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TOPOGRAPHIC CHANGE OF THE MEIGHEN ICE CAP

by

THOMAS WESTBY HAYTHORNTHTWAITE, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Arts

Department of Geography

Carleton University

Ottawa, Ontario

April 21, 1986

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Thomas Haythornthwaite

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ABSTRACT

The results of a levelling survey conducted in 1985 across the Meighen Ice Cap, Arctic Canada, were compared to 1960 data to determine the extent of topographic change. While most of the surface of this stagnant ice cap has been substantially lowered, the summit area has gained height. Maps used to illustrate the results of mass balance observations for the period 1959 to 1985 confirm these conclusions and show that the spatial pattern of change has been quite constant over time. Ablation is the dominant factor in mass balance spatial distribution. Because the ice cap has probably always been stagnant, current trends are likely to be countered by other mechanisms before thickening and steepening introduce ice motion.

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CHAPTER 1

INTRODUCTION

Meighen Island and the Meighen Ice Cap

Meighen Island (80°N , 99°W) borders the Arctic Ocean and lies to the west of Axel Heiberg Island, north of Amund Ringnes Island and northeast of Ellef Ringnes Island [See Figure 1.1]. The highest point, 268 m above sea level, is on the Meighen Ice Cap which in 1959 occupied about 85 Km^2 or about 10% of the island [Arnold, 1965]. Figure 1.2 shows the 1959 extent of the ice cap on the island.

As this thesis will demonstrate, the Meighen Ice Cap apparently does not flow, and so it is called a stagnant ice cap. Other examples of stagnant ice caps are found on Ellesmere, Melville, Axel Heiberg, Baffin and Devon Islands [Paterson, 1969]. However, the Meighen Ice Cap is unusual because it lies at an extremely low elevation. Only the outlets of large ice masses in the Canadian Arctic extend as low as even the highest part of the Meighen Ice Cap [Alt, 1975].

The importance of stagnant ice caps to geographic research is that their reaction to certain meteorological effects is immediate, instead of being delayed by the

Fig. 1.1 Meighen Island Location

lagging effect of glacier flow. The conditions involved are the accumulation and ablation of ice at or near the surface. The reactions may take the form of changes in surface elevation, or topography. Topographic changes, therefore, can only reflect the climatic history of the surface. If frequently monitored, changes to the topography offer relatively quick indications of climatic activity. If observed after a protracted period, the changes reflect an integration of the annual climatic patterns.

Maps of the ice cap ['Meighen Ice Cap', 1:25,000, 69H - 560B (Parts); 'Meighen Island (N 1/2)', 1:50,000, 69H - 560B (Parts); and 'Meighen Island (S 1/2)', 1:50,000, 69H] were compiled from 1959, 1960 and 1961 surveys and remote sensing, and were first published in a paper by Arnold [1965]. These maps provided the basis for most of the cartography in this thesis. On these maps major summer melt streams on the ice cap are shown as they were determined in 1960. Particular attention was paid by the compilers to the relict streams around the ice cap. Braided streams on the surrounding land were shown in their precise forms rather than conventionally. Ice thicknesses, derived from radio echo sounding, were provided for the entire ice cap. The depth at the highest and thickest part was found from a bore hole to be 121.2 m in 1965. A ridge joins the dome at the south to a smaller dome nearer the middle, and the entire northern half is thinner than 30 m [Arnold, 1965].

According to the maps, the island surface below 50 m a.s.l. is covered by silt, sand, gravel and coarse pebbles which have been classified as part of the Beaufort formation of post-Mesozoic age [Arnold, 1966, referring to Thorsteinson, 1961]. Most of the next 50 m is described as till, composed of thin clay and angular rock fragments, although the area is not recognized as ever having been glaciated. [Arnold, 1965; Alt, 1975]. Most of the island between 100 m and the highest part is covered by the ice cap. The greatest past extent of prolonged ice cover (as shown by stream patterns on the map) appears to be beyond the current north end [Arnold, 1965]. Shorelines of ponded water and ice-marginal streams occur in the presently ice-free southern part of the island. Many small semi-permanent snow patches lie on the remaining upper parts of the island. A recent unattached ice cover, now gone, may also have existed.

Thesis Purpose

The extraordinary precision of the 1959 and 1960 mapping was intended to permit comparison with future mapping for greater understanding of processes of change on the ice cap. Although Arnold, [1981] later felt that the total topographic changes over the first ten years were insufficient to be discernible by comparison with re-mapping, 25 years have now passed and routine annual mass

balance observations suggest that topographic changes ought to be observable now, especially if a more vertically accurate technique is employed. This thesis reports on the first attempt to make such observations. The mass balance data are presented and compared to differences observed between a profile survey and the 1960 map. Topographic changes are discussed in terms of the glaciological mechanisms that cause them. The thesis is intended to quantify topographic change on the ice cap.

Methodology

The period from 1959 to 1985 was chosen for study because it corresponds to the period of principal data availability. Two techniques were used in the research reported here:

1. Because the ice cap had been accurately surveyed a quarter of a century ago, it was decided to do a levelling survey to determine whether the topography of the ice cap had changed in the interim. Field work was conducted in 1985 by the writer and Mr Lundgaard to obtain these data.
2. Annual data from a mass balance stake network obtained by Polar Continental Shelf Project (PCSP) personnel since 1959 were compiled into mass balance maps using the ice-margin information obtained from visual interpretation of

various aerial photo sets flown during the study period.

The writer made these interpretations during the summer of 1984 and participated in the annual mass balance measurements of 1985 and 1986. Computer Assisted Cartography (CAC) techniques were used to produce mass balance maps for 1959-60 to 1985.

The research plan was designed to show how the topography has changed, and to show the spatial distribution of the phenomena that cause these changes. While it is not possible to compare the results directly, the two techniques appear to be compatible and a simple relationship between topographic change and climatic or glacial activity is identified. The derivation of climatic trends is the goal of other work related to that reported here. [See, in particular, the glaciological works of Koerner and Paterson, and the meteorological work of Alt in the bibliography.]

Organization of work

Chapter 2 discusses stagnant ice caps and the mechanisms of their topographic change, and the mass balance observations made by previous workers on the ice cap. Chapter 3 reviews the Survey and Cartographic techniques used to observe and illustrate change. Chapter 4 presents and discusses the results of these investigations. Chapter 5 interprets and evaluates the results, and suggests future work.

CHAPTER 2

MEIGHEN ICE CAP GLACIOLOGY

The first part of this chapter discusses the glaciology of the Meighen Ice Cap pertaining to its stagnant condition. The second discusses the mass balance history of the ice cap. The chapter continues with discussion of the relationship between topographic change and mass balance, and concludes with the mass balance observations that have been made since 1959.

Glacial Flow

Motion in dynamic ice masses may be caused by basal sliding and laminar deformation. Basal sliding can only occur if the base of the ice mass is at a pressure-reduced melting point due to loading by ice that is relatively thick or warm. Ice masses that are frozen to their bed do not slide [Paterson, 1981].

For our purposes, we can assume that ice deforms only when stresses exceed a certain threshold, and this will depend on the combined effect of ice thickness and surface slope. Stress is greatest near the base, and velocities are greatest at the steepest surfaces. An ice mass that is thin

and has no steep slope is likely to be stagnant [Paterson, 1981]. This is almost certainly the case for the Meighen Ice Cap.

In 1965 a thermal drill was used to obtain a 121.2 m core from the highest point of the Meighen Ice Cap [Koerner, 1968; Koerner, Paterson and Krouse, 1973]. This was the first complete ice core to be obtained in the Canadian Arctic.

Arnold [personal communication] points out that because the core is from the top of the dome, it probably contains ice that was formed under relatively flat conditions, so that conclusions drawn from those samples might not be representative of the entire ice cap. Nevertheless, Koerner and Paterson made a detailed examination of the core and published the following results and conclusions.

Examination of samples from the core showed generally equigranular crystals with no evidence of interlocking patterns or significantly preferred crystallographic orientation [Koerner, 1968]. No samples were found to have exclusively elongated bubbles with long axes normal to the surface. The ice fabric and texture throughout the core did not, therefore, exhibit strain, and so it was concluded that the ice cap has always been stagnant. Furthermore, Paterson declared that contemporary flow was "...expected to be small because the ice is cold (-16°C to -18°C) and nowhere more than 125 m thick." [Paterson, 1969, p 348]. The imp-

lication is that stress is so low that basal sliding is impossible and internal deformation unlikely. Paterson also referred to tellurometer measurements of stake locations conducted from 1960 to 1964 in the southern and steepest (and therefore most likely to flow) part of the ice cap. His conclusion was that "changes in surface elevation....from year to year are determined largely by the mass balance; the effect of flow is small." [Paterson, 1969, p 349]

It is not clear to what extent we should adopt this conclusion that the ice cap is stagnant. Current workers [Koerner and others, personal communications] seem to accept that it is. If there is, or has been flow in the past, we might expect to see some such evidence at the margin near the steepest parts of the ice cap. In fact, none has been reported.

