NORSK POLARINSTITUTT
SKRIFTER NR. 156

SIGMUND MESSEL

# Mass and heat balance of Omnsbreen – a climatically dead glacier in southern Norway

NORSK POLARINSTITUTT
OSLO 1971

DET KONGELIGE DEPARTEMENT FOR INDUSTRI OG HÅNDVERK

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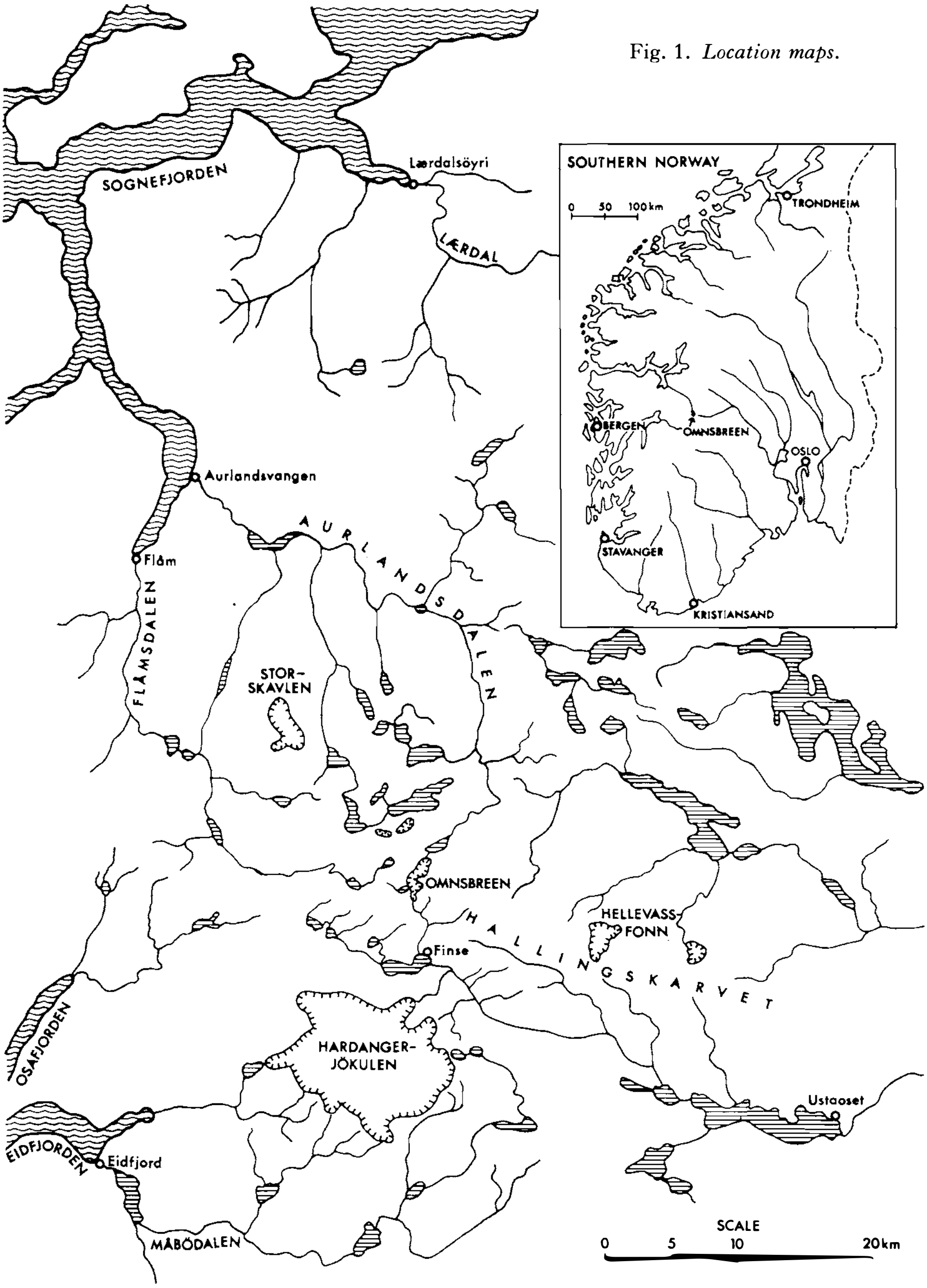
Manuscript received January 1971

Printed August 1971

# Contents

Fig. 1. *Location maps.*



## Abstract

Mass and heat balance studies of Omnsbreen (see map, Fig. 1) has been conducted from 1966 to 1970.

Mass balance shows a deficit of 460 g/cm$^2$ for the five years (Table II). Results of the heat balance studies are shown in Tables III, IV, and V; as a mean, radiation accounts for c. 52%, convection for c. 33%, and condensation for c. 15% of the ablation; rain and sublimation play an insignificant role (c. 0.5%).

In connection with the mass and heat balance measurements, the role of free water content and the refrozen meltwater has been investigated. Features about the radiation and the albedo are also discussed.

Both mass and heat balance measurements on Omnsbreen are compared with corresponding results from other glaciers in Norway (see Fig. 12 and Tables VI and VII).

## Introduction

Omnsbreen, situated west of the Hallingskarvet massif, on the watershed between Aurlandsdalen and the slopes toward Finse and Hallingdal (7°30'E, 60°39'N, see Fig. 1), covers an area of 1.52 km$^2$ (mapped in 1968) in heights from 1460 to 1570 m a.s.l. The glacier borders are well defined. Fig. 2 reveals the saddle-shaped figure of the glacier surface. A few rock islands are found in the northern part of the glacier. The glacier bedrock consists of Cambro-Silurian phyllite, strongly folded and metamorphosed.

The present glacier must be classified as a dead glacier, dynamically as well as climatically (see AHLMANN 1948, pp. 59–63). Measurements have revealed only slight or no movement of the ice masses. No crevasses exist today; numerous traces of closed crevasses, however, are seen all over the glacier surface. A few water holes and canyons in the ice (Figs. 3, 4, and 5) indicate that the glacier's mean thickness is not more than 20 m. Furthermore, even the highest part of the glacier is situated below the average equilibrium line (Fig. 6). Omnsbreen today is obviously a relic of the former active and more extensive ice masses, which had their centre near the glacier's present site. Morphological features as well as climatological estimations support the view that the ice masses must have been c. 70 m thicker around 1750, when the glaciers in southern Norway reached their maximum extension in historic times.

