regard, return beam vidicon (RBV) LANDSAT imagery of the field area may prove useful in continued monitoring of snow and ice conditions (see Frontispiece). Twenty seven relatively cloud-free images of the region were obtained for the first time in 1976 (May 14 to September 4). At this latitude the capabilities of the LANDSAT system are at their extreme northern limit and hitherto imagery had not been attempted. As can be seen in the Frontispiece, extensive snow cover was still present on the plateau on July 25, 1976, and low-level reconnaissance by Twin Otter aircraft on August 16, 1976, confirmed that snow cover was almost uninterrupted above 900m. It is very unlikely that any substantial ablation occurred above this elevation after August 16.

THE SIMMONDS ICE CAP

The Simmonds Ice Cap is located at the southern margin of an extensive upland surface on Lonesome Creek Promontory (between Archer Fiord and Conybeare Fiord to the north, Figure A.6.1). The summit of this 6.7 km^2 ice cap is at ∿1151m (3775 ft) and most of the ice cap is above 1050m (3444ft). Another small ice cap (Murray ice cap) is located ∿5km to the northwest; Murray ice cap is smaller (∿4.5 km^2) and lower in elevation (∿1070-1120 m according to photogrammetric spot height estimates). In addition, a small remnant ice patch southwest of Simmonds ice cap at ∿950m was visible on aerial photographs taken in 1959 (Plate A.6.2). Glaciation levels in the area were estimated by Miller et al (1975) to be between 1000m and 1100m,

