

ACCUMULATION ON THE DEVON ISLAND ICE CAP, NORTHWEST TERRITORIES, CANADA

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ABSTRACT. The pattern of accumulation on the Devon Island ice cap is described. There is an area of minimum accumulation encircling the highest part of the ice cap and 100–200 m. below it. Below this zone, accumulation gradually increases to a maximum near the ice-cap edge. The overall pattern is related to snow transport by katabatic winds. There is a regional accumulation pattern of high accumulation (ca. 40.0 cm. water equivalent) in the south-east part of the ice cap and an area of low accumulation (ca. 11.0 cm. water equivalent) in the north-west. This east-south-east to west-north-west accumulation gradient is related to cyclonic activity to the east in Baffin Bay, and it is probably intensified by the presence of open water in the same area.

RÉSUMÉ. *Accumulation sur la calotte de glace de l'Île Devon, Territoires du Nord-Ouest, Canada.* La distribution de l'accumulation sur la calotte de glace de l'Île Devon est décrite. Une zone à accumulation minima encercle la partie la plus élevée de la calotte de glace jusqu'à 100 à 200 m en-dessous. En-dessous de cette zone, l'accumulation augmente graduellement jusqu'à un maximum près du bord de la calotte de glace. La distribution générale de l'accumulation est liée au transport de la neige par des vents catabatiques. Il existe une distribution régionale de forte accumulation (environ 40,0 cm, valeur en eau) dans la partie sud-est de la calotte de glace et une zone à faible accumulation (environ 11,0 cm, valeur en eau) dans la partie nord-ouest. Ce gradient d'accumulation de est-sud-est à ouest-nord-ouest est lié à l'activité cyclonique vers l'est de la Baie de Baffin et il est probablement renforcé par la présence d'eau libre dans la même région.

ZUSAMMENFASSUNG. *Akkumulation auf der Eiskappe des Devon Island, Northwest Territories, Kanada.* Die Verteilung der Akkumulation auf der Eiskappe des Devon Island wird beschrieben. Das Gebiet geringster Akkumulation liegt um den Scheitel der Eiskappe in einer Zone bis zu 100–200 m Höhenabnahme. Unter dieser Zone nimmt die Akkumulation allmählich zu und erreicht ihr Maximum nahe am Eisrand. Die Gesamtverteilung ist mit dem Schneetransport durch katabatische Winde verknüpft. Regionale Besonderheiten treten mit hoher Akkumulation (ca. 40,0 cm Wasserwert) im Südost-Teil der Eiskappe und mit niedriger Akkumulation (ca. 11,0 cm Wasserwert) im Nordwesten auf. Dieser von Ostüdost nach Westnordwest gerichtete Akkumulationsgradient hängt mit der zyklonalen Aktivität gegen Osten zur Baffin Bay zusammen und wird vermutlich durch das Auftreten offenen Wassers im selben Gebiet verstärkt.

INTRODUCTION

During the period May 1961 to September 1963, Devon Island was the centre of a series of integrated scientific studies sponsored by the Arctic Institute of North America and under the leadership of S. Apollonio. The island was re-visited between May and August 1965 by a party of five under the leadership of the author. The glaciological studies were initially devoted to an examination of run-off conditions on Sverdrup Glacier, but later they developed into a mass-balance study of the Devon Island ice cap. This is the first of several papers describing this work and it is specifically concerned with snow accumulation on the ice cap.

Devon Island is one of the Queen Elizabeth Island group of the Northwest Territories, Canada (Fig. 1). Its ice cover lies mainly in the eastern part of the island and the main body of the ice cap covers 15,568 km.², which is 31 per cent of the island's total area. The main ice cap is the fourth largest in Canada and hence, excluding Greenland, it is one of the largest in the Northern Hemisphere. The main body of the ice cap, which rises to an altitude of 1,885 m. a.s.l. in its central part, covers 12,791 km.². This part of the ice cap is slightly asymmetrical with an east-west summit ridge, particularly pronounced in the east, dividing it into northern and southern regions. Another ridge begins approximately 19 km. south of the top of the ice cap and trends due south to within a few kilometres of Lancaster Sound. These ridges have an important effect on the distribution of the accumulation.