As can be seen from the map, Fig. 7, partly based on terrestrial photograms taken by Norges Geografiske Oppmåling in 1927, Omnsbreen must have been c. 25 m thicker than today. Aerial photographs as well as tourist reports from 1954–55 confirm that the glacier was then still in motion and c. 8 m thicker than

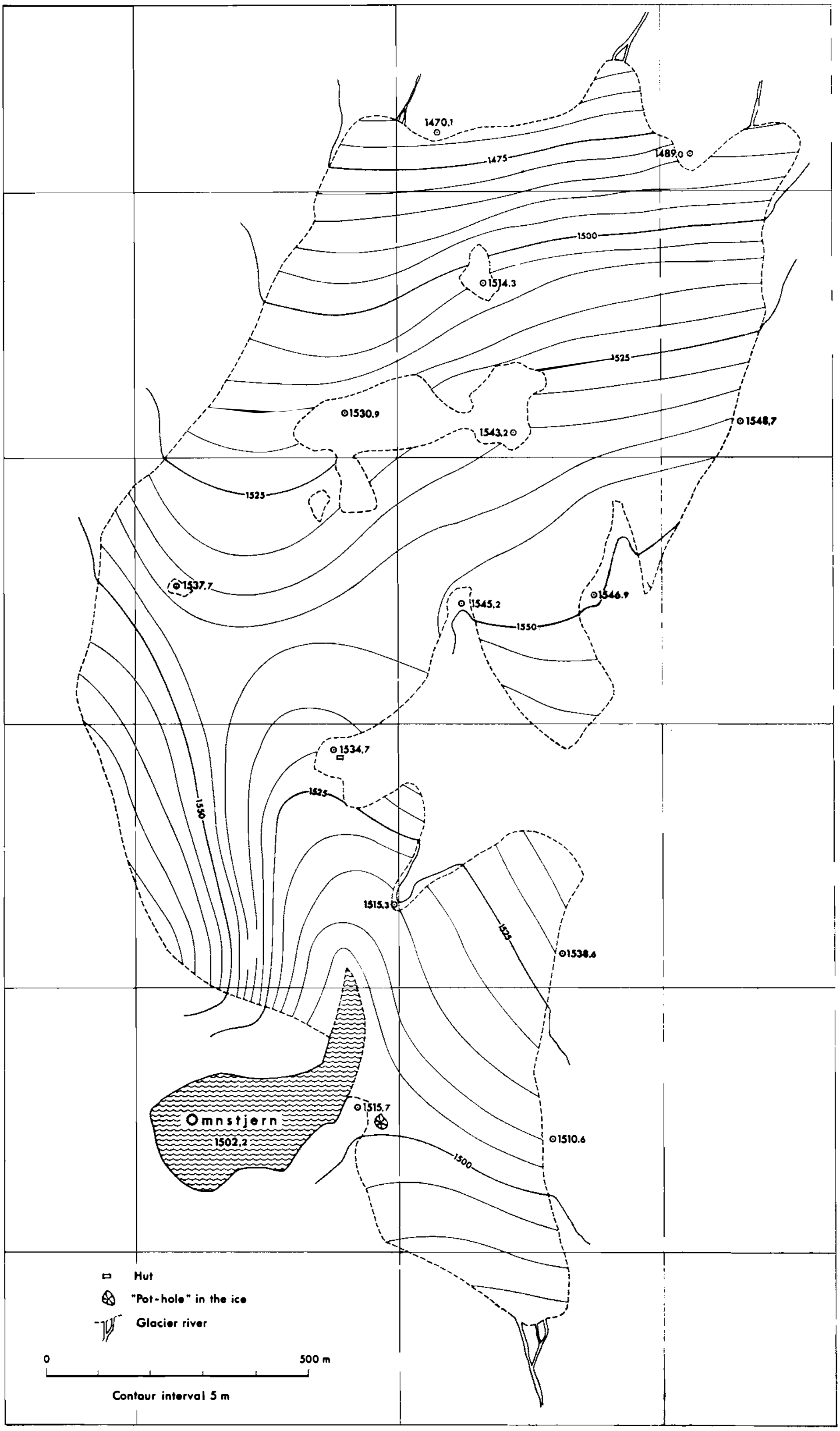


Fig. 2. *Map of Omnsbreen, performed in 1968 by means of tachymetric methods.*

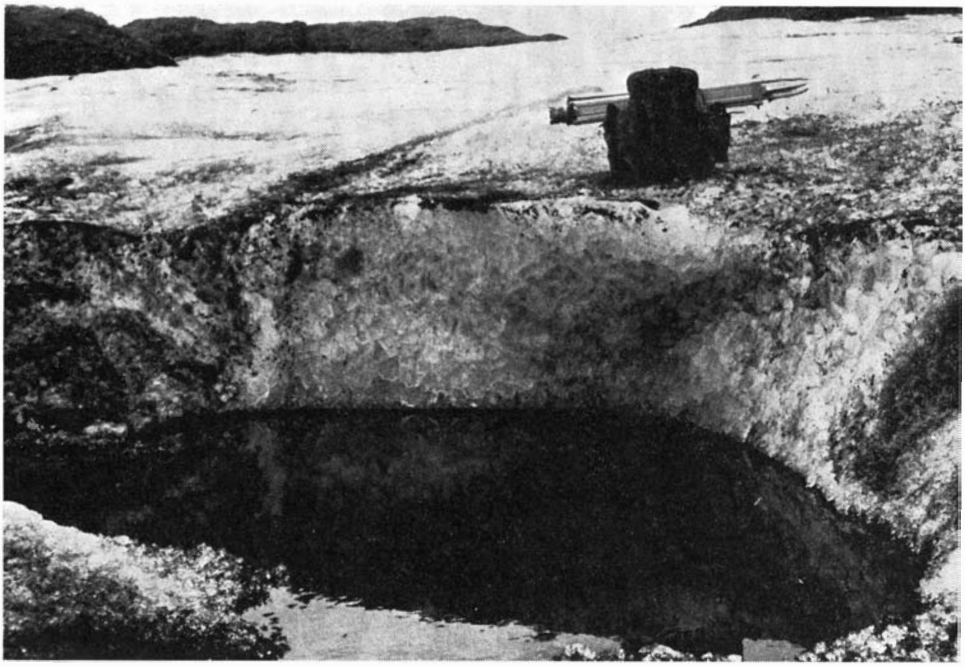


Fig. 3. *Water hole; note the exposed crystals, 10–16 cm in diameter.*

Fig. 4. *This "pot hole", c. 20 m deep, is probably carved out by whirling water and modified by the influence of meteorological ablation factors and slight movement in the ice masses. The glacier bed is exposed in the bottom.*

