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CLIMATIC CHANGES IN ARCTIC AREAS DURING THE LAST TEN-THOUSAND YEARS

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Y. VASARI
H. HYVÄRINEN
S. HICKS

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CLIMATIC CHANGE AND RELATED PROBLEMS IN NORTHERN ELLESMERE ISLAND, N.W.T., CANADA

G. Hattersley-Smith

Defence Research Establishment Ottawa,
Ottawa 4, Ontario, Canada

INTRODUCTION

The Defence Research Board has supported interdisciplinary studies in northern Ellesmere Island since 1953. Drawing on some of the results of this work, I shall first summarize our limited knowledge of the times of onset of (i) the climatic warming leading to general deglaciation and (ii) the subsequent fluctuation towards cooler conditions that led to the growth of ice shelves off the north coast of Ellesmere Island. I shall then review the present status of the Ward Hunt Ice Shelf; describe the unusual oceanographic conditions in Disraeli Fiord that result from the presence of the ice shelf; and look briefly at the peculiar structure of certain glacial lakes in the same area. All these phenomena are directly or indirectly related to climatic change. It will be seen that present climatic cooling appears to be affecting the Ward Hunt Ice Shelf, and I shall provide evidence of the same trend affecting the Gilman Glacier and adjoining ice cap and of a parallel deterioration in sea ice conditions in Nansen Sound. Finally, it will be worth looking at the possible information on past climate that could be obtained from deep coring on one of the main ice caps of northern Ellesmere Island.

INFERENCES ON CLIMATE IN THE LAST 10,000 YEARS

Glacial geological studies indicate that Tanquary Fiord became free of glacial ice at least 6,500 years ago. The evidence comes from radiocarbon dating of marine shells from the highest level at the head of the fiord (6,320 ± 140 BP; GSC-373) and of a sample from a nearby peat deposit (6,480 ± 200 BP; SI-

468). The climatic amelioration that caused deglaciation led to subsequent isostatic uplift at the rate of about 3.5 m/100 yr in the period from 6,500 to 5,000 B.P., as against an uplift of about .25 m/100 yr in the period since 5,000 B.P. (Hattersley-Smith and Long 1967). A long period of river erosion followed the recession of the ice, but after a climatic deterioration within the last 4,000 years glaciers advanced to reoccupy V-shaped valleys (Hattersley-Smith 1969). One such advance was responsible for the damming of Lake Tuborg (Fig. 2; see below). Some time after 3,000 BP ice shelves started to form off the north coast of Ellesmere Island; this approximate date is set by the radiocarbon age of the youngest driftwood so far discovered on beaches behind the Ward Hunt Ice Shelf (3,000 ± 200 BP; L-254D; Crary 1960). In the last 900 years the climate appears to have been relatively stable in so far as there has been little change in the terminal positions of most of the major glaciers, as shown for example by radiocarbon dating of plant material from deposits near the margins of the Air Force Glacier (Tanquary Fiord) and the Gilman Glacier. Both these main glaciers are advancing slightly, although many of the side glaciers have receded from well-marked terminal moraines, probably as a result of the climatic warming centred around 1930 (Hattersley-Smith 1963b, 1969).

