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THE MIDSUMMER HEAT BALANCE OF AN ALASKAN MARITIME GLACIER

By N. A. Streten *and* G. Wendler

(Geophysical Institute, University of Alaska, College, Alaska 99701, U.S.A.)

Abstract. The heat balance of an Alaskan mountain glacier located close to the sea is calculated for a period of 16 d in midsummer—a period which is typical of the summer in this region in its high cloudiness and in its temperature and humidity conditions. The radiative and the combined sensible and latent heat components are found to contribute equally to the observed high rate of ice melting.

Résumé. *L'équilibre thermique en mi-été d'un glacier maritime de l'Alaska.* L'équilibre thermique d'un glacier de l'Alaska situé près de la mer est calculé pour une période de 16 jours en mi-été, période typique de l'été dans cette région en ce qui concerne la fréquence des nuages et les conditions de température et d'humidité. On a trouvé que les constituants radiatifs et la combinaison de la chaleur sensible et latente contribuent à part égale à la rapidité élevée observée de la fonte.

Zusammenfassung. *Die hochsommerliche Wärmebilanz eines maritimen Gletschers in Alaska.* Für eine 16 tägige hochsommerliche Periode wurde die Wärmebilanz eines nahe dem Meer gelegenen Gebirgsgletschers in Alaska berechnet. Der gefundene hohe Bewölkungsgrad sowie die Temperatur- und Feuchtigkeitswerte sind typisch für den Sommer in dieser Gegend. Die Strahlung und der fühlbare und latente Wärmestrom zusammen, tragen gleichwertig zu der beobachteten, hohen Eisablation bei.

I. Introduction

The Worthington Glacier (lat. 61° 10′ N., long. 145° 45′ W.) (Fig. 1), is a small mountain glacier with an area of about 8 km² located in the Chugach Range approximately 28 km from Valdez in south central Alaska (Fig. 2). The glacier extends from a height of some 1 800 m flowing almost directly eastward with the tongue being located at an elevation of 820 m within 1 km of the Richardson Highway. The Worthington is a small detached part of an extensive glaciated region of the Chugach Range, which feeds a number of very large glaciers, notably the Tazlina, Nelchina, and Columbia, and further to the east, the smaller Shoup, Klutina, Valdez, and Tonsina glaciers.

Fig. 1. Worthington Glacier, general view looking south.

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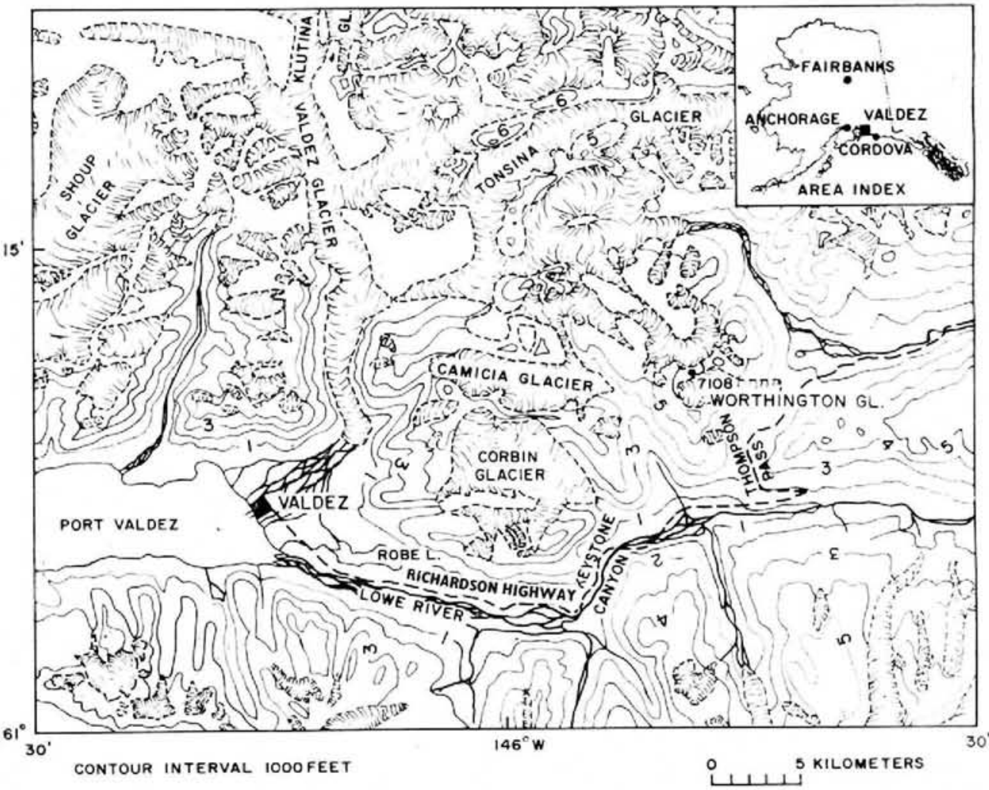

Fig. 2. Location map, south-central Alaska.

