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The Residual Snow Cover in the Canadian Arctic in July: A Means to Evaluate the Regional Maximum Snow Depth in Winter

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ABSTRACT. This paper examines the residual snow cover in the Canadian Arctic during the month of July in the period 1948-83 inclusive using air photographs. The study area includes the Ungava Peninsula, part of the District of Keewatin and the Arctic Archipelago, except for the mountainous regions to the west of the Labrador Sea, and Baffin Bay, where numerous snow fields and glaciers are present. In spite of the spatial discontinuity of the air photographs taken during the second half of July, the authors were able to study 555 519 km^2, or 46%, of the forementioned territory. Within this territory, 1899 km^2 are covered by residual snow during summer, or an average of 3336 $m^2 \cdot km^{-2}$. A correlation of $r = 0.93$ was observed between the residual snow cover in the different regions during the second half of July and the maximum snow cover thickness during winter measured by Environment Canada. A model permitting the estimation of the maximum snow cover thickness in regions where meteorological stations do not exist was formulated. The model is applicable at small and medium scales. In addition, the authors propose that the Hudson Strait region is the most susceptible to the formation of glaciers if one hypothesizes that the regions with the thickest residual snow cover are the most susceptible to glaciation.

Key words: snow patches, Canadian arctic climate, snowfalls, snow depth, glaciation

RÉSUMÉ. Cet article étudie la couverture neigeuse résiduelle dans l'Arctique canadien, à partir de l'analyse des photographies aériennes. La région étudiée comprend l'Ungava, une partie du Keewatin et les îles de l'Arctique, à l'exception des régions montagneuses à l'ouest de la mer du Labrador, et de la baie de Baffin où les champs de neige et les glaciers sont très abondants. En dépit de la discontinuité spatiale des photographies prises durant la deuxième moitié de juillet on a pu étudier 555 519 km^2 soit 46% du territoire inclu dans les limites assignées. À l'intérieur de ce territoire, 1899 km^2 sont recouverts de neige résiduelle au milieu de l'été soit 3336 $m^2 \cdot km^{-2}$ en moyenne. Cela représente 0.34% de la surface du sol. On a noté une corrélation de $r = 0.93$ entre le pourcentage de neige résiduelle de différentes régions durant la deuxième moitié de juillet, et l'épaisseur maximum de neige au sol en hiver, mesurée par Environnement Canada. Un modèle a été établi. Il permet d'estimer l'épaisseur maximum de neige au sol dans les régions où les stations météorologiques sont absentes. Le modèle peut s'appliquer à petite et à moyenne échelle. Par ailleurs on propose que les régions du détroit d'Hudson sont parmi les plus sensibles à la formation de glaciers si on prend comme hypothèse que les régions ayant le couvert de neige résiduel le plus important sont les plus sensibles à une englaciation.

Mots clés: plaques de neige, climat arctique, englaciation, chutes de neige, épaisseur de neige

INTRODUCTION

In a previous paper (Lauriol *et al.*, 1984), the spatial and temporal variations of snow cover in Ungava (Quebec) during summer were studied by means of air photographs. The following conclusions were reached: the number and surface area of snow patches are related to the previous winter's snowfall, the highest density of snow patches exists in the highland region bordering the Hudson Strait coast, which is also the zone characterized by the heaviest snowfalls, and field observations between 1975 and 1983 and air photographs taken during 1950-60 indicate an increase in area and number of snow patches.

In this paper, the authors use the principles and methods developed for the Ungava snow patches study to measure the area of the Canadian Arctic covered by snow patches in July and to determine the zone with the greatest number of snow patches.

Previous papers by Cook (1967), Pissart (1967), Bird (1967), St-Onge (1969), Billings (1974), Nicholson (1973), Koerner (1980a), Woo (1980), Woo and Sauriol (1980), Woo *et al.* (1982), Lewkowicz and French (1982), Séguin and Allard (1984), and Granberg (1986) have noted the effect of snow patches on arctic morphology, ecology, hydrology and permafrost. Papers have also been published to understand their dynamics: Outcalt *et al.* (1975), Tabler (1975), Granberg (1978), Schmidt and Randolph (1981), Fohn and Meister (1983). But there have been no attempts to quantitatively evaluate the distribution of snow patches in July throughout the Canadian Arctic. This paper deals with this question.

PHYSICAL SETTING

The study area (Fig. 1) includes the Ungava Peninsula, a large section of the District of Keewatin and the Canadian Arctic Archipelago, except for the mountainous zone to the east of the Labrador Sea, and the snow- and glacier-covered area surrounding Baffin Bay. All these areas are located at an altitude below to 600 m with the exception of a few small surfaces.

