

A HEAT-BALANCE STUDY ON McCALL GLACIER, BROOKS RANGE, ALASKA: A CONTRIBUTION TO THE INTERNATIONAL HYDROLOGICAL DECADE

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ABSTRACT. On the McCall Glacier, an Arctic glacier in the eastern Brooks Range, northern Alaska, a heat balance study was carried out during the summer of 1970 to investigate quantitatively the relationship between energy transfer, climatic parameters and melting processes. Considering the individual energy balance terms, it was found that radiation is the most important heat source for snow and ice melt. The melting period itself is only 11 weeks long, which is quite short. The evaporation overcompensates for what little condensation occurs, and amounts to about 2% of the total ablation. Evaporation is more important in the spring, but becomes decreasingly so during the summer. The melt water which percolates into the snow-pack and refreezes at a lower level is a more effective way of transporting energy into the ground than conduction, and is of importance during the beginning of the melt period. The summer balance is considerably less energetic than over the tundra north of the Brooks Range. The main difference is a higher surface albedo, and to a lesser extent the protected nature of the glacier in a deep valley on a N-S axis, which reduces the duration of possible sunshine by 39% in summer. These are the important factors in maintaining the McCall Glacier and other similar glaciers in an otherwise low precipitation area.

RÉSUMÉ. Une étude du bilan thermique sur le McCall Glacier, Brooks Range, Alaska: Contribution à la Decennie Hydrologique Internationale. Sur le McCall Glacier, un glacier arctique de la Brooks Range orientale, dans le Nord de l'Alaska, on a conduit une étude du bilan thermique durant l'été 1970, en vue d'une approche quantitative des relations entre les transferts d'énergie, les paramètres climatiques et les processus de fusion. En considérant chacun des termes du bilan énergétique, on a trouvé que le rayonnement est la plus importante source de chaleur pour la fusion de la neige et de la glace. La période de fusion elle-même est longue de seulement 11 semaines, ce qui est très court. L'évaporation fait plus que compenser l'apport d'une faible condensation et participe pour environ 2% à l'ablation totale. L'évaporation est plus importante au printemps mais le devient de moins en moins au cours de l'été. L'eau de fusion qui percole à travers le manteau neigeux et regèle à un niveau inférieur est un mode de transport d'énergie vers le sol plus efficace que la conduction, et se montre important pendant le début de la période de fusion. Le bilan estival est beaucoup moins énergétique que sur la toundra au Nord de la Brooks Range. La principale différence est un albedo de surface plus élevé, et, dans une moindre mesure, la position protégée du glacier dans une vallée profonde d'axe Nord-Sud qui réduit la durée possible d'illumination solaire de 39% en été. Tels sont les facteurs importants pour le maintien du McCall Glacier et d'autres glaciers similaires dans une zone par ailleurs très peu arrosée.

ZUSAMMENFASSUNG. Eine Untersuchung des Wärmehaushalts am McCall Glacier, Brooks Range, Alaska. Am McCall Glacier, einem arktischen Gletscher im östlichen Brooks Range Nordalaskas wurde im Sommer 1970 eine Untersuchung des Wärmehaushalts durchgeführt, um den Zusammenhang zwischen Wärmehaushalt, Klima und Ablation quantitativ zu erfassen. Aus Betrachtungen der Einzelfaktoren des Energiehaushalts ergab sich die Strahlung als wichtigste Energiequelle für das Schmelzen von Schnee und Eis. Die Schmelzperiode ist mit 11 Wochen recht kurz. Die Verdunstung überkompensiert die geringe Kondensation und trägt mit etwa 2% an der Ablation bei. Im Frühjahr kommt der Verdunstung eine grössere Bedeutung zu, welche jedoch während des Sommers abnimmt. Das Schmelzwasser, das in die Schneedecke eindringt und in tieferen Schichten wieder gefriert, ist eine wirkungsvollere Art des Wärmetransports als die Wärmeleitung; besonders wichtig ist es zu Beginn der Schmelzperiode. Der sommerliche Wärmehaushalt ist wesentlich energieärmer als der der Tundra nördlich des Brooks Range. Der Hauptunterschied besteht in der grösseren Oberflächenalbedo und — zu einem geringeren Grad — in der geschützten Lage des Gletschers in einem tiefen, nordsüdlich gerichteten Tal; hierdurch wird im Sommer die mögliche Sonnenscheindauer um 39% verringert. Das sind wichtige Faktoren für die Erhaltung des McCall Glaciers und anderer ähnlicher Gletscher in einem Gebiet mit vergleichsweise geringem Niederschlag.

1. INTRODUCTION

McCall Glacier lies in the eastern part of the Brooks Range, in the Romanzof Mountains, at lat. 69° 18' N., long. 143° 48' W. The glacier has an area of 6.22 km² and an altitude span from 1 340 to 2 720 m (Fig. 1). It is one of the few small glaciers which exist in the low precipitation environment of the Brooks Range at altitudes above 1 000 m. Most of these glaciers have northern exposures, and only a few face south, so that the energy balance, particularly its net radiation term, is unlikely to be an important factor in the presence of these glaciers.

