ICE TEMPERATURES AND HEAT FLUX McCALL GLACIER, ALASKA

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ABSTRACT

The U.S. National Committee-I.G.Y. supported a research station on the McCall Glacier, Alaska, at 2298/m asl. The station was in operation in the periods May-October 1957, and February-August 1958.

Synoptic and micrometeorological observations were taken as well as ice temperatures, to be used in a study of the energy exchanges between the glacier and its environment. The present paper deals with the ice heat transfer component, based on the ice temperature observations.

In July 1957 a hole was melted into the firn of the highest cirque's accumulation basin, to a depth of 91-½ m. Temperatures were measured by ten thermocouples from 31 July 1957 to 7 July 1958, except during November-February. In addition, temperatures were obtained between the surface and 3 m in another shallow hole. These temperatures were measured at ten different depths from 15 March to 24 June 1958.

Measurements at frequent intervals during the 11-month period showed a very small temperature gradient between 14 m and 91 m. The average of 17 measurements at 1372 cm was −0.9°C; the average at 9144 cm was −1.1°C. Observations indicate that at 7620 cm there was no change of temperature with depth during the period 26 October - 7 July. The shallow hole showed that the 0°C isothermal layer had descended below 3 m by 24 June. The heat transfer through the glacier surface has been computed for eleven periods from 26 October to 7 July, by using the change in mean temperature of each layer of firn and ice within each period. The heat flux has been compared to measured net radiation flux above the surface for periods when melting took place. Enough heat was available by radiation alone to melt 0.6 cm firn per day between 9 June and 7 July.

RÉSUMÉ

Le Comité National des États Unis (I.G.Y.) a fait établir une station de recherche sur le glacier McCall en Alaska, a une altitude de 2298 m au dessus du niveau de la mer. La station fonctionna durant les périodes de Mai à Octobre 1957 et de Février a Août 1958.

Des observations synoptiques et micrometeorologiques ainsi que des températures de glace furent prises afin d'étudier l'échange d'énergie entre le glacier et ses alentours. Ce rapport traite du flux de chaleur de la glace, basé sur les observations de temperature de la glace.

En juillet 1957, un trou fût percé dans le névé du basin d'accumulation d'un des plus hauts cirques, à une profondeur de 91-½ m. Les températures furent mesurées par dix thermocouples du 31 juillet 1957 au 7 juillet 1958 excepté pendant les mois de novembre à févirier. En outre d'autres températures furent obtenues entre la surface et 3 m d'un autre trou peu profond. Ces températures furent mesurées à dix différentes profondeurs du 15 mars au 24 juin 1958.

Les mesures prises à des intervalles fréquents pendant cette periode de onze mois montrèrent une très petite différence entre 14 m et 91 m. La moyenne des 17 mesures à 1372 cm était −0.9°C; la moyenne à 9144 cm était −1.1°C. Les observations indiquent qu'à 7620 cm aucun changement de température en profondeur pendant la période du 26 octobre au 7 juillet. Le trou peu profond indiqua que la ligne isotherme de 0°C était descendue en dessous de 3 m le 24 Juin. La transmission de chaleur à travers la surface du glacier a été calculée pour les onze périodes du 26 octobre au 7 juillet, en employant les différences de températures moyennes de chaque couche de névé et de glace durant chaque période. Le flux de chaleur a été comparé au flux de radiation net (mesure) au dessus de la surface. Assez de chaleur était disponible par simple radiation pour fondre 0.6 cm de névé par jour du 9 juin au 7 juillet.

Introduction

The McCall Glacier is a small valley glacier in the Romanzof mountains of the Brooks Range, at 69°18′N, 143°50′W. The five-mile long glacier heads in three cirques, the highest of which lies between 2130 m and 2350 m asl.

McCall Glacier was occupied in May 1957 by four men, who were to carry out a program of micrometeorology, ice motion studies and ice studies during the International Geophysical Year. In July 1957 a hole was melted into the firn of the accumulation basin of the highest cirque, to a depth of 91 m. Ten thermocouples were passed into the hole, and temperatures were measured frequently from 31 July 1957 to 7 July 1958, except during the months of November, December and January when the glacier camp unfortunately had to be unoccupied.

The hole was melted with an electrical hotpoint, designed and made in the electrical and mechanical shop of the California Institute of Technology. Power was supplied by a 4.9 kw Witte diesel generator. The melting was done over a 27-hour period, and the average rate of descent was 3.4 m per hour. A cable of ten copper-constantan thermocouples was prepared from no. 20 wire, employing a single constantan return. The thermocouples were placed at these levels: 150 cm, 305, 732, 1372, 2195, 3262, 4572, 6096, 7620 and 9144 cm. A Leeds and Northrup portable potentiometer was used for temperature measurements. At least two sets of readings were taken. If second measurements differed from the first by more than 0.005 mv (0.1°C), third reading was made and the two closests values averaged.