Located within the limits of the continuous permafrost zone, the study sites have mean July temperatures generally below 10°C. Annual snowfalls are 80 cm in the western zone but 150 cm on the Saglouc plateau (Gray, 1983) and on Baffin Island. During summer, total amounts of precipitation do not vary much between the western and eastern part of the Arctic. However, their occurrence varies greatly; in the west, the rainstorms are sparse but violent, while to the east they are frequent but less intense. The difference of rainstorm occurrence reflects the continental type climate of the west and the maritime type climate of the east (Bird, 1967; Maxwell, 1980, 1981).

The treeless environment of the Arctic permits the redeposition of surface snow and its accumulation in wind-protected areas. This results in snow patches that persist long after the ablation of surface snow cover, which is generally very thin. Accordingly, the snow patch distribution at the local scale reflects the topographic organization of a particular area. In the west, where sedimentary rocks predominate and present well-developed hydrographic networks, snow patches are mostly located in topographic irregularities associated with talwegs of

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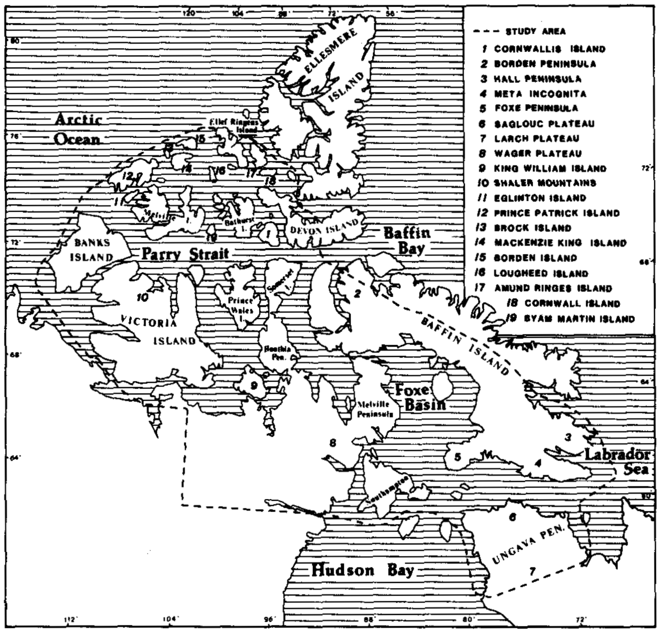

FIG. 1. Arctic Canada.

order one and two. In the east and in the District of Keewatin, crystalline rocks dominate and generally present a non-organized drainage pattern. In this type of topography, the snow patch pattern is strongly determined by the topographic irregularities (faults, diaclases or outcrops) due to the rock structure. In areas covered by till deposits or felsenmeer, snow patches have a tendency to take a crescent-like form.

METHODOLOGY AND OBJECTIVES

The objectives of this study were to identify the zones occupied by numerous snow patches to measure their surface area and to evaluate the relationship between the results and the Canadian climate normals published by Environment Canada. The snow patch areas were located using air photographs. These air photographs offer a higher resolution than satellite images, but their coverage is fragmented in time and space.

The following procedure was applied in order to estimate the

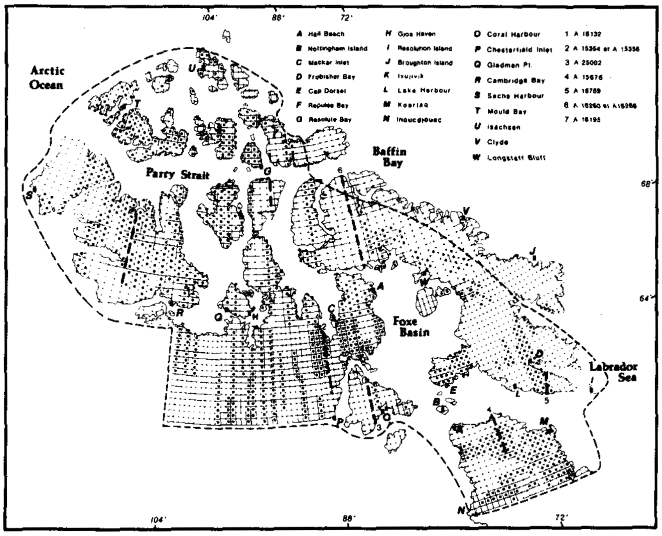

FIG. 2. Topographic map at 1:50 000 covered by air photographs within the two last weeks of July and location of flight lines and stations referred to in the text.

TABLE 1. Area covered by snow patches in July.