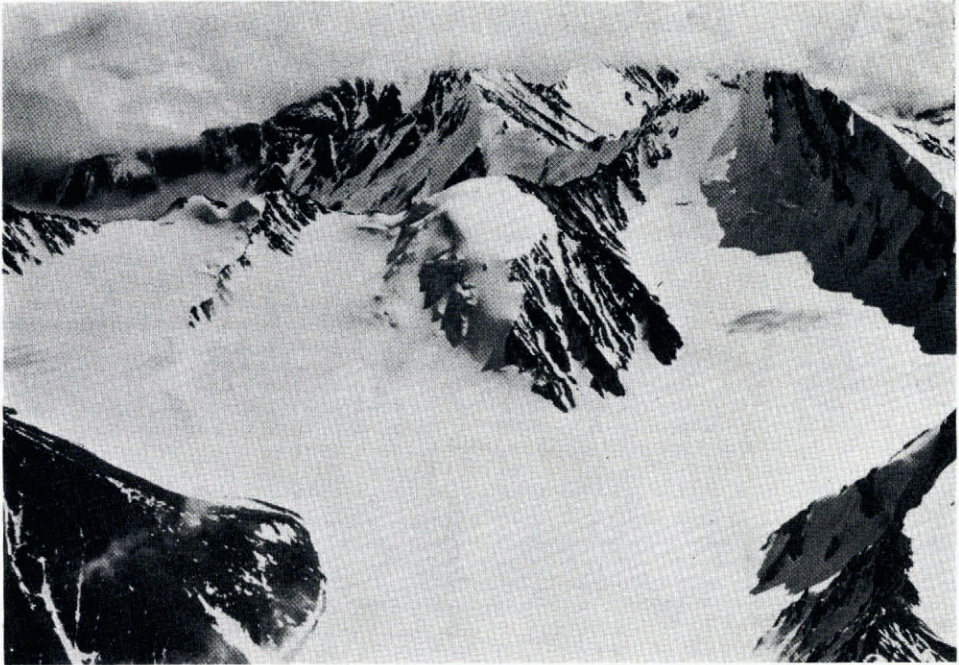


Fig. 1. Aerial view of the three accumulation basins of McCall Glacier looking towards the south.

To investigate this, a heat-balance study was carried out on the McCall Glacier in summer 1970 as part of a combined heat-, ice-, and water-balance investigation, which is being conducted under the auspices of the International Hydrological Decade (I.H.D.). McCall Glacier is the only Arctic glacier currently being studied in the United States of America, and is of special importance as it lies at the intersection of two glacier "chains" recommended for intensive study in the I.H.D.: the Arctic Circle and the American chains. It had been studied previously during the I.G.Y. (e.g. Keeler, 1959; Orvig, 1961; Orvig and Mason, 1963), and by us from 1969–72. The results of the mass and water balance for 1969 and 1970 have been published (Wendler and others, 1972, in press).

It is hoped that the present study will provide a better quantitative understanding of the relationships between energy transfer, climatic and meteorological elements, and melting processes. No attempt was made to integrate the heat balance over the whole glacier; rather, it was calculated for a single point at 1 730 m altitude.

2. PERIOD OF OBSERVATION AND INSTRUMENTATION

The observations started in summer 1969. However, as the micrometeorological instrumentation was not in good working condition until the end of the ablation season (August), the data of 1969 were not included in this study.

The observations started again on 7 April 1970, but as the ventilation system for the temperature sensors was not working before 17 May, only the period between 17 May to 31 August was analysed. On 1 September the micrometeorological measurements were stopped. This period includes the whole ablation season for the altitude on the glacier at which the measurements were carried out.

The observations were made about 100 m from the foot of the lateral moraine, somewhat east of the middle of the glacier tongue (see Fig. 2). The glacier slopes to the north at about 7° to the horizontal at this point, and this is also the general exposure of the glacier, which has a fairly simple geometry on a north-south axis.

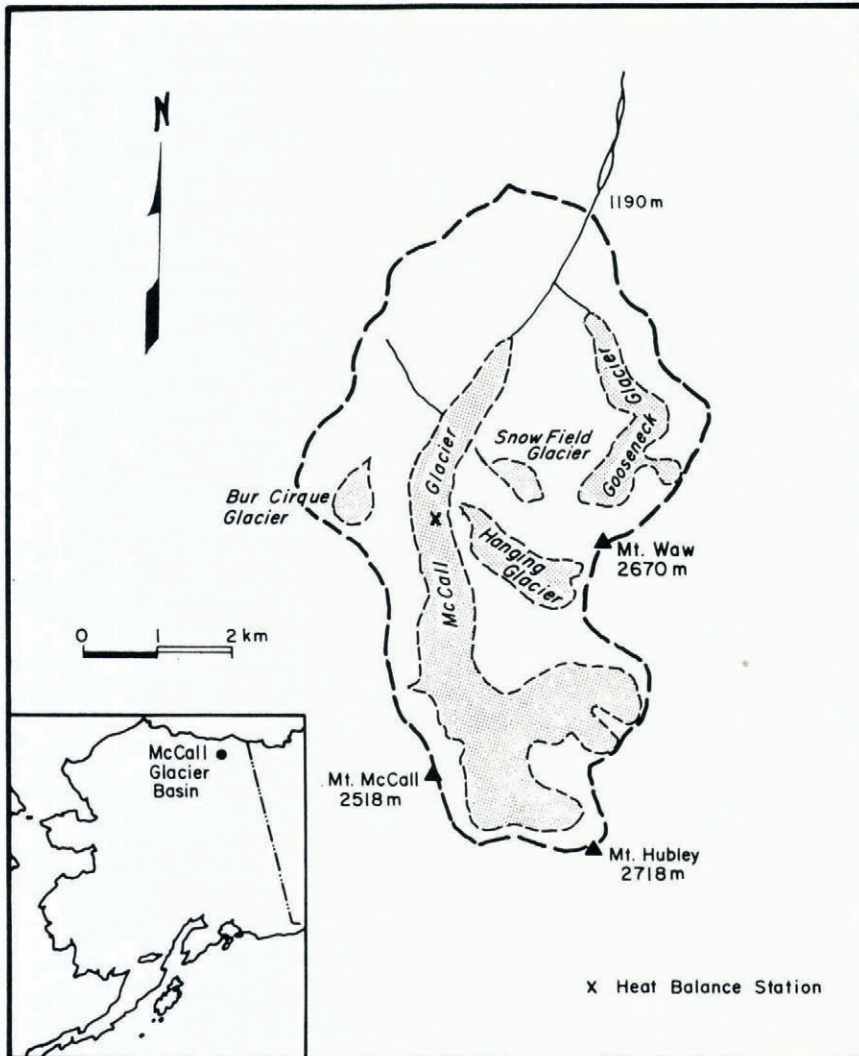


Fig. 2. Locality map of the McCall Creek Basin.