METHODS

Snow depths

In 1961 a mass-balance survey of the north-west side of the ice cap was started by S. Ekman and it was continued by the author throughout July and August. In May 1962, the

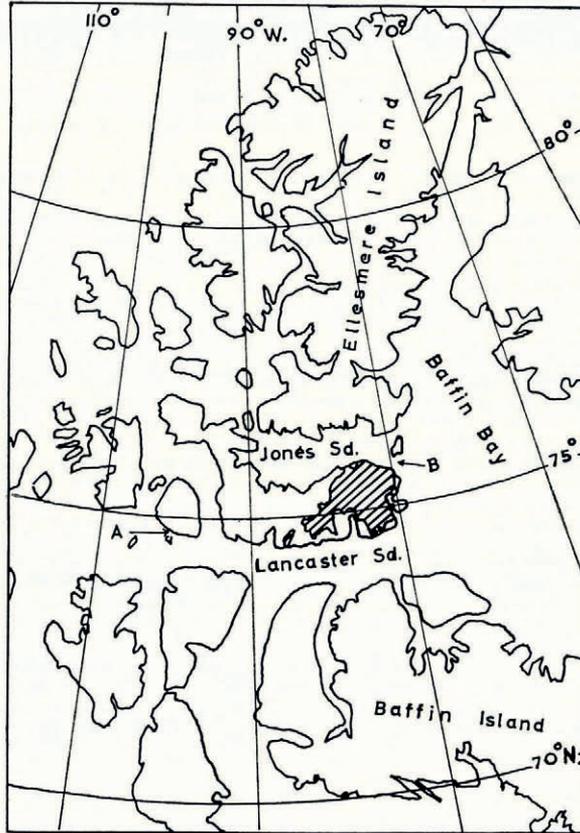


Fig. 1. Location map showing the position of the Devon Island ice cap (hatched). A. Resolute Bay; B. Lady Ann Strait

original series of stakes was extended to include the south-east, north and south-west parts of the ice cap. While setting up these traverses in May and June 1962, it was found expedient to make several snow probes through to the ice or the hard firn surface of the previous summer which formed a layer impenetrable to a light probe; five observations were made at 1 km. intervals on every traverse. This gave a comprehensive picture of spring snow depth for a large part of the ice cap, and snow probing was repeated in 1963 and 1965 for the same traverse lines and along an additional one farther east (Fig. 3). At altitudes above 1,550 m. a.s.l., in 1965, no hard firn surface remained from 1964 due to low melt in that summer. Snow depths were therefore measured in pits above these altitudes, where the information is consequently less detailed.

Densities

Densities were taken approximately every 3 km. using standard techniques; they showed very little variation from one place to another, although there was some correlation with snow depth on the north-west side of the ice cap. Here density showed a positive relationship with snow depth, although the top of the ice cap was an exception to this general rule (Fig. 2).

The spring snow pack on the Devon Island ice cap can be divided into two basic parts: an upper, dense fine-grained layer deposited in winter (October–April) and a lower, loose

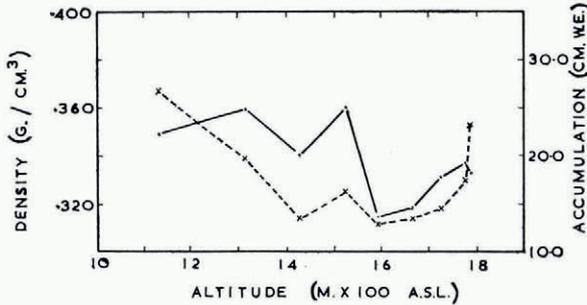


Fig. 2. The relationship between altitude, snow density and accumulation; north-west traverse, spring 1963. The dashed line represents accumulation

coarse-grained layer deposited in autumn (August and September). A fairly even snow cover on the ice cap is characteristic of autumn as only slight drifting takes place. In winter frequent re-sorting of the surface accumulation causes a greater variability in the accumulation so that variations in density of the snow pack in spring are generally reflections of variations in the thickness of the winter layer. The erosive action of katabatic winds is most persistent between 1,600 and 1,787 m. a.s.l., mainly removing winter snow; in 1963 some areas between these altitudes showed no dense winter snow accumulation at all. As a result, the mean density of the snow pack at these altitudes was low. The greater accumulation and higher density at 1,520 m. a.s.l. is due to sampling on a steep slope, which is an area of deposition for drifting snow, particularly in winter. Towards the summit of the ice cap, katabatic winds (if they exist at all) are too weak to cause drifting and winter snow can accumulate more frequently without a high initial density, so that the spring snow profile at the summit has a lower density than the mean for the whole ice cap. This positive relationship between snow depth and density serves to intensify the patterns shown by plotting snow depth (Figs. 3-6). In fact, apart from the north-west side of the ice cap, there was a very low order of correlation between snow depth and density ($r = 0.49$; significant at the 0.1 per cent level). As the standard error of the estimate of T_c (computed density) is very similar to the standard deviation from the mean of T (0.034 g./cm.^3 compared with 0.039 g./cm.^3), the regression equation has not been used to compute water equivalents of accumulation. Using the mean density values means that conversion to water equivalent does not alter the accumulation patterns shown by snow depth in Figures 3-6. Between 1961 and 1965, snow density showed very little variation from one region to another. The mean densities (in g./cm.^3) were 0.345 in 1962, 0.339 in 1963 and 0.351 in 1965; the standard deviations were 0.022, 0.020 and 0.035 g./cm.^3 , respectively.

