THE GLACIOLOGICAL STUDIES OF THE BAFFIN ISLAND EXPEDITION, 1950

Part IV: THE HEAT EXCHANGE AT THE SURFACE OF THE BARNES ICE CAP DURING THE ABLATION PERIOD

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Abstract. The heat exchange takes place in two stages: (i) the atmospheric heat causes melting of the whole of the annual snow accumulation and leads to the formation of slush rivers; (ii) some of the melt water refreezes to form a new layer of ice superimposed on the original ice, which is warmed by the latent heat yielded to it. A theoretical estimate of the rate of formation of the superimposed ice, and of the temperature change in the original ice, is given, which agrees reasonably with the actual measurements. A rough measurement of the melt water run-off checks with the observations of ablation and superimposed ice. The total energy available for melting is estimated approximately from the meteorological observations; it underestimates the actual ablation. About 70 per cent of the total ablation energy (47 cm. water, total ablation) is disposed of as melt water that is discharged from the ice cap surface; the remainder goes as sensible heat to the low temperature ice.

Résumé. L'échange de chaleur a lieu en deux phases: (i) la chaleur de l'atmosphère fait fondre la neige accumulée au cours de l'année et cause la formation de rivières de boue glacée; (ii) une partie de l'eau de fusion gèle à nouveau et forme une nouvelle couche de glace superposée à la première, laquelle est réchauffée par la chaleur latente qui lui est transmise. L'article donne une estimation théorique de la raison à laquelle se forme la couche de glace superposée et du changement de température dans la première glace; cette estimation s'accorde assez bien avec les résultats provenant de mesures réelles. La mesure approximative des ruissellements de l'eau de fusion permet vérifier les observations concernant l'ablation et la couche de glace superposée. L'énergie totale disponible pour l'ablation est estimée approximativement à partir des données météorologiques; le résultat sous-estime l'ablation réelle. Environ 70 pour cent de l'énergie totale d'ablation (ablation totale de 47 cm. d'eau) est absorbée par l'eau de fusion ruisselant de la surface de la calotte de glace, le reste est transmis sous forme de chaleur sensible à la glace de basse température.

Introduction

No permeable firn and only a thin layer of superimposed ice remained in the accumulation zone of the Barnes Ice Cap at the end of the ablation season. It is therefore of interest to examine in some detail the exchange of heat energy between the atmosphere, the melting snow, and the ice during the melting period. It will be noted from Part I * of this series of articles that, in effect, two simultaneous heat exchanges occur within a small vertical distance of each other, (1) at the snow surface, the atmospheric heat turns snow into water, and (2) at the original ice surface, some of this water is transformed back into ice and its latent heat is yielded downwards. The second stage of the heat exchange will be considered first, because it is of particular significance in Baffin Island.

Our studies were restricted to the ablation season, but it is important to realize that the stability of the ice mass is influenced considerably by the thin covering of snow in winter. Less than 1 m. of snow, density about 0·33 gm./cm.^{3}, exists during the coldest winter months and it allows the underlying impervious ice to be cooled to a large depth at all altitudes. The snow cover is quite uniform because, first, there is little change in altitude, except within a few kilometres of the edge, and secondly, wind drift causes much smoothing. The melt water cannot descend very far in summer, as it does in a deep bed of firn, and consequently most of the summer heat does not enter the ice cap, but is disposed of laterally in the form of melt water that is discharged completely from off the ice cap surface. There are not very substantial differences between the conditions at the summit and at the edge of the ice cap, particularly in winter. The main, but small, encouragement for plastic flow of the ice arises from the rather greater summer ablation quite close to the edge of the ice cap.

Ground Temperature Observations

The equipment described in Part III † was used to measure the temperature in the snow and ice at (i) Camp A1, altitude 865 m., (ii) in the ice at Camp A2X, 530 m., (iii) in massive gneiss rock

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* Parts I and II, *Journal of Glaciology*, Vol. 2, No. 11, March 1952, p. 2–23.

† Part III, *Journal of Glaciology*, Vol. 2, No. 12, November 1952, p. 115–21.

at Camp A2Y, 445 m., see Part I,* fig. 2, and Part II,* fig. 1. The duration and depth of the temperature records vary appreciably at these sites and each record is only of limited value. The records at Camp A1 are of most value, since they cover the whole ablation season, but they are too restricted in depth.