The radiation was measured with a PD-4 Davos radiometer. This instrument has four sensors, two of which are glass-shielded, the other two polyethylene-shielded, so that the incoming and reflected short-wave and the incoming and outgoing all-wave radiation can be measured independently. Long-wave incoming and outgoing radiation can then be computed as differences. The four radiative fluxes as well as the zero point and the instrument temperature were recorded continuously with "Siemens" six-channel galvanometric point recorders, which were located in a hut on the moraine about 140 m from the site of observations. As

back-up for the incoming short-wave radiation, a "Belford" actinograph was utilized. The radiation measurements were calibrated in the field against a standard Linke-Feussner actinometer, which had been calibrated by its manufacturer Kipp en Zonen, Delft, Holland.

Wind speeds and temperatures were measured in a logarithmic profile (0.5, 1, 2 and 4 m) above the glacier surface. The instrumentation was adjustable in height so that it could be at constant height above the surface (Fig. 2). "Raim" 3-cup micrometeorological wind sensors which have low starting velocities (0.3 m s^{-1}) were used to measure the wind speed. For every revolution of the anemometers, an electrical pulse was transmitted to "Sodeco" digital counters located, with the rest of the recording instruments, in the hut, and the integrated number of revolutions was printed out every half hour.

The air temperatures were measured with artificially ventilated thermocouples, and the ice or snow temperatures were measured with eight thermocouples buried in the ice down to a depth of 8 m; the output was continuously recorded on the "Siemens" point recorders. The dew points were measured with "Panasonic" aluminum oxide sensors situated at two altitudes (0.5 and 4 m); these sensors change their electrical resistance with increases and decreases of the atmospheric water-vapor pressure. The ablation was measured twice daily with ten small (5 mm) ablation stakes situated near the micrometeorological equipment, and the snow density and stratigraphy were measured occasionally during the time when there was snow cover at the site. At a later date (17 July) a meteorological shelter, containing a thermo-hydrograph calibrated against an Assmann psychrometer, and a maximum and minimum thermometer, was also placed near the micrometeorological equipment. With the help of these latter instruments the heat fluxes could be estimated, at least for melting conditions, during times when the micrometeorological instrumentation was being calibrated or not in working condition.

3. CLIMATOLOGY AND WEATHER CONDITIONS

The mean and extreme climatological conditions can be obtained from Table I. The mean temperature for the latter part of May (17–31) is negative (-1.0°C), and even the June temperature, at 0.5°C , is near freezing point. In July the highest mean monthly temperature 3.8°C , was observed, while in August it became colder again (1.3°C). The relative humidity

TABLE I. METEOROLOGICAL DATA, MCCALL GLACIER, SUMMER 1970

	May*	June	July	August	Whole period 17 May–31 August
Temperature $^\circ \text{C}$					
Mean	-1.0	0.5	3.8	1.3	1.2
Maximum	2.0	5.9	7.8	4.1	7.8
Minimum	-5.4	-11.4	0.2	-5.5	-11.4
Water vapor pressure mbar					
Mean	3.93	4.53	6.28	5.37	5.19
Maximum	4.88	6.66	7.57	7.17	7.57
Minimum	3.01	2.00	4.86	3.29	2.00
Wind speed m s^{-1}					
Mean	2.7	2.3	2.4	2.0	2.3
Maximum	3.8	4.8	5.8	3.7	5.8
Minimum	0.7	0.5	0.8	0.3	0.3
Cloudiness in tenths					
Mean	5.1	5.5	5.8	6.7	5.9
Maximum	10.0	10.0	9.5	10.0	10.0
Minimum	0.5	1.0	0.5	0.5	0.5

Maximum and minimum values given in the table are not the absolute maximum but represent the daily extremes.

* The observation period started on 17 May 1970.

like the temperature, showed an increase from 69% in May to 78% in July and then increased to a maximum value of 80% in August. The wind speed did not vary substantially during the summer months, but the cloudiness showed a steady increase from May (5.1 tenths) to August (6.7 tenths), a result which is in agreement with most other observations in the Arctic regions (e.g. Searby, 1968). Since no long-term climatological records exist for McCall Glacier, climatic trends can be determined from Barter Island, 90 km north of the glacier. Temperature means for the period 1 May to 31 August 1970 were 0.5° C colder than the long-term mean.

In Table II the diurnal variations of the meteorological elements are given. The highest variation in temperature was found in May, and the daily amplitude decreased steadily throughout the summer. This course was not followed by the water-vapor pressure, which showed its largest diurnal variation during the month with the highest temperature. However, this is not really surprising, as at higher temperatures the amount of water vapor the air can hold is much greater; the same temperature range—when assuming a constant relative humidity—would then result in a bigger diurnal variation in water vapor.