Mass Balance

The ice in a glacier increases in mass by accumulation and decreases by ablation. As stagnant ice caps have no flow, ablation and accumulation processes only change the surface elevation and composition. The mass balance or change during any one time period is the algebraic sum of accumulation and ablation expressed as mass added or removed per unit area. Mass balance data are normally multiplied by the density of the snow or ice to provide water equivalent

thickness values. A negative annual net balance causes surface thinning; thickening results from positive balances.

Summer melting occurs to some degree over the entire ice cap each year. In a moderately positive balance year, the melt-water percolates into the snow and refreezes at the previous summer's surface to form superimposed ice. If there is a highly positive balance the snow pack may be so thick that only the upper part becomes saturated during the next melt period so a layer of firn remains after the summer season. If a negative net balance year removes all snow and firn to expose the ice surface below, the run-off may also include water melted from the older ice. In negative balance years only an underlying firn layer can absorb any of the new run off, but there would still be a net balance loss.

Undeformed firn layers have been identified to a depth of 22 m at the core site [Koerner, 1968]. Below that, occasional firn layers have been compressed into ice, and comprise 10% of the core. The remaining 90% consists of superimposed ice. This accumulation mode is different from that of dry snow areas such as those found in higher altitude dynamic ice masses, although it is somewhat similar to conditions found between the equilibrium and firn lines of dynamic glaciers. The fact that parts of the ice, right down to bedrock, originated from firn confirms that the ice cap has always been stagnant because strain rates must al-

ways have been zero for the firn to remain undeformed [Koerner, 1968]. Because of the maximum possible depth at which firn is thought to be able to exist without being compressed into glacial ice, Koerner suggests that "...not more than 13 m of ice have ablated from the surface since the deepest firn layer, now at a depth of 22 m, was at a depth of 35m." [Koerner, 1968, p 423] Because relatively little ice can therefore have melted, it is therefore thought that the ice cap would not have been able to survive the climatic optimum and so it is unlikely to be a remnant of a larger ice mass from the Wisconsin period. Table 2.1 summarizes what is thought to be known of the history of the Ice Cap.

Alt [1975], studied the synoptic characteristics of Meighen's climate and related them to mass balance. She discovered that "...four distinct circulation configurations..." exist such that variations in their relative importance account "...for the observed climatic characteristics of that period." [Alt, 1975, p 14] Furthermore, she concluded that the ice cap's existence is because Meighen is effectively in the Polar Ocean, because it is high enough to be in most of the stratus and stratocumulous blown by north-westerly winds, because it is too small to dissipate that fog, and finally, because "...the ice cap, once formed, tends to increase or prolong cloud and precipitation through cooling and orographic effects." [Alt, 1975, p59] Alt

TABLE 2.1

CLIMATIC HISTORY OF THE MEIGHEN ICE CAP

Depth interval (m)	Estimated time interval yr BP	Climate and balance at core-site
0	Present-80	Ablation surface formed during period of negative balance which removed a maximum of 13 m of ice at the core site
0-24	8-390	Positive Balance
24-44	390-560	Relatively little summer melt, coldest period in ice cap's history, positive balance
44-54	560-660	Core-site on a well-drained slope, positive balance
54	660-2500/2000	Long period of negative balance which reduced the ice cap in size
54-116	2500/2000-?	Overall positive balance with several short periods of negative balance
116-121	?-3000/4500	Positive balance with the ice cap covering most of Meighen Island

after Koerner and Paterson [1974]

agreed that the ice cap originated after the Climatic Optimum, and suggested that it has been maintained since then principally by positive net balances in years having one specific circulation configuration that tended to counteract the strongly negative balances of another of the four types.

While an initial study [Arnold, 1965] found that snowfall was evenly distributed over the ice cap, Paterson's [1969] work based on longer records found that accumulation increases with distance from the south end of ice cap at an average rate of about 7 mm Km^{-1} . Note, however, that Paterson assumed that the PCSP winter and summer balance data adequately represented ablation and accumulation. The validity of this premise is discussed below.

In addition to winter snow, some snow occasionally falls in the summer, although as the average accumulation is probably less than 1 cm [Arnold, 1965] it is normally negligible. (This knowledge, however, is based on only a few years of record.) Additional accumulation can occur in the summer as rain, which causes considerable melt. This rain may drain off or contribute to the superimposed ice. Rime has been observed but it is thought to contribute only a very small amount to the accumulation [Arnold, 1965; Alt, 1975]

Most accumulation occurs as winter snow, which averages about 14 cm water equivalent over the entire ice cap.

Little work has been done on the probability of regional accumulation variations caused by snow drifting on Meighen, although it has been proposed [Johnson Jr., J.P.; & Arnold, personal communications]. Theoretically, evaporation and sublimation may also affect the mass balance of the ice cap. Koerner [Personal Communication] suggests that the effects of factors other than snow accumulation are probably small.

Various site characteristics influence the distribution of ablation and accumulation on a stagnant ice cap. Local relief of the bedrock or surrounding terrain probably influences accumulation because of scouring and drifting action of wind, and on ablation, especially where there are melt water channels, because of shading from and orientation of the sun. Elsewhere in the Arctic, semi-permanent snow patches often occur in sheltered areas and so the same effects probably influence the topography of stagnant ice caps [Arnold, 1965] wherever their surface shape provides a relative degree of protection.

Slope also plays a major role in the ablation process by its effect on drainage [Paterson, 1969]. If the terrain is relatively flat, more of the summer melt is likely to percolate into the snow pack instead of draining down slope. Under extremely flat conditions, water may even pond at the surface. The amount of run-off above any point is also important because the thermal and kinetic energy of the

meltwater can accelerate local ablation.

Paterson's [1969] study of overall ablation showed that the ablation rate decreased with increasing elevation at an average rate of 2.9 mm m^{-1} , varying widely over the ice cap. This rate is too great to be explained purely by environmental temperature lapse rates, which might cause about a 1°C drop over the 125 m relief of the ice cap. Ablation varies with distance eastward across the ice cap at an average rate of 12 mm Km^{-1} . This may be a reflection of increased ablation on steeper slopes, (because better drainage accumulates less superimposed ice) or, possibly, a tendency for there to be warmer and brighter mornings than afternoons. Because the ice cap is stagnant, it does not have crevasses, and so all drainage is over the surface or within any firn layer above the ice [Arnold, 1965]. The converse of the possible drifting phenomenon mentioned above might exist as wind scouring from the highest to lower parts, or perhaps, as has been suggested but not studied [Arnold, personal communication; Paterson, 1969], from the steep southern slope by katabatic winds. However, Koerner [Personal Communication] suggests that these effects must be small.

The direction of the prevailing wind could have a great influence on areal variation of mass balance. Areas that are relatively sheltered from the wind, either by the ice cap's dome or the surrounding terrain, are likely to capture

more drifting snow and to retain it longer through the ablation season [Arnold, 1966]. Conversely, exposed areas may tend to experience scouring and hence have a more negative balance.

Total relief is rarely great in stagnant ice caps and so temperature lapse rates probably only have a very slight influence on mass balance distribution. There may, however, be a non-causal relationship between elevation and ablation if the vertical distance below the highest parts of the ice cap tends to vary with the quantities of water that are likely to flow past during the summer. In other words, ablation might also be found to be indexed by distance to the nearest margin [Koerner, personal communication].

The heat budget forms an integral part of the understanding of summer ablation [Paterson, 1981]. Alt [1975, 1979 and discussion in Paterson, 1981] found that calculated values of the heat available to melt ice, based on observed meteorological conditions, compared satisfactorily with measured surface level changes throughout three summers on the Ice Cap.

Ice Cap History

The core evidence led to the following inferences about the ice cap's history that are relevant to topographic change:

Borehole temperature profiles led Paterson [1968] to conclude that the previous sixty years had been warmer there than had the 1960's, causing a slightly negative mass balance in that period for the highest parts of the ice cap. This can be interpreted to suggest that the highest elevation may have been decreasing.

Dirt layer concentrations and electrolyte conductivity values at different depths vary according to the amounts of wind-blown dust on the island in the past [Koerner, 1968; Koerner and Paterson, 1973; and Koerner and Fisher, 1979]. These levels are indicative of the changes in the amount of the island covered by the ice cap. The lowest 5 m of the core are relatively clean, suggesting that the ice cap began to exist in a period of complete snow cover on the island.

The $\delta^{18}\text{O}$ isotope profile [Koerner and others, 1973; Koerner and Paterson, 1973] showed no consistent trends and was difficult to interpret for two reasons.