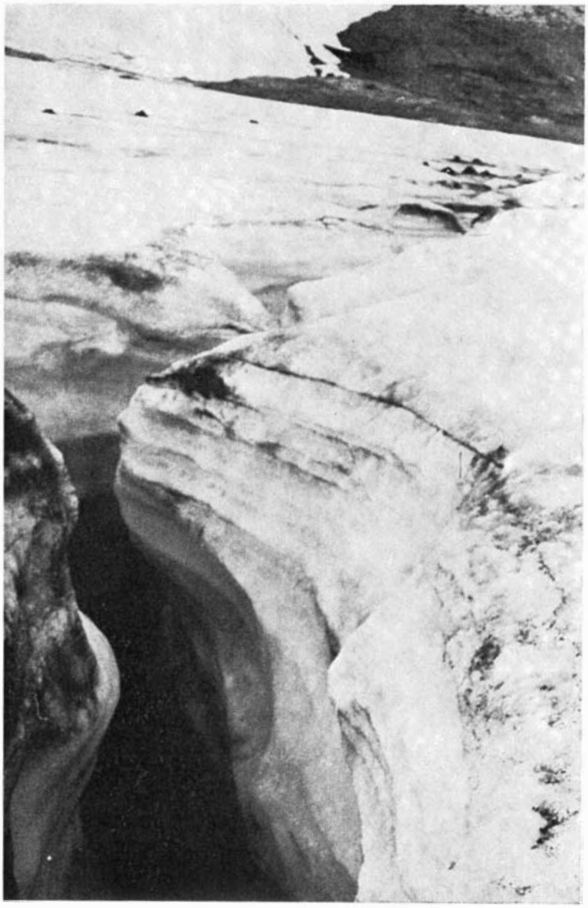
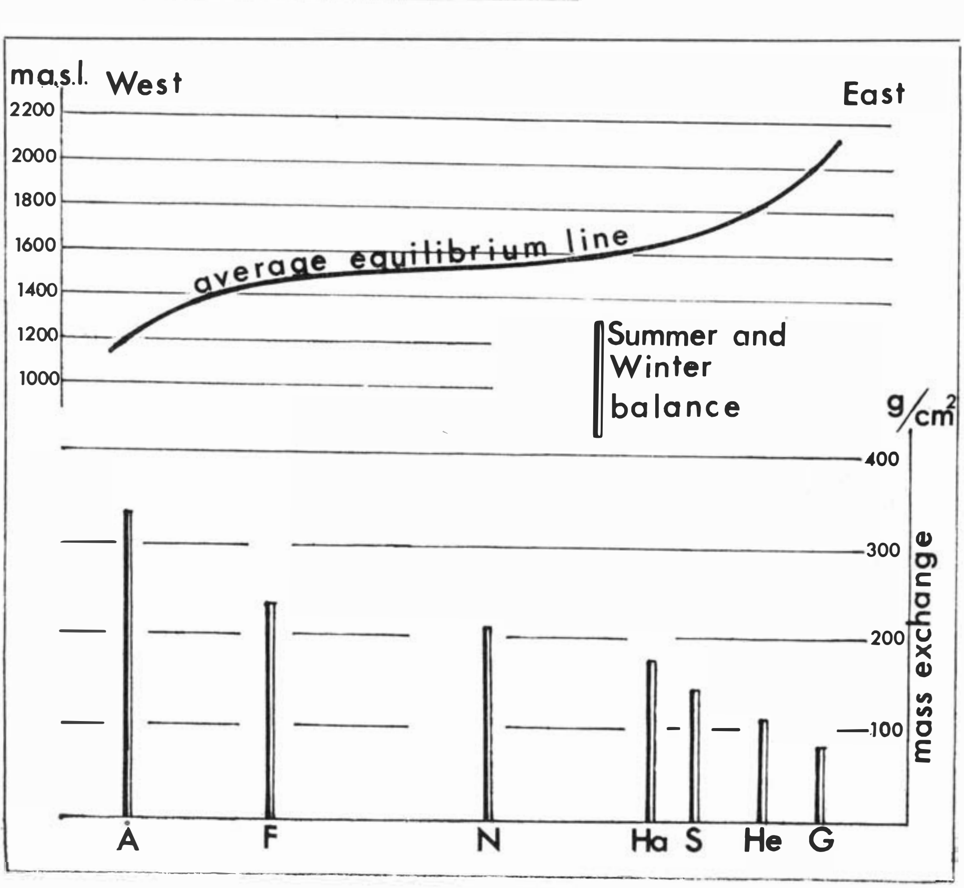


Fig. 5. *Canyon,c. 14 m deep, showing fairly regular meandering course.*

Fig. 6. *Mass exchange and equilibrium line calculated for steady state conditions on the examined glaciers in southern Norway.*

*G – Gråsubreen,*
*He – Hellstugubreen,*
*S – Storbreen,*
*Ha – Hardangerjøkulen,*
*N – Nigardsbreen,*
*F – Folgefonni,*
*Å – Ålfotbreen.*

(*Based upon a figure in* Pytte *1969.*)



