A TEMPERATURE PROFILE THROUGH THE MEIGHEN ICE CAP, ARCTIC CANADA

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ABSTRACT

Temperatures were measured in a 121 m borehole through the small (85 km^2) ice cap on Meighen Island, Arctic Canada. The ice cap is virtually stagnant: thus advection of ice is not a factor in determining the temperature distribution. Temperatures below 10 m depth were in the range −16 to −18 °C. Below 100 m, temperature varied linearly with depth at a rate which corresponds to a geothermal heat flux of 0.8×10^{-6} cal cm^{-2} sec^{-1}. The shape of the temperature—depth curve over the range 20 to 100 m can be explained if one assumes that (1) the mean annual temperature at the surface has decreased by some 1.5 °C since the year 1940 and (2) the mean annual surface temperature was increasing during the period 1880-1940, the total increase being about 3.5 °C.

RÉSUMÉ

Les températures furent mesurées dans un trou de forage d'une profondeur de 121 m percé dans la petite calotte glaciaire (85 km^2) de l'île Meighen située dans l'Arctique canadien. Cette calotte glaciaire est presque sans mouvement, de sorte que ses températures ne subissent pas l'influence de la glace venant des niveaux plus élevés. Les températures au-dessous de 10 m de profondeur se trouvaient dans la tranche −16 °C à −18 °C. Celles au-dessous de 100 m variaient linéairement avec la profondeur à raison d'un flux géothermique égal à 0.8×10^{-6} cal cm^{-2} sec^{-1}. On peut expliquer la relation température-profondeur telle qu'elle est indiquée par la forme de la courbe qui se dessine entre 20 et 100 m, comme étant conforme à l'hypothèse suivante : (1) que la température annuelle moyenne de la surface a diminué d'à peu près 1.5 °C entre les années 1940-1965 et que (2) entre les années 1880-1940 la température annuelle moyenne de la surface s'est accrue de 3.5°C au total.

INTRODUCTION

In 1965, a borehole was drilled through the thickest part of the small ice cap on Meighen Island. The main purpose was to obtain cores for study of the ice cap's history. In this paper, temperature measurements in the borehole are described and an attempt is made to explain the shape of the temperature-depth curve.

THE MEIGHEN ICE CAP

Meighen Island (latitude 80° N, longitude 99° W) lies in the northern part of the Canadian Arctic Archipelago. An ice cap, roughly oval in outline and about 85 km^2 in area, covers part of the island. The ice cap does not reach the sea at any point. The highest point on the ice cap, which is also the highest point on the island, is 268 m above sea level and lies some 2.5 km from the southern margin. The borehole, which reached the base of the ice at a depth of 121.2 m, was about 250 m (in distance) south of the highest point. This is the region where the ice is thickest. A gravity survey by Hornal (unpublished) indicated that the land under the ice cap has only gentle undulations. Arnold (1965, 1966) has described the ice cap in detail. His second publication includes a map at scale 1:25,000. (On this map, the borehole is shown some 350 m north of its true position.)

Arnold (1965) made mass balance measurements from 1959 to 1962: these have been continued by the author. The net balance of the ice cap has been negative in 5 of the 7 years of record. Values have ranged from $+35$ to -108 gm cm^{-2} yr^{-1}. In two years the whole ice-cap was an ablation area; in one year there was a gain in mass at all points. At the borehole, the average mass balance for the years 1959-1966 was -15 gm cm^{-2} yr^{-1}, the average accumulation (c^* in Meier's notation) 14 gm cm^{-2} yr^{-1}. Any mass gain on the ice cap is normally in the form of superimposed ice; but a thin layer of firn may remain at the higher elevations in exceptional years. Examination of the core from the borehole shows that formation of superimposed ice has been the normal mode of accumulation throughout the life of the ice cap.