Ice temperatures

The initial temperature curve, drawn from measurements on 31 July, showed that the hole was filled with water to within 25 m of the surface. Within another 24 hours the freezing level had descended to 58 m. By 6 August the freezing level had progressed downward to 91 m. A comparison of the 19 October curve with the profile of 30 September indicated that equilibrium temperatures had been reached about one month after the ice had been disturbed.

Measurements at frequent intervals during the 11-month period showed a very small temperature gradient between 1372 cm and 9144 cm. The average of 17 measurements at 1372 cm was −0.9°C; the average temperature at 9144 cm was −1.1°C. The temperature readings for the 7620 cm level for the period 26 October 1957 - 7 July 1958 indicate that at this level there was no change of temperature with depth, i.e., $\frac{\delta T}{\delta z} = 0$. This will be used in the calculation of heat flux, in the following. Figure 1 shows a plot of temperature profiles on certain days.

Temperature profiles were also obtained between the surface and 3 m during the period 15 March to 24 June, 1958. The site of these measurements was about 15 m from the deep hole. Ten copper-constantan thermocouples were placed at the surface and at 26 cm, 51, 75, 100, 133, 166, 200, 250 and 300 cm. On June 9, the first measurements of 0°C were made, the firn was then isothermal at 0°C to 30 cm. By 24 June, the isothermal layer had descended beyond the lowest thermocouple at 300 cm. Figure 2 shows a plot of temperature profiles on certain days.

Heat flux

The equation for heat flux computation may be written as follows: (Portman, 1954):

$$\varrho . c . \frac{\delta T}{\delta t} = k . \frac{\delta^2 T}{\delta z^2} \qquad (1)$$

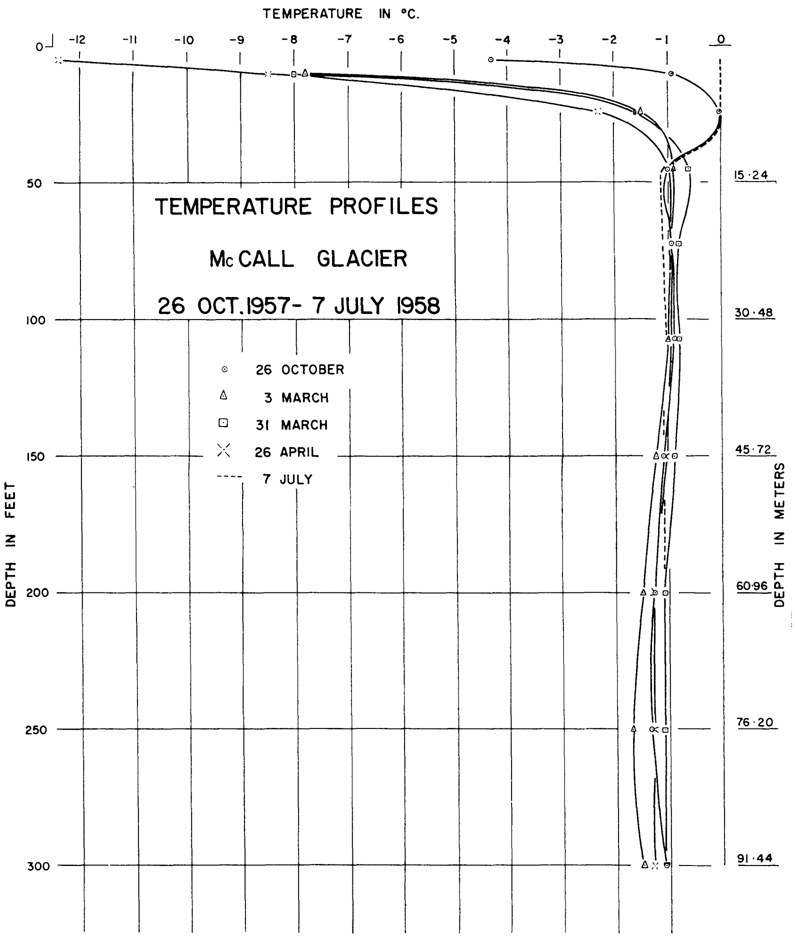

Fig. 1 — Temperature Profiles, McCall Glacier, 26 October, 1957 - 7 July, 1958

where

T = temperature, °C
t = time, seconds
Z = depth, cm
k = thermal conductivity, cal/cm, sec, deg.
ϱ = density, gm/cm^3
c = specific heat, cal/gm, deg.

setting $-k.\frac{\delta T}{\delta z} = q$ (i.e., heat flux in cal/cm^2, sec)

equation (1) can be written:

$$\varrho.c.\frac{\delta T}{\delta t} = -\frac{\delta q}{\delta z} \quad (2)$$

which reduces to (1) if the conductivity (k) is constant with depth.