THE WARD HUNT ICE SHELF

The ice shelves off the north coast of Ellesmere Island are important as climatic indicators (Hattersley-Smith 1960), as well as being the source area of the floating ice islands of the Arctic Ocean. We have analysed the results of ten years' (1958-68) record of accumulation and ablation on the Ward Hunt ice rise and of three years' (1965-68) on the Ward Hunt Ice Shelf (Fig. 1; Hattersley-Smith and Serson 1970). The net mass balances on the ice rise for the three years 1962-65 were positive, while the net mass balances for the other years on both ice rise and ice shelf were all negative. The records for the ice shelf started only in 1965-66 and refer to surface mass balance; we do not know what is happening on the underside, although in 1969 Dr. J.B. Lyons of Dartmouth College drilled through the ice shelf between Ward Hunt Island and the mainland in 47 m and found salt rather than fresh water beneath. While there is no close correlation between seasonal melt and mean monthly temperatures at Alert, the weather station about 200 km to the east-north-east, quite small deviations from mean summer temperatures appear to determine whether the mass balance is positive or negative. For this reason neither ice rise nor ice shelf should be considered as a relic glacial feature. I am suggesting, on rather meagre evidence perhaps, that we may be seeing the beginning of a period of renewed surface build-up following a period of net surface ablation at least since 1906. We know this date of 1906 because of finding on the surface of the ice shelf in 1954 the debris of one of Peary's camp sites (Hattersley-Smith et al. 1955). Because of the warm summer of 1954 when the net ablation was more than 600 mm H_2O, we once tended to assume that the ice shelf is thinning rapidly as a result of climatic warming and that this is the reason for massive calving in recent decades, as for example in 1961-62 (Hattersley-Smith 1963a). In fact the calving should much more appropriately be related to unusual tidal effects (Holdsworth 1971). To summarize, the ice about Ward Hunt Island has been ablating at an average rate of only about 60 mm/yr since 1958, and has actually been accreting at a rate of about 30 mm/yr since 1963.

We have made other investigations that may have an important bearing on the genesis and maintenance of the Ward Hunt Ice Self; these concern the oceanography of Disraeli Fiord and the limnology of small lakes near the coast to the south of the ice shelf (Fig. 1).

DISRAELI FIORD

The oceanographic data from Disraeli Fiord are of particular interest, for the near-surface waters of this fiord are blocked from the ocean by the Ward Hunt Ice Shelf, which occupies the outer 25 km of the fiord (Keys et al. 1969). South of the ice shelf there is perennial fiord ice or (in summer) limited open water up to the Disraeli Glacier front, a further 25 km. The freeboard of the ice shelf indicates that it is about 40 m thick across the mouth of the fiord. The fiord water was found to be virtually fresh to a depth of 44 m; this layer rests with sharp discontinuity on typical Arctic Ocean water to the bottom in depths of 200 to 300 m. There is a temperature minimum of about -1.7°C below the freshwater-saltwater interface. By contrast, observations in M'Clintock Fiord showed that since the disruption of the ice shelf in this fiord (Hattersley-Smith 1967) the surface water layer had been flushed out, so that temperature and salinity curves were similar to those for Arctic Ocean water off the coast. The situation in Disraeli Fiord raises the question of whether a flow of fresh water to the ocean just beneath the ice shelf, as the fiord receives seasonal melt water from the land, may have enabled the ice shelf to grow by bottom accretion of ice during the 3,000 years (maximum) of its existence (Crary 1960). A number of measurements indicate that tidal currents exist from the bottom up to 50 m depth, but that no measurable motion occurs above this level. The fresh water at 44 m is within 0.1°C of its freezing point, which makes it very likely that, locally at least, ice is accreting at the base of the ice shelf.

GLACIAL LAKES

In 1963 we discovered old sea water near the bottom of Lake Tuborg (Fig. 2) beneath 50 m of freshwater, and concluded that the lake had been cut off