(*a*) *Camp A1*

The observations at this site are plotted with time in the lower part of Fig. 1 (below). The gap in the observations during August arose because the recorder was in use at the other two camps and it was not possible to transfer it on account of the difficulties of travel. The depths of the observations in the snow are given as 15 and 60 cm. from the surface, but the depths are nominal, because adjustments in depth did not always keep pace with the accumulation and settling of the surface snow. The observations in the ice are at depths of 25,147 and 300 cm. below the original ice surface. The site of the 147 and 300 cm. observations is about 50 m. distant from the position of the other observation points. The temperature distribution with depth is given for the days 23 and 30 June, 15 July, and 1 and 27 August in Fig. 2 (p. 160). The full line curves in both the above figures are theoretical and are discussed later. The temperature observations should be considered in relation to the air temperature variation, the depth of snow and of superimposed ice given in Part I, Figs. 7 and 10.

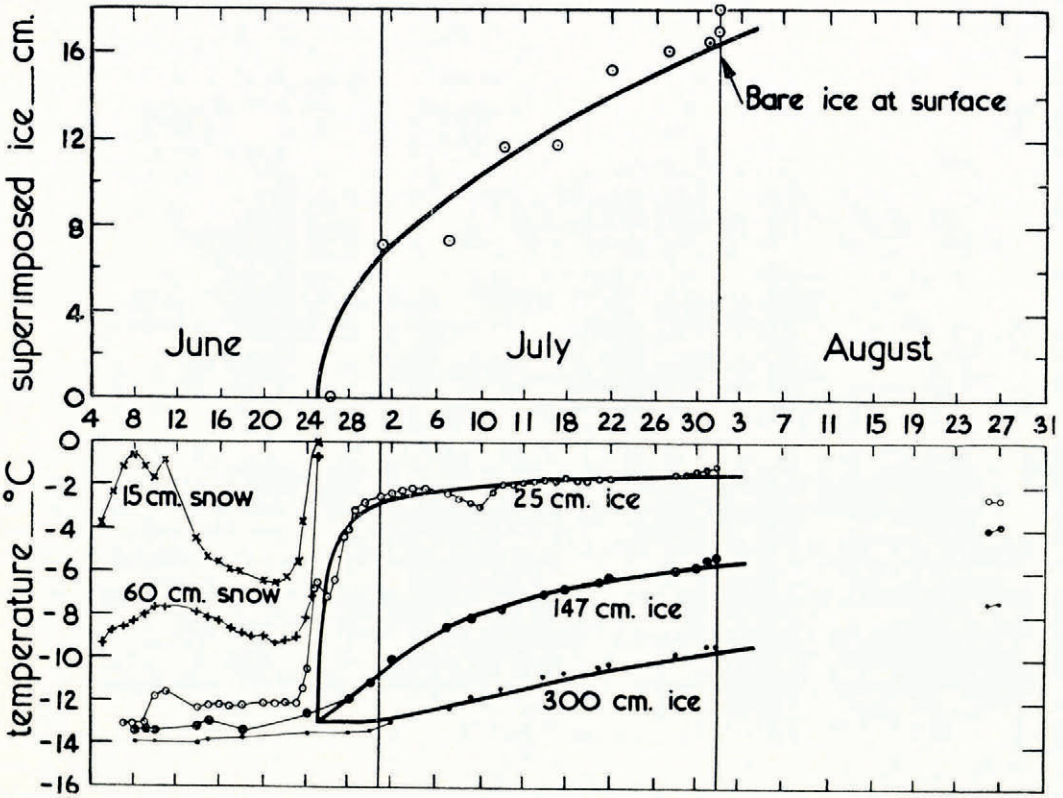

Fig. 1. The upper part of the figure shows the increase in thickness of superimposed ice with time, the lower part shows the changes in temperature of the snow and ice. The heavy curves in both parts of the figure are theoretical; the observations are plotted as points. The site is Camp A1

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* Parts I and II, *Journal of Glaciology*, Vol. 2, No. 11, March 1952, p. 2–23.

(*b*) *Camp A2X*

The observations in the ice here are restricted to the latter part of July and the month of August, after the snow had melted away; they are plotted with time in the upper part of Fig. 3 (p. 161). The depths of the measurements are at 246,475 and 930 cm. relative to the ice surface on 3 July; the fall in the level of the surface (ice ablation, $\rho=0\cdot91$) is given. The ice became cleared of snow about 26 June at this site. For the period of measurement, the temperature remained constant at $-10\cdot7°$ C. at 930 cm.