The glacier is surrounded entirely either by exposed rock or outwash deposits with the peak immediately to the west of the glacier rising to 2 160 m. The region is one of high precipitation. Valdez records a mean annual total precipitation of 62.37 in (1 584 mm) of water equivalent, with a maximum in September of 8.4 in (213 mm), while the annual fall at the Thompson Pass, located only a few kilometers from the glacier tongue and at the same elevation is probably in excess of 90 in (2 286 mm). Snowfall depths are recorded in the pass only in the winter months. For the four months November to February, the average over nine years totaled 424.8 in (10 790 mm), but individual months have recorded falls over 225 in (5 710 mm).

In July the normal monthly precipitation at Valdez is 4.72 in (120 mm) and in June the minimum monthly figure of 2.61 in (66 mm) is recorded. It is probable that those months are also those of lowest precipitation in the catchment of the Worthington Glacier.

II. The Period of Observation and the Instrumentation

The observation period extended from 15 h on 16 July 1967, to 15 h on 1 August 1967—a duration of 16 whole days.

The meteorological instruments were set up on the tongue of the glacier some 50 m from the shore of the melt-water lake at its terminus (Fig. 3). The radiation measurements were made with the newly developed PD4 Radiation Balance Meter (Physikalische-Meteorologisches Observatorium—Davos, Switzerland, Fig. 4). This instrument has very nearly the same sensitivity in regions both of short- and long-wave radiation and utilizes Lupolen—a poly-

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Fig. 3. Instrument exposure, Worthington Glacier.

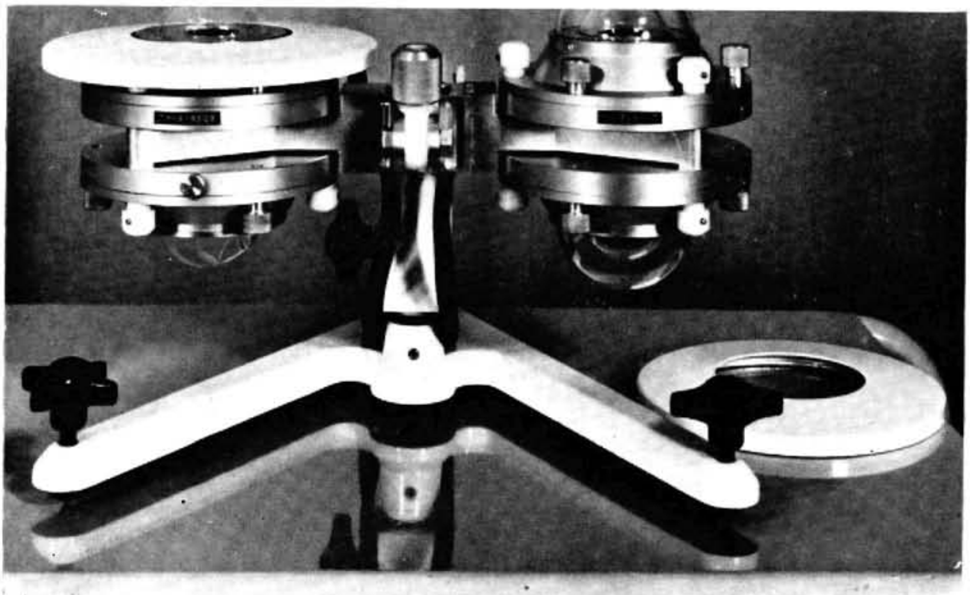

Fig. 4. PD4 Davos radiometer on laboratory stand. Note double glass domes on right and Lupolen shielded sensors on left.

ethylene product—in the dome shielding the long-wave sensors (Funk, 1961). The instrument has the further advantage that all four receiving surfaces are installed on the same plane metal support, which ensures that the sensors are always parallel to each other. At high latitudes, where low sun angles are more frequent, this arrangement has a considerable advantage, since even a small deviation from the horizontal position may result in apparent large differences in the radiation. A six-channel Speedomax recorder was used in conjunction with the radiometer; four channels for the input from the sensors and one each for the zero point and instrument temperature. A small generator and voltage and phase regulator provided power for the recorder. The radiation instrument had been calibrated by the manufacturers in the spring of 1967. However, it was possible to carry out a field calibration over the short-wave range using a standard Linke-Feussner Actinometer and millivoltmeter. This was done on the morning of 27 July with the PD4 receiver horizontal. The calibration constant was found to be unchanged.