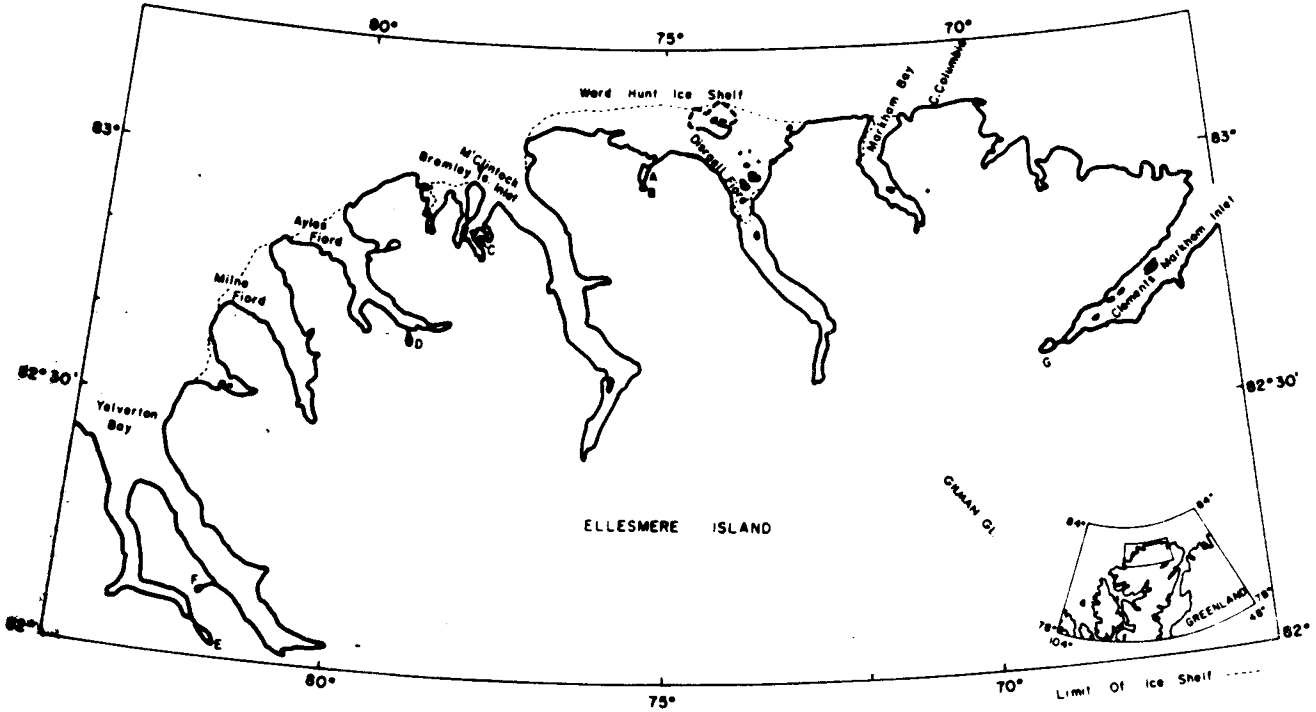
80°
75°
70°
83°
82° 30'
82°
Ward Hunt Ice Shelf
Markham Bay
C. Columbia
M'Clintock Inlet
Bromley Is.
Ayles Fiord
Milne Fiord
Yelverton Bay
Disraeli Fiord
Clements Markham Inlet
Gilman Gl.
ELLESMERE ISLAND
GREENLAND
84°
78°
104°
48°
A
B
C
D
E
F
G
Limit Of Ice Shelf ----

Fig. 1.