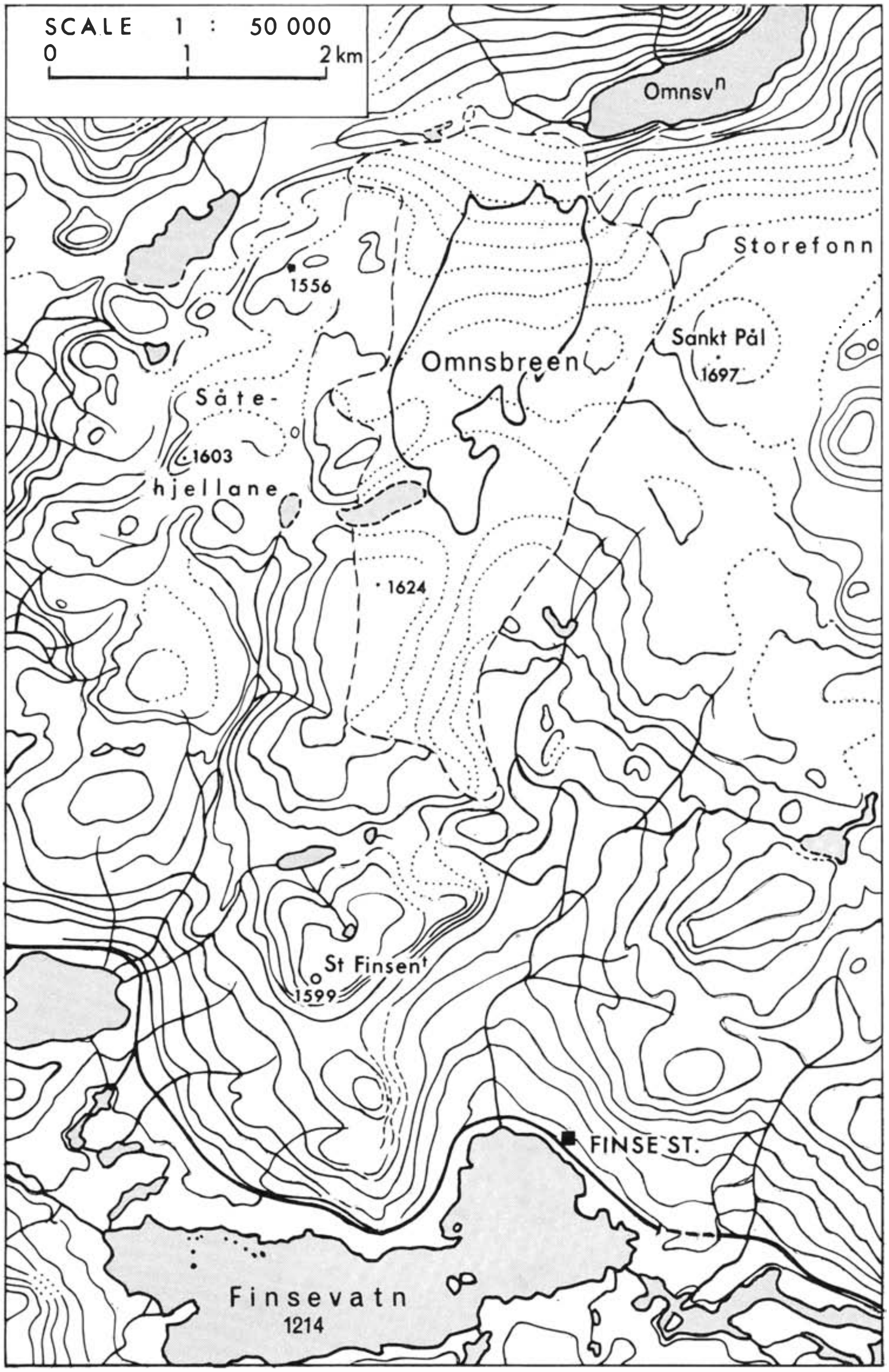


Fig. 7. *Section of a map made by Norges Geografiske Oppmåling, based partly upon terrestrial photograms taken in 1927. The present glacier limit of Omnsbreen is marked.*

today. No closer examination of Omnsbreen has previously been published, except a few words by STRØM (1959, pp. 8–9), commenting on a picture of a quite impressive sub-glacial stream tunnel coming out in the southern part of the glacier. This picture was taken in 1950 (LIESTØL, pers. comm.). The tunnel is now mainly collapsed.

The flat and even surface of Omnsbreen makes the glacier fairly suitable for mass and energy balance studies. The vertical extent of only 110 m might, however, be regarded as an unfavourable aspect, because no representative diagrams showing mass balance as a function of height in actual areas can be obtained.

The glacier is quite easily accessible from Finse. Transport of equipment takes in winter time c. 20 min. by weasel. In 1968 a hut was erected on a rock peak close to the glacier. The hut served as a workshop, and was also used for accomodation.

## Climate

Omnsbreen is situated on the climatologically rough watershed between the western and the eastern parts of southern Norway. Recordings at the meteorological station Slirå (1300 m a.s.l.), situated c. 5 km south-west of Omnsbreen, shows the following: The area is frequently under the influence of lows from west and south-west. Wind forces reach 6 Bf or more on c. 160 days of the year. In the period November—March, wind forces of 6 Bf or more occur on an average more than every second day. By far the most frequent winds come from the western sector, although south-easterly winds constitute a considerable part of the wind pattern.

There is precipitation in the area on c. 250 days yearly, and more than 95 days are foggy. Fig. 8a gives a picture of the precipitation. Fig. 8b shows that July is the warmest month (+5.2°C) and February the coldest (–11.4°C).

## Mass balance 1966–70

### TERMINOLOGY AND METHODS

A close study of the mass balance of Omnsbreen has been performed during the last 5 balance years. The terminology used is in accordance with that published by UNESCO (Technical Papers in Hydrology, 1968, reprinted in The Journal of Glaciology, Vol. 8, No. 52, pp. 3—7). The mass balance terms are shown graphically in Fig. 9.

The field methods are all traditional (see ØSTREM and STANLEY 1969). The measurements were made according to the stratigraphical system based on the existence of an observable summer surface, which is assumed to be formed at the time of summer minimum mass. Aluminium and steel stakes were drilled into the ice (Fig. 10) and used as references.

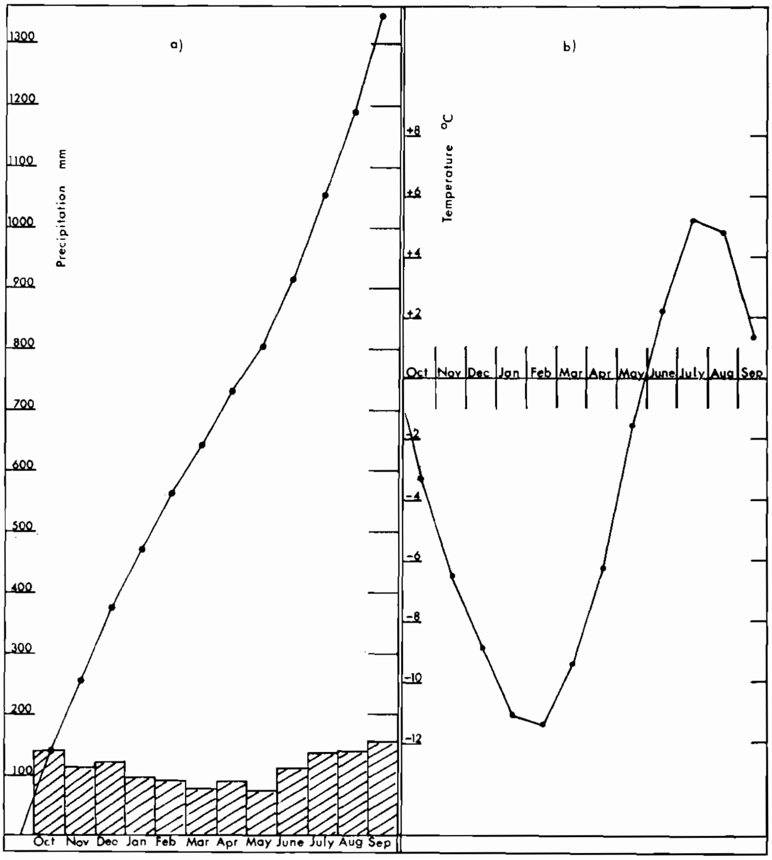
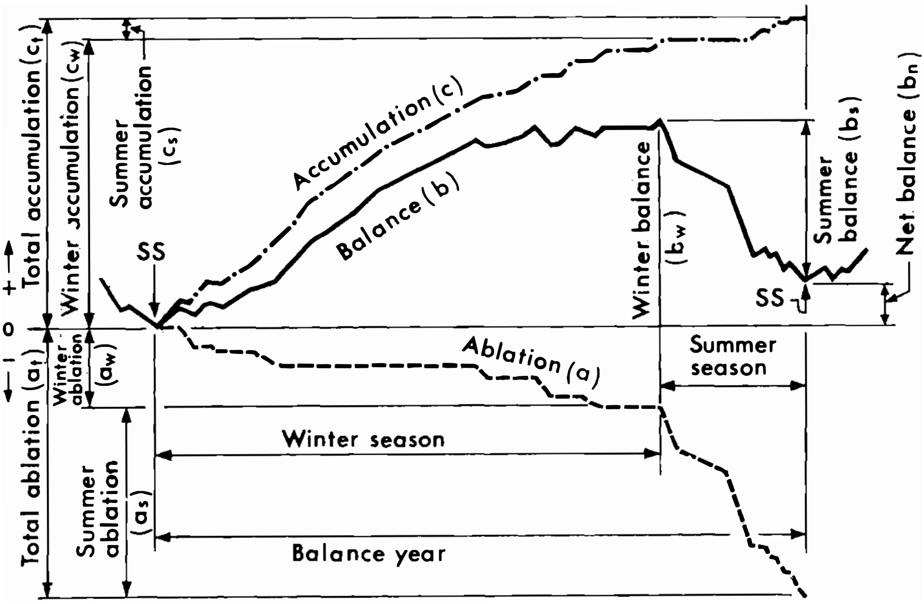