A thermograph and hygrograph exposed in a louvred screen at a height of 1.4 m above the ice surface provided a continuous record of temperature and relative humidity. A thermistor and a Bendix carbon hygrometer sensor were also exposed at a height of 0.5 m and the output recorded on two Esterline-Angus recorders. These instruments were initially compared with the thermograph and hygrograph in the screen, an Assman psychrometer being used as the basic calibration instrument. A Woefle-type mechanical wind recorder provided a basic continuous record of average windspeed and direction at a height of 1.9 m above the ice and was checked for consistency with a second similar instrument exposed at approximately the same height on the edge of the glacier, some 50 m distant. Two portable fan anemometers (Isuzu type) which were initially tested against each other and the Woefle instrument were used in the determination of the wind profiles (see below). The measured ablation was taken as the average reading of four stakes located close to each other near the radiation instrument. The mean deviation of the observed daily ablation values at the individual stakes from the average value of all stakes (7 cm) was 0.6 cm or ±9 per cent.

III. Meteorological Conditions during the Period of Observation

(a) *The average and extreme conditions:* The mean and extreme conditions observed during the period are tabulated in Table I and the mean daily data in Figure 5.

Table I. Mean and Extreme Meteorological Data, Worthington Glacier 16 July to 1 August 1967

Element	*Maximum*	*Minimum*	*Mean*
Screen temperature °C	16.1	5.6	9.6
Screen water vapor pressure mm Hg	10.7	6.1	7.5
Windspeed m s^{-1}	4.5	1.1	2.1
Cloudiness tenths	10	1	8
Daily ablation cm	11.2	4.4	7.0

Notable is the high cloudiness which must be considered typical for this part of Alaska in summer. The average summer cloudiness for Cordova and Valdez, which are on the coast, is also of the order of 80 per cent. Similar average figures would be expected in the Worthington Glacier area, as it is located in essentially a coastal region close to the crest of the pass across the Chugach Range at this point. The low interdiurnal variation in temperature and the high water vapor pressure are further indicative of the maritime nature of the region, and are what would be expected in the mean at this location when compared with the long-term mean data for summer at Valdez and Cordova and in view of the discussion of Watson (1959). The association of the mean daily ablation with the daily mean values of cloudiness, temperature, and vapor pressure are evident in Figure 5.

(b) *Diurnal variations:* The mean diurnal variations in the various meteorological elements are given in Table II.

TABLE II. DIURNAL VARIATION IN METEOROLOGICAL CONDITIONS, WORTHINGTON GLACIER
16 JULY TO 1 AUGUST 1967
(Based on 3-hourly observation)

Element	*Mean maximum*	*Time*	*Mean minimum*	*Time*	*Mean range*
Temperature °C	11.2	12–15 h	8.3	0–3 h	2.9
Water vapor pressure mm Hg	7.9	12–18 h	7.2	3–6 h	0.7
Windspeed m s^{-1}	2.7	9–12 h	1.7	18–21 h	1.0

The low diurnal range of temperature and humidity further indicate the maritime nature of the location. Cloudiness showed no marked diurnal variation, but was possibly slightly higher in the late afternoon. The diurnal variation in ablation was, of course, difficult to determine, but a series of measurements indicated a probable maximum of up to 0.7 mm h^{-1} close to noon and a minimum of 0.1 mm h^{-1} during the night hours.

The period of observation is very short, but it seems that it can be considered fairly typical of the long-term mean conditions over much of the summer in this region.