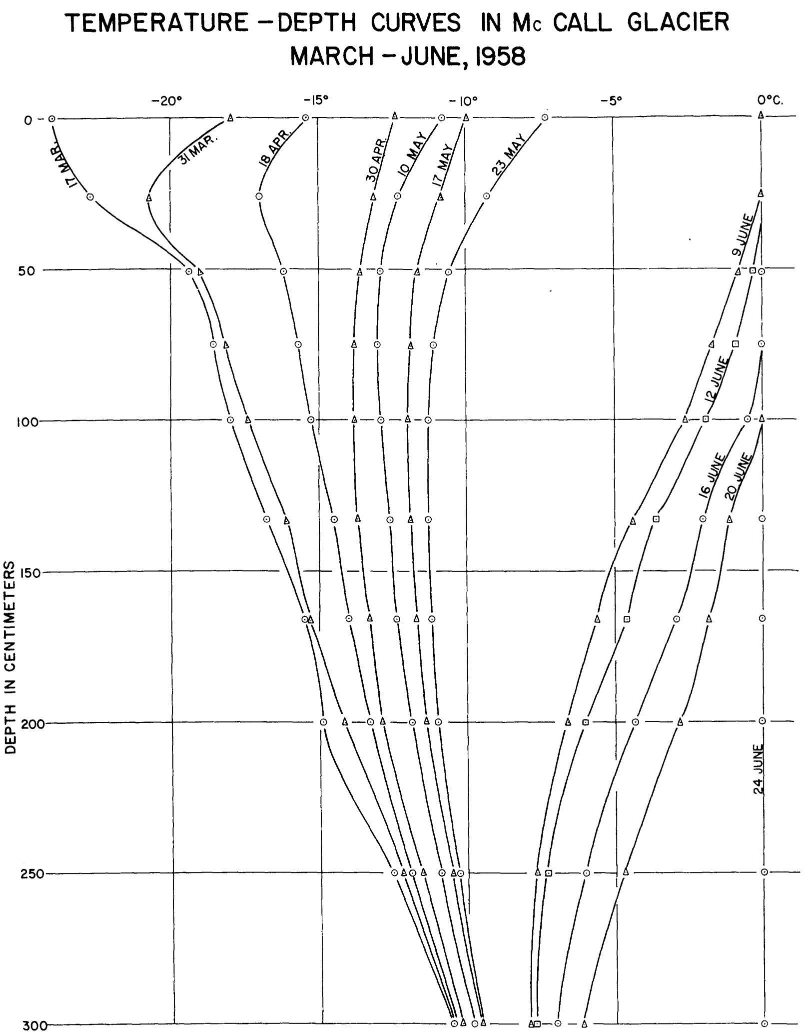

Fig. 2 — Temperature — Depth Curves in McCall Glacier, March-June, 1958

Equation (2) can be multiplied by dz and integrated from the surface ($Z = 0$) to a depth Z:

$$\int_0^z \varrho . c \frac{\delta T}{\delta t} . dz = q_0 - q_z \tag{3}$$

or

$$q_0 = q_z + \int_0^z \varrho . c . \frac{\delta T}{\delta t} . dz \tag{4}$$

To obtain q_0 (heat flux through the surface) from heat capacity ($\varrho.c$) and temperature observations, we must find a depth (Z) where $q_z = 0$; i.e. q_z can be determined by evaluating the integral from the surface to a depth (Z) where $q_z = k. \frac{\delta T}{\delta Z} = 0$. Such a depth may be found from the vertical temperature profiles (Portman, 1954). The heat flux through the surface is then equal to the heating or cooling of the ice column. Information is thus necessary about the values at various depths of density, specific heat and ice temperature.

As mentioned above, the level of no change of temperature with depth seemed to lie around 7620 cm, and this depth was taken for Z in the integration. The surface of the glacier ice was taken to be the 305 cm level. The value for c (specific heat) was taken as 0.48 cal/gm, deg. and the density of the glacier ice was assumed to vary linearly with depth from a value of 0.40 gm/cm^3 at 305 cm to 0.80 gm/cm^3 at 9000 cm.