At least part of every winter's accumulation is lost in the following summers. In negative balance years, the entire winter accumulation and some of the underlying ice are missing. Any periods of protracted negative balance at the core site can only be represented by discontinuities because the accumulation record from that period is missing.

The record in the existing ice is modified by isotopic enrichment during melt water percolation. This varies the relationship between the measured $\delta^{18}\text{O}$ values and the

actual temperatures represented so that interpreted climate tends to be too cool [Paterson, 1973]. ($\delta^{18}\text{O}$ analyses and ice core dating are discussed by Fisher and Koerner [1980] and Koerner and Russell, 1979).

Because the bubble content of the ice at 24-44 m depth is relatively high, it is thought that relatively little melting occurred in the summers represented, so this part probably represents the coldest period of the ice cap's history. However, in the same interval the $\delta^{18}\text{O}$ values, are less negative, an observation normally indicating warmer conditions. This paradox may be due to greater retention of summer precipitation on the ice cap, which would result in 'warmer' annual $\delta^{18}\text{O}$ values.

Because the 54 m depth marks a major discontinuity in the $\delta^{18}\text{O}$ isotope, bubble content, and acidity profiles (and the trend of increasing crystal size with depth ends just below this level), this level has been proposed as a relict ablation surface. It has been dated on the basis of the temperature/depth profile as occurring about 500-600 years ago [Koerner and Paterson, 1973]. The break at 55 m in the trend of increasing crystal size with depth could be related to temperature, with the coarse ice between 55 and 115 m having been deposited in warmer summers than layers above and below. The coarse crystal section could also have been formed while slopes were more gentle and drainage slower. The relatively flat core site may be unrepresentative

of general drainage on the ice cap, although we do not know that the bore hole location has always been the highest point. Once the ice cap was sufficiently thick, slopes developed that reduced the likelihood of slush and ponds at the core site. A decrease in the area occupied by the ice cap might have contributed to the development of a slope at the core site where there is currently none. Any period in which the equilibrium line (separating positive net balance areas from negative net balance areas) is on or above the ice cap ought also to steepen slopes because there will be more melting at lower altitudes.

Topographic Change

A steady state condition (in which the net balance remains zero for a long period and the dimensions of the ice cap remain constant [Paterson, 1981]) is sometimes found in dynamic glaciers. No such condition can exist for stagnant ice caps because the elevation of the equilibrium line (normally defined as that line dividing an upper zone having a positive net mass balance over the year from a lower zone having a negative one [Paterson, 1981]) can not remain constant without the glacier thickening above that line, thinning below it, and a general steepening of slopes. The related negative balance in the outer regions causes the margin to retreat and nunataks (peaks of hills or high

ground that are surrounded by ice) to appear, enlarge, or coalesce. (Because there is no flow, steady retreat may occur when the overall balance of the ice cap is zero.).

Although a dynamic ice cap can remain in a steady state condition, this is not possible for stagnant ice caps.

Stagnant ice caps can only be maintained over the millenia by periods of positive balance over the whole ice cap so that the margins may readvance and the surface elevations over the lower parts may increase. This is supported by Alt's (1975) conclusion.

Mass Balance Observations

Accumulation and mass balance observations have been conducted on the Meighen Ice Cap almost every year since the initial stake network was installed in 1959. This ice cap, therefore, shares with the White Glacier on Axel Heiberg Island the distinction of having the longest Canadian mass balance record [Paterson, 1981].

Single mass balance observations of the Meighen Ice Cap are normally made in April or May, allowing measurement of a winter balance and the annual balance ending the summer before. It should be measured just before melt begins, although this is frequently impractical. Observations are made at 35 vertical stakes frozen into holes over a network covering the entire ice cap. Measurements are normally made

with a standard carpentry tape measure stretched from the top of the stake to the snow, firn, and ice surfaces. Additional snow and firn depth measurements are made at four adjacent pits. Snow and firn densities are measured from samples obtained with a tube thrust vertically into the snow to the previous summer's melt surface. Occasionally, a granular or otherwise fragile layer, which would spill out of the sample tube, may have to be cut into a measured block. With either method, the sample is then sealed and subsequently weighed. It has been common practice to calculate winter balances with just a few density observations because, while the thickness variation is measured at every stake, measurements over several years have shown that densities vary very little over the ice cap. These observations provide the winter balance data.

The difference between the ice level on the pole and that of the preceding year's observation is multiplied by an ice density based on core observations (normally 870 Kg m^{-3}). This produces the net mass balance Kg m^{-2} for the balance year that ended with the end of the previous summer. The difference between that net balance and the corresponding winter balance, (the one measured twelve months previously) provides the balance for the summer of the previous calendar year. Mass balance observation is discussed particularly by Alt [1975], Arnold [1965], Koerner [1985] and Paterson [1969].

A weakness of the single-visit measuring system is that there is no way of measuring any winter ablation or summer accumulation, nor is it possible to ensure that the visits coincide with the thickness maxima. If more accumulation comes after the measurements are made, then neither it nor the ablation that removes it will be accounted for accurately. In three balance years, (1963/64, 1968/69, and 1974/75) this happened to such a degree that the summer balances value calculated from the winter and annual data were positive for many zones.

The observation date is not always the same, and the actual maximum thickness date is never predictable. If there is a significant length of time between observation and the maximum thickness date, additional variations may be introduced. These can be partly accounted for by setting an arbitrary date for the winter-summer transition and artificially adjusting the measured accumulation value according to the number of days that the measured balance year varies from the standard one. Accumulation added to a winter balance value, for instance, is subtracted from the summer balance data. Even with this accounting system, (which was not applied to the data used in this thesis) systematic weaknesses are inevitable unless constant monitoring is possible.

Stake Network

The original stake network was partly installed in 1959, and completed in 1960. It had 36 stakes, although one northerly stake (not included in the thesis data) had already fallen victim to margin retreat in August 1960 [Arnold 1965]. These stake locations are marked on the published 1:25,000 Meighen Ice Cap map as horizontal control points. Initially, neighboring stakes had to be intervisible. The relatively close proximity of the higher stakes is therefore an indication of the original convexity of the dome.

For estimates of the mass balance of the entire ice cap the balance data are multiplied by the representative areas. The latter are determined by the Thiessen procedure and contain all points closer to the enclosed stake than to any other [Arnold, 1965 and 1981]. The average stake density is about $.5 \text{ Km}^{-2}$. While we might expect to learn more about the glaciology of the ice cap from a larger number of stakes, the benefit would be small, because accuracy increases only with the square root of the stake density [Arnold, 1981]. While sophisticated data noise filters, (e.g., applying data for several local stakes to each point on the ice cap instead of just the nearest ones) were used by Arnold [1981] on the White Glacier, they are not feasible for Meighen because the stake density is an order of magnitude lower. While the original stake network was neither

even nor ideal (there was a ratio of about 18:1 between the largest and smallest representative zones), comparisons between the mean values of the accumulation data and the same data weighted according to the size of the representative zones show little difference. This suggests an even distribution of snowfall over the ice cap [Arnold, 1965,]. This gives a preliminary indication that the main determinant of mass balance spatial distribution is ablation.

The original network remained unchanged for a decade, but observations were not always made at every stake. In 1970 five new stakes were added to the ice cap to reduce the size of some of the larger representative zones and to provide more data for the intermediate elevation regions. (In fact, although stakes were added, the ratio between the largest and smallest zones grew to about 25:1.) In 1975, the three most northerly stakes were abandoned, because the stakes tended to melt out. Attempts to redrill them had, on one or two occasions, led to accidental measurement of the ice cap thickness (of the order of 1.5 m).

The stakes were originally given designations such as '3N2E' (for third line north, second stake east from the base camp) by Arnold [personal communication] and these continue to be used by field and laboratory workers for both the original and subsequently added stakes. However, this thesis adopts Paterson's [1969] numerical system (for the original stakes he designated #1-#35) and the numbers (#36-

#40) assigned to stakes which were added after his Meighen paper. Appendix 1 includes a table of the old and new designations.

Some of the first type of stake, which were magnesium alloy right-angle bars still exist at the intermediate elevations where the mass balance has close to zero. (It is not certain, however, that all are originals.) Stakes installed or replaced since the early 1960's have been of bamboo, wood, or of aluminum alloy tubing. Aluminum, which is now used exclusively, is the more durable material but it is not invulnerable to breakage by wind or rime build-up.

It has frequently happened that measurements are not made for each stake every year. For three of the years since observations began no visit was made to the ice cap at all. For other years only some of the stakes were measured. Reasons for missing data include the following:

- 1) Stakes not found; usually due to fog.
- 2) Stakes fell out because of highly negative net balances.
- 3) Stakes missing due to such positive mass balances that they are covered.
- 4) Logistical difficulties.
- 5) Stakes found to be misidentified and the data therefore uncertain. (In the 1985 field season, some stakes were discovered to have incorrect labels.)
- 6) Measurement of the wrong stakes in cases where re-

placements are confused with originals.