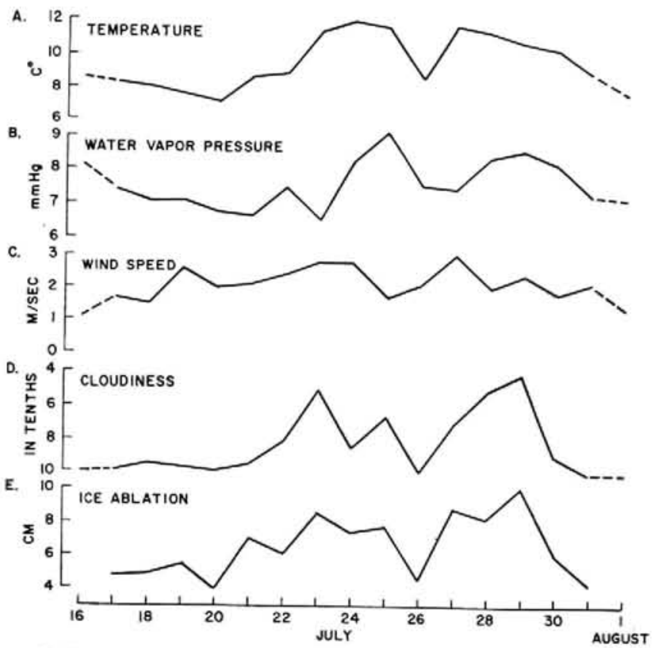

Fig. 5. Daily averages of meteorological elements, Worthington Glacier, summer 1967.

IV. THE HEAT BALANCE AT THE GLACIER SURFACE

The heat balance has been calculated for individual 24-hour periods because the melting proceeds throughout the whole day and night. As the glacier tongue can be considered "temperate", there is no heat flux into or out of the glacial ice and in the heat balance equation only three terms need be considered:

(a) the net radiation budget,

(b) the sensible and latent heat flux, and

(c) the ice melt at the surface.

(a) *The net radiation budget:* The mean value of the radiation budget over all wavelengths was measured as 262 cal cm^{-2} d^{-1} (127 J m^{-2} s^{-1}) or a total of 4 190 cal cm^{-2} (175 MJ m^{-2}) for the whole period of observation. The maximum daily figure was 490 cal cm^{-2} (20.5 MJ m^{-2}) on 29 July and the minimum 132 cal cm^{-2} (5.51 MJ m^{-2}) on 31 July. The mean value of the long-wave radiation balance over the period was only −6 cal cm^{-2} d^{-1} (−3 J m^{-2} s^{-1}). The highest value of +4 cal cm^{-2} d^{-1} (+2 J m^{-2} s^{-1}) occurred on 30 July, and the minimum of −39 cal cm^{-2} d^{-1} (−19 J m^{-2} s^{-1}) on 23 July, a day of relatively low cloudiness. Due to the high mean cloudiness in the period, the long-wave balance is quite often positive as the clouds (usually low St, Sc, or Ns) would frequently have higher radiative temperatures than the 0°C of the glacier surface.

Thus for this period of observation the long-wave radiation makes only a very small contribution to the net balance which is dominated by the variations of the short-wave contribution.

A series of measurements of the albedo yielded a mean value of 19 per cent. This is rather low for glacier ice (cf. Dirmhirn and Trojer, 1955) but the Worthington Glacier ice is rather dirty, being flecked with small chips of glacial debris in many places. In Figure 6 is shown the daily course of the albedo. Higher values are recorded in the mornings and evenings rather

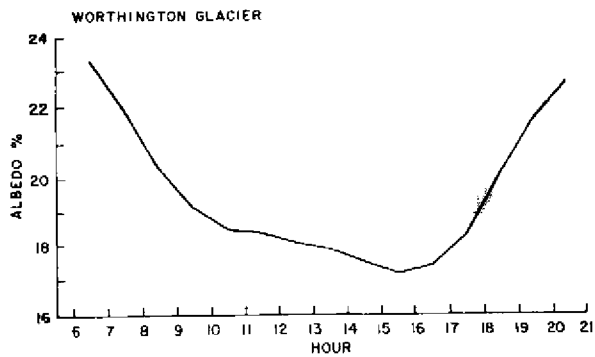

Fig. 6. Daily course of albedo, Worthington Glacier, summer 1967.

than during the main part of the day. As the surface is always at melting temperature, this is apparently due to the occurrence of some direct reflection when the sun is at a low angle. This effect agrees with the observations made by Hubley (1957). It was also found that with higher cloudiness the albedo was itself higher. This indicates that the direct solar radiation is absorbed more than the sky radiation. This might be explained in terms of the different distribution of wavelength for direct as opposed to sky radiation, and by the results of Ambach (1963) that albedo is some function of wavelength. However, the period of observation is, of course, too short and the cloudless periods too few to determine any clear relation.