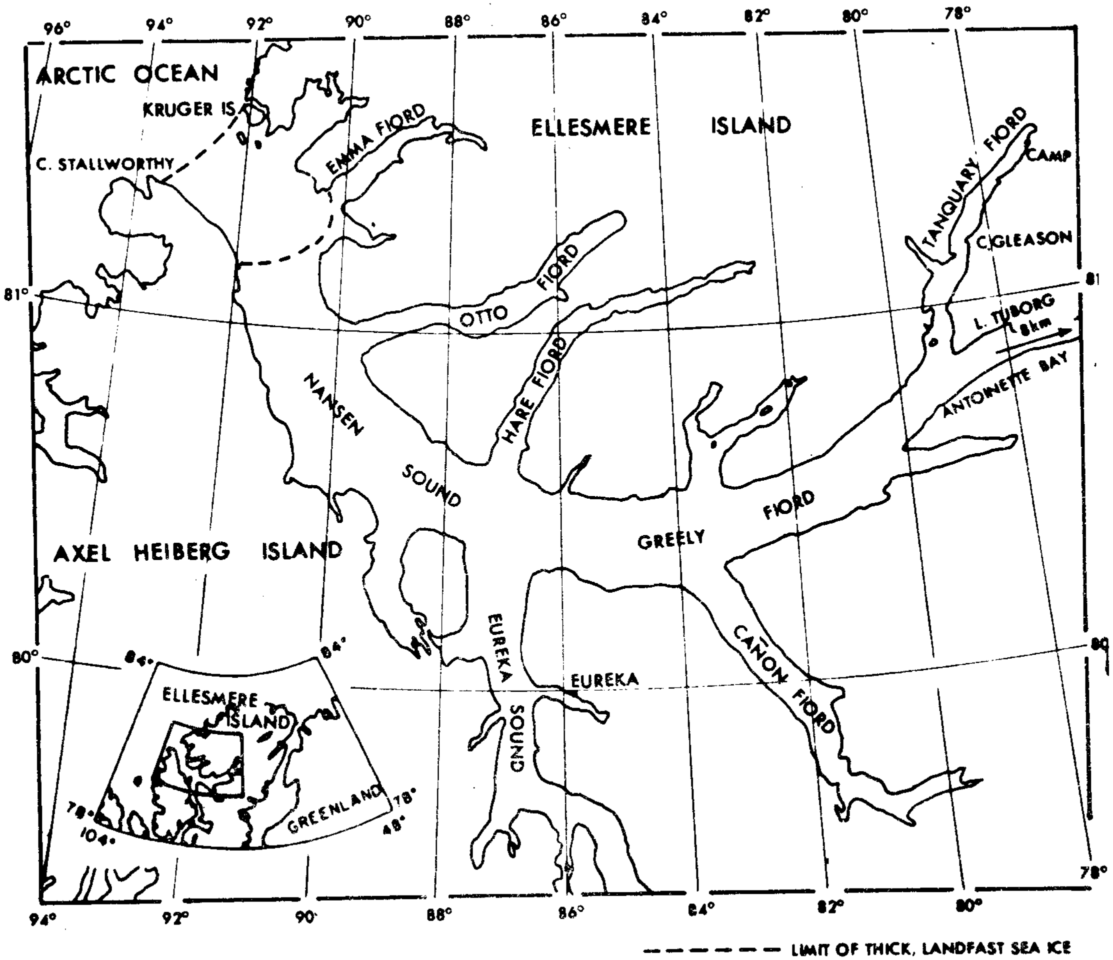
ARCTIC OCEAN
KRUGER IS.
C. STALLWORTHY
EMMA FIORD
ELLESMERE ISLAND
TANQUARY FIORD
CAMP
C. GLEASON
OTTO FIORD
L. TUBORG
8km
ANTOINETTE BAY
HARE FIORD
NANSEN SOUND
GREELY FIORD
AXEL HEIBERG ISLAND
EUREKA SOUND
EUREKA
CAÑON FIORD
ELLESMERE ISLAND
GREENLAND
96°
94°
92°
90°
88°
86°
84°
82°
80°
78°
81°
80°
104°
48°
LIMIT OF THICK, LANDFAST SEA ICE

Fig. 2.

from Greely Fiord by advance of the glacier that now dams the western end of the lake (Hattersley-Smith and Serson 1964). The radiocarbon age of the seawater indicated that the lake was cut off about 3,000 years ago (Long 1967). We were thus alerted to the possibility that other lakes in the area might contain old seawater trapped either by glaciers or by post-glacial rise of land. For this reason, in 1969, we decided to investigate lakes near the north coast of Ellesmere Island. Three of the lakes visited (lakes »A», »B», and »C» in Fig. 1) showed density stratification similar to that observed in Lake Tuborg, with temperature maxima as high as +10°C at depths of 15 m. We concluded that seawater was trapped in these lakes by post-glacial rise of land, and attributed the warm layer to the trapping of solar radiation beneath a permanent ice cover (Hattersley-Smith et al. 1970). It is hoped to obtain a radiocarbon age for the seawater in one of these lakes (»B» in Fig. 1) which is at an elevation of 23 m above sea level. In this way we may arrive at a rate for the post-glacial uplift on this coast and be able to decide what effect it had on the development of the ice shelves.