7) Broken stakes that prohibit tying in to previous years' data.

8) Missing or undecipherable records.

Because the net annual balance calculation requires observations from two successive years, missed measurements mean that the net balance for two balance years cannot be directly determined for the stake in question. It is possible, however, to determine the net balance for the double balance year that includes the missing observation date. No balance for the winter and summer balance seasons preceding the missing visit can be determined. Because some stakes may always be missed, and because the missing data from the past cannot be replaced, various methods of treating incomplete data have been developed. Ideally, a new representative area map ought to be drawn each time for the available data. Workers in the past have adopted the simpler practice of numerically allotting appropriate (but estimated) fractions of the missing representative areas to neighboring zones. Another practice is to ignore the omissions and simply to calculate average values from the remaining data. More complex statistical treatments, like that of Lliboutry [1974] have not been applied to the Meighen Ice Cap data. (For the maps in this thesis, where there are only net data

for a double year, the first year's value is shown as missing and the value is applied in the second year.)

Mass Balance Data

Tables of the winter, summer, and net mass balance data for the Meighen Ice Cap are shown in Appendix 2. Except for the data published by Arnold [1965] and Paterson [1969], these data were compiled from various notes and tables that have been accumulated by the Glacier Physics Section since data collection began. The data collection is characterized by inconsistencies in the methods of notation and calculation, a shortage of annotations and data for unknown stake designations. Making these data usable proved to be the most difficult part of the entire thesis research.

CHAPTER 3

INVESTIGATION TECHNIQUES

Two glacial monitoring techniques were adopted for investigation of the Meighen Ice Cap mass balance phenomena of the last 26 years. In 1985 a topographic profile was levelled across the ice cap by the writer and Luhnsgaard in order to be able to make a comparison with the 1960 map. In addition maps were compiled to illustrate winter, summer, and net mass balances for every stake zone for each of the 26 years of measurements. This chapter discusses the techniques used; the results are presented in Chapter 4.

Survey Investigation

The goal of the topographic survey was to help establish the degree and types of topographic change that occurred since the earlier survey. This was done by comparing a precise levelling survey completed in 1985 with the 1960 map which was derived from photogrammetric analysis of aerial photographs.

Levelling route

The levelling traverse was 7260 m in length (of which about 657 m was on the adjacent ice-free land). It involved a range of elevation of about 140 m. The elevation and distance along the traverse for 88 points on the ice surface were obtained. The greatest western slope was about 4%, while the eastern slope occasionally reached 6.5%. The surface was a patchwork of hard sastrugi, with a variable strength crust, intermixed with softer dry snow having little load bearing capacity. The traverse was conducted in late April, when the sastrugi on this part of the ice cap were oriented northeast-southwest and micro-relief rarely exceeded 15 cm.

The traverse was intended to run between horizontal control points located on ice-free ground on each side of the ice cap. These control points are marked by 45 gallon oil drums. This route was selected partly because it provided an easily reproducible profile that could be compared to existing mass balance observations and because it passed close to the camp site. Figure 3.1 shows the profile along the same traverse derived from the 1960 photogrammetry.

Field Work

The surveying equipment used consisted of a Wild Heerbrugg NA2 automatic level, a Wild T-2 theodolite, a 4 m long

FIG. 3.1 Survey Traverse Profile

millimetre-resolution stadia rod, and a Keuffel & Esser Microranger II with four AEG equilateral prisms mounted in a tripod-compatible holder. Survey markers were three-foot green bamboo-horticultural canes. Support equipment included a long-track snowmobile, Nansen sled, and two-way portable radios, all of which worked well.

As there is no point on the line from which both ends are visible, the bearings from each end were intended to be determined by theodolite sights to four additional horizontal control points, a pair of which were expected to be visible from each end. While the field party was on the ice cap, the weather remained unsuitable for surveying until well after all other tasks on the ice cap had been completed, (and after an initial three day period when all work was impossible.) When surveying began, the visibility was poor on the east side of the ice cap and fair but hazy to the west. Only one of the two additional control points was visible from the west end of the line, and despite having been draped with high visibility orange surveying flags, it was barely visible through the theodolite. Because conditions were worse on the east side, it was decided to begin setting out the line on the basis of the single available observation. A temporary marker was placed about half way up the western slope according to the pre-calculated theodolite bearing. Additional temporary poles (made from 4 m aluminum poles stuck by hand through the snowpack to the

ice) were then placed about 1 Km apart towards the summit and down the east slope. These were located by plunging the theodolite telescope after centering it visually on the line extended from a pair of previously established poles. When this stage was nearly completed it became clear that the line had missed the control point by about 100 m, equivalent to a net directional error over the 7.3 Km distance of about half a degree. The source of this error must lie in either or both of the original theodolite bearing, (which could have been off-level if the optical plumb were faulty), and the extension of the line across the ice cap by repeated aiming and plunging of the theodolite (which can introduce as much as 1' error each time). To facilitate resurveys, a 15 gallon drum was placed at the eastern end of the actual traverse, and another drum was placed about 100 m beyond the western control point. Precise information on the location of the survey is included in Appendix 3.

Ice elevations and distances relative to one end were desired for the maximum feasible number of survey points along the traverse. The points had to be as close to the line as possible, but expediency and personnel constraints made the optimal technique of locating with the assistance of a theodolite from the ends impractical. Instead, the points were located visually as the work progressed along the line. This allowed the levelling to proceed at very nearly the speed that could have been achieved after accu-

rate pre-placement of markers. Subsequent observation from the ends showed that the greatest lateral variation from the correct line was about 5 m. As the line is nearly perpendicular to the contour lines over the whole traverse, these deviations have a negligible local and zero cumulative effect on the elevation results.

For logistical reasons the survey was conducted in eastern and western halves, each progressing from the highest part towards its end. A common marker was kept in the middle so that the halves could be precisely joined. Canes were stuck through the snowpack with a rubber mallet as far as the ice to mark survey points. Because a representative sample of these canes was found to vary in length by less than 5 mm, they permitted reasonably accurate measurement of snow depth along the traverse. Those data are included in Appendix 4.

Elevation changes between pairs of canes were obtained by the stadia levelling technique. The tripod and level were set up beyond the advancing line of canes so that the instrument was on the line and above the level of the surface at the cane. It was not essential that the instrument be placed exactly on the line. The rod would be placed gently on the snow beside the bamboo and a backsight reading taken and recorded. Because a bubble device on the rod was unavailable the back-and-forth rod rocking technique (in which the level operator indicates when the lowest hori-

zontal reading is obtained) was used to help the rod person judge when the rod was vertical. Vertical readings were made to the nearest millimetre. The rod person would then move to a new location beyond the tripod, and would attempt to select the survey point on a stable sastrugi surface. There was probably an unconscious bias to locate the rod on high points, but it is thought that any variation from the mean local level would not exceed 0.1 m. Furthermore this would not affect the overall results as they are calculated from the ice level rather than the snow surface. It was important that the instrument height be maintained between foresights and backsights, and where hard sastrugi were unavailable, a new, firm surface was made by breaking through any crust and compacting the snow with a boot. Foresight readings would then be taken to the new cane. When a set of readings was complete, the tripod was moved forward and the procedure repeated.

The length of the survey steps was limited by the need to keep the vertical separation of adjacent survey points less than the height of the rod, which was 4 m. Surveying over steeper slopes required shorter intervals. It was often difficult to locate the level on stable surfaces that would allow the operator to step close enough to make observations. A technique of breaking the crust very locally by stepping heel-first, so as to avoid radiating cracks, was used. Where the level had to be located on unstable sur-

faces, any crust was thoroughly broken first. The levelling procedure requires sights in two directions, a minute or two apart. Frequently, small deviations of the bubble in the levelling device over this interval indicated some movement of the apparatus between observations. Errors introduced to the observations should be negligible because the apparatus incorporates a pendulum prism that makes it self-leveling within a reasonable tolerance. Thus, the observation plane is kept horizontal and observation deviations are strictly limited to the vertical displacement of the apparatus, which is extremely small unless more than one tripod foot is displaced.