Fig. 8. *Precipitation, a), and temperature, b), conditions in the Omnsbreen district. The curves are based upon recordings at the meteorological station Sliraa, c. 5 km SW of the glacier.*



SS= time of formation of a summer surface

Fig. 9. *Mass balance terms used in the present paper. The balance as measured at a point is illustrated in relation to time.*

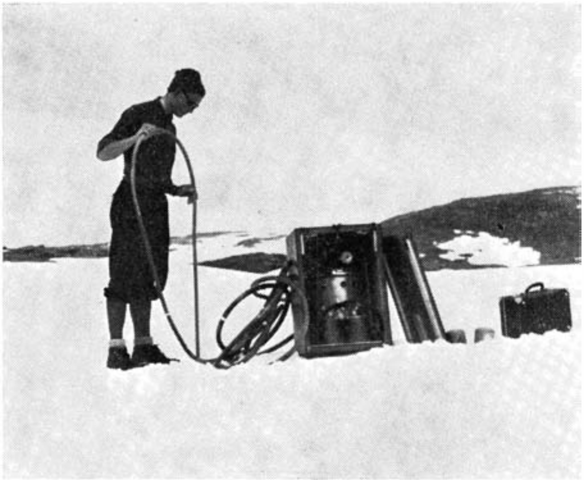


Fig. 10. *For drilling stakes and thermistors into the ice a steam-operated drill, described by* HOWORKA *(1965, pp. 749–750), was employed.*

## LENGTH OF WINTER AND SUMMER SEASONS

Table I shows the dates which separated the winter and summer seasons in the 5 years investigated. The dates are based upon direct weather-observations. It is worth noticing that the beginning of the winter season can vary c. 3 weeks before or after 2 October, which we on the glacier can put as the "normal" date for the transition from summer into winter, although conditions in October 1969 were abnormal.

The transition from winter into summer on the glacier appears not to vary more than ± 2 weeks from 27 May.

From the above given dates we can conclude that in the Omnsbreen district the summer season as a mean is slightly more than half the winter season in duration.

Table I

*The length of winter and summer seasons*

| Balance Year | Winter season | | Summer season |
|---|---|---|---|
| 1966 | 13 Oct. – | 25 May – | 22 Sept. |
| | 224 days | 120 days | |
| 1967 | 22 Sept. – | 11 June – | 2 Oct. |
| | 262 days | 113 days | |
| 1968 | 2 Oct. – | 15 May – | 19 Sept. |
| | 225 days | 126 days | |
| 1969 | 19 Sept. – | 22 May – | 23 Oct. |
| | 245 days | 154 days | |
| 1970 | 23 Oct. – | 2 June – | 27 Sept. |
| | 222 days | 117 days | |
| Mean 1966–1970 | 4 Oct. – | 27 May – | 1 Oct. |
| | 235 days | 126 days | |

## WINTER, SUMMER, AND NET BALANCE

The results of the mass balance investigations on Omnsbreen are given in Table II. A clear retreat of the glacier is apparent. In the balance year 1969 Omnsbreen melted catastrophically, as did most of the glaciers in southern Norway. The reasons for this were a winter poor in precipitation and a long and relative hot summer. Not since 1947 was the climate so unfavourable for glaciers. The surface of Omnsbreen sank about 280 cm. The other extreme in the 5-year period of investigation was the mass surplus of 49 g/cm$^2$, measured in the balance year 1967. The mean yearly net balance value of –92 g/cm$^2$ makes it quite clear that Omnsbreen has no chance of keeping its present features, unless the climate becomes noticeably harsher. It may seem astonishing that we still find a glacier in this area today. Two phenomena, the wind-blown snow and the refreezing of meltwater, can partly explain why. The refrozen meltwater will be discussed in the following chapter.

The accuracy of the results is calculated to be 5% or better, owing to relatively numerous nets of stakes, careful recordings of snow depth and snow density, and a relatively even surface of the glacier during the summer. About 400 snow-depth measurements per km$^2$ were made at the end of the winter seasons. Three pits for density measurements were dug every spring. In the 5 years of investigation some stakes were broken down by wind and hoar in the course of the winter, and had to be replaced. Some difficulties concerning the redrilling of stakes and

Table II

*Results of mass balance investigations on Omnsbreen*

| Balance year | Mass balance for the whole glacier B | | Mass balance per area b |
|---|---|---|---|
| 1966 | winter | (2.18 ± 0.10) · $10^6$ ton | (144 ± 6) g/cm$^2$ |
| | summer | (3.45 ± 0.12) –»– | (228 ± 9) –»– |
| | net | (–1.27 ± 0.16) –»– | (–84 ± 11) –»– |
| 1967 | winter | (3.36 ± 0.15) –»– | (221 ± 10) –»– |
| | summer | (2.60 ± 0.09) –»– | (172 ± 6) –»– |
| | net | (+0.76 ± 0.18) –»– | (+49 ± 12) –»– |
| 1968 | winter | (3.35 ± 0.15) –»– | (220 ± 10) –»– |
| | summer | (3.62 ± 0.09) –»– | (238 ± 6) –»– |
| | net | (–0.27 ± 0.18) –»– | (–18 ± 12) –»– |
| 1969 | winter | (1.64 ± 0.08) –»– | (109 ± 5) –»– |
| | summer | (5.52 ± 0.11) –»– | (368 ± 7) –»– |
| | net | (–3.88 ± 0.14) –»– | (–259 ± 9) –»– |
| 1970 | winter | (1.56 ± 0.07) –»– | (112 ± 5) –»– |
| | summer | (3.67 ± 0.14) –»– | (262 ± 10) –»– |
| | net | (–2.11 ± 0.15) –»– | (–150 ± 11) –»– |
| Mean values 1966–70 | winter | (2.42 ± 0.09) · $10^6$ ton | (161 ± 6) g/cm$^2$ |
| | summer | (3.77 ± 0.11) –»– | (253 ± 8) –»– |
| | net | (–1.35 ± 0.14) –»– | (–92 ± 10) –»– |