RESULTS

The results (Figs. 2-6) show that snow depth on the ice cap does not vary according to altitude but rather according to:

- i. Distance from the top of the ice cap.
- ii. Irregularity and steepness of slope.

The first of these two variables is a regional phenomenon with two causal factors and the second is mainly a local effect.

The snow accumulation pattern is similar from year to year. There is an overall increase in accumulation from the centre of the ice cap towards its margins and a very steep east-south-east to west-north-west accumulation gradient. The increase in snow depth towards the ice-cap margin is greatest in the south-east, where accumulation increases by more than

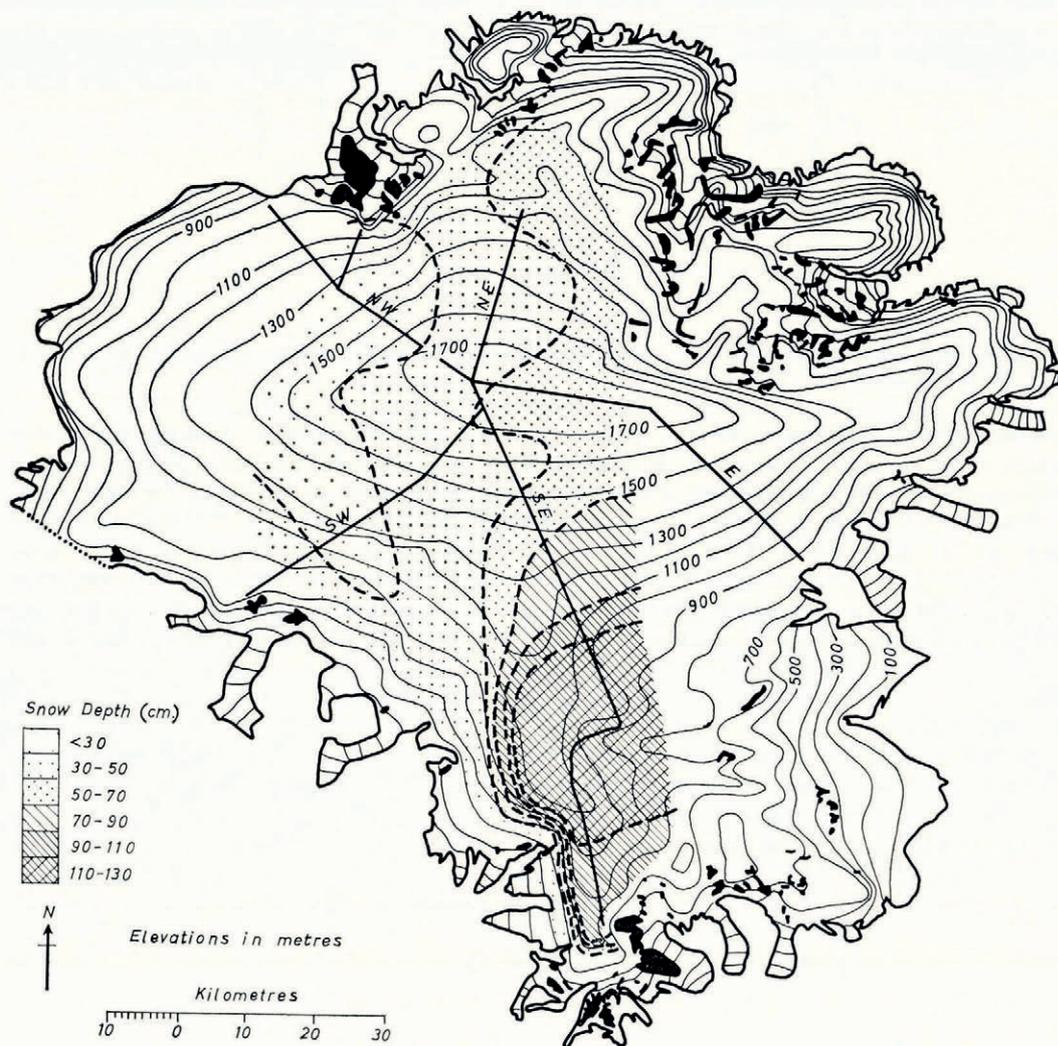


Fig. 3. Snow accumulation on the Devon Island ice cap; spring 1962. The traverse routes are shown. In 1962 routes connected the lower ends of the south-east and south-west traverses but the east and summit traverses were not run. In 1963 and 1965 main traverses were as shown, but in 1965 the south-west to south-east connecting route was replaced by one joining the lower ends of the south-east and east traverses. Mean snow density = 0.345 g./cm.^3