Ice flow in the vicinity of the borehole is expected to be extremely small, as the surface slope there is only about 1°. The position of a stake, set in the ice at this location, was determined in 1960 and again in 1964. No movement was detected. These measurements were part of a survey of stakes in different parts of the ice cap. The surveys were sufficiently accurate to detect a movement of about 30 cm yr^{-1}. Except perhaps for one stake where the results were on the borderline of statistical significance, the positions were unchanged. This result was not unexpected as the ice is cold (-16 to -18 °C) and at none of the stakes does the calculated basal shear stress exceed 0.3 bar. Koerner (not yet published) has measured the c-axis orientation of crystals in samples from different depths in the core. The absence of any strongly preferred orientations, even in the basal ice, "strongly suggests a lack of past or present ice movement".

From study of the cores, Koerner has reached other conclusions which are important to the interpretation of the temperature profile. These are:

(1) The ice cap is not a remnant of a large Wisconsin ice cap, but probably began to form 2000 to 3000 yr ago;
(2) There is no evidence that the ice cap (at the borehole) has ever been more than 15 or 20 m thicker than it is now;
(3) A period of negative mass balance (at the borehole) began some time during the present century. The ice cap has thinned by between 5 and 15 m during this period.

Methods

The borehole was drilled by the author using a thermal coring drill designed by the U.S. Army CRREL for holes less than 500 m deep in cold ice. The meltwater produced is pumped into a tank inside the drill. After each 1.6 m the drill is raised to the surface for removal of core and meltwater. The diameter of the hole is about 15 cm. The top 3 m were cased to keep out surface meltwater.

When the base of the ice cap appeared to have been reached, the drill was kept running for several hours; but it only progressed 1 or 2 cm. The drill came to the surface coated in mud and the drill head was marked, as if by stones, in two or three places. For these reasons, it is considered certain that the borehole reaches the base of the ice.

Temperatures were measured with a Fenwal Type GB32J2 thermistor. The thermistor was lowered down the hole and allowed to remain for 20 to 30 minutes at each depth before measurements were made. At least four readings were made at each point. Measurements were always made starting at the top and working downwards. Temperatures at the bottom were also measured with two other thermistors as a check. Resistances were measured on a six-place Wheatstone Bridge. The voltage was kept sufficiently low for self-heating of the thermistor to be negligible. The thermistors were calibrated beforehand at the Applied Physics Division of the National Research Council of Canada, and the calibration checked after each season's measurements.

The calibration had an accuracy of ± 0.01 °C, so the accuracy of absolute temperatures cannot be better than this. However, in the field, the thermistor resistance was read to the nearest ohm, which corresponds to a temperature interval of 0.0015 °C. Temperature differences between adjacent points may therefore be accurate to better than ± 0.01 °C.

Temperatures were measured ten days after drilling was completed in July 1965, and again in June 1966 and May 1967. Temperatures down to a depth of 20 m vary during the year and so the different sets of readings cannot be compared with each other. Below 20 m, the 1965 temperatures were consistently higher than the others; the differences ranged from 0.03 to 0.12 °C. These differences almost certainly resulted from heating of the ice by the drill. Below 20 m, the 1966 and 1967 measurements were in close agreement. The mean difference between them was 0.005 °C, the maximum difference 0.027 °C. This close agreement suggests that, by 1966, the drilling disturbance had died away. The differences remaining can probably be ascribed to inaccuracies in measurement. (The signs of the differences may be non-random however. Between 45 and 80 m the 1966 temperatures are the lower; elsewhere the reverse is usually the case. This cannot be explained at present.)

In addition to these measurements, the thermistor was lowered to the bottom of the hole at intervals during the drilling, and readings taken every few hours over a period of 12 to 20 hours. These were analysed as follows. At each depth, temperature was plotted as a function of time after drilling stopped. Temperature decreased with time and at a decreasing rate. With two exceptions, equilibrium temperatures, obtained by extrapolating these curves, were within 0.05 °C of the temperature measured 10 days after drilling was completed. The two exceptions can probably be attributed to incomplete removal of meltwater from the hole at these points. Temperatures measured during drilling were always measured at the (then) bottom of the hole, with the thermistor touching the ice. Their agreement with subsequent readings, after allowance is made for drilling disturbance, indicates that the latter should not have errors due to possible convection of air in the borehole, or because the thermistor was not necessarily in contact with the ice. Also, calculations show that temperature gradients in the borehole are about an order of magnitude smaller than the theoretical gradient required for the onset of convection. (The gradients in the top few metres are a possible exception.)