TABLE II. DIURNAL VARIATIONS IN METEOROLOGICAL CONDITIONS, MCCALL GLACIER, SUMMER 1970

<i>Period</i>	<i>Element</i>	<i>Air temperature</i> °C	<i>Water vapor pressure</i> mbar	<i>Wind speed</i> m s ⁻¹
May*	Mean maximum	2.6	4.73	5.2
	Mean minimum	-4.2	3.13	0.5
	Mean range	6.7	1.60	4.7
June	Mean maximum	3.1	5.96	5.6
	Mean minimum	-3.2	3.49	0.7
	Mean range	6.3	2.47	5.0
July	Mean maximum	7.4	8.11	5.8
	Mean minimum	2.3	5.13	0.9
	Mean range	5.1	2.98	4.9
August	Mean maximum	3.8	6.59	4.9
	Mean minimum	-0.3	4.51	0.8
	Mean range	4.1	2.08	4.1
Whole period 17 May-31 August	Mean maximum	4.5	6.35	5.5
	Mean minimum	-1.7	4.07	0.7
	Mean range	5.4	1.28	4.7

* The observation period started on 17 May 1970.

The daily mean values of the climatic parameters are given in Figure 3. Naturally, there is a great deal of variation in these values, and it can be noted that there are extended periods during which no freezing occurs at all. Nevertheless the melting season is only 2-3 months long.

4. HEAT BALANCE AT THE GLACIER SURFACE

The heat-balance equation at the glacier surface consists of the following components.

$$(RB)_s + (RB)_L + S + L + B + M = 0$$

with $(RB)_s$ the short-wave radiation balance, $(RB)_L$ the long-wave radiation balance, S the sensible heat flux, L the latent heat flux, B the heat flux in the snow or ice, and M the snow or ice melting.

All fluxes which bring energy towards the surface were considered to be positive, while the fluxes taking energy away from the surface were considered to be negative. Other fluxes, e.g. rain, were estimated, but were so small that they could be neglected.

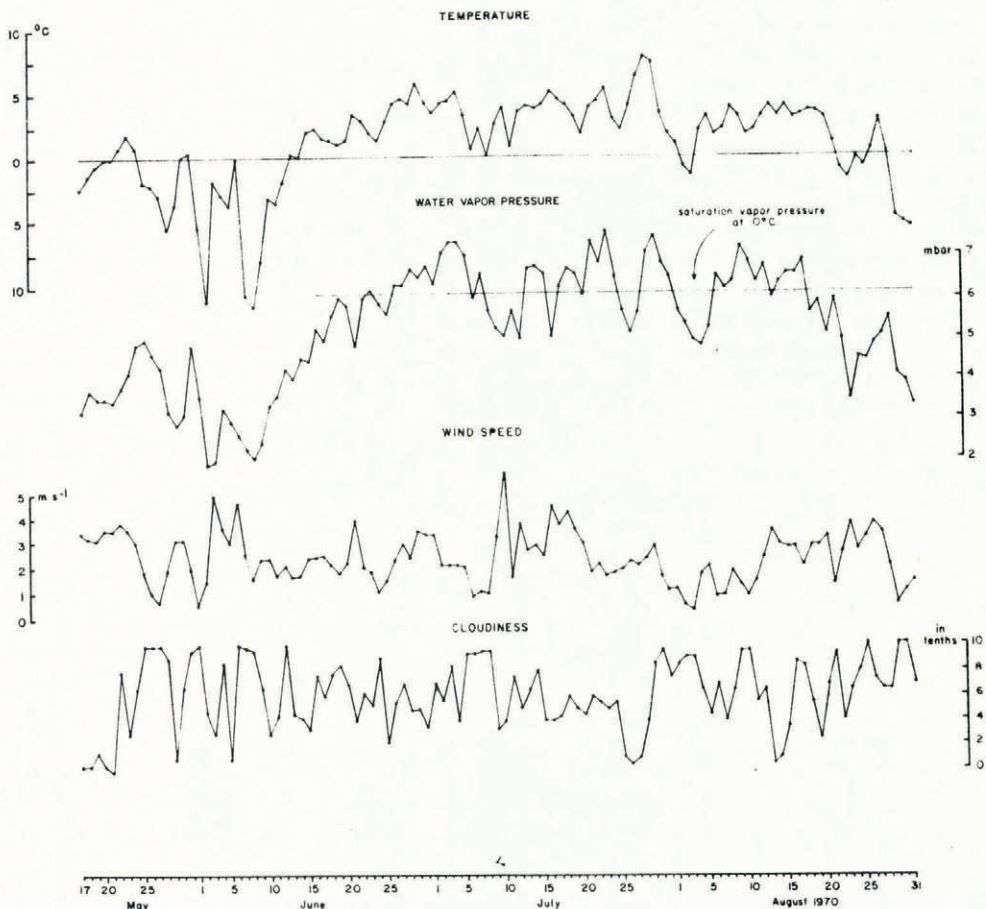


Fig. 3. Daily averages of meteorological elements, McCall Glacier, summer 1970.

A substantial potential error could be introduced by neglecting advective heat fluxes, which could not be estimated. The topography and nature of the surrounding terrain of the glacier makes it almost certain that on many occasions heat was advected to the measuring site, but the magnitude of this effect is unknown.

The period of measurements was subdivided into four phases:

- (a) pre-melting period 17 May–12 June
- (b) melting period, snow 13 June–17 July
- (c) melting period, ice 18 July–28 August
- (d) post-melting period 29 August–31 August.

The distinction between these four phases is not perfect, as on some warm days in spring some melting occurs, and cold spells happen during the whole melting season; however distinctive differences are still observed during these periods. Furthermore, it should be noted that the last period consists of only three days, and therefore, the values found for this period are not necessarily typical for the early post-melting phase.

(a) *The radiation balance*

A summary of the radiative fluxes which were obtained with the PD-4 Davos radiometer (Fig. 4), is given in Table III. For the pre- and post-melting periods, negative values were found for the radiation balance while they were positive during the melting period. The short-wave incoming radiation decreases during the summer. This is an effect of the increasing cloudiness coupled with the decreasing day length during the latter part of the summer. The albedo is high (nearly 80%) for the fresh snow covers which exist during the pre- and post-melting periods and decreases during the melting period to 58% (snow) or 48% (ice) respectively. The value for ice (48%) agrees with values found for superimposed ice (Holmgren, 1971), but is too high for glacier ice; Wendler and Ishikawa (1973) found a value of 29%.