Slope-distances were obtained with a microwave electronic distance measurer, consisting of a transmitter/receiver and associated electronics (the master unit), and a set of equilateral prisms in a tripod-mounted holder (the slave unit). The four available prisms permitted shots of up to about 1500 m under the conditions encountered. The master unit was powered by a truck battery and required a snowmobile and sled for transport. Master unit relocations were minimized by taking shots to as many survey points as possible from each site. This prevented almost all slave unit location errors from contributing any cumulative error to the survey. The assistant would set the slave unit over the remote point and await a radio or visual instruction to proceed. The range limitation and the convexity of the ice

cap forced occupation of about a dozen survey points by the master unit. Ambient environmental conditions fortuitously permitted an easily-remembered zero temperature-pressure instrument setting. The master/slave offset adjustment was arbitrarily set to zero and appropriate compensation was made at the data reduction stage. Because the survey missed the target control point, no satisfactory assessment of the ranging error could be made. The greatest possible source of error is probably in the locating of the slave and master units over the survey points.

The raw data were subsequently transferred onto a microcomputer spreadsheet. This permitted easy processing of fore and back sights, distance readings and snow depths. Actual heights and distance were calculated for all survey points. True horizontal distances were corrected for slope by using the levelling measurements to allow for different heights. The snow depth data were tied to the survey point locations to provide a profile of the previous summer's ice level. All calculation was done on one interactive spreadsheet file so that any correction of original data or formulae could be passed through all related calculations immediately. While the results are presented graphically in Chapter 4, the actual survey data derived are presented in Appendix 5.

Cartographic Investigation

Choropleth (or fixed zone) maps of the winter, summer and net mass balance of the stake representative zones were produced from PCSP data and the margin locations derived from aerial photography. These maps utilize the Thiessen representative zone method discussed earlier. While they were intended primarily for examination of distribution of mass balance for different parts of the ice cap, averaging the data (with weighting according to the representative zone areas) also permits correlation of the overall climate. Where some stakes provide data that differ from the overall average it is important to determine accurately the size of their representative zones. This is difficult where marginal adjustment is extensive and required examination of available aerial photographs.

Remote Sensing imagery of the Margin

Imagery of the high Arctic ought to be obtained between late July and mid August when the landscape is most free of snow. The first aerial photograph of Meighen is thought to be one that was taken 15 August, 1946. Arnold [1965] compared it to 1950 trimetrogon coverage and concluded that "...some recession seems to have taken place in valleys leading from its south-west edge." Arnold [1965] also compared the 1950 coverage with that taken on 5 August, 1959

and 15 August, 1960, which were the photo sets used to produce the 1:50,000 and 1:25,000 topographic maps of Meighen Island. His observations of change over this period were that "The ice cap was wasting slowly..." [p. 400] and that nunataks continued to emerge and enlarge.

Because resources for quantitative photogrammetry were unavailable for this research, the imagery was visually examined by the writer and comparisons made between all available overlaps, photo sets, and the two maps. The principal objective was to observe margin advance and retreat. Where marginal change was observed the lines were plotted on a 1:25,000 map. These were then digitized for production of maps for the various dates.

This work was not intended to replace the 1:25,000 and 1:50,000 maps (which are examples of cartographic excellence); rather it establishes trends from all the available coverage so that the nature of marginal change could be determined. The available aerial imagery dates from 1959 to 1975.

Details of the imagery used are provided in Appendix 6. Examination of LANDSAT imagery proved to be of very limited value to this investigation. Its resolution is only sufficient to show marginal changes of the order of hundreds of metres. While LANDSATs I and II were in operation, orbits crossed Meighen every nine days. Frequent cloud or fog in the summer permitted very few unobstructed images.

However, a suitable day in each of 1977 and 1982 provided somewhat helpful extension of the aerial photo coverage, although prints of a large enough scale for proper interpretation were not obtained. The data from high latitudes are no longer routinely collected and a special request to obtain the needed information would have had to be accompanied by US\$300 in advance, which was prohibitive. The operation would also have required pre-identification of a cloud-free morning which would be impossible because Meighen is normally foggy in summer.

Future coverage will probably have to be obtained by aircraft, although proposed launches of the space shuttle into polar orbit from California might permit manual high quality imagery from space.

Mapping

The summer, winter, and net mass balance data used are in units of g cm^{-2} water equivalent (w.e.). It should be remembered that the summer balance data are algebraically derived from the winter and net balance data which were measured in the field, and that there are certain flaws in the data. The data are classified according to an equalized category system. A relatively large number of classifications is used to illustrate the subtle data variations,

especially at near-zero conditions to avoid spurious effects often associated with skewed category systems.

Three representative zone configurations were used to reflect the addition and abandonment of stakes over time. The margins are altered with each configuration to reflect the adjustments observed from the aerial photos. The maps were automatically plotted after the basic geographical and thematic data were obtained and processed. They are presented and discussed in Chapter 4.

CHAPTER 4

INTERPRETATION OF RESULTS

This chapter presents the results of the survey and cartographic investigations. Conclusions derived from each investigation are made here. Conclusions about changes to the ice cap as a whole are made in Chapter 5.

Survey Investigation

The topographic profile was surveyed in only one direction and was not closed. Nevertheless, the vertical difference between the two ends (allowing for a short traverse from the eastern end to the control point) could still be compared to the geodetic data. This produced a vertical discrepancy of 1.05 m. Errors in the original survey, or due to solifluction around the control point markers or the adjacent terrain in general are possible causes of this discrepancy. Arnold [1965] warned that tests for solifluction ought to be made before resurveying, but this was not considered necessary before the 1985 levelling. Few points were surveyed on the slope between the ends of the line and the ice cap margin, and even fewer are available from the map, so examination of that data is of no use in

reconciling the profiles. Because the source of error could not be pinpointed, the vertical discrepancy was numerically distributed throughout the survey data to provide the best possible profile. Figure 4.1 illustrates the 1960 and 1985 profiles with this correction applied to the latter.

The margins could not be located precisely during surveying because of snow cover, although Lundgaard, [personal communication] who has extensive experience on Meighen, confirmed that they lie at the lowest points of the profile. The ice near the margin is clearly very thin, and is probably bounded by meltwater streams in the summer. In addition, the first survey point up the slope towards each end was the first to strike gravel below the snow. Comparison of this information and the map suggests that the western margin has retreated about 70 m and the eastern one 130 m over the 26 year study period.

The profiles reveal that the ice elevation has decreased for those parts below 185 m above sea level on the west and 192 m on the east. A small bump at the summit of the 1985 survey is caused by drifting around the buildings erected in the 1960's. This validates the ~~decision to abandon~~ a nearby stake in 1962. Figure 4.2 illustrates the relationship between the surveys by comparing the interpolated heights at every 200 m across the traverse. Except for the extreme differences at the summit, the change in height varies from a gain of about 7 m (or about 0.28 m per year) near

FIG. 4.1 Profile Elevations (m)
[solid: 1985; dashed: 1960]

Fig. 4.2 1960 & 1985 Profile Comparison

the summit to a maximum loss of about 8 m (or about 0.32 m per year) near both margins.

Cartographic Investigation

The maps derived from the PCSP winter, summer, and net mass balance data for 1959-1960 to 1984-1985 are shown in Figures 4.3.1 to 4.3.26. Figure 4.4 shows the average data for the entire period. It is readily apparent that winter balance tends to be fairly constant both across the ice cap and through time. The only significant variation from the norm was the 1963-1964 winter balance (Figure 4.3.4), which was generally slightly more positive than usual. Summer balance varies more, both spatially and temporally, and it is chiefly because of this that the net balance varies. Two seasons, 1959-1960 and 1961-1962 (Figures 4.3.1 and 4.3.3) were particularly negative. Note also that summer balances are occasionally positive over most of the ice cap, especially 1963-1964, 1974-1975, and 1983-1984 (Figures 4.3.5, 4.3.16, and 4.3.25). In most years there are at least some isolated areas with indicated positive summer balances due to accumulation after measurement. It is likely that, for several years, the missing data for the northernmost zones correspond to particularly negative balances that caused the stakes to melt out. In general it can be said that the sum-

Fig. 4.3.2 1960-1961 Mass Balance

Fig. 4.3.11 1969-1970 Mass Balance

cm w.e.

Winter Balance

Summer Balance

Net Balance

Fig. 4.3.14 1972-1973 Mass Balance

Fig. 4.3.15 1973-1974 Mass Balance

Fig. 4.3.15

Winter Balance

Summer Balance

Net Balance

Fig. 4.3.18 1976-1977 Mass Balance

cm w.e.

Winter Balance Summer Balance Net Balance

Fig. 4.3.24 1982-1983 Mass Balance

cm w.e.

Winter Balance

Summer Balance

Net Balance

mer and net balances are more positive in the central, higher zones.

The combined significance of the results of the ice cap investigations are compared and discussed in Chapter 5.