Results

Temperature measurements, except those made during drilling, are listed in table I. Interpretation of the results in terms of long-term changes in temperature has been restricted to measurements at depths greater than 20 m. Figure 1 shows this part of the temperature-depth curve. Means of 1966 and 1967 measurements have been used. The standard error of each mean is estimated to be 0.01 °C.

Comparison with other temperature profiles

Almost all ice cap temperature profiles so far published have shown a negative temperature gradient (decrease of temperature with increase of depth) in the top 100 or 200 m and sometimes to greater depths. See, for example, papers by Robin (1955), Bogoslovski (1958), Hansen and Landauer (1958), Mellor (1960), Gow (1963). An increase in mean annual temperature at the surface of the ice cap, during the years when the ice was being deposited as snow, would explain the negative gradient. Robin (1955) pointed out that ice flow could provide an alternative explanation. Ice

TABLE I

Temperature (°C) measured

Depth (m)	1965	1966	1967
1.32			−22.416
2.24			−23.122
3.15			−22.729
4.06			.032
4.57	−17.36	−20.043	
4.72			−21.359
5.18		−19.770	
5.33			−20.791
6.10		−19.255	.078
7.62	−18.83	−18.526	−18.850
9.14		−17.795	.047
10.67	−18.04	.393	−17.489
12.19		.079	.252
13.72			.164
15.24	−17.19	.013	.124
16.76		.051	.118
18.29		.201	.119
19.81		.099	.121
21.34			.116
22.87	−16.98	.101	.104
24.38			.088
30.48	.91	.027	.031
38.10	.87	−16.954	−16.962
45.72	.84	.916	.909
53.34	.80	.865	.855
60.96	.74	.816	.800
68.58	.68	.744	.718
76.20	.61	.674	.656
83.82	.52	.567	.580
91.44	.43	.477	.490
99.06	.31	.375	.372
106.68	.19	.222	.249
114.30	.07	.099	.121
121.16	−15.89	−15.962	−15.957

at depth has flowed from higher parts of the ice cap, where it was laid down as snow at the lower air temperatures prevailing there. Mellor (1960), however, considered that most of the observed negative gradients were too large to be attributed solely to ice flow. He therefore concluded that climate must have changed as well.

The profile in the Meighen Ice Cap is unusual in that, although the temperature gradient decreases with decrease of depth, at no point does it become negative. The profile does however resemble one measured by Bogoslovski (1958) in "almost stagnant" ice near Mirny Station, Antarctica. The lower portion of Bogoslovski's temperature-depth curve is linear. He interpreted its gradient as the geothermal gradient. He attributed the reduction in gradient in the upper part of the profile to the effect of the small amount of ice flow.

On the Meighen Ice Cap, the temperature profile was measured near the highest point of an ice cap which is virtually stagnant and which is unlikely to have ever been much thicker than it is now. Any explanation in terms of ice flow is therefore excluded. In the next section, an attempt is made to explain the profile in terms of recent changes in surface temperature.