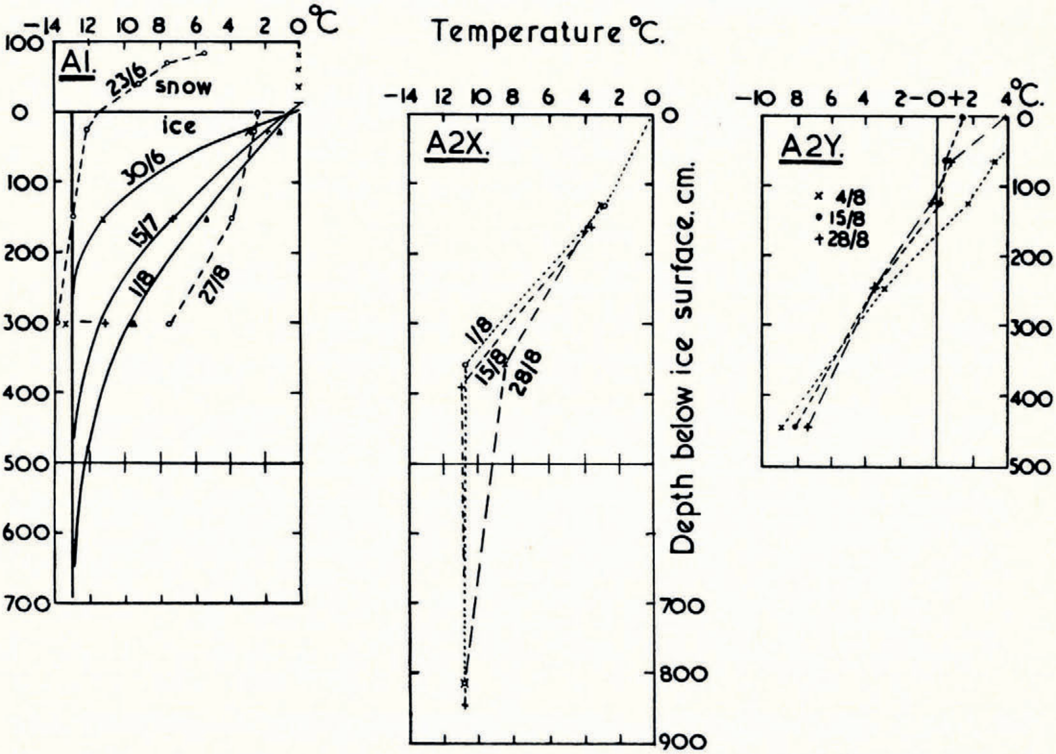

Fig. 2. The distribution of temperature with depth in the ice at camps A1 and A2X, and in rock at camp A2Y, on selected dates. The full-line curves on the A1 diagram are theoretical

(*c*) *Camp A2Y*

The observations in the gneiss rock are limited to August; they are plotted against time in the lower part of Fig. 3, and against depth in Fig. 2. During this period the ground is beginning to cool down, because of the lower air temperature and the considerable cloud cover in August. The maximum depth of the 0° C. isothermal appears to be about 160 cm. This depth may be rather large because several fissures in the rock may have access to air at a horizontal distance of about 15 metres, when the ice has thawed out of them. The snow cleared from the rock surface about 15 June and no permanent snow existed by the end of August.

The temperature–depth observations at all three sites are assembled together in Fig. 2 for purposes of comparison. The atmospheric conditions at A2X and A2Y must be very much the same, and because the specific heat per unit volume of gneiss is about $1\cdot3$ times the value for ice it is evident that much more heat has been transferred into the rock than into the ice in the summer. The data are not sufficient to warrant quantitative discussion, but clearly at A2X heat is lost continuously in melting ice, while at A2Y, the rock surface is clear of snow longer and the absorptivity of that surface is comparatively large.

The Melting of the Snow and the Formation of "Slushers"

The process of heat exchange between the snow and the ice, particularly at Camp A1, can be followed from the description of the method of nourishment in Part I. Before we arrived at the end of May, the layer of low temperature snow must have warmed appreciably. Further snow storms in June decreased its temperature (see Fig. 1), and on 21 June the snow temperature was lower than it had been at the beginning of the month.