GILMAN GLACIER AND ADJOINING ICE CAP

Returning to the idea that northern Ellesmere Island has entered a period of cooler summers, we may look briefly at results of studies on the Gilman Glacier and adjoining ice cap (Fig. 1). After work there in the spring of 1967, following previous work (Hattersley-Smith 1963b), we concluded that the four summers 1963-66 were the coldest sequence of summers since before 1925, that the former percolation facies of the ice cap above 1,800 m had been changed to an almost dry-snow facies, and that the equilibrium line on the glaciers had been lowered to an elevation of about 900 m from a mean of about 1,200 m above sea level for the years 1957-63. Further work by R.B. Sagar in 1968 indicated highly positive net budgets for the period 1962-67 (c. +230 x $10^6 m^3$ H_2O) and for the year 1966-67 (c. +50 x $10^6 m^3$ H_2O). It is of interest to note that cool summers in 1963, 1964 and 1965 resulted in sharply positive mass balances on the ice cap of Devon Island (R.M. Koerner, personal communication).

NANSEN SOUND

We might expect the recent cooler summers off the north coast of Ellesmere Island to have caused build-up of fast ice, as for example in Nansen Sound (Fig. 2). A good deal of information has been obtained by our field parties on sea ice thicknesses in the Nansen Sound fiord system. First-year ice, which covers most of the inner parts of the fiords, ranges in thickness from 2 to 2.5 m in Tanquary and Greely fiords. However, in Hare and Otto fiords first-year ice as thin as 1.15 m can occur, probably because of deeper snow cover in these fiords. Second-year ice, which is frequently found in the outer parts of the fiords and is common in Nansen Sound, reaches thicknesses of 3 to 3.5 m. Much older sea ice is also encountered, and near the mouth of Nansen Sound there is a plug of multi-year ice that is believed not to have broken up for at least eight years. From field work in May 1969, H. Serson concluded that the ice plug reaches a thickness of 6 m or more over an area of about 1,000 km^2, from a line joining Kruger Island to Cape Stallworthy southward to a line running southwestward from Emma Fiord to the coast of Axel Heiberg Island (Fig. 2). We plan detailed investigations of this interesting feature, which we suggest relates to cooler summers since 1962, following the warmer post-1925 period that was recognized in our earlier glaciological work (Hattersley-Smith 1963b). It seems that ice conditions at the northern end of Nansen Sound are getting back to what they were in the early part of this century, when travellers reported very old unbroken floes. Indeed R.E. Peary's description in 1906 suggests that an ice shelf covered the mouth of Nansen Sound at that time (Peary 1907). By contrast, in 1932, H.W. Stallworthy reported new pressure ice over this area (Polar Record 1934).

It is clear therefore that present climatic conditions off the north coast of Ellesmere Island allow very thick, landfast sea ice to form up to the point where it may be regarded as incipient ice shelf. On the one hand, the ice plug in Nansen Sound could improve ice conditions in the channel to the south by barring the drift of ice from the Arctic Ocean. On the other hand, the ice plug should favour the build up of a surface layer of freshwater from runoff, and this could lead to a thickening of the ice to the south. In this connection it is worth noting that studies of a relict plankton fauna in the glacially dammed Lake Tuborg lead to the likely conclusion that the waters of the Arctic Archipelago were of generally lower salinity 3,000 years ago than today (Bowman and Long 1968), a condition that could have been caused by blockage of channels leading from the Arctic Ocean by ice shelves.