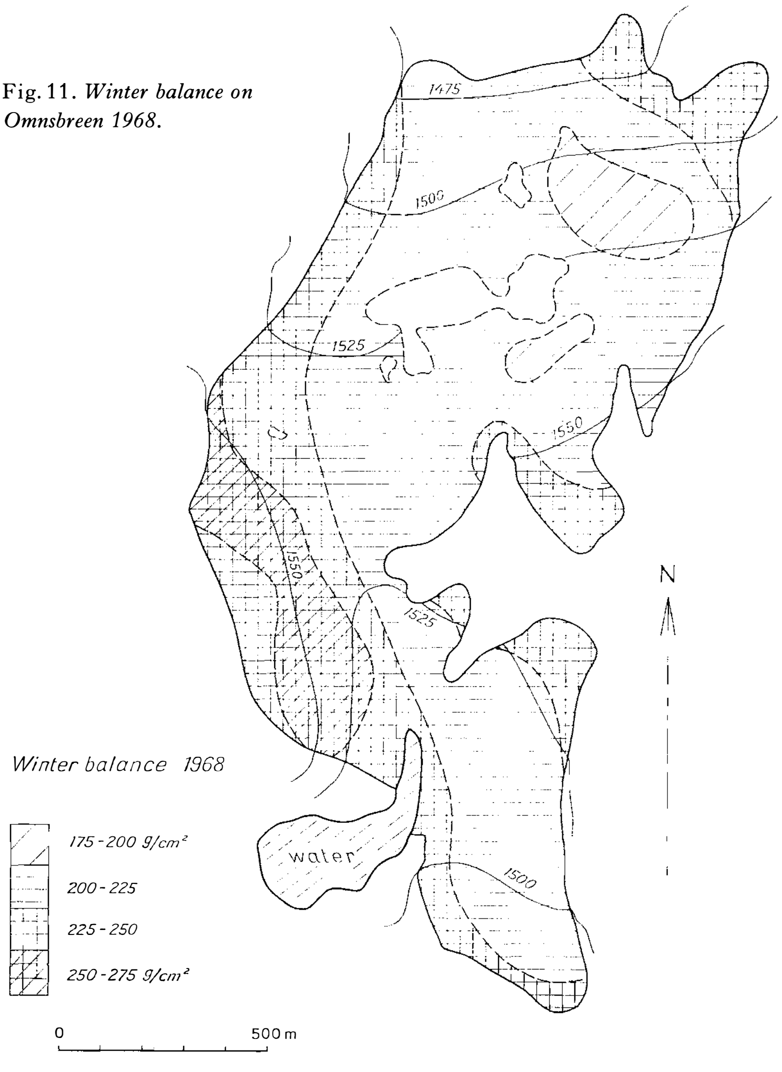
density measurements also occurred. In summer 1970 quite a lot of the stakes had to be removed to replace lost stakes on Hardangerjøkulen. Therefore, the accuracy in the winter and the summer balance will vary somewhat, as Table II confirms.

Snow mass distribution representing the winter balance does not show any noticeable change from one year to another. A typical map presenting the winter snow mass is that from 1968 (Fig. 11).

## COMPARISONS WITH OTHER GLACIERS EXAMINED IN NORWAY

Fig. 12 gives the net balance as a function of height for 15 glaciers examined in Norway. The balance year 1968 is typical for the curves' mutual position. All the curves, however, will of course be displaced horizontally from year to year, depending on the totals of winter snowfall and summer melting. The curves representing the most maritime glaciers are on the far right of the diagram for southern

Fig. 11. *Winter balance on Omnsbreen 1968.*



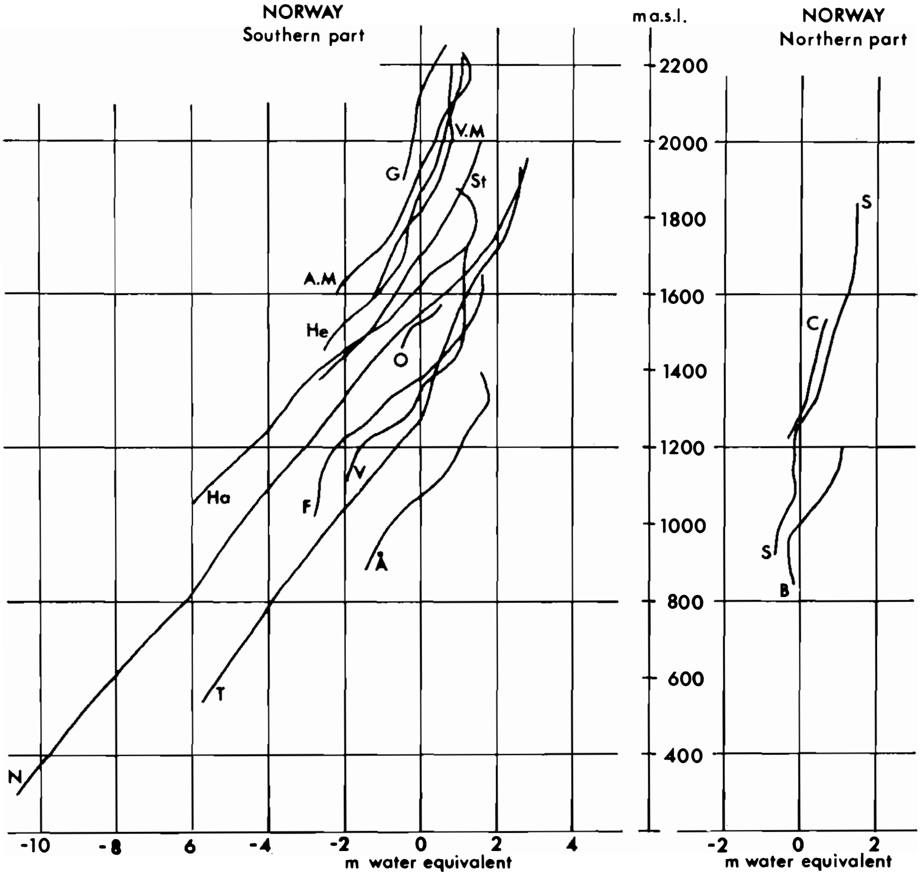


Fig. 12. *Net balance curves for the examined glaciers in Norway 1968. Southern part: Å – Ålfotbreen, F – Folgefonni, T – Tunsbergdalsbreen, V – Vesledalsbreen, O – Omnsbreen, N – Nigardsbreen, Ha – Hardangerjøkulen, St – Storbreen, V.M. – Vestre Memurubre, He – Hellstugubreen, A.M. – Austre Memurubre, G – Gråsubreen; northern part: B – Blåisen, S – Storsteinfjellbreen, C – Cainhavarre.* (*Partly taken from* PYTTE 1969.)