200 per cent. Elsewhere the increase is approximately 10–15 per cent. This increase (outside of the very high increase towards the south-east) could be the result of either down-slope snow drift by katabatic winds or increased atmospheric instability, and hence precipitation at the edge of the ice cap.

Katabatic winds are a normal feature of periods free from cyclonic disturbances, and according to their velocity and snow-surface conditions snow may be transported down-slope. It was common to experience periods of calm on the ice-free plateau surrounding the ice cap while down-slope winds blew on the ice cap itself. It therefore seems reasonable to assume that the ice-cap margin is a region of deposition during such conditions. It was similarly observed that, although a katabatic wind might be noticeable very close to the sum-

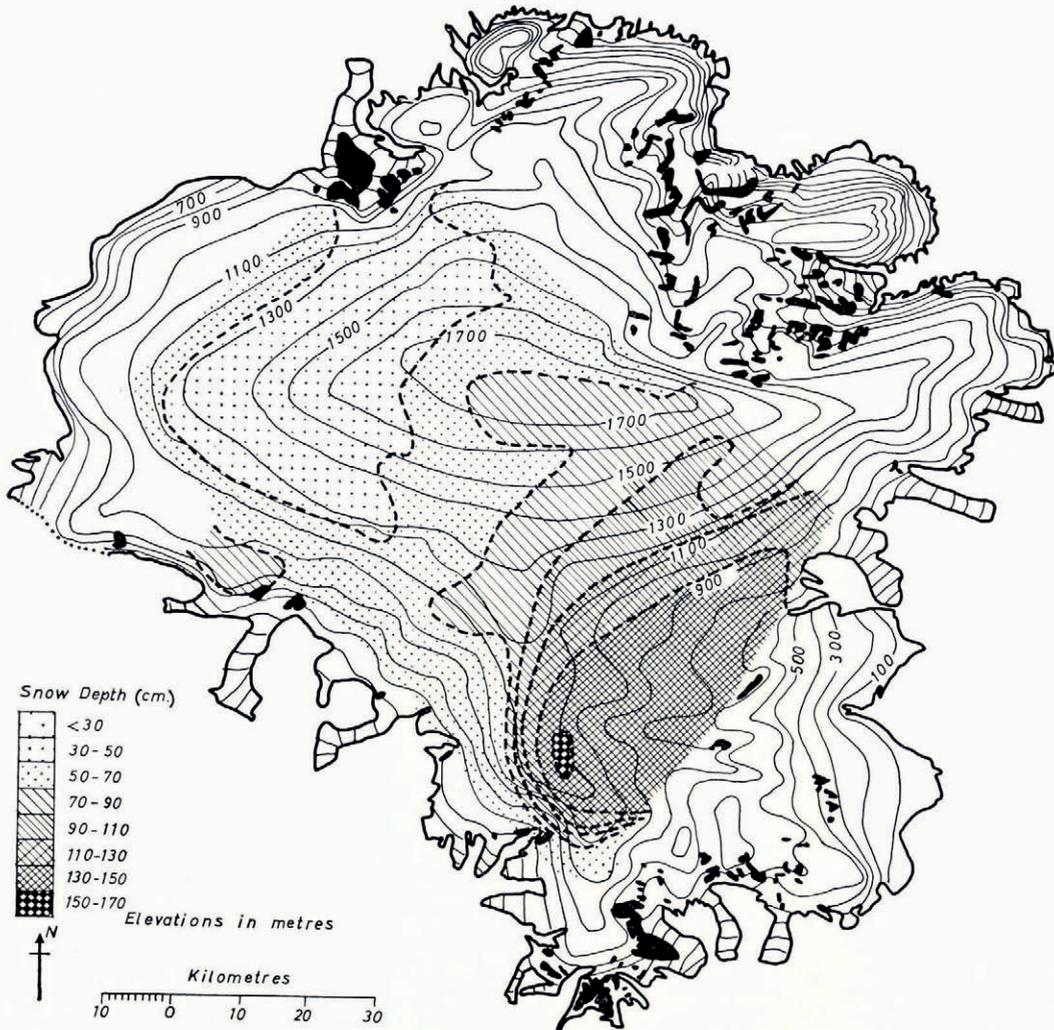


Fig. 4. Snow accumulation on the Devon Island ice cap; spring 1963. Mean snow density = 0.339 g./cm.^3