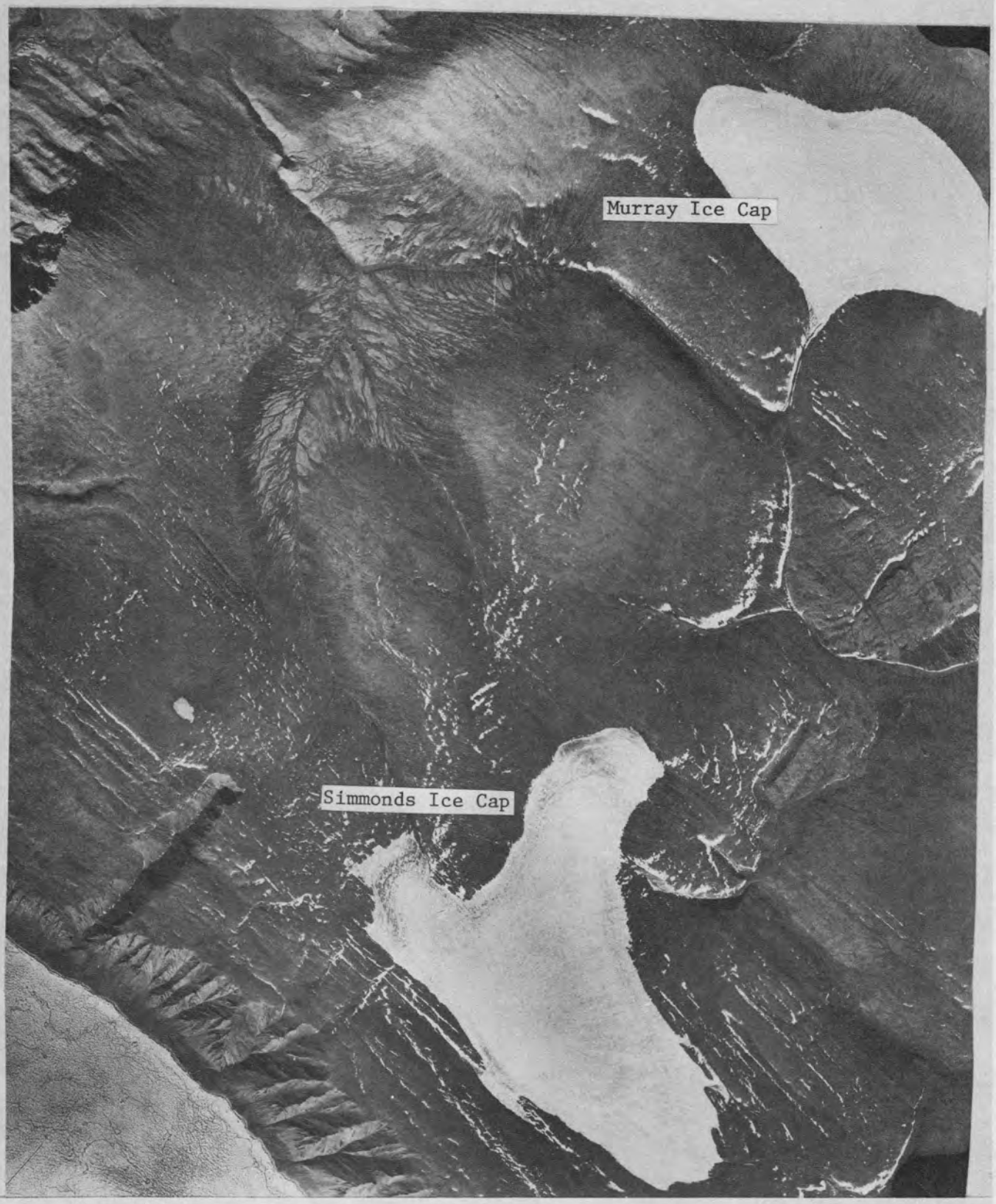

Plate A.6.2 Vertical aerial photograph (approximate scale 1:80,000) showing Simmonds and Murray Ice Caps and adjacent hill summit with snow patch, July 9, 1959. Note almost complete absence of snow cover on both ice caps and surrounding plateau. c.f. Frontispiece of LANDSAT image obtained July 26,1976. Copyright Canadian Government;air photograph A-16610-43.

hence these ice caps are at their extreme elevational range. Monitoring of snow accumulation on adjacent high-elevation plateau surfaces and mass balance measurements on these small ice caps will provide useful information on (1) the response of low elevation ice caps to recent climatic fluctuations and (2) the mechanism of glacierization in the region, particularly the concept of 'instantaneous glacierization' (Ives et al 1975).

Mass balance and recent climate

A network of 18 stakes was established on Simmonds Ice Cap June 7-10, 1976 (Figure A.6.2 and Table A.6.1). The original plan to establish a stake network in 1975 had to be abandoned due to logistical problems. Similar difficulties prevented a return to the ice caps at the end of the 1976 ablation season. Nevertheless, the stake network will serve as a baseline for future mass balance studies.

Photographs of the ice cap on July 9, 1959 indicate that the entire surface was denuded of snow and firn and that the exposed ice had a banded appearance. Preliminary studies on the ice cap in early June, 1976, indicate that firn was present on the ice cap down to its margins. Total water equivalent to the superimposed ice layer ranged from 18.1 cm (at the summit, 1151m) to 9.9 cm at 1067m (stake 1) on the flat western edge (Figure A.6.2 and Table A.6.1). Pits were dug at 7 sites (Table A.6.1) and snow stratigraphy, density and temperatures were recorded. Mean snow temperature gradient in the upper 40cm was 0.25°C cm^{-1}. Thermisters placed at -50cm and -80 cm in the underlying ice (at stakes 14 and 18) recorded englacial temperatures of -16.0 and -18.3°C respectively. At nearly all sites a relatively dense (0.32 to 0.36) wind-packed surface layer is found over a depth hoar zone of lower density (0.25-0.27). These layers together comprise the winter