CHAPTER 5

CONCLUSIONS

The aim of the thesis has been to identify the nature of topographic change to the Meighen Ice Cap between 1961 and 1985 and how this change may reflect climatic change. The results are supported by mass balance measurements carried out during the same period. The two data sets have not been directly compared because uncertainties and discontinuities in the record make it impossible to determine quantitatively the long-term topographic change from the mass balance data. However, it is apparent that the ice cap as a whole has undergone a period of net balance loss, but the highest part remains an exception. The ice cap has been retreating steadily over the past quarter century. This is because ablation, which has controlled net balance, is greatest at lower elevations.

Paterson [1969] and Alt [1975] suggested that the Ice Cap exists because the ablation is lower than for neighboring glaciers, and suggested that this is due to the high incidence of summer fog. Paterson also showed that the ice cap could not continue to survive the negative mass balance regime observed in the early 1960's for more than a few hun-

dred years. This conclusion is supported and reinforced by the current 26-year record, although Paterson's record did not reveal the fact that the highest parts have a significantly positive balance. If current steepening trends continue, and if the feedback mechanisms discussed earlier do not moderate this trend, the ice cap may begin to flow before it melts away. Because it has probably never flowed in the past this would be a new phase in its existence.

Methodological Critique

Survey Investigation

It would have been desirable for the 1985 survey to have been tied more accurately to the control points. Considering the way in which the results were to be used, however, a more controlled traverse would have had no inherently greater value over the one that was used. Greater confidence could have been placed in the profile obtained if the vertical discrepancy between the survey and the geodetic data were smaller. This could probably have been achieved if it had been possible to carry out the levelling in both directions. Perhaps the precise location of the original survey monuments, in relation to the oil drums, could have been determined from the surveyors' notes. The error was, however, of about an order of magnitude less than the elev-

ation change observed over most of the ice cap, and so it is considered not to affect the conclusions drawn from the topographic change which has clearly occurred.

In the future, less time should be spent verifying the ranging. The stadia method of distance measuring with the level apparatus is sufficiently accurate for the requirements of this type of glaciological work and the benefits of reduced logistic difficulties and increased speed outweigh the lower level of accuracy.

Cartographic Investigation

One of the more difficult parts of the study, the Thiessen zone allocation, was conducted manually instead of automatically. Given freer use of a Computer Automated Cartography (CAC) facility such as that used for this thesis it would be practical to develop an algorithm to generate a Thiessen base file from a given set of outline segments and stake locations. Such a program would simplify generation of the different base maps required each time stakes were added or abandoned. An important additional benefit would be the capability to produce base files for each year to allocate parts of zones for stakes lacking data to the neighboring zones. Because of the ease of measuring zone areas with the CAC facility, complete mass balance data could then be accurately produced with minimized losses due

to missing data. This would be useful wherever the net and winter balance must differ because of changing configurations (due to different measurement seasons), where the two observations required for net balance alone were related to different configurations, or where individual data are unavailable. The system could compare zones of the same designation and different years and season observed and calculate data based on weightings of the relevant areas. This would then permit further adaptations, including statistical analyses of the importance and spatial representativeness of individual stakes.

A weakness of mass balance mapping in unstable marginal areas has been pointed out by Koerner (personal communication). If a margin advances or retreats, the calculated mass balance will be in error according to the ratio of the assumed and true representative areas. As much data as possible on margin retreat ought to be obtained to allow workers to minimize this error. CAC techniques could be adopted to provide estimates of changing margin locations by interpolating within and extrapolating from known years' locations. These estimates could also be influenced by fixed surveys along traverses that span the possible margin locations, the mass balance at stakes close to the margin, and a rough three dimensional model of the bedrock topography.

Recommended Future Work

The question of whether or not there is any ice flow on the Meighen Ice Cap, and if so to what extent it occurs, has not been satisfactorily resolved. However, any flow must clearly be small and so renewed strain observations are probably not needed.

There has been unnecessary confusion over stake identification in the past. Different systems for stake labelling have been tried and yet stakes with contradictory labels have been discovered and data with extraordinary stake designations recorded. This has occurred because of confusion over location in the frequent foggy conditions and by field workers other than those who normally measure the ice cap. However, the consequences of incorrect labelling and the resulting rejection of dubious data, or the inadvertent inclusion of incorrect data from subsequent work, is to be avoided. This problem must be addressed and resolved. Various types of tags have been used, but the best identification system seems to be to scribe or pencil the stake code on the stake itself and to remove or erase all other markings. It is also essential that up-to-date maps of the network be maintained as the experience of the field worker currently employed cannot be relied on forever.

If it had been feasible for this thesis, a quantitative analysis of the topographic change trends and of the stress

threshold for strain would have been undertaken. If much greater resources had been available, new remote sensing might have been obtained and quantitatively interpreted.

The survey could usefully be repeated as often as every five years, so as to monitor change with increased time resolution. Now that the traverse has been established and certain techniques refined, it needs only about two days to be resurveyed. This has been incorporated into the long range field plans of the Glacier Physics Section.

The improved techniques proposed in the discussion of the cartographic investigation ought to be considered and either a search of established similar techniques or development of the ideas presented ought to be undertaken. Greater benefits, for both climatological and glaciological purposes, can be derived from the data set if the true representative areas near margins or relocated stakes are known and measured on an annual basis. The mass balance database system currently being applied to the Melville Ice Cap [Koerner, personal communication] will be immensely useful for Meighen. These projects could be applied to the existing data for Meighen as easily as to new data, although greater future benefits for mass balance will be derived only if up to date margin locations are found and marked. New remote sensing or scattered small surveys at strategic locations about the ice cap may be the simplest way of

acquiring this data. This should have a very high priority in future planning.

Koerner [1985 and personal communication] is developing ways of treating missing mass balance data for application to the Melville Ice Cap, and has worked on a method of deriving purely climatological data from the Meighen Ice Cap that incorporates only a small stake farm or a single traverse of stakes. Such a method would probably eliminate the need for annual visits to the entire ice cap. Paterson [1969] discussed climatological monitoring of Meighen by simple observation of mass balance at a fixed elevation or of the elevation of the equilibrium line, but the feasibility of such an approach still needs testing.

Priorities

It is not clear to what extent we should adopt the original conclusion that the effect of flow is negligible. If it is thought that continued glaciological research is needed, a renewed strain net programme ought to be considered. However, it is probably more important now that we increase our climatological understanding of the Meighen Ice Cap.

The importance of continued ice cap mass balance observations cannot be over-emphasized, especially as we become more concerned about our environment and the possibilities

and implications of climate change. This is particularly true for the Meighen Ice Cap, so that new records may be added to and compared with the most established one. However, there is a great need for an improved method of data storage and processing for the Meighen Ice Cap and other mass balance networks maintained by the Glacier Physics Section. A programme of this nature is now being developed by Koerner [personal communication]. Ideally, such a system ought to incorporate a computer data base that records all original field data for subsequent processing as and when required. The system should be software rather than language based to facilitate transfer to other systems and for ease of initiation, maintenance and use.

While there is general agreement that climatological studies are important, work such as this seems to be coming under increased risk of funding cutbacks, even at a time when investment towards greater understanding would probably pay off handsomely in the future. Therefore, it is prudent to develop newer methods of climatological data collection that would not be so affected by cutbacks, even if this involves a sacrifice of some of the direct glaciological benefits being obtained by current methods.

The method that seems most ideal is repetition of the survey conducted for this thesis. Although probably not faster than the current annual mass balance observations, the survey could be done less frequently and less regularly

without losing much accuracy. Furthermore, only the markers for the ends of the survey need to be preserved, and as these are well off the ice, they would be available for a long period.

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2 OF 2

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STANDARD REFERENCE MATERIAL 1010a
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APPENDIX 1

MASS BALANCE STAKE DESIGNATIONS

The numeric stake designations are those created by Paterson [1969] except #36 to #40 which are designations first used in this thesis for the stakes added in 1970. The alphanumeric designations are those used by Arnold and other workers.

Alphanumeric	Numeric	Alphanumeric	Numeric
5N2W2N	1	3N5W	11
5N2W1N	2	3N4W	12
6N	3	3N3W	13
5N3W	4	3N2W	14
5N2W	5	3N1W	15
5N1W	6	3N	16
5N1E	7	3N1E	17
5N2E	8	3N2E	18
4N	9	3N3E	19
3N5W	10	3N4E	20

continued...