mit ridge of the ice cap, it was seldom strong enough to remove snow for the first 5 km. below the ridge. Over the winter there must occur a varying set of boundary conditions within which some area remains for a maximum period of time in the erosional zone and another area in the depositional zone. Other conditions being equal, these will coincide with areas of minimum and maximum accumulation. Therefore, in addition to the increase in accumulation towards the ice-cap margins, there is a zone of minimum accumulation encircling the highest part of the ice cap and a few hundred metres in altitude below it.

The north-west traverse (Fig. 6) shows these features clearly. Along this traverse snow probes in May 1963 showed a decrease in snow depth from a point 1.5 km. from the summit ridge to a near minimum 11.5 km. farther on. There is a subsequent slight increase in snow depth which is maintained until a significant increase begins 27 km. from the summit (11 km. from the ice-cap edge). The latter increase is largely the result of increased snow accumula-

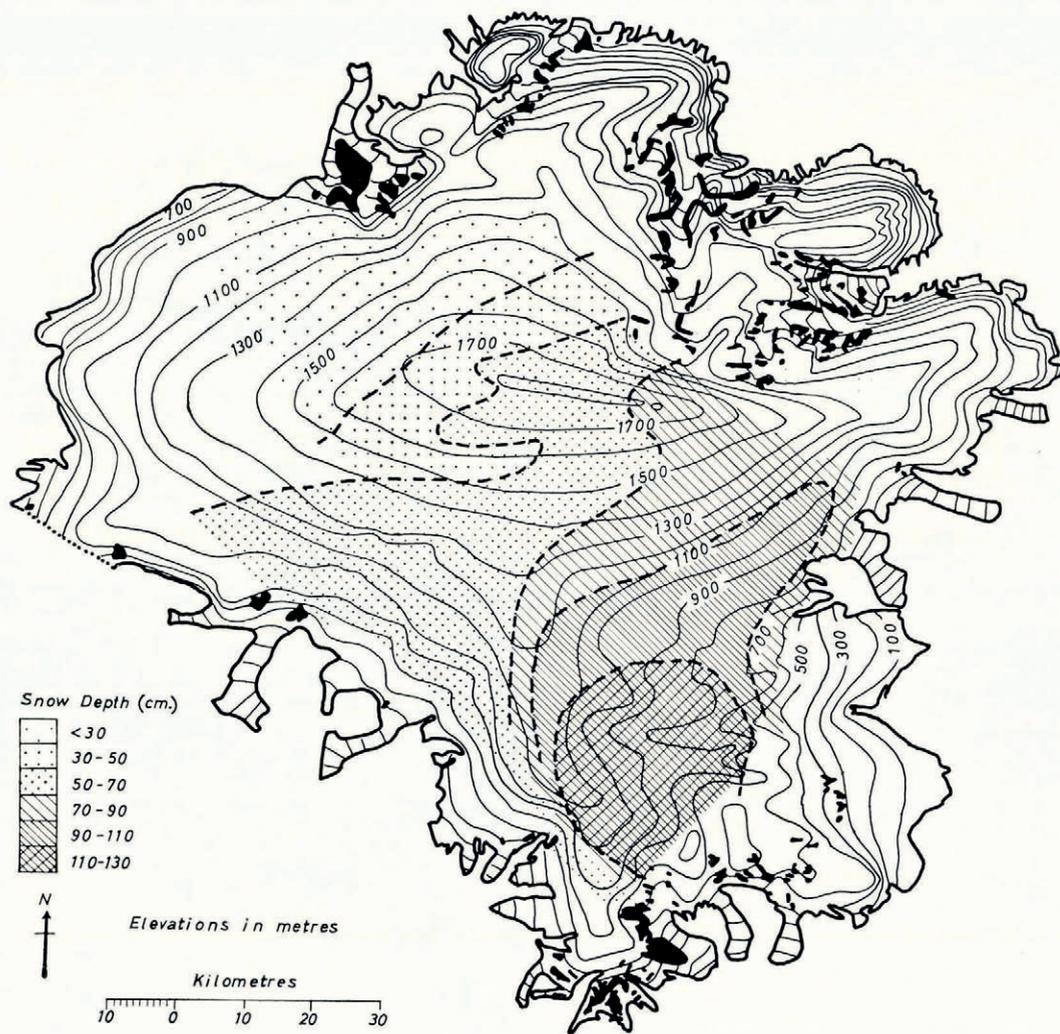


Fig. 5. Snow accumulation on the Devon Island ice cap; spring 1965. Mean snow density = 0.351 g/cm^3