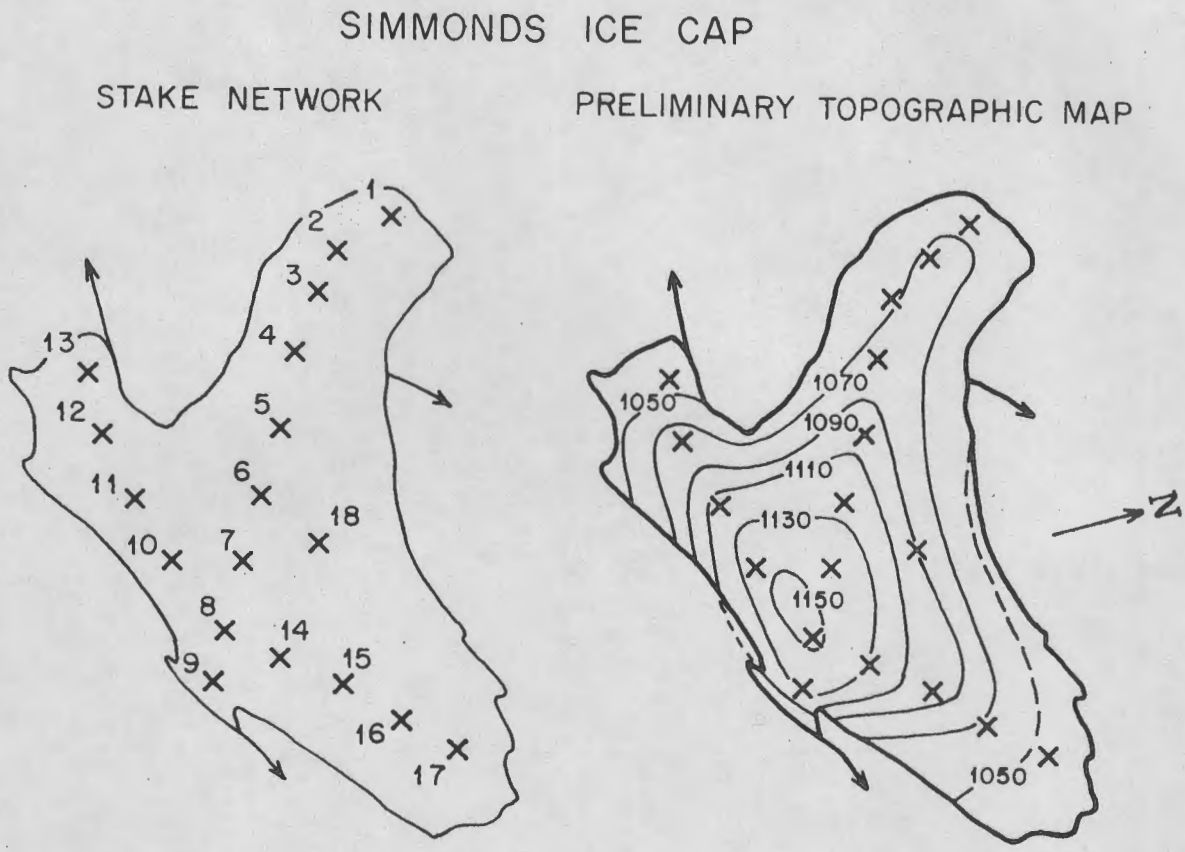

Figure A.6.2 Preliminary topographic map of Simmonds Ice Cap showing stake network established in June 1976.

Table A.6.1

Altimetric measurements of stake elevation & water equivelant above ice surface

Stake /	elevation (m)	Pit[1]	Total w.e.(cm) above ice
8	1151		18.1
7	1144	x	18.1
10	1140±5	x	14.7
9	1132		12.7
14	kk3k	x*	18.3
6	1123		15.0
11	1119		12.9
5	1099	x	12.5
15	1098		12.8
18	1091	*	14.0
12	1077		14.0
4	1076		12.5
2	1074		11.2
16	1069	x	13.7
3	1068	x	11.2
1	1067	x	9.9
13	1048		12.5
17	1043		11.9

Footnote:
1. Density & temperature measurements taken;

* asterisk indicates thermister set in ice (see text).

accumulation which ranged from 6.7cm (at 1067m) to 13.6cm at (1144m). By comparison, September 1975 to May 1976 precipitation at Alert was ∿8.9cm (water equivelant). At elevations above ∿1130m a complex firn stratigraphy was noted suggesting that for several years equilibrium line elevations had been below this elevation and that in recent years the ice cap had maintained a small accumulation area. Although the 1975-76 net balance could not be measured, LANDSAT imagery of the area taken on July 25,1976 shows continuous snow cover on the plateau down to ∿900m. Weather conditions in the area were not favorable for substantial ablation in the following three weeks (extensive snow cover was present on the plateau down to ∿900m on August 16,1976) and it seems unlikely that the ice caps ended the year with a negative balance. By contrast, measurements on the (lower elevation) ice cap north of Hall Basin (Figure A.6.1) gave a net balance for 1975-76 of -0.72m (as reported by H.Serson in Ice,number 53).

In view of the presenceof firn down to the margin of the Simmonds Ice Cap (and possibly on the adjacent plateau) it seems likely that the ice cap has gained mass in recent years. The particularly cold summer of 1972 in all probability resulted in a very positive balance year for 1971-72. Reconnaissance of the two small ice caps near St Patrick's Bay(north of Hall Basin,Figure A.6.1) on August 20 and 21,1972 indicated that winter snow cover was extensive on the surrounding plateau for at least a kilometer and "the ice margin is encroaching on previously snow-free ground" (Hattersley-Smith and Serson,1973). Such conditions would have been even more extensive on the higher plateau around Simmonds Ice Cap and it seems likely that the ice cap has maintained an overall positive balance since that time. Further studies of Simmonds and Murray Ice Caps and adjacent hill summits will determine to what extent the ice caps are gaining mass under present climatic conditions and if 'permanent' snow cover is developing on the plateau.