(b) *The sensible and latent heat fluxes:* These fluxes were calculated using Prandtl's relation (Lettau, 1939, 1949). The recording anemometer and the two hand anemometers were used to obtain a number of wind profiles during each day at different times, each profile being based on wind runs over approximately a ten-minute period. Because continuous measurement of wind profile was not possible with the anemometers available, it was necessary to calculate a mean value of the roughness parameter Z_0 based on the mean of all these observations of the profile. The resulting mean value of Z_0 was 0.18 with an absolute range of from 0.09 to 0.51. The roughness parameter was found to be smaller in the night measurements and when conditions were overcast, the surface then being smoother than when exposed to full sunlight. This single value of Z_0 which was used in all further calculations for the period is in reasonable agreement with the observations of Hoinkes (1953) who obtained a mean value of 0.172 in the Alps and Untersteiner (1958) who quotes a mean value of 0.15 by night and 0.20 by day for measurements in the Karakoram.

The friction velocity U_* was determined from the wind-speed measurements using this mean value of Z_0 in the equation

$$\bar{U}_z = 5.75 U_* \log \frac{Z - Z_0}{Z_0},$$

yielding a value of U_* for particular wind speeds of between 6 cm s^{-1} and 26 cm s^{-1}.

The eddy diffusivity K_a for adiabatic conditions may then be obtained from the relation

$$K_a = \rho U_* \gamma (Z_1 + Z_0)$$

where γ is the Kármán constant.

A corrected value K of the eddy diffusivity in non-adiabatic conditions can be obtained from the equation due to Lettau (1949)

$$K = \frac{K_a}{(1+x)^2}$$

where x is the dimensionless Richardson number and

$$x = \frac{g\gamma^2 (Z + Z_0)^2}{T U_*^2} \frac{d\theta}{dZ}.$$

The calculation of the value of K for a height of 1.50 m yielded values of 0.4 to 1.6 g cm^{-1} s^{-1} which agree well with the measurements of Ambach (1963), Hoinkes (1953) and Untersteiner (1958).

If temperature and vapor pressure follow a logarithmic distribution, it can be shown that the sensible heat flow S and the latent heat flow L are given by the equations

$$S = 0.24 K t \frac{dT}{dZ}$$

and

$$L = 600 K t \frac{0.623}{P} \frac{de}{dZ}.$$

As no continuous profile measurements were available the assumption of a logarithmic temperature and humidity profile was made in the calculation or dT/dZ and de/dZ. In this case the expression for the gradients is

$$\frac{dT}{dZ} = \frac{k_t}{Z}$$

where

$$k_t = \frac{\Delta T}{2.3 (\log Z_1 - \log Z_2)},$$

and similarly for de/dZ.

Thus, using the values of temperature and relative humidity measured at the two fixed heights above the surface, the gradients of both were derived and the sensible and latent heat fluxes calculated. This was done on a three-hourly rather than a daily basis in order to minimize errors due to the higher wind speeds during the day usually occurring near the time of maximum temperature. The mean and extreme daily values of the fluxes are shown in Table III.

As the air temperature was always above the freezing point, the sensible heat flux was always positive. High humidity and relatively warm temperatures throughout the period resulted in the latent heat being also always positive.

The extreme high values of both the sensible and the latent heat occurred on the warmest day in the period, viz. 24 July, and the lowest values of both also occurred on the same day, 18 July, the day of lowest mean wind speed.

TABLE III. SENSIBLE AND LATENT HEAT FLUXES, WORTHINGTON GLACIER 16 JULY TO 1 AUGUST 1967

Flux	*Sensible*		*Latent*	
	cal cm⁻²	MJ m⁻²	cal cm⁻²	MJ m⁻²
Daily average	141	5.9	97	4.1
Total (16 days)	2 260	94.7	1 550	64.9
Maximum daily	229	9.6	153	6.4
Minimum daily	86	3.6	59	2.5

(c) *The observed ice melt:* During the whole period 1.12 m of ice melted requiring 8 140 cal cm^{-2} (340 MJ m^{-2}), the corresponding daily figures being 70 mm and 508 cal cm^{-2} (21.2 MJ m^{-2}). This is a very high ablation, particularly if the high cloudiness of the area is considered.