tion on steep slopes, thus outweighing decreased snow accumulation on the brows. The accumulation on the plateau at the foot of the ice cap is very even, indicating a sharp discontinuity in the character of the snow accumulation between the sloping ice-cap surface and the more level plateau. The greatest accumulation anomaly is in fact at the base of the ramp terminating the ice cap. Increases towards the ice-cap edge were still evident in 1962 and 1965 but of a lower order, and they are not apparent in Figures 3 and 5, where the isohyet interval is 20 cm.

The most striking accumulation increase approaching the ice-cap margin is in the south-east. Here the increase cannot be explained in terms of down-slope transport by katabatic winds because it is maintained beyond 35 km. where there is no change in the altitude of the ice-cap surface. A steady increase of snow depth begins 19 km. from the top of the ice cap and this rate of increase steepens appreciably 35 km. from the top. The latter increase

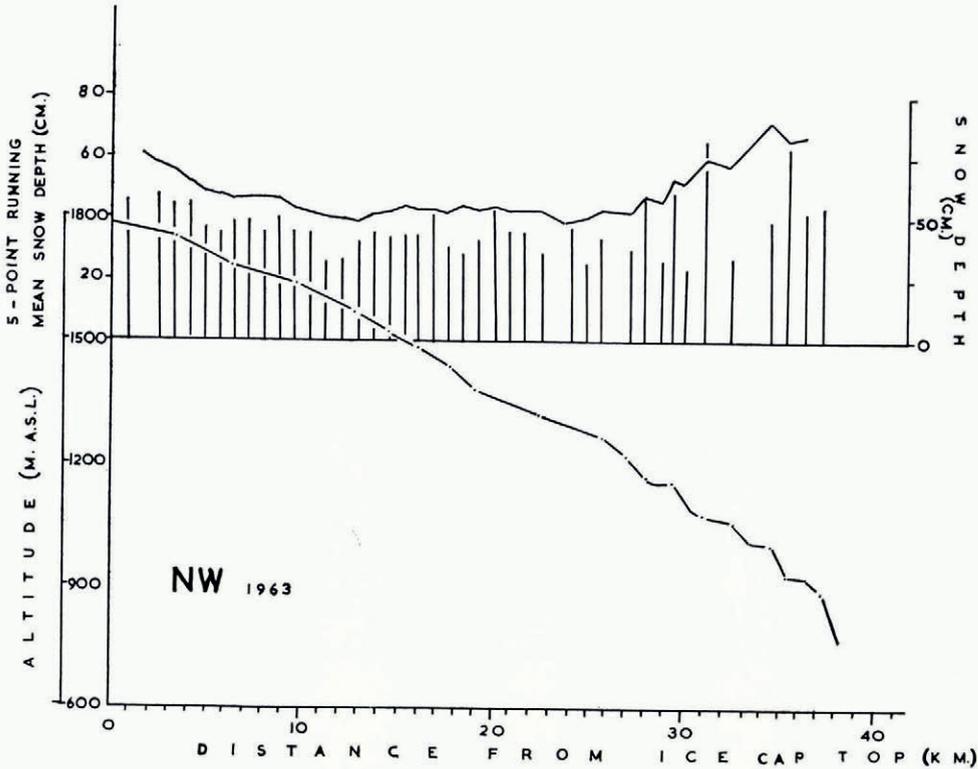


Fig. 6. Snow-depth profile on the north-west traverse; spring 1963. The lower profile is of the ice-cap surface

is closely connected with cyclonic activity in Baffin Bay, which remains open for most of the year. Moist air from Baffin Bay moves up-slope over the cold Devon Island ice-cap surface and it deposits most of its moisture content before it reaches the western side of the ice cap. The precipitation pattern is therefore largely orographic and the highest precipitation appears to be confined to an area south of the summit ridge and east of the north-south ridge which ends 15 km. north of Lancaster Sound.