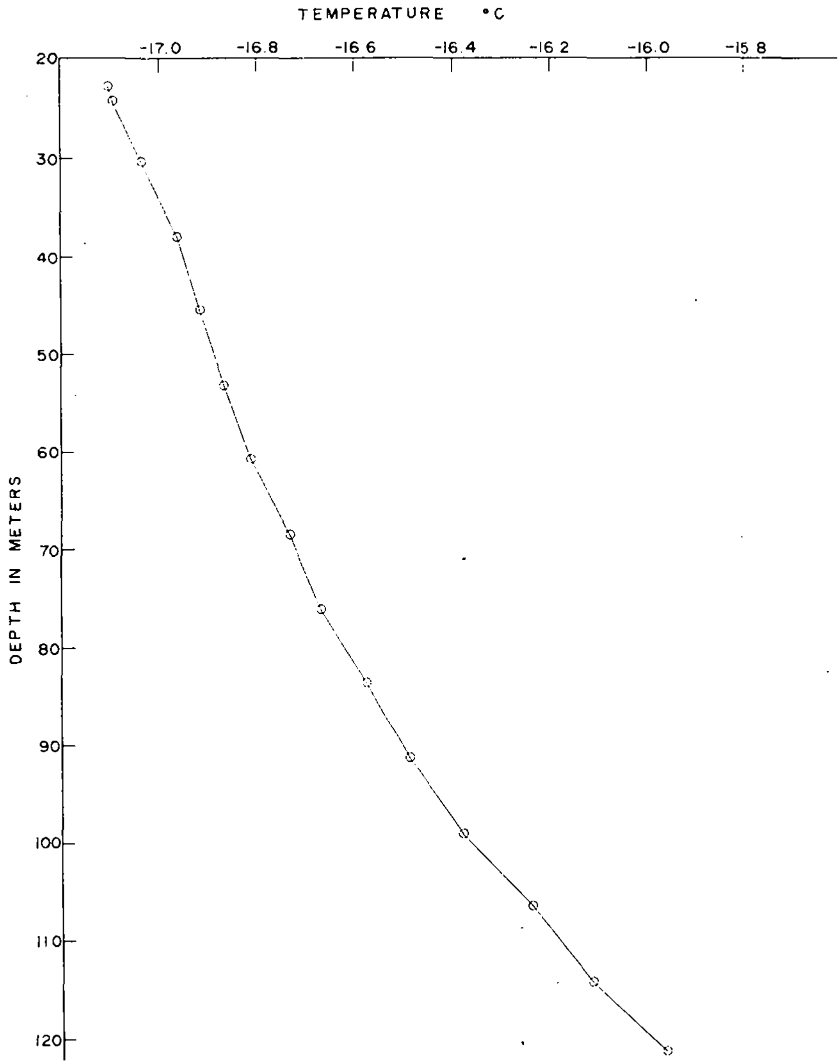

Fig. 1 — Measured temperature profile.

Interpretation of temperature profile

In the following analysis, the ice cap is regarded as a semi-infinite medium, of uniform thermal diffusivity, with its surface temperature a given function of time. The solution of the equation of heat conduction for this case gives the temperature at different depths and times. One tries various functions for the surface temperature, and various times periods, and selects that for which the solution fits the observations satisfactorily.

One must also assume an initial condition, that is, what form the temperature-depth curve had at the time when the surface temperature started to change. The simplest assumption is that the ice cap was isothermal. This is not realistic however. The next simplest assumption is that the temperature gradient was the same at all depths. Whether such a condition could have existed depends on the ice cap's history. The analysis in Appendix I provides some justification for taking a uniform gradient as the initial condition. In the observations (fig. 1) the four lowest points lie close to a straight line of gradient 0.0187 °C m^{-1}. This value is taken as the initial gradient. It corresponds to a geothermal heat flux of 0.8×10^{-6} cal cm^{-2} sec^{-1}, or about 55 per cent of the world-wide average value.

In this analysis, the net mass balance of the ice cap at the borehole is assumed to be zero. The vertical velocity term in the heat conduction equation can then be omitted. This assumption will be justified later.

The equation of heat conduction thus reduces to

$$\partial\theta/\partial t = k\partial^2\theta/\partial y^2 \tag{1}$$

Here θ denotes temperature, t time, y depth below the surface and k thermal diffusivity.