The heat balance is shown diagrammatically on a daily basis in Figure 7. In Table IV, the

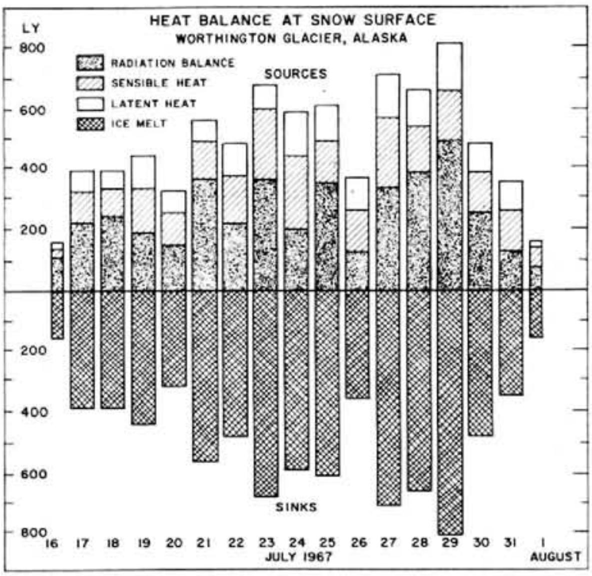

Fig. 7. Heat balance of Worthington Glacier surface, summer 1967.

TABLE IV. THE COMPONENTS OF THE HEAT BALANCE, WORTHINGTON GLACIER 16 JULY TO 1 AUGUST 1967 AND PERCENTAGE COMPARISONS

Component	*Total*		*Daily*			*A*	*B*	*C*	*D*	*E*	*F*
	cal cm⁻²	MJ m⁻²	cal cm⁻²	MJ m⁻²	%	%	%	%	%	%	%
Radiative	4 190	175	262	11.0	51	68	69	78	94	74	86
Sensible	2 260	94	141	5.9	29	32	25	22	6	26	14
Latent	1 550	65	97	4.1	20	−2	6	−8	−8	−74	−24
Melting	−8 140	−340	−508	−21.1	−100	−98	−100	−84	−58	−26	−54
Heating from ground	—	—	—	—	—	—	—	−8	−34	—	−22

A = Ambach and Hoinkes (1963) (20 days), snow, Alps (Kesselwandferner).
B = LaChapelle (1959) (37 days), snow, Blue Glacier, Washington, U.S.A.
C = Ambach (1963) (38 days), ice, Greenland.
D = Untersteiner (1961) (14 days), ice, drifting ice station, Arctic Ocean.
E = Gold and Williams (1961) (14 days), snow, Ottawa, Canada.
F = Wendler (1967) (18 days), snow, Fairbanks, Alaska.

components of the balance are shown both as totals, and on a daily basis, together with a comparison of the percentage contribution of each term and with that determined by other authors. It should be noted that the comparisons are made on the basis that the total heat input from all sources and the total heat received by all sinks both equal one hundred per cent.

The experiment is subject to a number of errors. The chief difficulty was the absence of a method of obtaining continuous wind profiles for the determination of the variation of Z_0 throughout the period, and in having only two measurements of temperature and relative humidity over the ice surface. The most accurate measurements were those of the radiation balance which, taking into account the several possible sources of error in the measurement system is of the order of ± 5 per cent. Taking into account the assumed constancy of Z_0 which affects the values of the eddy diffusivity K, as well as the possible errors in the measurement and calculation of the temperature and relative humidity gradients, the calculation of the sensible and latent heat fluxes is considered to be accurate to within ± 7 per cent. The greatest inaccuracy comes in the measurement of the ablation which is estimated to be only within ± 9 per cent.

It will be observed in Table IV that a balance is not achieved between the components of the sources and sinks the difference being 1.7 per cent. In view of the sources of error mentioned above this value is considered reasonable.

V. Conclusion

Several features are of interest in the measurements:

(a) Fifty-one per cent for the net radiative contribution as an energy source is low owing to the high mean cloudiness of over 80 per cent.

(b) Twenty per cent for the latent heat contribution is extremely high owing to the continuous condensation at the relatively high air temperature and humidity experienced in the period.

(c) Twenty-nine per cent for the sensible heat is high, but not excessively so.

In total then, the radiative component and the net eddy heat transfer contribute equally to the ice melting. Comparison of a series of photographs taken at the glacier between 1937 and the present indicate a considerable retreat of the ice. However, they are not sufficiently detailed to permit any numerical assessment of its extent.

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