So far it has not been possible to explore the north-east area of the island any farther east than the line of the northern traverse but ice-covered mountains along and east of Belcher Glacier indicate high accumulation. The dominant precipitation direction appears to be from the east-south-east. The regional sastrugi direction in the spring of 1961, 1962, 1963 and 1965 was east-south-east to west-north-west with in most cases a secondary (though occasionally primary) down-slope orientation. It is very likely that this general circulation often backs up the katabatic direction on the north-west slope to cause drifting snow, thereby accentuating the precipitation shadow effect.

An example of the concentration of high precipitation in the south-east part of the ice cap can be seen from the observations of 11 and 12 August 1965 when the glaciological field party was held up by strong easterly winds and heavy snowfall. In two days at lat. $74^{\circ}9' N.$, long. $81^{\circ}7' W.$ (1,032 m. a.s.l.) the snowfall amounted to 7.0 cm. water equivalent. Subsequent measurements showed that north of this point the snowfall over the same period decreased, so that 17 km. farther north-west (1,153 m. a.s.l.) it amounted to only 1.5 cm. water equivalent. At higher altitudes and on the north-west side of the ice cap there was no more than 1.0 cm. water equivalent additional accumulation.

The greatest percentage variations in snow accumulation from year to year occur on the west and north-west sides of the ice cap. For example, in the spring of 1963 the mean snow depth on the north-west and south-west sides of the ice cap was 70 per cent higher than in the spring of 1962. On the south-east side, the snow depth was only 17 per cent higher. The increase was most noticeable towards the ice-cap margins in the south-west and north-west. Whereas in 1962 the winter snowfall formed only 30 per cent of the total water-equivalent accumulation up to the spring and autumn snow the remainder, in 1963 the winter snowfall formed 50 per cent of the water-equivalent total in the south-west and north-west. On the south-east side, in the region of high accumulation, there was almost the same mass of winter accumulation in each year. In 1965, on the north-west and south-west sides of the ice cap, ca. 40 per cent of the September–May accumulation fell during the winter and the remainder in the autumn of 1964. In the south-east about 50 per cent was deposited in the winter.

The other source of increased winter or summer accumulation towards the ice-cap margin is from precipitation during unstable conditions produced by the ice/rock contrast at the edge of the ice cap. Cumuliform cloud was frequently observed around the edge of the ice cap (personal communication from B. Holmgren) and R.C.A.F. aerial photographs taken during the summer months show a line of cumuliform cloud along the north-west edge of the ice cap. Some precipitation is caused by this instability in summer but it amounts to only a few centimetres of snow. As the surface contrast is reduced in winter with the arrival of a snow cover on the plateau, it is doubtful whether instability of this type has an appreciable effect in that season.

Frequent re-distribution of winter precipitation by katabatic winds allows local effects of changes in slope to become pronounced. Undulations in the surface are a characteristic of the ice cap towards its margin and these major irregularities in slope often approach to within a few kilometres of the summit. Their effect is to re-distribute snow with maximum accumulation on the concave part of the slope and minimum accumulation (often zero) on the convex brow. This variation in accumulation has an important later effect on the course of melt-water formation, superimposition of ice and ablation in general.

Summer accumulation

The accuracy with which winter accumulation can be measured cannot be repeated at the end of summer because the probing technique is no longer practical due to re-freezing of melt water in the current budget year's snow pack. There is also very little time available for field measurements between the end of the melt season and the end of the field season. The final positive mass change picture is therefore less accurate than the interim spring one. It is also impossible to determine summer accumulation accurately in the ablation zone except by direct measurement of precipitation. As summer precipitation control was maintained at only two sites in the ablation zone, it is intended to discuss briefly summer accumulation only for the firn zone.

Summer accumulation usually bears a positive relationship to altitude (Table I), but

TABLE I. SUMMER ACCUMULATION, SOUTH-WEST TRAVERSE, 1963

<i>Altitude</i>		<i>Accumulation</i>
m.	a.s.l.	cm. water equivalent
1,729		13.8
1,636		13.9
1,555		12.9
1,469		12.0
1,410		7.6
1,370		8.3
1,200		7.7

this relationship is not sufficiently marked to effect a final positive relationship between altitude and the budget year's accumulation which in the south-east is still strongly inverse. In 1961 and 1962, summer precipitation formed less than 10 per cent of the total budget year's accumulation above the firn line on the north-west side of the ice cap (i.e. < 1.0–2.0 cm. water equivalent in 10.0–20.0 cm. water equivalent). In 1962, summer accumulation was everywhere of a very low order (generally 5.0 cm. water equivalent), but the south-west side of the ice cap bore the greatest increases (up to 7.7 cm. water equivalent). 1963, with a much higher summer precipitation (a mean of 10.0 cm. water equivalent over the whole firn zone), similarly showed a very pronounced maximum on the south-west side of the ice cap, where the summer precipitation formed up to 40 per cent of the budget year's positive mass change. In the autumn of 1965 there was time only to examine the south-east and north-west traverses, and the observations showed low summer accumulation on the north-west side (1.0–10.0 cm. water equivalent) but higher accumulation (5.0–17.0 cm. water equivalent) on the south-east side. All that can be said from these observations (which exclude 1964 when no attempt was made to distinguish the seasonal boundaries in the annual layer) is that there appears to be higher summer accumulation in the south-west than elsewhere. In autumn the accumulation pattern is relatively even but in winter there is a very pronounced east-south-east high to west-north-west low accumulation trend.