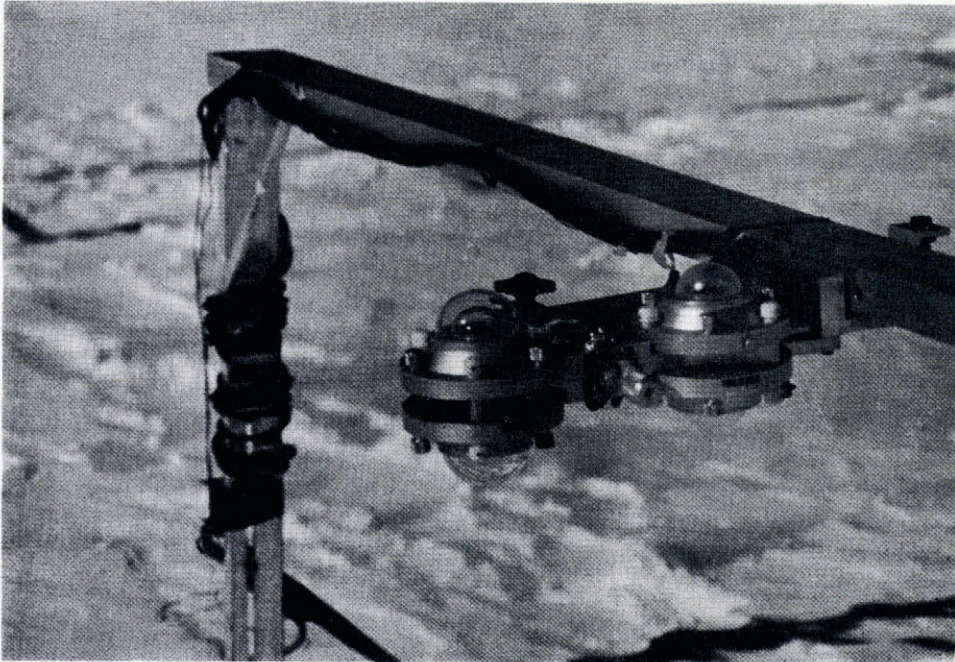


Fig. 4. PD-4 Davos radiometer. Note double glass domes (left) and Lupolen-shielded sensors (right).

The high value is explained by two snowfalls during the melting period, which raised the mean albedo for this period appreciably as shown in Figure 5. The snowfall of 1 and 2 August in particular raised the albedo substantially for about eight days. Thus new snowfalls in summer are extremely important for the mass balance, as has been pointed out before (e.g. Hoinkes, 1968), both by modifying the radiation balance and by adding to the mass balance of the glacier. For example, for the total ablation period on McCall Glacier during 1970, the amount of solid precipitation added to the annual mass balance was about 10%. The energy required to melt this mass was about equal to the energy lost due to the increased albedo of the new snow cover, reducing the absorbed radiation.

(b) *Sensible and latent heat fluxes*

The eddy fluxes were calculated from profile measurements with instruments on a 4 m high tower (Fig. 6) using Prandtl's relation (Lettau, 1939, 1949; Prandtl, 1956). In doing

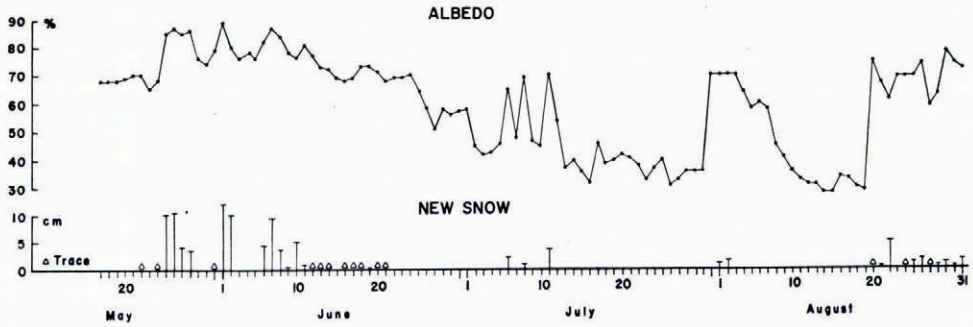


Fig. 5. Daily mean albedo and new snowfalls on McCall Glacier, summer 1970.