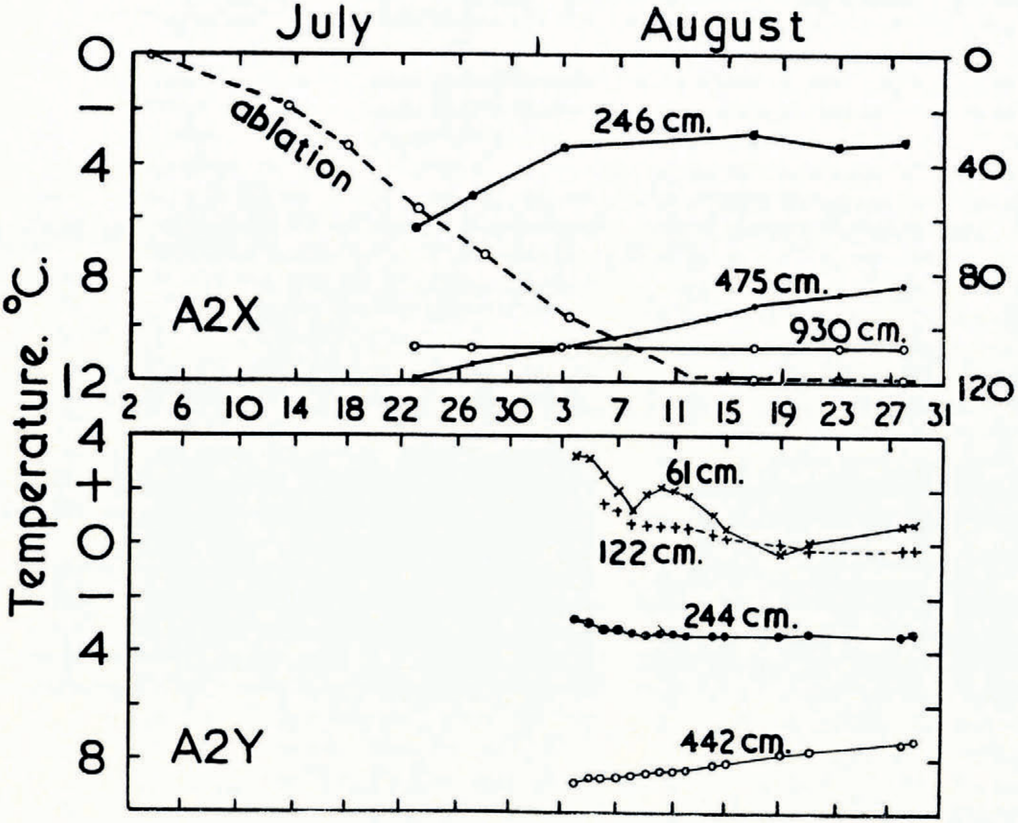

Fig. 3. Change in temperature with time: upper part, in ice at Camp A2X together with ice ablation; lower part, in rock at Camp A2 Y

Summer came suddenly. Between about midday of 23 June and the evening (or perhaps rather earlier in the day) of 25 June, the whole of the snow reached its melting point and the temperature at 25 cm. deep in the original ice rose suddenly. Apart from a slight fall in temperature in the upper part of the snow during storms around 10 July, the snow continued to melt until it had disappeared at the beginning of August.

No heat can be conducted through the melting snow because there is no thermal gradient, but the melt water percolating downwards transports heat. The water, on reaching the ice surface, refreezes because of the strong thermal gradient there. The melt water in yielding latent heat to the ice, raises its temperature and reduces its thermal gradient, which in turn reduces the rate of yielding latent heat and the rate of formation of superimposed ice.

Inspections always showed excess water standing on the ice during the ablation period, but the local dip in the 25 cm. ice temperature curve around 10 July indicates a short drought. Apart from this, the rate at which melt water accumulated was greater than the rate at which it was able to yield latent heat to the cold ice beneath.

The amount of water that accumulated on the ice in places was excessive. At first the excess melt water seeped to the bottoms of slight valleys and later to local flat areas. In both cases the melt water rose to meet the descending snow surface. The surface became blue. The capillary tension in the snow was then almost zero and the snow had become saturated slush with the flow properties of water. Consequently, in the gentle valleys with a gradient of only 1°, the entire layer of slush commenced to flow suddenly like a river. Such rivers were commonly called "slushers." The movement started violently in a limited area soon after the surface appeared blue and, as it progressed downhill, an ever-increasing quantity of slush became gathered in the limited width of the saturated zone. Thus the turbulent surface of the slusher rose in waves above the general level of the surrounding snow surface. In this situation the edges of the slusher were able to drain slightly, the capillary tension acted again, and narrow levees of drained slush were formed that tended to confine the moving slush and to maintain a high flow channel.

The whole of the slush from a channel 10 km. long could be discharged in a couple of hours. Thereafter the channels became open melt water rivers with hard ice beds and the water from the surrounding snow layer slowly seeped in, just as an ordinary river drains the sub-soil. The ice bed of the channel deepens because it is cleared of snow and exposed to radiation earlier than the surrounding ice.

In the vicinity of Camp A2 the slushers occurred on 25 June and around Camp A1 on 18–20 July. Their occurrence is influenced by both the state of the ablation process and by the topography of the catchment area. The slushers commonly occur in the same channels for a number of years, but not always, because abandoned branches were found late in the ablation season. Old courses become by-passed, particularly where a valley broadens and flattens, on account of the violent start of the slushers, their high flowing tendency, and the slow distortion of the ice.

The refreezing of the descending melt water continued on the surfaces surrounding the melt water rivers (there were about six major rivers between Camps A1 and A2) until the new ice appeared at the surface. This happened at Camp A2 about 13 July and at Camp A1 about 31 July.