The following values were therefore used for the glacier ice (not for the top 300 cm):

Thickness (cm)	Depth (cm)	ϱ (density)	c (specific heat)	$\varrho.c$ (heat capacity)
	305	0.40		
427	520 middle of layer A	0.41	0.48	0.20
	732			
640	1050 middle of layer B	0.44	0.48	0.21
	1372			
823	1780 middle of layer C	0.47	0.48	0.23
	2195			
1067	2730 middle of layer D	0.51	0.48	0.25
	3262			
1310	3920 middle of layer E	0.58	0.48	0.28
	4572			
1524	5340 middle of layer F	0.64	0.48	0.31
	6096			
1524	6860 middle of layer G	0.71	0.48	0.35
	7620	0.75		

For the top layer of 300 cm, the average value of heat capacity was assumed to be 0.20 cal/cm^3, deg. Only one temperature measurement was made in the upper 300 cm on 26 October 1957, namely at 152 cm. A linear temperature gradient was assumed from the surface to 305 cm. This gave a surface temperature of -8°C, and a set of assumed temperature values in the top layer. On 3 March 1958 no temperature measurements were taken in the top layer; a surface temperature was obtained by extrapolating down to the snow surface the lower part of the air temperature curve from measurements above the surface at 10 cm and 30 cm. This gave a surface temperature of -20°C which corresponded closely to the surface temperatures actually measured in the period 15 March to 31 March. A linear temperature gradient was again assumed from the surface to 305 cm depth, and the necessary temperatures for various depths in the top layer thus obtained.

The following values were used for the top 300 cm:

layer	thickness (cm)	$\varrho.c.dz$ (cal/cm^2, deg.)
1	26	5.2
2	25	5.0
3	24	4.8
4	25	5.0
5	33	6.6
6	33	6.6
7	34	6.8
8	50	10.0
9	50	10.0

Evaluating the integral now involved only the examination of the temperature records in order to obtain the change in mean temperature for each layer of firn and ice from the beginning to the end of each period, i.e., from one set of temperature readings to the next.

RESULTS

The results are presented in the following:

Surface heat flux (cal/cm^2)

Period	Dates	$\int_0^z \varrho.c.\delta T.dz$ surface to 300 cm	$\int_0^z \varrho.c.\delta T.dz$ 305-7620 cm	Total (cal/cm^2)
I	26 Oct/57 – 3 Mar/58	− 567	− 732	− 1299
II	3 March – 17 March	− 150	+ 404	+ 254
III	17 March – 31 March	+ 49	+ 196	+ 245
IV	31 March – 11 April	+ 87	− 397	− 310
V	11 April – 26 April	+ 52	− 40	+ 12
VI	26 April – 10 May	+ 79	+ 742	+ 821
VII	10 May – 17 May	+ 43	− 773	− 730
VIII	17 May – 9 June	+ 406	− 375	+ 31
IX	9 June – 12 June	+ 32*	+ 7	+ 39*
X	12 June – 24 June	+ 233*	+ 990	+ 1223*
XI	24 June – 7 July		+ 107	+ 107*

(*) After 9 June, the total surface heat flux included heat used in melting surface snow. All of the amount of heat used in melting is not included in the above figures, since the melt water drained down slope and disappeared into crevasses.

The results indicate an average heat flow through the surface as follows, in cal/cm², min.

Period	Dates	Flux ly/min	Measured net radiation flux above surface, ly/min
I	26/10 - 3/3	−0,007	
II	3/3 - 17/3	+0.013	
II	17/3 - 31/3	+0.012	
IV	31/3 - 11/4	−0.020	
V	11/4 - 26/4	+0.001	
VI	26/4 - 10/5	+0.041	
VII	10/5 - 17/5	−0.072	
VII	17/5 - 9/6	+0.001	
IX	9/6 - 12/6	+0.009*	+0.071
X	12/6 - 24/6	+0.071*	+0.051
XI	24/6 - 7/7	+0.006*	+0.045

The measured net radiation flux above the snow surface for periods IX, X and XI (Orvig, 1961) gave values of + 0.071 ly/min, + 0.051 ly/min and + 0.045 ly/min. Due to the lag in conduction of heat into the firn and ice, there is no good correlation between these figures and those for heat flux into the glacier in the same periods. The totals for that part of the ablation season which lay between 9 June and 7 July are as follows:

Period	Heat Flux into glacier, cal/cm²	Net radiation flux above surface, cal/cm²
9 June - 7 July	+1369	+2041

There was thus available for melting 672 ly in this period, from radiation alone. Air temperatures indicated that there must also have been available some heat, for melting and evaporation, by turbulent flux. An approximate value for the amount melted can be obtained by using the above value of available energy, 672 ly. With a density of 0.5 gm/cm³, the total melting in this period (28 days) becomes 16.8 cm (0.6 cm/day). The rate of melting must increase as the top layers become isothermal.

As the net radiation and ice temperature measurements were not complete through a full year, the total fluxes cannot be compared. By disregarding the melt water which drained away from the area one can assume that the total annual net flux through the surface of the glacier should be zero. Such balance would require a surface heat flux in the period 7 July - 26 October of − 393 cal/cm², or approximately − 0.002 ly/min.

This is in fair agreement with the average flux values for the preceding and subsequent periods, shown in the table of average heat flow for the eleven periods.

REFERENCES

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