DISCUSSION

The accumulation pattern described in this paper has effected variations in the distribution of the percolation, saturation and superimposed ice zones from one part of the ice cap to another. The altitude of the firn edge reaches its highest elevation in the north-west (1,490 m. a.s.l.), passes through 1,470 m. a.s.l. on the northern side, 1,400 m. a.s.l. across the south-west and eastern traverses, and it is at its lowest elevation in the south-east (1,370 m. a.s.l.). There is a firn outlier in the south-east region where accumulation reaches its maximum and where ablation (even in the very warm summer of 1962) is insufficient to melt all the budget year's snow. The saturation line generally reaches its highest elevation in the north-west (1,350 m. a.s.l. in 1963) and its lowest in the south-east (1,270 m. a.s.l. in 1963). The equilibrium line shows a similar trend and in 1963 it ranged from 860 m. a.s.l. in the north-west to 724 m. a.s.l. in the south-east.

The cause of the accumulation pattern, which in the regional sense is a reflection of the precipitation pattern, is related to the effect of general atmospheric circulation in the eastern Canadian archipelago and the availability of moisture from the surrounding water bodies. The author's own observations from early May to late August in 1961, 1962, 1963 and 1965, and the winter of 1961–62 showed that Baffin Bay was open for at least 4 months every year, as was Lancaster Sound south of the Devon Island ice cap. Jones Sound, west of long. 81.5° W. (roughly west of the northernmost part of the ice cap), remained frozen over from January until July in 1962, but the area east of this remained open throughout the entire winter. In 1961, 1963 and 1965 Jones Sound was frozen over right to Lady Ann Strait by the spring. The *Ice atlas of Arctic Canada* (Swithinbank, 1960) shows that, from approximately 4–5 years of observations, large parts of Lancaster Sound and Baffin Bay are open for at least 75 per cent of the year. It also shows that the likelihood of open water close to the east coast of Devon Island is even greater. Hence there is a greater availability of moisture in the east than in the west during the winter months and, although the records for Resolute Bay (over 300 km. to the west) do not indicate a high frequency of easterly winds at the 800 mb. level, the sastrugi direction on the ice cap does. Benson (1961) found an increase in accumulation with approach to Baffin Bay on the western flanks of the Greenland Ice Sheet. With the evidence set out in this paper, this indicates the importance of Baffin Bay as an influential area of cyclonic activity (Rae, 1951; Hare and Orvig, 1958). It is not yet possible to say to what extent the accumulation pattern is due to the open water itself. Cyclonic activity in

this area is dependent on general circulation and it might produce the present accumulation pattern on the Devon Island ice cap even in the absence of open water in Baffin Bay. If this is so, then a decrease in precipitation might be expected, moving northwards along the west coast of Greenland and on the east coasts of Baffin and Bylot Islands. Some impedence to the movement of cyclones northwards might be presented by the narrowing of Baffin Bay just to the north-east of Devon Island. The Devon Island ice cap might then benefit by higher precipitation on its eastern flanks. Although it may not cause the accumulation pattern on the Devon Island ice cap, the open water in Baffin Bay probably serves to intensify it.

Temperatures from 10 m. depth and below in the firn above 1,780 m. a.s.l. on the ice cap show a gradient ranging from -21.1°C . at long. 81.45°W . (1,858 m. a.s.l.), through -23.3°C . at long. 81.9°W . (1,879 m. a.s.l.) to -24.0°C . at long. 82.45°W . (1,787 m. a.s.l.). There is no decrease in summer melting westwards along this line to effect differences in temperatures at depth in the firn. This gradient once more reflects the influence of cyclonic activity over Baffin Bay and it indicates an increasing severity of winter temperature conditions westwards. Since similar amounts of melt water are formed in summer at each altitude (in fact there is slightly more at the lower but most westerly site), the effect of Baffin Bay on the climate of the ice cap must be reduced to a minimum in summer.

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