Island/Territory	Area (km^2)	Air photo coverage (km^2)	(%)	Average snow cover (m^2·km^{-2})	Area covered by snow (km^2)	%
King William	12 656	7973	(63)	0	0	0.0
South of Boothia Pen.	23 906	18 455	(77)	169	3	0.01
Lougheed	1237	1237	(100)	262	0.3	0.026
Eglington	1406	1406	(100)	275	0.4	0.028
Cornwall	2193	1645	(75)	333	5	0.033
Prince of Wales	27 000	24 570	(91)	344	8	0.034
Amund Ringnes	5175	1397	(27)	500	0.7	0.050
Byam Martin	956	(100)	500	0.5	0.5	0.050
Ellef Ringnes	11 868	9257	(78)	538	5	0.054
Baffin S.W.	58 368	14 008	(24)	1042	15	0.104
Victoria	191 137	133 795	(70)	1131	151	0.113
Banks	69 693	23 696	(34)	1137	27	0.113
Prince Patrick	14 568	10 926	(75)	1150	13	0.115
Boothia	29 250	9828	(40)	1284	15	0.128
Bathurst & surroundings	16 312	9787	(60)	1500	15	0.150
MacKenzie King & Borden	7425	3192	(43)	1595	5	0.160
N.W.T. (64°-68°N)	256 250	82 000	(32)	2241	184	0.224
Melville	34 031	26 885	(79)	3776	101	0.378
Cornwallis	7256	7256	(100)	4437	32	0.444
Somerset	26 720	5878	(22)	5000	29	0.500
Grinnell Pen & West Devon Is.	23 625	11 812	(50)	5270	63	0.527
Baffin N.W.	95 323	28 569	(30)	5621	160	0.562
Baffin Centre	52 224	19 322	(37)	6161	119	0.616
Melville Pen.	50 625	35 435	(70)	6256	222	0.626
Ungava	91 152	51 956	(57)	9670	502	0.967
Southampton	42 187	5062	(12)	12 794	65	1.279
Baffin S.E.	51 200	9216	(18)	17 092	158	1.710
Total	1 203 743	559 519	(46)	av. 3336	1899	0.34

snow-covered areas of the Arctic. Since the most intensive period of air photo coverage lies within the two last weeks of July (Fig. 2), only photographs taken during this period were considered. There is at least one aerial coverage for 46% of the study area for the period 1948-83.

The sampling of photographs was structured on the National Topographic System: each topographic map at 1:50 000 having an aerial coverage during the last two weeks of July had one photograph considered for measurement selected on the basis of its proximity to the centre of the map.

The area covered by the easily detectable snow was measured using a transparent sheet of metric graph paper overlaid on the photograph. The snow cover was obtained by adding the individual snow areas on a given photograph; the results are expressed in $m^2 \cdot km^{-2}$. The area covered by snow patches is extrapolated from the average snow patch cover of a given spatial unit (island, region) given by the average of all the photographs measured within the area considered. The number of snow patches present on each photograph was only used to show the evolution of the number of snow patches along topographic profiles (Fig. 2).

The percentage of snow-covered surface within the two last weeks of July was compared with the Canadian climate normals (Richardson, 1980; Environment Canada, 1982a,b). We chose the average established for the 1950-79 period at 21 stations of the Arctic. For the greater surface areas, we used the average of 2-3 stations. In total the relationship between the percentage of snow-covered surface and the maximum snow depth in winter was established from 11 points, and the relationship with the snowfall, thawing and freezing index was established from 13 points.

RESULTS AND INTERPRETATION

Total Area Covered by Snow Patches

Although each photograph accounts for only a brief period of summer and for a specific year, the authors have attempted to reconstruct the distribution of snow patches throughout the Arctic.

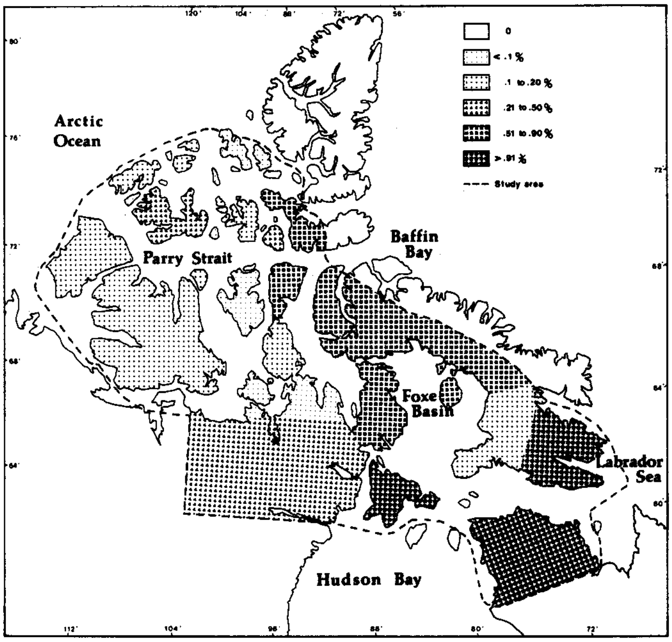

FIG. 3. General distribution, in percentage, of snow patches in July throughout the Arctic.