Norway. As can be expected, the equilibrium line increases with the continentality. The equilibrium line for the 3 glaciers examined in northern Norway is also demonstrated.

A glance at Fig. 6 in connection with Fig. 12 confirms the fact that Omnsbreen has a more maritime mass exchange than would be predicted, considering the glacier's geographical site. Results from all the 5 years of examination show that Omnsbreen has c. 70 g/cm$^2$ higher winter balance than areas at the same level on Hardangerjøkulen, just 10 km south. Wind-blown snow masses constitute most of this extra supply to the trough-shaped area where Omnsbreen is situated.

The measurements 1966–70 have also revealed that the net balance of Omnsbreen has been from 75 g/cm$^2$ to 100 g/cm$^2$ higher than the net balance of the corresponding areas on Hardangerjøkulen. Further investigations have shown that the ablation during the summer season in the two mentioned areas differs only slightly. The summer balances, however, are calculated to be from c. 5 g/cm$^2$

to c. 30 g/cm² less than the ablation values. As early as 1966 it became clear that refrozen meltwater played a prominent part in the mass exchange of Omnsbreen, and a close study of the problem was started in 1967.

## Refrozen meltwater and its role in the mass exchange

Every year some meltwater will refreeze when it sinks from the glacier surface to underlying layers in the glacier, which have negative temperatures. For ordinary active temperate glaciers this process takes place mainly at the transition from winter to summer and during the first part of the summer period. In the snow and in the firn several ice layers are formed. Where the summer surface consists of ice (mainly in the lowest part of the glacier), a relatively thick layer of superimposed ice is built up. The heat released by the freezing causes the temperature in the glacier to increase. In the firn area the temperature reaches 0°C throughout in the course of a normal summer, we are here still speaking about temperate glaciers. In the lower part, where the trickling water from the melting glacier surface does not penetrate the summer surface, the heat flux from the freezing zone is usually insufficient to raise the temperature to freezing point throughout the ice mass. Several measurements, on Omnsbreen as well as on other glaciers, show that only the uppermost 1—2 m of the ice are warmed up to 0°C, assuming that no crevasses exist in the area.

The slightly tilted and uncrevassed surface of Omnsbreen causes considerable water masses to become refrozen when summer shifts into winter, particularly in years when the snow that has fallen during the last winter is only partly melted when the frost sets in about the beginning of October. Slush, in places up to 80 cm thick, is then transformed into ice.

It may be open to discussion whether the refrozen meltwater should be taken as a supplement to winter accumulation or as a deduction from summer ablation. In the literature no general agreement has existed concerning this question. For the writer it seems most natural to subtract the mass of refrozen meltwater from the ablation during the summer period to obtain the summer balance. It should be noted that during the refreezing process only englacial mass transport takes place. The transport of material away from the glacier is prevented by the process outlined above. We have to bear in mind also that winter balance is defined as maximum balance in the course of a balance year.

Calculations of refrozen meltwater in early summer have been published by several scientists, for example SCHYTT (1949, pp. 222—227), AMBACH (1961, pp. 169—189), and LIESTØL (1967, pp. 12—16). Here we can mention briefly that, using thermistors for temperature registrations (see Fig. 13), the cold-reservoir used to freeze trickling water from the glacier surface until time of maximum ice thickness (usually when c. 50 cm of the winter snow is left) is on Omnsbreen calculated to 515 cal/cm² in 1968, 383 cal/cm² in 1969, and 447 cal/cm² in 1970.

The formulae used is $F = c \cdot \rho \cdot \int_0^{z_T} T(z)dz$

Fig. 13. *The resistance (measured in ohms) for calibrated thermistors drilled down in the ice masses is registered with a model of Wheatstone's bridge.*

where $\rho$ signifies the density and c the specific heat of ice. (Only the ice formed upon the summer surface is calculated here. It can be mentioned that in the snow cover 4—7 cm of ice lenses and ice layers were observed yearly just after the snow was wetted throughout.) T marks the temperature in various depths down to $z_T$, where temperature change in the course of the actual period is zero.

This energy deficit, formed during winter time, is compensated by the heat released when the meltwater freezes. The energy developed by the heat release, Q, cannot, as the above mentioned authors have stated, be expressed as

$$Q = (\rho_{\text{new ice}} - \rho_{\text{snow}}) \cdot L_{\text{ice}} \cdot \Delta h$$

where $\rho_{\text{snow}}$ signifies the density of wet snow, found by ordinary weighing. ($\rho_{\text{new ice}}$ = the density of new-formed/superimposed ice, about 0.87 g/cm$^3$. $L_{\text{ice}}$ = the latent heat of fusion, 79.6 cal/g. $\Delta h$ = the thickness of newly-formed ice, composed of refrozen meltwater and snow). The density of dry snow has to be used in the calculations.

Measurements presented in the following chapter give support to an estimate of the mean free water content in the snow equal to 12% of weight in the freezing period. The measured density of the wet snow amounts ordinarily to c. 0.55 g/cm³. As will be explained in the next chapter, the density of dry snow, $\rho_{dry}$, then will be c. 0.49 g/cm³. The thickness of newly-formed ice has to be expressed as

$$\Delta h = \frac{\rho \cdot c \cdot \int_{0}^{z_T} T(z)\, dz}{(\rho_{new\ ice} - \rho_{dry}) \cdot L_{ice}}$$

In 1968 the thickness was calculated to 15.5 cm, in 1969 to 10.2 cm, and in 1970 to 14.3 cm. It can be stated that these values differ c. 15% from corresponding values calculated when free water content is not incorporated. The role of free water will be discussed more in detail later.

Direct measurements, with the help of 5 stakes drilled into the ice, gave as mean values 16.3 cm in 1968, 10.7 cm in 1969, and 13.8 cm in 1970.