When winter set in during August the melt water rivers at Camp A1 were still flowing fairly deep, but by about 12 August the channels had become blocked with drifting snow. The East River was excavated on 25 August. About 1·5 m. of first dry and then wet snow overlaid deep-blue water. The water contained loose rounded ice crystals, the size of a pea, and it was obviously in the process of freezing solid. Some of the water had soaked upwards into the snow drift as though it was a layer of blotting-paper. At Camp A2 no melting of the ice occurred after 13 August. During the rest of that month there was both rain and snow in considerable amounts, but melting continued to prevent the snow lying deep and the melt water channels were still discharging when we left.

MELT WATER DISCHARGE OF THE EAST RIVER

The total accumulation was 48·8 cm., water equivalent, for the budget year 1949/50 at Camp A1, and the amount of superimposed ice remaining as net accumulation was 12·7 cm. of ice (11·5 cm. water equivalent). Hence the total run-off of melt water is about 37 cm., if evaporation, which appears to be quite small, is neglected.

The run-off may be checked roughly from the few discharge measurements that were made of the East River adjacent to Camp A1. The river catchment above the camp was estimated to be 4·5 km.^{2}. The channel section was sounded and the surface water velocity measured by timing surface floats with a stop-watch on three occasions. The time of these records and the mean run-off in cm. of water per day, assuming a ratio of mean channel velocity to channel surface velocity of 0·7, are given below:

Time			*Run-off* (*cm./day*)
July 22.	22.45 hr.	. .	1·7
July 29.	11.00 hr.	. .	1·5
July 30.	19.00 hr.	. .	1·7

The depth of the river water did not vary noticeably, except during the initial outburst lasting a few hours, when it started as a slusher on 18 July. The flow became well blocked with snow drifts during a snowfall of 12 cm. on 12 August and therefore the river had discharged the total run-off of about 37 cm. in 26 days at a fairly uniform rate of 37/26 = 1·4 cm./day, a value that agrees surprisingly well with the roughly measured discharges.

Theoretical Analysis of the Rate of Increase of Superimposed Ice and of the Temperature Change in the Ice at Camp A1

It is possible to make a theoretical check on the total amount and rate of accumulation of superimposed ice and the temperature changes in the original ice at Camp A1 by the theory of heat conduction.

There was a small conduction of heat through the snow layer before melting started. The quantity of heat transferred to the ice in the first three weeks of June was quite small and it is reasonable to assume approximately that the ice temperature was everywhere −13° C. just before the snow melt commenced (see Fig. 1). When the entire snow layer reaches its melting point, no further heat is conducted through it, but the melt water at 0° C. continuously yields latent heat to the ice, refreezes, and raises its surface. The problem is to estimate both the rate at which this surface rises, and the temperature in the ice. Conduction problems of this type have been discussed by Lightfoot (see Carslaw *and* Jaeger,[1] Sections 31 and 107).*

The particular conditions of our problems are shown diagrammatically in Fig. 4 (below).

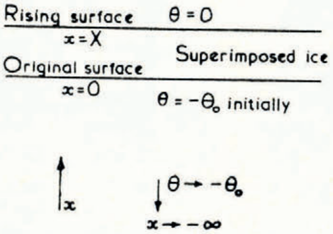

Fig. 4. Boundary conditions for heat conduction problem

The symbols in Fig. 4 and the following equations are as follows:

x	vertical distance, positive upwards (cm.)
θ	temperature (°C.)
t	time (sec). and T (days)
L	Latent heat of fusion of ice (80 cal./gm.)
a	thermal diffusivity of ice (0·011 cm.^{2}/sec.)
ρ	density of ice (0·91 gm/cm.^{3})
K	thermal conductivity of ice (cal./cm.^{2}sec.°C.)
c	specific heat of ice (0·50 cal./gm.°C.)

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* Mr. E. C. Sewell, of the Building Research Station, kindly drew our attention to the solution and helped in the calculations.

The equations to be satisfied are:

$$\theta=0, \quad x \geqslant X \qquad (1)$$

$$\frac{\partial^2\theta}{\partial x^2}=\frac{1}{a}\frac{\partial\theta}{\partial t}, \quad -\infty<x<X \qquad (2)$$

$$\theta \rightarrow -\theta_0, \quad x \rightarrow -\infty \qquad (3)$$

$$\theta=-\theta_0, \quad t=0, \quad x<0 \qquad (4)$$

$$-K\left[\frac{\partial\theta}{\partial x}\right]_{x=X-0}=-L\rho\frac{dX}{dt} \qquad (5)$$