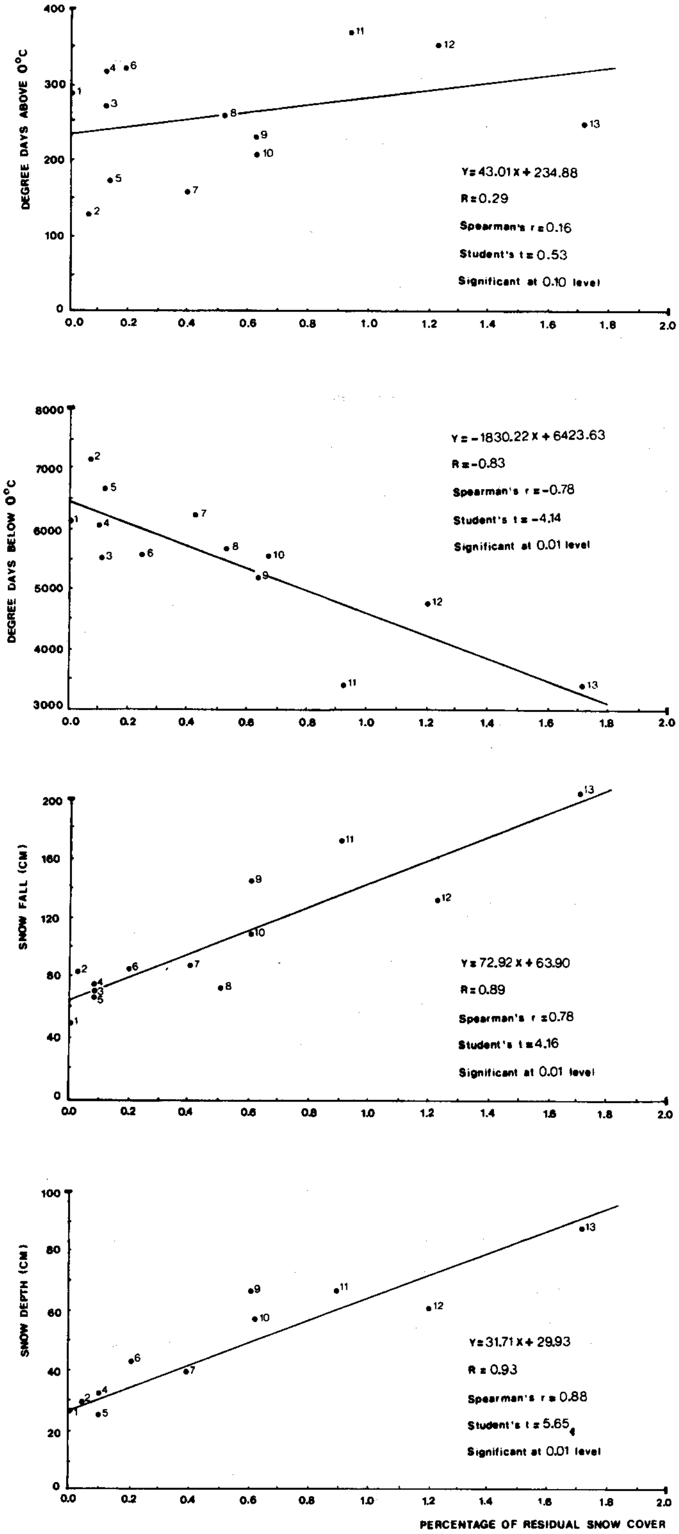

FIG. 4. Relation of measured percentage of snow-covered area in July to climate normals. The numbers relate to Table 2.

Figure 2 shows the topographic maps covered by the photographs during the second half of July, and the results are depicted in Table 1. The total area studied covers 555 519 km^2, or 46% of the total area; 1899 km^2, or 0.34%, is snow covered.

Snow cover percentage increases from west to east (Fig. 3). In the west, the snow-covered areas account for <0.3 of the total area. However, to the east they increase to 0.5% on Resolution Island, 0.6% on Melville Peninsula, 0.9% in the Ungava Peninsula and 1.7% on Meta Incognita. The only exception is Foxe Peninsula, with a snow cover of 0.1%.