It is perhaps not unreasonable to suggest that we may now be facing a period of worsening sea ice conditions in the Canadian Arctic Islands of which shipping authorities should be aware. It is well known that ice conditions off Iceland have deteriorated in the last few years (Kristjansson 1969), and ice conditions off east Greenland in 1969 were the worst in more than a hundred years (B. Fristrup, personal communication). At the same time, if the ice plug in Nansen Sound does reach the status of an ice shelf, defined as landfast ice with a freeboard of more than 2 m, it might acquire some legal significance from an extension of practice in Antarctica where ice shelves are »assimilated to land».

POSSIBLE FUTURE INVESTIGATIONS

It would certainly be of interest to know more about the climatic history of northern Ellesmere Island over the last few thousand years. A promising way of doing this would be to put down a deep corehole on the large ice cap northwest of Tanquary Fiord, although there are no present plans for undertaking such work. Radar sounding in 1966 showed that this ice cap is up to 800 m thick; to the west it feeds the Otto Glacier which is a rare example of a high Arctic glacier that is known to have surged (Hattersley-Smith et al. 1969). Deep pit studies on the ice cap in 1970 showed that the mean annual accumulation over the last 20 years is about 140 mm H_2O. This means that a core through the deepest part of the ice cap might represent a time span of 5,000 to 6,000 years, extending well back into the Climatic Optimum. The information on climatic fluctuations to be gained from a deep ice core in northern Ellesmere Island might be far more detailed and relevant to areas bordering the Arctic Ocean than the information gained so brilliantly from the deep core at Camp Century, Greenland (Johnsen et al. 1970). The higher elevations of the ice cap in Ellesmere Island are within the zone where the greatest variations of surface melting between cold and warm summers are likely. The stratigraphy is therefore typified by layers of bubbly ice, representing cool periods, and layers of clear of less bubbly ice, representing warmer periods. These features should facilitate climatic deductions from core analysis and confirm results from oxygen isotope analysis. There is the further possibility that radar sounding can be used to correlate reflecting horizons within the ice over wide areas. It is suggested that the effect of minor climatic fluctuations on ice stratigraphy is more marked in Ellesmere Island than in Greenland where the ice sheet by its very size must act as a damper on climatic change. The recent work in Greenland (Johnsen et al. 1970) shows a cyclicity in climatic oscillations and leads to the prediction of a continued cooling trend over the next 10 to 20 years, which agrees well with the trend that we see in northern Ellesmere Island. It is likely that similar work in northern Ellesmere Island would uncover valuable new data bearing on climatic cycles and relevant to the present status of both land and sea ice in this area bordering the Arctic Ocean.

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Discussion

J. Labeyrie:

If I understand the process of ice-shelf formation correctly, some supercooled water below the base of the ice layer (at the contact with the sea) is continuously transforming into ice crystals, and the ice-layer is therefore continuously growing from this inferior face.
We have therefore, along a vertical cut, the inverse situation of that which happens in a normal sedimentation process, e.g. on the bottom of a lake receiving sediments. In the case of the ice-shelf the upward accretion of crystals is continuously smoothing the eventual irregularities of the bottom.

G. Hattersley-Smith:

We believe - although we have no proof - that ice is accreting at the base of the ice shelf by the freezing of cold, perhaps supercooled, fresh water. If this is so, the accretion should tend to smooth out irregularities of the undersurface of the ice shelf.

W. Blake, Jr.:

Is there any morphological evidence at the inner edge of the ice-shelf? What is happening where the ice-shelves meet the coast, and how long ago did they first form?

G.H.-S.:

At the edge of the Ward Hunt Ice Shelf, near the moat that separates the ice shelf from the land, there is in one area an irregular line of large and small boulders. These can only have arrived on the ice shelf by sliding down ice ramps, which must formerly have existed as shorefast features connecting the ice shelf with the land.

W. Blake, Jr.:

I wonder, have such boulder lines been found on the raised beaches? This might provide evidence as to how long ago ice shelves existed along the northern coast of Ellesmere Island.
Do any ice shelves extend so far up-fiord that they meet glaciers and if so what is happening there? Do the ice shelves then go over to the Antarctic type?