TABLE III. RADIATIVE FLUXES, MCCALL GLACIER, SUMMER 1970

	Average				Maximum				
	1	2	3	4	1	2	3	4	
Short-wave incoming	520	496	349	243	708	747	580	256	Ly d ⁻¹
	21.7	20.7	14.6	10.2	29.6	31.2	24.2	10.7	MJ m ⁻² d ⁻¹
Short-wave outgoing	398	292	163	195	552	489	293	205	Ly d ⁻¹
	16.6	12.2	6.8	8.1	23.1	20.4	12.2	8.6	MJ m ⁻² d ⁻¹
Short-wave balance	122	204	186	48	192	415	372	51	Ly d ⁻¹
	5.1	8.5	7.8	2.0	8.0	17.3	15.5	2.1	MJ m ⁻² d ⁻¹
Long-wave balance	-149	-59	-50	-61	-68	35	16	-57	Ly d ⁻¹
	-6.2	-2.5	-2.1	-2.5	-2.8	1.5	0.7	-2.4	MJ m ⁻² d ⁻¹
All-wave balance	-27	145	136	-13	50	338	330	-9	Ly d ⁻¹
	-1.1	6.1	5.7	-0.5	2.1	14.1	13.8	-0.4	MJ m ⁻² d ⁻¹
Albedo	77	58	48	80	89	73	74	81	Ly d ⁻¹
	3.2	2.4	2.0	3.3	3.7	3.1	3.1	3.4	MJ m ⁻² d ⁻¹
	Average				Minimum				
	1	2	3	4	1	2	3	4	
Short-wave incoming	520	496	349	243	301	92	181	234	Ly d ⁻¹
	21.7	20.7	14.6	10.2	12.6	3.8	7.6	9.8	MJ m ⁻² d ⁻¹
Short-wave outgoing	398	292	163	195	255	42	69	187	Ly d ⁻¹
	16.6	12.2	6.8	8.1	10.7	1.8	2.9	7.8	MJ m ⁻² d ⁻¹
Short-wave balance	122	204	186	48	37	50	64	47	Ly d ⁻¹
	5.1	8.5	7.8	2.0	1.5	2.1	2.7	2.0	MJ m ⁻² d ⁻¹
Long-wave balance	-149	-59	-50	-61	-271	-134	-218	-64	Ly d ⁻¹
	-6.2	-2.5	-2.1	-2.5	-11.3	-5.6	-9.1	-2.7	MJ m ⁻² d ⁻¹
All-wave balance	-27	145	136	-13	-214	-10	-127	-17	Ly d ⁻¹
	-1.1	6.1	5.7	-0.5	-8.9	-0.4	-5.3	-0.7	MJ m ⁻² d ⁻¹
Albedo	77	58	48	80	68	32	28	79	Ly d ⁻¹
	3.2	2.4	2.0	3.3	2.8	1.3	1.2	3.3	MJ m ⁻² d ⁻¹

- 1 pre-melting period, 17 May–12 June.
- 2 melting period, snow, 13 June–17 July.
- 3 melting period, ice, 18 July–28 August.
- 4 post-melting period, snow, 20–31 August.

this, it was assumed that no advection takes place. Furthermore, the transfer or austausch coefficient found for momentum exchange is assumed to be identical with the transfer coefficient for sensible and latent heat exchange, which is not necessarily correct for non-adiabatic conditions (Webb, 1965). During adiabatic or near-adiabatic conditions, logarithmic profiles were fitted to the wind observations to obtain a mean value for the roughness parameter z_0 for ice of 0.24 cm. This value is in good agreement with those quoted by other

investigators (e.g. Hoinkes, 1953; Untersteiner, 1957; Streten and Wendler, 1968). For snow, a mean value for the roughness parameter of 0.09 cm was found, which again is comparable with values found by numerous other authors under similar conditions (e.g. Liljequist, 1957; Wendler and Streten, 1969).

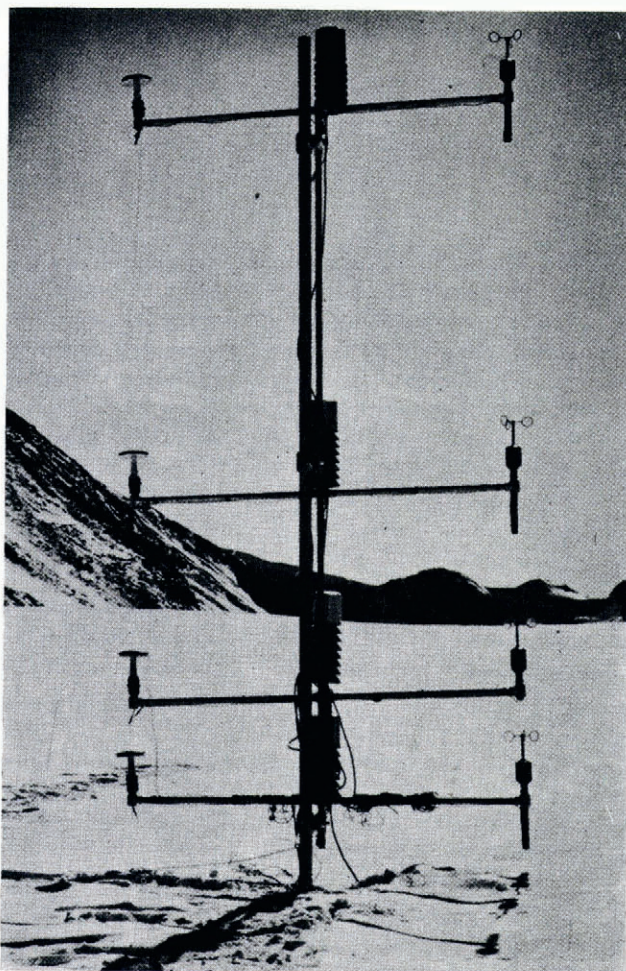


Fig. 6. Micrometeorological tower on McCall Glacier. Note the ventilated temperature sensors (left), the humidity sensors (center). The sensors shown are not the "Panasonic" sensors mentioned in the text, but are "Pernix" sensors installed at a later stage (not used during 1970). Also note the wind-speed sensors (right).

For non-adiabatic conditions, correction was applied to the austausch coefficient according to Lettau (1949):

$$A = \frac{A_a}{(1+x)^2}$$

where A is the austausch coefficient, A_a the austausch coefficient for adiabatic conditions, and x a dimensionless stability criterion similar to the Richardson number.

The mean corrections for the four periods—pre-melting, melting snow, melting ice, and post-melting—were found to be -7 , -15 , -14 and -31% respectively, which means, that

owing to the generally stable air above the glacier surface, the eddy fluxes were somewhat suppressed.

Applying this correction, the eddy fluxes listed in Table IV were computed from the temperature and water-vapor profiles measured above the glacier surface.