The solution for X, the thickness of superimposed ice, at time t is:

$$X=2A\sqrt{at} \qquad (6)$$

where A is a constant given by:

$$Ae^{A^2}[1+erfA]=\frac{c\theta_0}{L\sqrt{\pi}} \qquad (7)$$

The temperature in the ice, $(x<X)$, is given by:

$$\theta=\theta_0\left[-1+\frac{erfc\left(-\frac{x}{2\sqrt{at}}\right)}{1+erfA}\right] \qquad (8)$$

where $erfA$ is the error function of A, and $erfc\left(-\frac{x}{2\sqrt{at}}\right)$ is $1-erf\left(-\frac{x}{2\sqrt{at}}\right)$

The numerical values of the thermal constants can now be inserted in the above equations. When the snow layer reached its melting point on 25 June, there was a small temperature gradient in the upper part, $x<0$, see Fig. 2. But, from several aspects, it appears that the gradient is of opposite sign below the level of our observations. Hence no large errors are likely if the initial temperature of the ice is taken as $-\theta_0=-13°$ C. Thus substituting in equation (7), $\theta_0=13°$ C., $L=80$ cal./gm., and $c=0{\cdot}50$ cal./gm.°C., we get: $A=0{\cdot}044$.

Then taking $a=0{\cdot}011$ cm.^{2}/sec., equation (6) gives:

$$X=2{\cdot}71\sqrt{T} \qquad (9)$$

where T is in days, and X is in centimetres.

The equation (9) is plotted as a curve in the upper part of Fig. 1, where it will be seen that there is reasonable agreement with the plotted points of Baird's measurements, see Part I.

At values of $-x$ of 25,147 and 300 cm., corresponding to the depths of the actual temperature observations in the ice, the equation (8) becomes:

$$\theta_{25}=13\left(-1+0{\cdot}95erfc\frac{0{\cdot}40}{\sqrt{T}}\right) \qquad (10)$$

$$\theta_{147}=13\left(-1+0{\cdot}95erfc\frac{2{\cdot}3}{\sqrt{T}}\right) \qquad (11)$$

and $$\theta_{300}=13\left(-1+0{\cdot}95erfc\frac{4{\cdot}8}{\sqrt{T}}\right) \qquad (12)$$

respectively.

These equations (10), (11) and (12) are plotted as heavy curves in Fig. 1., lower part, where they provide tolerable agreement with the observations plotted as points.

There is some difficulty in deciding exactly when the accumulation of superimposed ice started. The snow temperature reached the melting point on 25 June, the day before measurements of the thickness of superimposed ice were commenced. But the temperature of the thermistor at 25 cm. in the original ice started to rise rapidly even earlier, and fell somewhat on 26 June. This early rise is probably a false one, because this thermistor was the only one that was not frozen into position with water when installed early in June. Local excess melting, caused by radiation on the vertical thermistor lead near the surface, may have caused a premature descent of melt water. It is assumed that $T=0$ on 25 June. The more rapid rise in the actual ice temperature at the end of July, see Fig. 1., probably arises from radiation penetrating the ice that is almost clear of snow.

The heavy curves in Fig. 2 are calculated from equation (8) for the 30 June, 15 July and 1 August; the plotted points are the corresponding observations. It can be shown that the formation of superimposed ice produces a 0·1° C. change at a depth of 730 cm. in the original ice on 1 August, when the new ice was exposed at the surface.

The formation of superimposed ice is likely to be a common phenomenon on high polar glaciers where the precipitation is small. Table I gives the thickness (cm.) of ice formed for several values of T (days) and of θ_0° C., assuming there is no initial temperature gradient in the ice.

TABLE I

T days	θ_0° C.				
	2	4	8	16	32
5	0·97	1·9	3·7	7·3	14
10	1·4	2·7	5·3	10·3	20
20	1·9	3·8	7·5	14·7	28
40	2·7	5·4	10·6	20·7	40

Table I shows, for example, that 28 cm. of superimposed ice would be formed from adequate melt water descending for 20 days on to the surface of an ice mass, which is initially at a uniform temperature of −32° C.

THE TOTAL HEAT EXCHANGE BETWEEN THE ATMOSPHERE AND THE SNOW DURING THE ABLATION PERIOD AT CAMP A1

Measurements were made by Orvig[3] of the air temperature, the wind speed and the humidity at two or three levels above the ice cap surface at 2-hour intervals from 08.00 to 22.00 hours at Camp A1. Continuous records were kept of sunshine duration with a Campbell-Stokes recorder and of air temperature with a thermograph in the Stevenson screen. The rainfall was measured in the usual way. The observations are deficient therefore in precise measurements of incoming and outgoing radiation (no instruments were obtainable) and in night-time observations of humidity and wind. There is also a gap of 15 days' observations of humidity during the ablation period (a broken sling thermometer could not be replaced on account of travelling difficulties).