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APPENDIX 7

METEOROLOGICAL OBSERVATIONS 1975: JUDGE DALY PROMONTORY AND ALERT

Judge Daly Promontory (81° 24'N, 65° 17'W; 168m)

	Tmax	Tmin	Tmean °C	RH.max %	R.H.min	Precip:mm
June 29	5.5	2.5	4.0	96	61	
30	5.5	2.3	3.9	96	74	Tr
July 1	6.7	3.0	4.85	100	82	4.0
2	8.6	1.5	5.05	98	66	Tr
3	6.7	4.0	5.35	85	66	Tr
4	4.5	-1.1	1.7	99	80	Tr
5	3.1	-1.1	1.0	96	75	
6	8.0	2.1	5.05	86	64	
7	12.0	6.0	9.0	74	47	
8	7.6	0.6	4.1	99	57	
9	6.0	0.0	3.0	98	66	Tr
10	3.1	-1.0	1.0	100	80	
11	6.5	-0.5	3.0	100	62	Tr
12	7.9	1.4	4.65	95	58	
13	6.0	0.5	3.25	98	62	
14	8.2	2.0	5.1	94	58	
15	10.8	4.0	7.4	78	51	
16	4.9	1.8	3.35	95	79	
17	12.1	2.4	7.25	91	58	
18	10.6	1.3	5.95	99	65	
19	11.6	1.4	6.5	97	58	
20	12.1	6.4	9.25	71	40	
21	11.5	4.9	8.2	78	46	
22	11.0	3.9	7.45	87	51	
23	13.2	8.1	10.65	66	42	
24	10.0	1.4	5.7	94	60	
25	3.3	-0.8	1.25	100	84	.06
26	0.0	-1.1	-0.55	97	93	.04
27	3.3	-0.7	1.3	96	82	2.4
28(to 1500 hours EST)	2.2	0.4	(1.3)	95	88	Tr
$\bar{x}$	7.42	1.85	4.63	92	65	Σ 6.5
s	3.51	2.39	2.79	9.5	13.9	

Footnotes:

1. Temperature & humidity data for Judge Daly Promontory were obtained from a recording thermohygrograph. As the response of this instrument is slower than a maximum or minimum thermometer, or a dew cell, it is unlikely that actual extremes of temperature or humidity were recorded. An irregular field work schedule made systematic comparison with max/min thermometer impossible. At Alert, however, hourly Tmax & Tmin observations will include actual highest & lowest daily values. Overall period mean temperatures are probably comparable.
2. Observational day 0000EST to 2400 EST; continuous activeographic measurements of total solar radiation receipts were also made but reduction to daily totals has not yet been undertaken.

Alert, (82° 30'N, 62° 20'W, 63m a.s.l)

	Tmax	Tmin	Tmean (°C)	Precip:mm
June 29	6.1	-1.67	2.22	2.03
30	5.0	0.56	2.78	
July 1	5.0	0.56	2.78	0.76
2	6.67	0.0	3.34	Tr
3	5.56	0.56	3.06	0.25
4	7.78	1.11	4.45	Tr
5	7.78	2.22	5.0	
6	11.11	0.0	5.56	
7	5.56	0.0	2.78	
8	12.22	1.11	6.67	Tr
9	3.33	0.0	1.67	Tr
10	7.78	0.0	3.89	
11	7.78	0.56	4.17	
12	1.11	-0.56	0.28	Tr
13	1.67	-0.56	0.56	Tr
14	1.67	-0.56	0.56	Tr
15	3.89	-1.67	1.11	Tr
16	1.11	-2.22	-0.56	
17	3.89	-0.56	1.67	
18	1.67	-1.67	0.0	
19	3.89	-1.11	1.39	
20	12.78	0.0	6.39	
21	13.89	3.33	8.61	
22	13.33	3.89	8.61	
23	13.89	3.89	8.61	
24	5.0	-1.67	1.67	Tr
25	7.78	-1.11	3.34	Tr
26	8.89	0.56	4.73	
27	4.44	1.11	2.78	1.27
28	9.44	-0.56	4.44	.25
$\bar{X}$	6.67	0.18	3.42	Σ 4.56
s	3.91	1.56	2.54	

Cover photo:

Ella Bay base camp,
northeastern Ellesmere Island
(81° 5'N, 70°W).