TABLE IV. EDDY HEAT FLUXES, MCCALL GLACIER, 17 MAY-31 AUGUST 1970

	<i>Pre-melting</i> 17 May-12 June	<i>Melting snow</i> 13 June-17 July	<i>Melting ice</i> 18 July-28 August	<i>Post-melting</i> 29 August-31 August
Sensible heat flux	+31 1.3	+51 2.1	+47 2.0	+8 Ly d ⁻¹ 0.3 MJ m ⁻² d ⁻¹
Latent heat flux	-30 -1.3	-20 -0.8	-17 -0.7	+9 Ly d ⁻¹ 0.4 MJ m ⁻² d ⁻¹

It can be seen that the mean sensible heat fluxes were positive for all four periods. The highest values were found to be about 50 Ly d⁻¹ (2 MJ d⁻¹) when melting occurred, the result of a strong temperature gradient above the glacier surface and relatively strong winds.

The latent-heat fluxes were negative for the first three periods, which means that evaporation exceeds condensation. The highest value was found during the pre-melting period.

The amount of evaporation decreases during the summer, and in late summer (post-melting period), the condensation exceeds the evaporation, and a positive flux towards the surface is found. This again is understandable, as the relatively warm summer air is now cooled, and can therefore hold less moisture, hence condensation takes place.

(c) Heat flux in the glacier ice

The heat flux into or out of the glacier ice could be calculated from the temperature measurements which were made at eight points down to a depth of 8 m and the known values of density and specific heat of snow and ice. The mean flux values obtained are shown in Table V.

TABLE V. HEAT FLUX IN THE ICE, MCCALL GLACIER,
17 MAY-31 AUGUST 1970

	<i>Pre-melting</i>	<i>Melting snow</i>	<i>Melting ice</i>	<i>Post-melting</i>
Heat flux in the ice	-6 -0.3	-29 -1.2	-10 -0.4	+3 Ly d ⁻¹ 0.1 MJ m ⁻² d ⁻¹

During the first three periods, a downward flux, that is a warming of the ice or snow, was observed, while during the post-melting period, a flux towards the surface was measured. During the pre-melting period the flux is small, as snow is not a good conductor of heat. The high value for the snow-melting period is at first glance astonishing, especially as the top snow layer becomes isothermal and no heat can be transferred through it by conduction. However, the melt water percolates into the snow-pack, and part of it refreezes at a lower level, releasing its latent heat and transporting a much greater amount of heat than can be carried by conduction. In midsummer (melting ice), the heat is transported by conduction only, as ice is not permeable to water, except frequently in the uppermost layer, which fractures into a permeable honeycomb structure. In this top isothermal layer, which has a maximum thickness of about 10 cm, heat is transferred by percolating melt water and radiation only. As ice is a better conductor than snow (ten times better than snow of density 0.3 Mg m⁻³) more heat is conducted during the melting periods. During the post-melting period the flux is towards the surface, but is small, owing to the presence of new, low-conductivity snow.

(d) *Heat for snow and ice melt*

To melt either snow or ice, latent heat energy of 330 kJ kg^{-1} is required. The amount of snow or ice melt was measured carefully twice daily with ten thin (5 mm) ablation stakes. Owing to the effects of settling of the snow and density changes, it is very difficult to measure daily values of snow ablation accurately. A mean standard deviation of 24% was found in the daily variation of the surface level between the 10 stakes.

It is easier to measure the ice ablation, but the standard deviation is nearly as large for daily values (18%), since the amount of ice melt is on the average about half that of snow melt, and hence the inaccuracy in reading the ablation stakes becomes more important.

The maximum daily ablation values of the ten stakes were about 5.1 cm for snow and 6.1 cm for ice, with mean values of 3.1 cm snow and 1.9 cm ice, while during both periods cold spells occurred, in which no ablation took place at all for a 24 h period. In Table VI the mean and extreme values for the energy used for melting are given. It can be seen that energy available for melting increased by almost 50% after the snow cover had melted.

TABLE VI. HEAT FLUXES FOR SNOW AND ICE MELT, McCALL GLACIER, SUMMER 1970

	<i>Melting snow</i> 13 June–17 July	<i>Melting ice</i> 18 July–28 August
Average	91 3.8	134 Ly d^{-1} 5.6 $\text{MJ m}^{-2} \text{d}^{-1}$
Maximum	142 5.9	441 Ly d^{-1} 18.4 $\text{MJ m}^{-2} \text{d}^{-1}$
Minimum	0 0.0	0 Ly d^{-1} 0.0 $\text{MJ m}^{-2} \text{d}^{-1}$

(e) *The heat balance as a whole*

The heat balance is shown diagrammatically in Figure 7, and the percentage values are given in Table VII. It can be seen, not surprisingly, that the radiation balance is the largest source of heat for melting. This has been shown numerically by many previous investigations for different snow and ice terrain, e.g. on glaciers by LaChapelle (1959) and Ambach and Hoinkes (1963), on ice sheets by Ambach (1963) and for the seasonal snow cover by Gold and Williams (1961) and Wendler (1967); summaries are given by Geiger (1965) and Kondratyev (1969).

The study is subject to a number of errors,

(a) theoretically by the two assumptions:

- (1) no advection takes place,
- (2) the Austausch coefficients for momentum, sensible and latent heat are identical;

and (b) by the errors in the measurements.

The assumption of no advection is likely to be inaccurate, as discussed previously, but no estimate can be made of the magnitude of the error due to this. The second assumption is also not likely to be quite valid, since neutral conditions of stability occurred rarely and the air was generally in stable equilibrium. The actual errors in measurements can be estimated better. The errors in the radiation measurements are estimated to be within $\pm 5\%$ under normal conditions. However, owing to new snowfalls, and occasional breakdowns of the instrumentation, making interpolations necessary this accuracy probably decreased to $\pm 8\%$. This includes the small error introduced due to the radiative fluxes having been measured on a horizontal surface, while the glacier is inclined to the horizontal at about 7 deg. The eddy fluxes are believed to be within $\pm 10\%$.