The estimate of the amount of heat received by the snow from the atmosphere has been restricted therefore to the total received during the ablation period. The interpretation of the weather data is based on previous semi-empirical studies of the same type.[2, 4, 6, 7]

The heat balance equation[6] during the ablation period, in gram.cal./cm.^{2}, is:

$$80H=\alpha I-R+Q_a+600F.$$

where H denotes total ablation (melting plus evaporation) in cm. of water.
I ,, incoming radiation.
α ,, absorptivity of the snow or ice surface to incoming radiation.
R ,, outgoing radiation.

Q_a denotes heat received from the air layer above the surface.
F ,, amount of condensation in cm. of water, which is negative if evaporation occurs.

In our case, Q_a is always positive because the air temperature increased with height. Except for the last 4 days of the ablation period when ice was exposed at the surface, no heat could be received or lost by conduction from below and the item has been omitted from the above equation. The total duration of the ablation season was 41 days from 25 June, when the snow layer reached the melting point, until 5 August when winter set in. The total ablation is the total accumulation, 48·8 cm., less 5 cm. of rain that fell in July, plus 3·4 cm. of melted superimposed ice, *i.e.* 47 cm. ablation.

Each of the three terms: the radiation $\alpha I - R$, the convection term Q_a, and the condensation term $600F$ are now considered separately.

(*a*) *The radiation term, $\alpha I - R$.*

It appears to be reasonable to take $\alpha = 0{\cdot}4$ for a melting snow surface, and $\alpha = 0{\cdot}6$ for a melting ice surface.[8]

In the absence of incoming radiation measurements it is necessary to use the Angot values I_a (Napier Shaw[5]) of the total radiation to be expected if the atmosphere were perfectly transparent, and to use a general correlation between I, I_a and n/N (the ratio of actual/possible hours of sunshine) in the form $I = I_a(A + Bn/N)$. The values of $A = 0{\cdot}18$, and $B = 0{\cdot}55$ obtained by Penman[4] have been used.

For the ablation period, 25 June to 31 July, when there was a melting snow surface, $n/N = 0{\cdot}29$, $\alpha = 0{\cdot}4$ and $I_a = 34{,}600$ cal./cm.^{2} The corresponding value of αI is 4700 cal./cm.^{2}.

For the short ice ablation period, 1–4 August, n/N is also 0·29, $\alpha = 0{\cdot}6$, and $I_a = 3160$ cal./cm.^{2}, giving $\alpha I = 640$ cal./cm^2.

The total value of αI is therefore $4700 + 640 = 5300$ cal./cm.^{2}, equivalent to an ablation of 67 cm. of water.

The outgoing long-wave radiation from the melting surface is assumed to be 205 cal./cm.^{2}day, when the sky is cloudless. This is the value used by Wallén.[8] For the relation between cloudiness and effective outgoing radiation R, the correlation in terms of duration of sunshine, $R = 205\,(0{\cdot}1 + 0{\cdot}9n/N)$, adopted as a provisional expedient by Penman,[4] is used. The greatest proportion of cloud consisted of stratus forms and fog (about 175 hours). The term $(0{\cdot}1 + 0{\cdot}9n/N)$ becomes identical for fog conditions, $(n/N = 0)$, with the one used by Sverdrup[7] and by Wallén.[8]

For the total ablation period of 41 days, $n/N = 0{\cdot}29$, therefore, $R = 3000$ cal./cm.^{2}.

The radiation term $\alpha I - R$, therefore amounts to:

$$5300 - 3000 = 2300 \text{ cal./cm}^2\text{. or } 29 \text{ cm. ablation.}$$

(*b*) *The convection term Q_a*

This term may be expressed by the equation:

$$Q_a = c_p A \frac{d\theta}{dz} T$$

where c_p is the specific heat of air at constant pressure (0·24 cal./gm.°C.).

A	eddy conductivity (gm./cm.sec.)
θ	potential temperature (°C.)
z	distance above snow surface (cm.)
T	time (sec.)

The value of A at a particular height above the surface is a function of the wind velocity at that height, and of the temperature and wind velocity gradients. It is necessary to examine therefore the variations in temperature and wind velocity with height.

The mean wind velocities during the ablation period at elevations of 213 and 700 cm., according to the six-hourly daytime observations [3] are 400 and 510 cm./sec. respectively. These observations suggest that the wind velocity increases with height according to the equation:

$$\frac{u}{u_1}=\left(\frac{z}{z_1}\right)^{1/n_u}, \text{ where } n_u=4{\cdot}9$$

and u is the velocity at height z.

The mean two-hourly daytime potential temperatures at 92,396 and 700 cm. above the surface are 1·2, 2·4 and 3·1 °C. respectively, and these temperatures vary with height according to:

$$\frac{\theta}{\theta_1}=\left(\frac{z}{z_1}\right)^{1/n_\theta}, \text{ where } n_\theta=2{\cdot}2$$

and θ is the potential temperature at height z.