Let T denote the deviation of each observed temperature from the assumed initial temperature. (In fig. 1, T is the horizontal distance between each point and the straight line which would pass through the lowest four points.) Thus

$$T = \theta - \theta_0 - Gy$$

where $G = 0.0187$ °C m^{-1} and θ_0 is a numerical constant. If θ is a solution of equation (1), T will obviously be a solution also. Thus we try to determine a function $T(0, t)$ for the surface temperature, so that the corresponding solution $T(y, t)$ equals the observed temperature deviation at each depth y. An harmonic function was taken,

$$T(0, t) = A \cos \omega t \tag{2}$$

The solution for this case is given by Carslaw and Jaeger (1959, p. 65), namely

$$T(y, t) = A \exp\left(-y\sqrt{\omega/2k}\right) \cos\left(\omega t - y\sqrt{\omega/2k}\right) \tag{3}$$

There is also a transient term in the solution. We assume that this can be neglected. This implies that the surface temperature has been of the form (2) for several cycles.

Values of $T(y, t)$ were computed at different depths y, for various values of amplitude A, time t, and ω where $2\pi/\omega$ is the period of the oscillation. Figure 2 shows the temperature-depth curve for $A = 1.75$ °C, $2\pi/\omega = 120$ yr, and $\omega t = 1.3$ or $t = 25$ yr. The observed deviations from the linear temperature gradient are also shown in figure 2. All the observations are within 0.02 °C (or twice the estimated standard error of the observations) except for the points at 22.9 and 30.5 m. The differences there are about 0.03 °C.

The curve for $A = 2$ °C, $2\pi/\omega = 100$ yr, $\omega t = \pi/2$ or $t = 25$ yr also fits the observations fairly well. If the period is decreased to 75 yr or increased to 150 yr, agreement becomes much less satisfactory. Curves based on the solutions for $T(0, t)$ a linear function of time, and a step function, do not fit the observations very well.

The values $A = 1.75\,^{\circ}\mathrm{C}$, $2\pi/\omega = 120$ yr, $t = 25$ yr in equation (2) imply that the surface temperature is now $A(1-\cos\omega t)$ or about 1.5 °C below its maximum value. Thus the interpretation is that during the past 25 yr the mean annual surface temperature on the Meighen Ice Cap has decreased by about 1.5 °C. For about 60 yr before this the temperature was increasing; the total increase amounted to about 3.5 °C.

If this interpretation is correct, temperatures in the upper part of the borehole should be decreasing at present, while those in the lower part should be increasing. Calculations show that such changes are too small to be detected over an interval of