The date of the start of thaw shows no relationship to the distribution of snow-covered surfaces at the end of July. Even if the thaw started in early June in southeastern Baffin Island and northern Ungava, the residual snow cover is greater than in the northern islands, which had only one month of thaw. Generally the relation between the number of degree days above 0°C and the surface covered by snow patches throughout the Arctic is weak, as indicated by the Spearman and Student coefficients shown in Table 2 and Figure 4.

The relationship is slight between the number of degree days below 0°C and the percentage of snow-covered surface. Southeastern Baffin Island and the northern part of Ungava, which have an average of 3000 degree days below 0°C, have a percentage of residual snow cover greater than that of Cornwallis or Ellef Ringes islands, which receive 6267 and 7139 degree days respectively. The Spearman correlation coefficient is of −0.78 and the Student's test gives −4.14 (Table 2; Fig. 4). The negative relationship is perhaps explained by the fact that the coldest regions receive less snowfall, and consequently the depressions in which wind-blown snow accumulates are emptier than in areas with greater snowfall.

The relationship between the percentage of snow-covered surface and the snowfall total measured at various meteorological stations in the Arctic is stronger (Table 2; Fig. 4). But the snowfall data are apparently unreliable. The error in snowfall evaluation is 100-300% at the Resolute Bay meteorological station (Woo *et al.*, 1983), a problem that occurs across the Arctic. In the Soviet Union the underestimation of precipitation is 40-50% along the Arctic Ocean coast (Bochkow and Struzer, 1970) and in Alaska it is 200-400% at Point Barrow (Black, 1954).

The maximum snow depth normals in winter show a better relationship to the percentage of residual snow-covered surface. The Spearman's rank correlation coefficient is 0.88. With a significance level of 0.01, the Student's test gives 5.65. This supports the initial hypothesis that the thicker the winter snow cover is, the more numerous are the snow patches in summer throughout the Arctic.

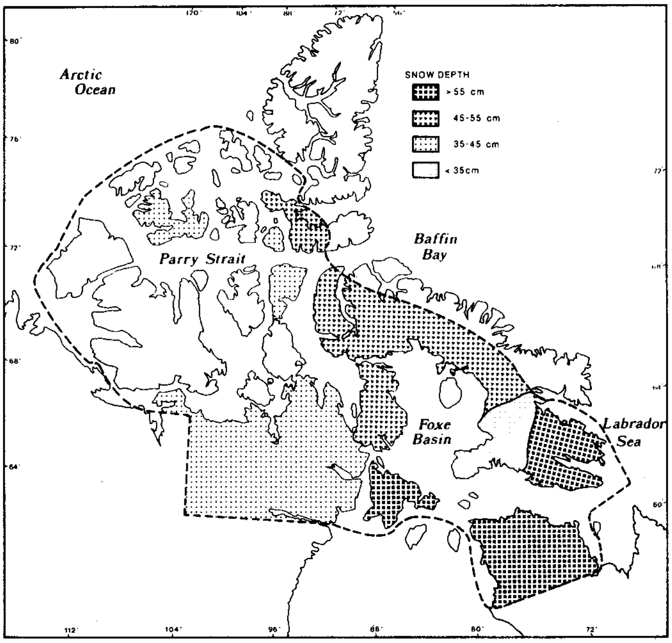

FIG. 5. Map of hypothetical maximum snow depth in winter throughout the Arctic.

Thus it is possible to determine the maximum snow cover thickness in regions where no meteorological station exists but the percentage of residual snow is known. So snow on Melville Island and the northern part of Baffin Island ranges between 30-35 cm, and the island on the east coast of the Arctic Ocean, Prince of Wales Island, King William and the Foxe Peninsula have a maximum thickness <30 cm (Fig. 5). However, without verification, these results are intended as a hypothesis for future work from satellite images. In selecting a few regions with meteorological stations, we hope to verify with the help of

TABLE 2. Climate normals used to evaluate the relationship between climate and percentage of residual snow cover in July in the Canadian Arctic