...continued

Alphanumeric	Numeric	Alphanumeric	Numeric
1N	21	5E	31
4W	22	1S	32
3W	23	2S	33
2W	24	3S	34
1W	25	4S	35
0	26	2N1E	36
1E	27	2N1W	37
2E	28	2N2W	38
3E	29	1S1E	39
4E	30	1S1W	40

APPENDIX 2

WINTER BALANCE DATA

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
	/60	/61	/62	/63	/64	/65	/66	/67	/68	/69	/70	/71	/72	/73	/74	/75	/76	/77	/78	/79	/80	/81	/82	/83	/84	/85
01	16	20	12	15			19	16	14	4	16	22		25	34		6	13								
02	14		22	24		19	13		16	12	12	14		19	14		8	16		8						
03	12	21	16	22		24	19		16	22	20	17		23	27	18	12	22			20					
04	14	26	12	30		22	20	10	17	9	10			26	7	21	10	15					11	16	16	
05	11	20	18	20		27	14	12	15	12	9	14		22	10	18	8	16		5	16			9	19	
06	18	22	25	27		21	15	8	20	14	18	8		18	17	22	6	12		4	10					
07	8	12	13	26		22	16	9	22	19	13	20		21	14	16	11	13			20		12	20	13	
08	5	15	15	32		26		7	16	17	10	25		23	16	18	21	16					7	16	14	
09	15	17	13	31		21	18	11	16	14	14	13		14	7	22	10	16			16			15	14	
10	12	22	16			21	15		16	13	11	22		5	7	16	6	15					9			
11	14	17	12			14	11		20	12	8	18		15	11	19	6	14		5	16		12	9	13	
12	14	13	12	11	30	16	16	6	15	16	8	20		11	14	20	7	15		3	16		6	16	16	
13	16	18	9	12		20	14		17	17	8	18		18	11	19	7	18					7	12	14	
14	14	20	19	10	32	14	15	16	17	15	7	16		16	12	16	8	13		5	22		5	16		
15	15	21	14	24	39	14	13	5	11	14	8	17		17	11	22	19	11		5	13		10	15	12	
16	16	19	16	22	35	17	13	7	14	16	7	16		14	8	15	13	12		5	16		12	12	9	
17	13	18	16	20	25	17	17	8	12	17	6	20		14	9	16	9	12		4	17		6	13	11	
18	5	14	16	17	25	16	11	6	17	13	9	15		16	9	16	8	10		5	19		2	11	17	
19	5	14	15	20	17	15	10	5	18	14		13		14	4	12	11	7					7	16	12	
20	17	18	11	20	31	15	15	7	1	22	8	18		18	12	16	9	10			17		5	14	11	

continued...

...continued

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
	/60	/61	/62	/63	/64	/65	/66	/67	/68	/69	/70	/71	/72	/73	/74	/75	/76	/77	/78	/79	/80	/81	/82	/83	/84	/85
21	20	17	13	19	35	14	18	12	23	14	10	21			11	9	17	8	4					7	16	14
22	13	24	8	16	29	14	17	15	21	12	9	17			18	13	14	7	15		21			16	12	16
23	13	19	13	21	38	11	17	5	21	15	10	16			13	11	15	10	17					4	16	16
24	12	18	20	21	26	14	15	7	17	15	6	13			16	3	14	9	11					6	14	14
25	14	23	16	20		14	16	8	18	17	9	16			11	10	12	7	7					8	16	18
26																								5	15	15
27	12	19	16	19	28	15	16	7	27	16	9				20	6	14	9	4					4	14	16
28	21	18	19	22	33	16	13	9	24	18	9	15			17	7	18	8	12					4	17	13
29	13	20	15	21	34	15	15	8	24	17	9	15			19	6	15	6	8					4	14	16
30	14	18	31	26	30	16	13	7	20	18	9	16			19	11	14	5	12					4	17	13
31	15	15	13	24	27	16	19	4	16	21	9	14			16	8	17	7	12		14			9	17	15
32	7	11	16	24	24	9	14	8	16	13	8				8	4	8	12	10		16			4	10	
33																										
34	7	15	12	17	29	6	14	6	9	14	8	13			7	4	2	10	5	5	14			3	18	11
35	6	11	15	13	31	4	11	6	13	9	7	11			8	2	7	8	5					4	11	8
36															14	15	20	9	15		22			13	12	14
37															14	9	15	10	9		18			3	16	17
38															18	14	15	10	14		18			2	20	10
39															8	3	8	9	11	3	18			6	12	
40															4	4	6	9	11	4	10					

SUMMER BALANCE DATA

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
01	-125	-73	-147				-19	-13	-22		-30	-82			-48												
02	-98		-138				-31		-34	4	-18	-72			-24				-35								
03	-107	-50	-138				-18	-34	-8	-20	-18				-27	-20	-9										
04	-105	-46	-134				-22	-31	-19	-8	-20				-27	-31	-13								-67	4	
05	-106	-39	-133				-14	-29	-2	-17	-12				-22	-15	-10							-46	-52		
06	-87	-33	-132				-19	-22	-49	-32	-17	-18	-76		-33	-17			-30								
07	-110	-53	-135				-12	-10	-39	-7	-10	-13	-68		-21	4	-12								-43	-11	
08	-127	-52	-137				-18			-14	-19	-15	-74		-21	-38	-3								-38	-8	10
09	-90	-40					-15								-14		-9	-2									
10	-102	-39	-129																								
11	-97	-36	-125				-15			-12	-19	-72			-25	-12	-7	-30	-9						-34	2	7
12	-84	-29	-119				10	-15	-24	-9	-10	-14	-66		-18	-6	-6	-22	-21						-46	-38	5
13	-76	-27	-94				-6			-14	-7	-52			-26	-2	1	-30								-22	8
14	-82	-18	-91				9	-3	-16	-30	3	-4	-50		-12	3	-4	-24	-18						-33	-44	
15	-75	-16	-110				6	-6	-28	-7	9	-4	-50		-16	12	-6	-24	-21						-18	-30	12
16	-79	-12	-103				2	-4	-21	-55	5	0	-50		-13	9	-1	-19							-28	-24	13
17	-83	-31	-111				14	-14	-18	-34	-5	0	-46		-16	8	3	-29	-16						-11	-26	10
18	-92	-29	-116				15	-14	-16	-19	-12	-4	-16		-24	-6	-6	-32	-22						-18	-44	6
19	-106	-31	-119				16	-18	-27	-26	-20	-15	-52		-21	-12	0	-46							-57	-1	1
20	-69	-14	-88				11	2	-7	5	26	-14	-46		-8	8	-4	-10							-21	-11	18

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	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
21	-64	-10	-90		5	16	-23	15	-16	29	-7	-43			-12	14	-4	-19									
22	-85	-29	-128	-57	1	-12	-40	-15	-13	-37	-8	-75			-43	-16	-4	-42						-11	12		
23	-80	-33	-115	-77	7	-6	-24	-3	-9	-20	-6	-104			-16	9	-13							-23	18		
24	-79	-24	-98	-30	14	-14	-9	6	-9	-5	8	-50			-15	1	-2	-30	-15					-19			
25	-19	-93			-12	-10	3	-6	16	-11	-39			-7	12	0	-24	10						-15	25		
26																											
27	-66	-16	-93	-10	11	-2	-11	8	-14	3	0				-5	0	-18	-22						-19	14		
28	-66	-16	-79	-27	12	-2	-16	10	-17	16	-8	-44			-7	21	1	-22	-9					-16	16		
29	-87	-18	-99	17	11	0	-17	13	-20	11	-3	-43			-11	17	-7	-21	-13					-26	12		
30	-91	-25	-100	-14	16	-10	-25	11	-12	-5	-2	-49			-8	11	-2	-32	-6					-39	22		
31	-89	-34	-130	-16	16	-23	-32	2	-5	-21	-15	-61	9			6	-8							-44	6		
32	-76	-6	-93	-37	16	10	-21	10		-9					-8	15	-2	-37						-11	18		
33																											
34	-96	-14	-93	-31	11	-5	-16	12		5	1	-56			-18	-31	-3	-31						-14	5		
35	-97	-27	-137	-52	6	1	-24	-2	-23	-1	-17	-89			-27	-3	-28	-56	-43					-36	16		
36															-9	-6	-4	-25							18		
37															-15	10	-2							-18	15		
38															-12	3	-4								13		
39															-16	12	-3	-35						-27	25		
40																1	-11		-42						8		

NET BALANCE DATA

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
01	-109	-53	-135						-8		-14	-60		-51	-24												
02	-84	-14	-116			0			15	-6					-5												
03	-95	-29	-122		31	-7			-18	2	3	-55			-4	7	9										
04	-91	-20	-122		28	4	-14	-9	9		-10				-2	-23	9	-69									
05	-95	-19	-115		27	5	-17	2		3	-7				0	-4	8										
06	-69	-11	-107		25	7	-14	6	3	2					-15	0											
07	-102	-41	-122			3	-6	-40	-10	3	-5	-56			-17	0	18	4									
08	-122	-37	-122							-3	-10	-45			2	-22											
09	-75	-23			35	9	8	-28	9	4	1	-55			0		18										
10	-90	-17	-113		21	3			2	6	-4	-53				-3	14										
11	-83	-19	-113		30	-1				0	-11	-54			10	-1	12	-23									
12	-70	-16	-107	-34	40	1	-8	-34	6	7	-6	-46			-7	-6	14	-15	-6								
13	-60	-9	-85		27	14				3	1	-34			-20	-9	9	20	-23								
14	-88	-2	-72	-25	41	11	-1	-13	8	18	3	-34			13	4	14	12	-16	-5							
15	-80	5	-96	-51	45	8	7	-23	4	23	4	-33			8	1	23	16	-5	-10							
16	-63	7	-87	-2	37	13	-8	-48	9	16	1	-34			24	-1	17	14	-8								
17	-70	-13	-95	-8	39	4	-1	-26	7	17		-26			14	-1	18	18	-20	-4							
18	-87	-15	-100	-31	40	2	-5	-13	5	9	-3	-1			-34	-8	3	10	-24	-13							
19	-101	-17	-104	-33	33	-4	-17	-21	-2	-1	3	-39			1	-7	-8		-34								
20	-52	4	-77	-5	42	17	8	12	27	46	-6	-28			31	10	20	11	-2								

continued....