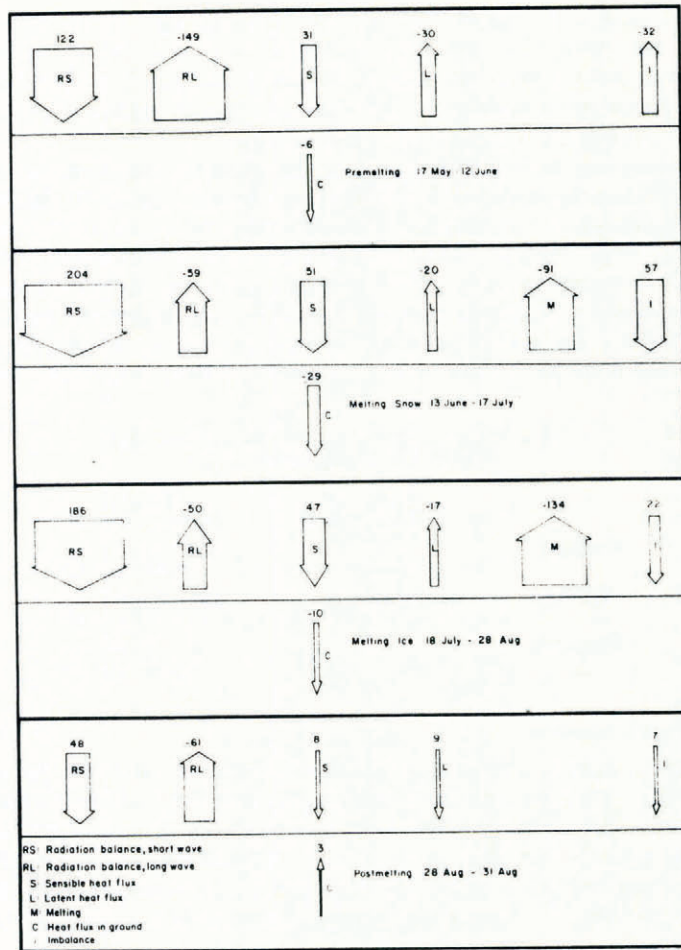


Fig. 7. Mean daily values in Langleys of the components of the heat balance for four periods of summer 1970, McCall Glacier (1 Langley = 41.9 kJ m⁻²).

TABLE VII. THE COMPONENTS OF THE HEAT BALANCE, MCCALL GLACIER, 17 MAY-31 AUGUST 1970

(Expressed as percentages of the heat energy source)

	Pre-melting 17 May-12 June	Melting snow 13 June-17 July	Melting ice 18 July-28 August	Post-melting 29 August-31 August
Radiation balance (short-wave)	+80	+80	+80	+71 %
Radiation balance (long-wave)	-97	-23	-21	-90 %
Sensible	+20	+20	+20	+12 %
Latent	-20	-8	-7	+13 %
Melting	0	-36	-57	0 %
Conduction	-4	-11	-4	+4 %
Imbalance	-21	+22	+11	+10 %

A certain indication of the accuracy of this study is given by the imbalance of the heat balance. Expressed as a percentage of the important heat source, the short-wave incoming radiation, the imbalance was found for the four periods: pre-melting, melting snow, melting ice, and post-melting, to be 6, 11, 8 and 3%, respectively. These values fall within the error limits quoted above. Expressed in percent of the combined heat sources, in which the balance of each contributing term is given, the imbalance appears higher: -21, 22, 11 and 10%.

5. CONCLUSIONS

Several features of the relationship between mass and energy balance of McCall Glacier are of interest. As elsewhere, the most important contribution to snow and ice melt is radiation. This contribution amounts to about 60% of all energy sources. On the other hand, the magnitude of the radiation balance in summer is only about half of that of the tundra north of the Brooks Range at Barrow (Kelley and others, 1964; Kelley and Weaver, 1969; Weller and others, 1972). This means that while the winter values, which consist mostly of long-wave radiation, are probably not greatly different for both snow-covered Arctic locations, the annual radiation balance is considerably less energetic on McCall Glacier. This is so despite the presence of fairly persistent low stratus cloud decks at Barrow, which generally cover the area north of the Brooks Range, but are below the altitude of McCall Glacier. Both high surface albedo and, to a lesser degree, the screening of the sun by the mountains surrounding the glacier, which reduces the duration of sunshine on the glacier surface by a mean of 39% in summer, combine to give a low radiation balance, favorable to the continued existence of the glacier.

In the ablation process, evaporation is responsible for only about 2% of the total ablation; the rest occurs by melting. This is a fairly typical value, reproduced quite well at other Arctic locations (Weller and others, 1972). The contribution of evaporation to the ablation is more important in spring, when it accounts for 100% of the ablation, of course, before the snow begins to melt, but its importance in actual energy and percentage terms decreases as summer progresses. When melting commences at the snow surface, the melt water percolates into the snow and refreezes at lower levels in the snow pack. This is a very effective way of transporting energy into the substratum, other than by conduction. Melting also occurs frequently in the top 10 cm of the ice, after the snow has melted, to create an isothermal layer across which heat is transported by melt water circulating in the loose lattice of melting ice crystals, and by radiative transfer.

In recent years, the annual mass balance of McCall Glacier has been negative in 1969, 1970, 1971, and 1972, the years during which its balance was studied intensively. Fahl (unpublished) has recently shown what type of large-scale synoptic pattern over northern Alaska determines the growth of the glacier mass by precipitation. The present study has attempted to show how physical processes of energy exchange at the glacier surface determine its reduction.

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