No.	Region	% of residual snow cover[1]	Station	Degree days above 0°C (May, June and July)[2]	Degree days below 0°C[2]	Snowfall[3] (cm)	Snow depth[4] (cm)
1	King William	0.00	Gladman Point	287.2	6 120.5	51.2	27.2
2	Ellef Ringnes	0.054	Isachen	127.9	7 139.7	81.3	29.7
3	Banks	0.113	Sachs Harbour	271.4	5 525.6	75.9	no data
4	Victoria	0.113	Cambridge Bay	323.7	6 028.0	76.8	31.9
5	Prince Patrick	0.115	Mould Bay	158.9	6 692.9	71.3	26.8
6	Kewatin, N.W.T.	0.224	Chesterfield and Gladman	333.2	5 525.5	81.0	41.3
7	Cornwallis	0.444	Resolute	163.6	6 267.6	83.8	39.0
8	Baffin North	0.562	Arctic Bay	255.9	5 524.0	71.0	no data
9	Baffin Centre	0.616	Longstaff Bluff, Dewar Lake and Clyde	235.4	5 116.0	144.0	65.0[5]
10	Melville Peninsula	0.626	Mackar Inlet and Hall Beach	216.4	5 706.4	109.0	54.4
11	Ungava Peninsula	0.967	Deception, Inukjuak and Koartaq	372.9	3 265.9	171.0	65.0[6]
12	Southampton Island	1.279	Coral Harbour	355.3	4 823.2	131.9	60.4
13	Baffin South East	1.710	Frobisher, Resolution Island and Boughton Island	245.1	3 284.3	215.0	83.0[7]

[1] Table 1.
[2] Environment Canada, 1982a.
[3] Environment Canada, 1982b.
[4] Richardson, 1980.
[5] Dewar Lake missing.
[6] Deception missing.
[7] Resolution Island missing.

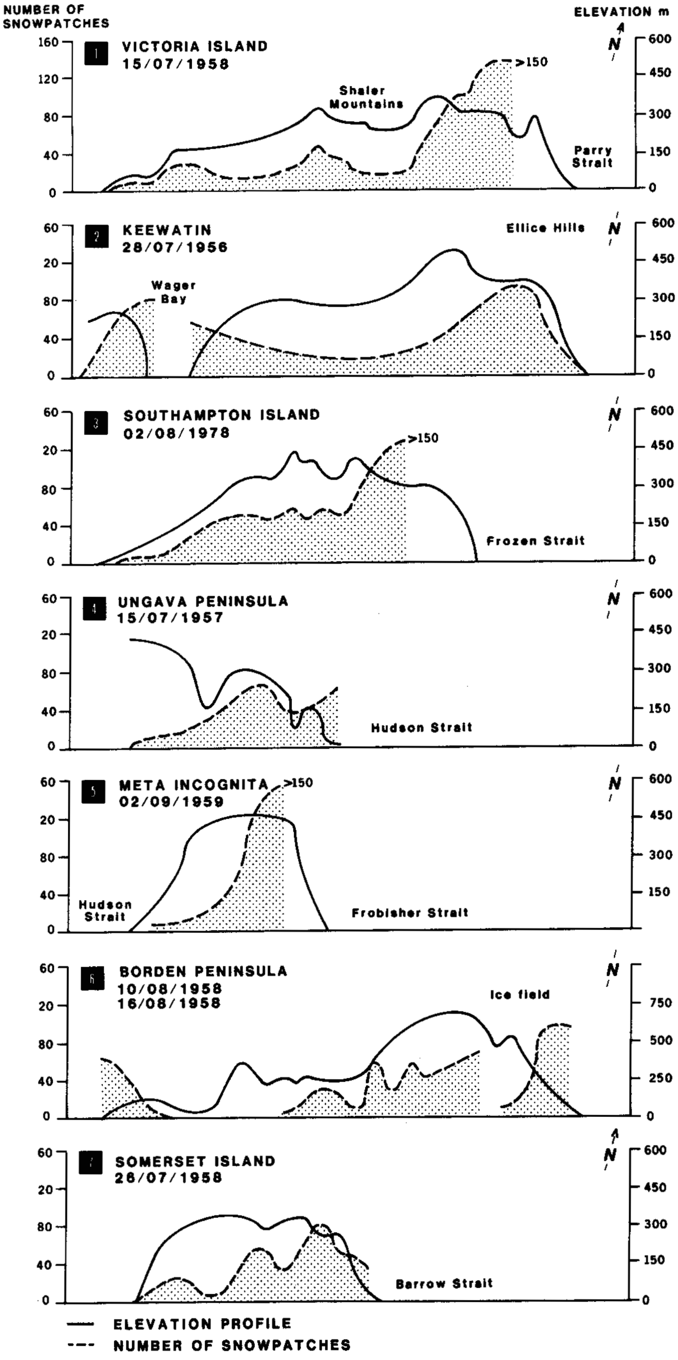

FIG. 6. Spatial evolution of the number of snow patches along flight lines referred to in Figure 4.

satellite images the degree of precision possible using the relationship between snow depth and snow patches on an annual basis.