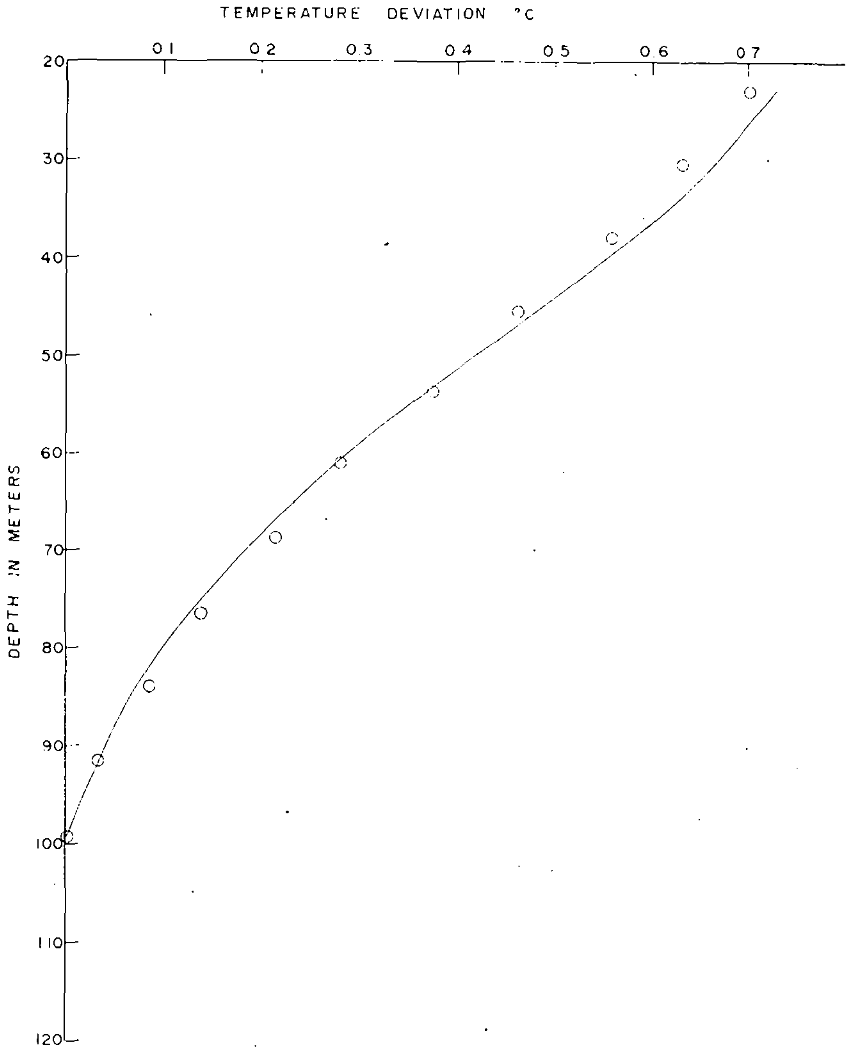

Fig. 2 — Comparison of theoretical curve with observed temperature deviations (points).

1 yr. But if, as expected, the borehole remains open for several more years, it should be possible to check this.

Two assumptions made in the analysis have to be justified. First is the assumption that the level of the ice surface remains constant. In fact, at the borehole site, the ice cap is at present losing an average of 17 cm of ice a year. It is likely that this trend started sometime during the present century. (Koerner, unpublished.) The change in surface level will affect the temperature distribution in the ice. However, an ablation rate of 17 cm yr^{-1} for 50 yr means a loss of 8.5 m of ice. At the maximum temperature gradient in the borehole (0.0187 °C m^{-1}), 8.5 m represents a temperature change of 0.16 °C. This is small compared with the postulated changes of surface temperature. Thus it is adequate to assume that the surface level of the ice cap has remained unchanged during the recent changes of surface temperature.

The second assumption is that thermal diffusivity does not vary with depth. In ice caps in which the uppermost 50 or 100 m consist of firn one must allow for the lower diffusivity of firn compared with ice. In the Meighen Ice Cap however, even the surface layers consist of ice; the only firn occurs in a few thin layers at various depths. In this case it is sufficiently accurate to use one value of diffusivity throughout. The value taken was 0.01 cm^2 sec^{-1}. This was derived from the position, in the temperature profile, of the maximum corresponding to the previous summer's maximum surface temperature. This value is relatively low. For example, Cameron and Bull (1962) obtained a value of 0.015 cm^2 sec^{-1} for glacier ice at Wilkes Station, Antarctica. Use of their value in the present analysis would reduce the time scale by about 18 per cent.

Relation between surface and air temperatures

The interpretation has so far been in terms of "surface temperature" by which we imply the mean annual temperature of the surface layers of ice. This is not necessarily equal to the mean annual air temperature. In some cases these may not even be positively correlated. Krenke (1961) has pointed out that a decrease in mean annual air temperature might transform part of an ice cap from an area of superimposed ice accumulation to one where firn is formed. All the summer meltwater would then refreeze in the firn. The increased supply of latent heat would increase the temperature of the near-surface layers. In such a case, mean annual surface and air temperatures would be negatively correlated. However, superimposed ice formation has always been the dominant mode of accumulation on the Meighen Ice Cap. In this case, mean annual surface and air temperatures will probably be positively correlated. The correlation may not be very high however, because one factor in warming the surface ice is the latent heat released as superimposed ice is formed. The amount of superimposed ice will vary from year to year and is unlikely to be closely related to variations in mean annual air temperature.