The indices of the above power laws appear to be reasonable in relation to previous studies, and in these circumstances the equation for the eddy conductivity used by Wallén[8] has been adopted:

$$A=1{\cdot}8\times 10^{-4}u_z\,.\,z^{\left(\frac{n_\theta-1}{n_\theta}-\frac{1}{n_u}\right)}$$

It follows then that the convection term is:

$$Q_a=\frac{1{\cdot}8\times 10^{-4}}{n_\theta}\,.\,c_p\,.\,u_b\,.\,b^{-1/n_u}\,.\,\theta_a\,.\,a^{-1/n_\theta}\,.\,T$$

where u_b is the wind speed at height b, and θ_a is the potential temperature at height a.

On substituting u_b = 400 cm./sec., b = 213 cm.,
θ_a = mean day and night-time screen temperature = 0·9° C.
and a = 92 cm.
we have: Q_a = *1100* cal./cm^2. or *14* cm. water ablation.

(*c*) *The condensation term*

The data on the variation of vapour pressure with height are meagre, for 15 days during the ablation period there is no information. The mean values for the remaining days are as follows:

Height (cm.)	92	700
Temperature °C.	0·9	2·6
Vapour pressure (mm.Hg.)	4·54	4·29

There is a net decrease in vapour pressure with height and hence a net evaporation, but a study of the individual observations shows that the gradient is irregular. Quite often there is an increase in vapour pressure from the surface to 92 cm., followed by a decrease higher up. In these circumstances it is not reasonable to assume that the vapour pressure and the temperature distributions follow the same laws.

Rough estimates show however that the net evaporation is not likely to amount to more than about 0·5 cm. of ablation and can be neglected for our purposes.

SUMMARY OF THE HEAT EXCHANGE

It is convenient to work in cm. ablation units, *i.e.* units of 80 cal./cm.^{2}.

The total measured ablation is *47 cm.* and is made up of 48·8 cm. total accumulation, less 5 cm. rain falling in the melting period, plus 3·4 cm. of melted superimposed ice.

The total ablation accounted for from the atmosphere is the sum of the radiation and convection terms, *i.e.* 29+14=*43 cm.*

It will be noted that the two estimates do not agree. It is considered that the measured ablation is the most reliable value and that the main error probably lies in the incoming radiation estimate. First, a 6 per cent increase in α, which is not known precisely, would account for the error, and secondly, the correlation term for sunshine duration $(0{\cdot}18+0{\cdot}55n/N)$ possibly underestimates the radiation in overcast conditions. Observations in high latitudes, summarized in Wallén[8] show that the incoming radiation during cloudy weather can be considerably greater than the above term suggests, and has a considerable seasonable variation. But in view of the variations between the various high latitude observations there seemed to be no merit in using them in this case.

The 47 cm. of energy received during the melting season is disposed of in the following ways:

(i) the formation of superimposed ice yields 16·5 × 0·91 = 15 cm. as sensible heat to the underlying ice, because equation (5) shows clearly that $\int_0^t K\frac{\partial\theta}{\partial x}dt=\int_0^X L\rho dX$.

(ii) the remainder (about 70 per cent) 32 cm. units together with the 5 cm. of rain is discharged as run-off water to the rivers and lakes surrounding the ice cap. Admittedly, a small amount of this water, which cannot be estimated, yields more heat to the ice by running into the few narrow crevasses and refreezing.

Thus a considerable proportion of the summer energy never enters the ice cap.

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MORE ABOUT ADVANCING AND RETREATING GLACIERS IN PATAGONIA

By LOUIS LLIBOUTRY
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ABSTRACT. Contrary to prevailing opinions, the glaciers of south Patagonia have normally been stationary or have advanced during the last twenty years. Exceptions can be accounted for by a lag due to a long travel through narrow passes or by the lowering of waters in the terminal lake at the foot of a rocky cliff.

RÉSUMÉ. Contrairement à l'opinion admise, les glaciers du Sud de la Patagonie ont été normalement stationnaires ou ont avancé au cours des vingt dernières années. L'on peut rendre compte des exceptions par le déphasage dû à un long parcours à travers des étranglements, ou par un abaissement des eaux dans le lac terminal, au pied d'une barre rocheuse.

THE writer was a member of the French alpine expedition which made the first ascent of Monte Fitz Roy,* lat. 40° 16′ S., on the Argentine–Chilean frontier, and stayed in that district from 25 December 1951 until 15 February 1952.

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* This mountain is shown on some maps as Cerro Fitz Roy, Cerro Chaltel or Fitz Roy Peak.—*Ed.*