Local Variation of Snow Patches

There are zones both in the east and the west that have a greater abundance of snow patches. Local variations in snow patch distribution are reflected in the profiles established from air photograph flight lines (Figs. 2 and 6). They show that on the islands and peninsulas an asymmetry exists between zones of snow patch abundance and those of sparse snow cover. The

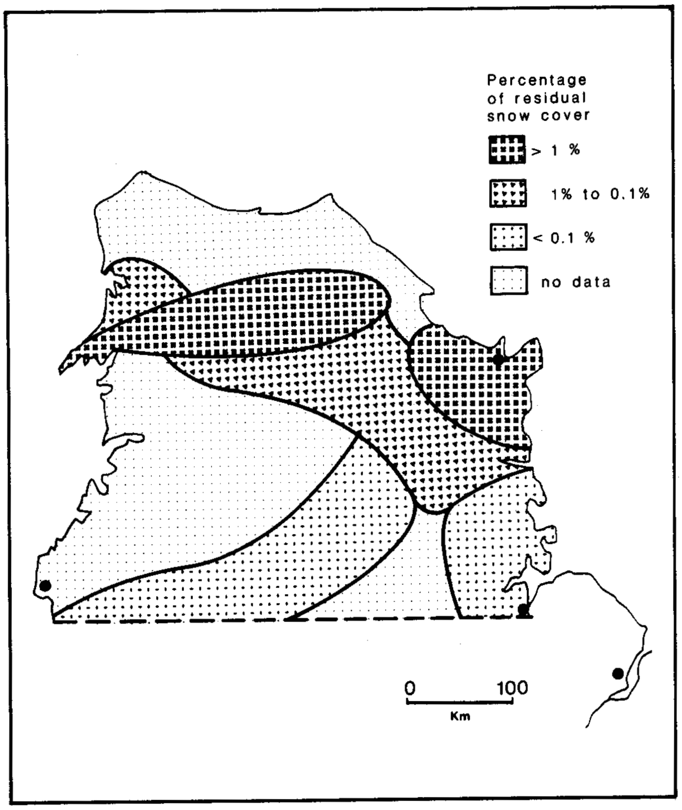

FIG. 7. Distribution of snow patches 16-30 July in the Ungava Peninsula (Lauriol *et al.*, 1984).

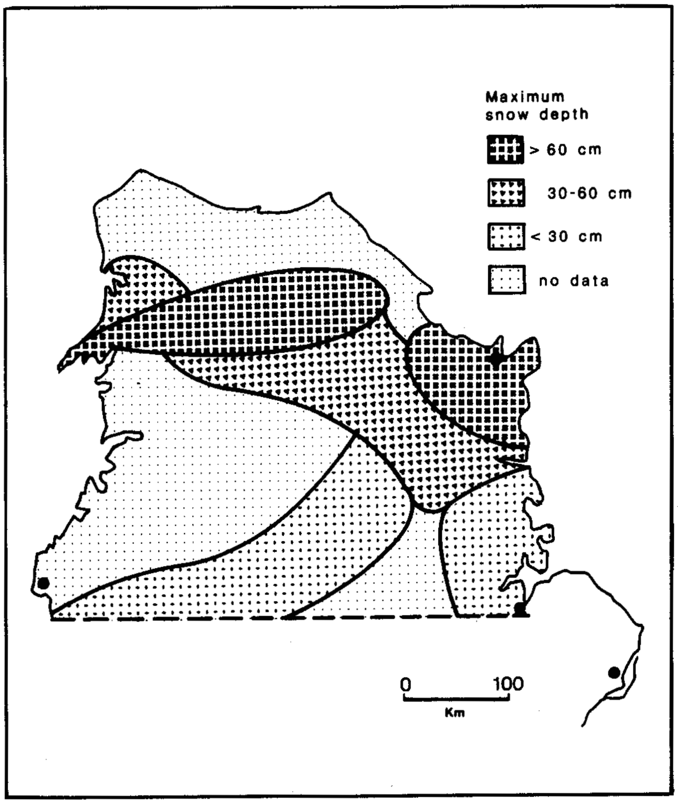

FIG. 8. Hypothetical distribution of maximum snow depth in winter in the Ungava Peninsula.

zones of abundant snow patches occur in the northern parts of the topographic units and near the sea, particularly on Meta Incognita, Ungava Peninsula, Southampton Island, Victoria Island, Somerset Island and the District of Keewatin. In the northern part of these regions, the snow patches are located down to sea level, as noted previously by Bird (1967) and Brochu (1972).