The inferred trend in surface temperature (increase until about 1940, decrease thereafter) does however agree with the recent trend of mean annual air temperatures in the Arctic. See, for example, a paper by Mitchell (1961). Comparison with records of individual weather stations seems hardly justified: the station nearest to Meighen Island which has a record of adequate length is Upernavik in West Greenland, some 1300 km away. The present results are also consistent with those of a study by Hattersley-Smith (1963). He examined a core from an ice cap in northern Ellesmere Island, some 500 km north-east of Meighen Island. He found that the number of ice layers in the firn had decreased since 1940 and interpreted this as a trend towards cooler summers.

Summary

Any application of a mathematical model to a physical situation involves simplifying assumptions. In the present case we have assumed:

1. Variations of mean annual surface temperature for the past 100 yr or more can be represented by a simple cosine law;
2. Previous to this, there was a period in which the temperature gradient in the ice cap was the same at all depths;
3. This uniform temperature gradient was equal to the present gradient in the lowest 20 m of the ice cap.

In addition to these assumptions, we have used a history of the ice cap derived from indirect evidence and have extrapolated mass balance data for the past 7 yr to longer periods of time.

If these assumptions are made, one can obtain a theoretical temperature-depth curve which fits the observations closely at all depths below 20 m. This suggests that the relation assumed for the surface temperature is a good approximation. This relation indicates that the mean annual surface temperature at the borehole site has decreased over the past 25 yr. Before this, the temperature increased for some 60 yr. Estimated magnitudes are an increase of 3.5 °C, followed by a decrease of about 1.5 °C.

APPENDIX I

The initial condition

The problem is to determine whether the Meighen Ice Cap has been in existence long enough for a uniform temperature gradient to have been established in it. An analysis by Tien (1960) can be used to study this.

The ice cap is assumed to have uniform and constant physical properties, and to grow at a constant rate U from zero initial thickness. There is a constant geothermal heat flux Q at its base. The surface temperature changes at a constant rate A per unit time. (By this last relation one can allow for the fact that snow will be deposited at progressively lower temperatures, as the ice cap surface rises during its growth. The relation could also be interpreted as a climatic change.) To obtain a solution of the heat conduction equation, one must also assume that no geothermal heat escapes from the ice cap surface.

The solution is

$$T = T_0 - Qy/K + (A/U + Q/K)\, h(1-\delta) \qquad (4)$$

Here T is the temperature at height y above the base at time t after the ice cap started to grow, T_0 is the initial temperature at the base, h is the ice thickness at time t, K is thermal conductivity, and δ is a function of y and t defined by

$$\delta = \frac{8}{\pi^2} \sum_{n=0}^{\infty} (2n+1)^{-2} \cos\left[\left(n+\frac{1}{2}\right)\pi y/h\right] \exp\left[-\left(n+\frac{1}{2}\right)^2 \pi^2 kt/h^2\right]$$

Here k is thermal diffusivity.

Since the cosine is numerically less than 1, since the exponential term has its greatest value when n is zero, and since

$$\sum_{0}^{\infty} (2n+1)^{-2} = \pi^2/8$$

it follows that

$$\delta < \exp(-k\pi^2 t/4h^2)$$

for all values of y.

Now $k = 31.5 \text{ m}^2 \text{ yr}^{-1}$ and if we assume that the ice cap grew to a thickness of 120 m in 1000 yr, we find that δ is less than 0.005. This is small compared with unity and so can be neglected in equation (4). This equation then shows that the temperature gradient in the ice cap is linear and equal to the geothermal gradient. Thereafter, the temperature gradient will remain the same if the ice thickness and the surface temperature do not change.

The actual history of the ice cap will of course have been much more complex than assumed here. However we have shown that a uniform gradient is not inconsistent with what is known about the ice cap's history. As information is insufficient to derive any more complex initial condition, a uniform gradient has been taken.

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DISCUSSION

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In confirming the observations of the author I wish to mention that we have observed in Central Greenland (Station Jarl-Joset) slight indications of a "cold lake" dating back to the last century (10 m depth).