G.H.-S.:

I have not made a special effort to find boulderlines on raised beaches. The ice shelf in Milne Fiord is continuous with the very large trunk glacier at the head of the fiord, but this ice shelf definitely does not go over to the Antarctic type. By radio-echo sounding we have shown a sharp change in ice thickness at the point of junction between glacier ice and ice shelf. There is some deformation of the ice shelf by the glacier, for the two features do *not* move as a unit.

J. Malaurie:

Can you be kind enough to point out the main differences between your curve and Dansgaard's curve concerning temperature for the last 10,000 years?

G.H.-S.:

I have not made a detailed comparison with Dansgaard's curve as I do not have enough positive dates. I can only say that Tanquary Fiord was clear of glacial ice by 6,500 years ago (when peat was already forming at the head of the fiord), that there was a glacial advance in at least one area about 3,000 years ago and that the Ward Hunt ice shelf is not more than 3,000 years old.

Y. Herman:

Today ice islands fridt freely throughout the Arctic basin and gradually melt. By basal melting shallow water organisms and coarse minerogenic debris incorporated in the ice islands are dropped onto the sea floor.
Would you assume that during periods of solid, permanent sea-ice cover over the entire Arctic basin ice islands would not be able to move throughout the Arctic, and hence no displaced shallow water organisms would be found in the central basin during these intervals?

G.H.-S.:

If there was a solid, permanent ice cover over the entire Arctic Basin, I have no doubt that it would prevent the transport into the Arctic basin of shallow water organisms and mineral debris by breaking shorefast ice, calving ice shelves and glaciers.

W. Blake, Jr.:

Ice islands do move through the Arctic Islands even though there is a heavy pack ice cover - presumably they must have moved through the Arctic Ocean in the same way despite the heavy pack ice cover.

H.H. Lamb:

I am greatly interested in the observations of the amount of increase in thickness of the sea ice in the Ellesmere fjords during the colder years sice 1961. One sometimes hears, or sees, apparently contradictory statements that the polar pack-ice is not thickening. Such disagreements probably depend on region and must occur because of differences of experience in different parts of the Arctic.
The pattern of the atmospheric circulation has changed in the recent colder years in such a way that situations with three cold troughs in the upper westerlies have become much commoner instead of the previous prevalence of one or two. Hence the greatest cooling seems to be around Novaya Zemlya and Franz Josef Land where cyclonic cold situations have become frequent. The thickening of the sea ice should be greatest around there, but it should also be great towards N. Greenland because of more frequent northerly winds associated with the Novaya Zemlya cyclones.

G.H.-S.:

I note Prof. Lamb's remarks with interest. My observations do not refer to the ice conditions in the Arctic Ocean, but strictly to the ice of the fiords and channels in and about Northern Ellesmere Island. I agree that statements about the increase in thickness of ice in the Arctic Ocean are based on insufficient or ill founded data.

A. Weidick:

Since the ice cap of northern Ellesmere Island is covering a substratum of very rugged topography, the dating of ice cores will be extremely difficult, because of complex flow patterns.

G.H.-S.:

Dr. Weidick is quite right. The ice caps of northern Ellesmere Island cover a mountainous sub-glacial topography. It would be necessary to choose a site for deep coring with great discrimination. It is partly for this reason that the ice cap of Devon Island (where the bedrock is relatively smooth) was chosen by Dr. W.S.B. Paterson for the first deep coring in the Canadian Arctic Islands, although an ice cap in Northern Ellesmere Island was also considered.

J. Labeyrie:

Have you been able to determine the rate of accumulation in the last ten years or so by looking at the position of the characteristic bomb debris layers?

G.H.-S.:

In 1961 we took samples in a deep pit on an ice cap in Ellesmere Island at 1800 m to see if we could detect bomb debris, but the results of analyses at Chalk River Atomic Research Establishment were inconclusive.