If we assume a relationship between the percentage of residual snow cover during the second half of July and the maximum winter snow cover, we are able to graphically represent the latter on both a large and a local scale. Thus in Ungava the zones with >1% of the surface covered by residual snow would have had a winter snow cover >50 cm. The zones with surface cover varying between 1 and 0.1% would have a winter snow pack ranging between 50 and 30 cm. The zones with residual snow-covered surfaces <1% would have had a winter snow pack <30 cm (Figs. 7 and 8). These results give a clearer picture of the distribution of the maximum snow cover thickness than the one obtained by joining by isolines the data collected at a few meteorological stations (Fig. 9).

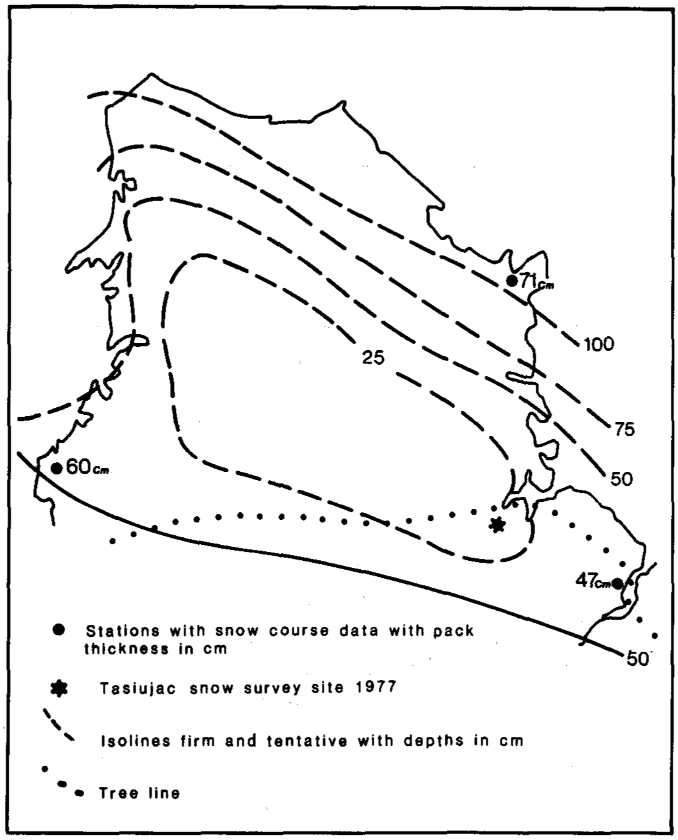

FIG. 9. Isolines on maximum snow depths (in cm) for Ungava snow courses during the winter 1976-77 (Gray, 1983).

DISCUSSION

Besides the potential for cartography of the maximum snow depth in winter throughout the Arctic, this study can contribute to the discussion of the geographical origin of englaciation in the Arctic on the basis of the following hypothesis: regions with the greatest residual snow cover in July are the most susceptible to englaciation.

Accordingly, the onset of glaciation would proceed first in the Hudson Strait area, where the snow patches cover up 10% (100 000 m^2·km^{-2}) in July. Similarly, Melville Peninsula, the western part of Baffin Island, Somerset Island, the western part of Devon Island and the upland and northeastern coasts of Victoria and Melville would be covered by more snow patches.

It is difficult to relate the results of this model of englaciation to the more detailed ones of Williams (1978) and Andrews and Mahaffy (1973), since their models do not have the same assumptions. Nevertheless, we want to stress that the northern Ungava plateau is a more sensitive region to englaciation than suggested by these authors. Glaciers were absent on the Ungava plateau 5000 years after the onset of glaciation in the model of Andrews and Mahaffy (1973); the maps of Williams (1978) show only a small part of the Ungava plateau with a perennial snow cover. The reason for this divergent interpretation lies apparently on their erroneous record of the snowfall in the Ungava Peninsula: for example, the map of Gagnon and Ferland (1967) gives 40 cm of snowfall in the north Ungava, whereas Gray (1983), from a detailed study of meteorological data, gives more than 140 cm. The consequences of the error in the evaluation of the snowfalls in the Ungava Peninsula occur also in the model of glacial inception during the Wisconsinan in eastern Canada proposed by Occhietti (1982).

A second point to note is the influence of elevation in the problem of the geographical origin of glaciation. Ives *et al.* (1975) propose that an englaciation would occur following a lowering of the July freezing level height, an increase of snowfall and a change in the pattern of the atmospheric circulation (Lamb and Woodroffe, 1970; Loewe, 1971; Barry *et al.*, 1975; Andrews and Mahaffy, 1973; Koerner, 1980b). The present study shows that it is not only the uplands that can be affected by these changes in the meteorological conditions, but also the northeastern coast of each geographical unit.

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