....continued

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
	/60	/61	/62	/63	/64	/65	/66	/67	/68	/69	/70	/71	/72	/73	/74	/75	/76	/77	/78	/79	/80	/81	/82	/83	/84	/85	
21	-44	7	-77		40	30	-5	27	7	42	3	-22		30	-1	23	13	-10									
22	-72	-5	-120	-41	30	2	-23	0	8	-25	1	-58		-33	-25	-3	10	-36					-13	-5	28		
23	-67	-14	-102	-58	45	5	-6	2	12	-5	4	-88		19	-3	20	3						23	-7	31		
24	-67	-6	-78	-9	40	0	6	13	8	10	15	-37		19	2	4	11	-21	-4	11	-9	30	-15				
25		4	-77		57	2	6	11	12	33	-2	-23		16	4	22	11	-16	17			27	-8	39			
26																											
27	-54	3	-77	9	38	13	6	15	13	19	9	-28		31	-15		15	-9	-17	24	-7	31	-11	30			
28	-45	2	-60	-5	45	14	-3	19	7	34	1	-29		28	10	28	19	-15	3	13	-15	32	-11	29			
29	-74	2	-84	38	45	14	-3	21	4	28	6	-28		24	9	23	9	15	-5	13	-18	37	-22	26			
30	-77	-7	-69	12	46	6	-11	18	8	13	7	-33		23	10	22	12	-27	6	-23	-9	32	-35	39			
31	-74	-19	-117	8	43	-7	-14	6	11	0	-6	-47		16		14	9				-37	13	-35	23			
32	-69	5	-77	-13	40	19	-7	18		4					0	19	6	-26			-8	20	-6	28			
33																											
34	-89	1	-81	-14	40	1	-2	18		20	9	-43		21	-11	-28	-1	-21		-4			-12	34			
35	-91	-16	-122	-39	37	5	-13	4	-10	8	-10	-78			-19	-2	-21	-49	-38			15	-32	23			
36														22	4	20	16	-16		4				34			
37														12	-1	19	12										
38															6	17	11										
39														16	-8	15	5	-26		-4	-9	1	-25	27			
40														17		5	-5		-31								

APPENDIX 3

SURVEY ROUTE

The survey was intended to connect the east and west horizontal control points located at UTM 8877333.04 / 499831.64 and 8876615.47 / 492610.50 (Geodetic survey codes 60914 and 60903) respectively and marked by 45 gallon oil drums.

For reasons explained in the text, the actual survey connected the western control point with a new point bearing $44^{\circ}22'44.1''$ and 176.33 m from the eastern control point. The UTM of this new point is 8377456.37 / 499957.67. A red 15 gallon oil drum has been placed there.

Additional location guides are a second 15 gallon drum placed on an extension of the survey line about 100 m further west than the western control point, and an aluminum pole (currently representing stake #24) drilled into the ice cap on the line and in the region that appears to be maintaining a fairly neutral balance.

APPENDIX 4

SURVEY DATA

The following table shows the elevation, relative to the west control point, found for the survey points on the ice cap from west to east.

range (m)	height (m)	range (m)	height (m)	range (m)	height (m)
0	0	2913	74	5568	106
49	-2	2998	77	5624	102
107	-6	3077	80	5674	99
196	-8	3155	83	5725	96
283	-9	3238	85	5771	92
403	-9	3302	88	5824	89
463	-8	3374	91	5878	85
556	-5	3438	94	5922	81
673	-2	3513	97	5967	78
783	1	3588	100	6019	75
870	4	3659	103	6069	71
966	6	3720	106	6113	68
1077	9	3834	109	6161	64
1206	13	3875	111	6212	61
1310	16	3922	113	6259	57
1413	20	3977	115	6311	54
1511	23	4038	118	6365	50
1595	26	4090	120	6420	47
1673	28	4152	123	6512	44
1755	31	4217	125	6565	38
1841	34	4282	128	6617	34
1947	38	4395	131	6677	31
2038	41	4564	134	6728	28
2126	44	4676	138	6789	25
2204	47	4772	136	6849	22
2268	49	4889	135	6907	19
2338	52	5011	133	6963	16
2429	55	5103	130	7025	13
2492	57	5175	127	7087	10
2555	60	5252	124	7144	8
2630	63	5318	121	7212	10
2703	65	5385	117	7322	10
2785	69	5440	114	7398	15
2848	71	5509	110		

The following table shows the vertical variation between the 1960 and 1985 elevations for points at every 200 m along the traverse. δh represents the change over the intervening period.

range	δh	range	δh	range	δh
(m)	(m)	(m)	(m)	(m)	(m)
200	-2.7	2600	.9	5000	7.0
400	-7.7	2800	2.1	5200	6.2
600	-7.5	3000	3.4	5400	5.6
800	-6.7	3200	4.0	5600	4.4
1000	-5.9	3400	4.9	5800	4.3
1200	-5.6	3600	5.4	6000	2.1
1400	-4.8	3800	4.4	6200	.3
1600	-3.9	4000	4.5	6400	-1.1
1800	-3.1	4200	5.3	6600	-2.8
2000	-2.1	4400	5.5	6800	-4.1
2200	-1.5	4600	9.4	7000	-5.8
2400	-.3	4800	9.6	7200	-8.2

APPENDIX 5

SNOW DEPTHS ALONG SURVEY TRAVERSE

range (m)	snow depth (cm)	range (m)	snow depth (cm)	range (m)	snow depth (cm)
0	3	2913	63	5568	58
49	1	2998	62	5624	61
107	34	3077	55	5674	63
196	31	3155	52	5725	47
283	35	3238	52	5771	60
403	47	3302	46	5824	43
463	79	3374	51	5878	57
556	73	3438	58	5922	59
673	75	3513	69	5967	44
783	64	3588	49	6019	34
870	58	3659	66	6069	67
966	66	3720	83	6113	58
1077	82	3834	64	6161	47
1206	56	3875	59	6212	44
1310	62	3922	86	6259	44
1413	57	3977	62	6311	44
1511	55	4038	57	6365	52
1595	56	4090	66	6420	87
1673	65	4152	57	6512	51
1755	75	4217	45	6565	40
1841	59	4282	50	6617	41
1947	55	4395	68	6677	68
2038	70	4564	77	6728	47
2126	43	4676	53	6789	60
2204	52	4772	75	6849	47
2268	58	4889	63	6907	36
2338	42	5011	44	6963	44
2429	54	5103	64	7025	82
2492	66	5175	61	7087	77
2555	50	5252	62	7144	73
2630	58	5318	56	7212	38
2703	59	5385	52	7322	28
2785	58	5440	65	7398	21
2848	47	5509	85		

APPENDIX 6

AERIAL PHOTO COVERAGE

Aerial photography of the Meighen Ice Cap has been taken sporadically since the 1940's. The photo sets that are for the study period were taken in 1959, 1960, 1972, 1973 and 1975.

The 1959 coverage consists of two north-south lines that provide good coverage of the ice cap, although at a small scale. This coverage was used to produce the 1:50,000 topographic maps of the whole island.

The 1960 imagery provided several lines of high quality. This coverage was used to produce the 1:25,000 map of the ice cap, and so, as with the 1959 coverage, there was no need to reinterpret either set.

The 1972 coverage is almost useless for the purposes of this investigation, because there is too much snow on the ice and rock. (This might suggest that there was unusually high summer snow accumulation, but no summer balance data for that season are available for confirmation.)

The 1973 coverage is by far the most useful for our purposes. Although at a small scale, three lines cover the ice cap so that there is good overlap and interpretation is easy for all but the southwest corner.

Finally, the 1975 coverage is of the largest scale but is little use. Only a small part of the margin is covered and it is complicated by widespread snow patches.

END

14.08.87

FIN