The freezing of slush on the glacier at the end of the summer was carefully studied in all the 5 years of investigation. The measured values (mean values for 13—18 stakes) varied greatly from year to year:

1966: 6 cm thick ice
1967: 42 » » »
1968: 23 » » »
1969: 4 cm thick ice
1970: 16 » » »

The free water content in the slush amounts to c. 60%. Thus, the newly-formed/superimposed ice had displaced the net balance in the mean c. +15 g/cm² yearly.

Together with the wind-blown snow, the refrozen meltwater can partly explain why Omnsbreen can exist today, with a climate that ordinarily only allows glaciers to exist c. 200 m higher up in the same area, or c. 30 km farther west in southern Norway. The word 'partly' is used because we have to bear in mind that Omnsbreen is a relic of a dominating ice complex covering the area earlier. The wind-blown snow and refreezing phenomena, it now seems, will just about help to extend the lifetime of the final ice masses for c. 20 years, if the climate should not turn noticeably harsher.

## Free water content in snow and ice

### INSTRUMENTS AND METHODS

In early summer (or other times when the snow temperature increases to 0°C) thin water films and small water droplets form between the snow grains. In the high mountain region of southern Norway it takes about two weeks from the time when the summer season sets in until the snow fallen the previous winter is wet throughout. At the same time the snow density increases from c. 0.44 g/cm³ to c. 0.54 g/cm³.

The water so formed is in glaciological literature termed free water (in some publications called capillary water, thaw water, or liquid water).

Several methods of obtaining values of free water in snow have been described earlier. Useful calorimeters have been constructed by Yosida (1940, pp. 91—102 and 1960, pp. 574–576). Among others Outa and Kinhoshita (1955, pp. 21–22), Yosida (1955, pp. 73–75) and La Chapelle (1956, pp. 769–771) have described centrifugal machines, while dielectrical methods are explained instructively by Kuroiwa (1954, pp. 61–62) and Ambach et al. (1965, pp. 247–252).

For the investigations on Omnsbreen the calorimeter designed by Yosida (1960, p. 575) has been generally used. Yosida sent a calorimeter to be employed in the author's measurements; his gift and advice are very much appreciated.

In addition to Yosida's calorimeter an ordinary calorimeter had to be employed when a crushed thermometer in the calorimeter given by Yosida put the instrument out of function for some weeks. A centrifugal separator (hand-centrifuge) was tested also, but without success. An electro-calorimeter, a sketch of which is drawn in Fig. 14, was constructed at Norsk Polarinstitutt in 1968. Accuracy within ± 1% free water was obtained for 65 of 68 tests in the laboratory. The tests were of the same character as those described by Yosida (1960, p. 576). The instrument's dependence on electric current (220 volts) should, however, be emphasized. The electro-calorimeter was used for testing the other methods above. Both Yosida's calorimeter and the ordinary calorimeter gave results with an accuracy of ± 2% free water content or better.

A brief mention should be made of the fact that, when using the ordinary calorimetric method, the mass of dry snow, $P_d$, i.e. the snow mass which is actually melting, is found from the relation

$$(P_W + C_c)\,(T_W - T_{W+S}) = L_i P_d + P_S T_{W+S}$$

where $P_W$ is the mass of hot water with temperature $T_W$ filled in the calorimeter with capacity $C_c$. $T_{W+S}$ is the mixing temperature of hot water and wet snow mass,

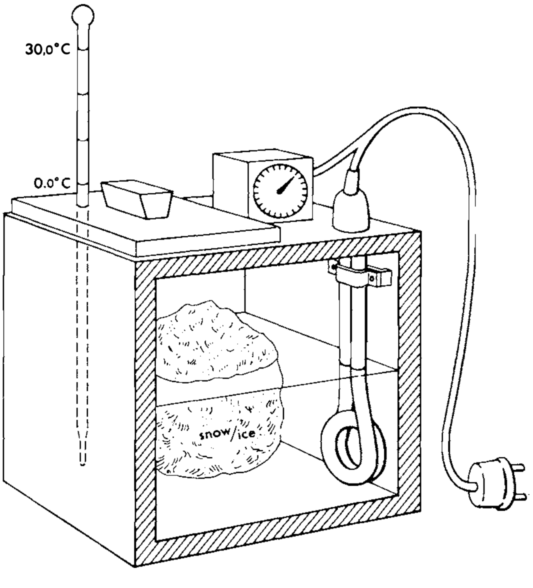


Fig. 14. *Sketch of the electro-calorimeter used to measure the free water content. The heat element yields 450 watts when connected to the mains (220 volts).*

$P_s . L_i$ signifies the latent heat of fusion for ice. Free water content, in percent of weight, comes out then as

$$F = 100(1 - P_d/P_s).$$

In the method presented by Yosida (1960, pp. 574—577) the calculation of F is in principle just the same, although a little more complicated, because two calorimeters are used joined to each other.

By using the electro-calorimeter the electric element yields a heat equal to kWt in the course of a time, t, when W is the element's effect and k is the electric heat equivalent (0.239 cal/Joule). This heat will melt the dry snow mass, $P_d$, and then warm up the whole system to the final temperature, $T_f$, which has to be just on the upper side of 0°C. The warming up requires an energy equal to $(C_c + P_s)T_f$; consequently $kWt = P_d L_i + (C_c + P_s)T_f$. $P_s$ can be weighed directly, and F comes out as shown above.

## RESULTS

The six profiles of the snow layer, shown in Fig. 15, should be representative concerning the content of free water in the snow in the course of the summer season. It seems that the free water content decreases a few percent from c. 17%, which is the mean value found early in the summer. This decrease evidently has direct connection with growing and rounding of snow grains during the period. The high values of free water found immediately above most of the ice layers in the snow and above the summer surface (consisting of ice) are of course due to the impermeable character of these layers.

In ice the measurements performed are not as trustworthy as those performed in snow. Just a few calculations are made. The results from Omnsbreen should indicate that 2% is a serviceable value.

The values given in Fig. 15 refer to measurements performed around midday. Depending on ablation conditions, the free water content in the uppermost snow layers varies considerably in the course of a day. A quantitative expression for this variation is given in Fig. 16. The night-frost by clear sky is clearly reflected as well as the stable ablation conditions on overcast days with normal summer temperatures. This variation is important to bear in mind when calculating the correction for free water content in the ablation.

## CORRECTION FOR
## FREE WATER CONTENT IN THE ABLATION CALCULATION

When measuring the ablation by use of an ablatograph (see Liestøl 1954, pp. 431—432), one has to reduce the directly measured ablation, obtained by ordinary depth and density measurements, by a value which depends on the free water content to obtain the actual snow mass melted (i.e. the mass wasting of dry snow). As mentioned above, the values of free water content measured in the uppermost layers cannot be used in this calculation. On Omnsbreen the mean values obtained

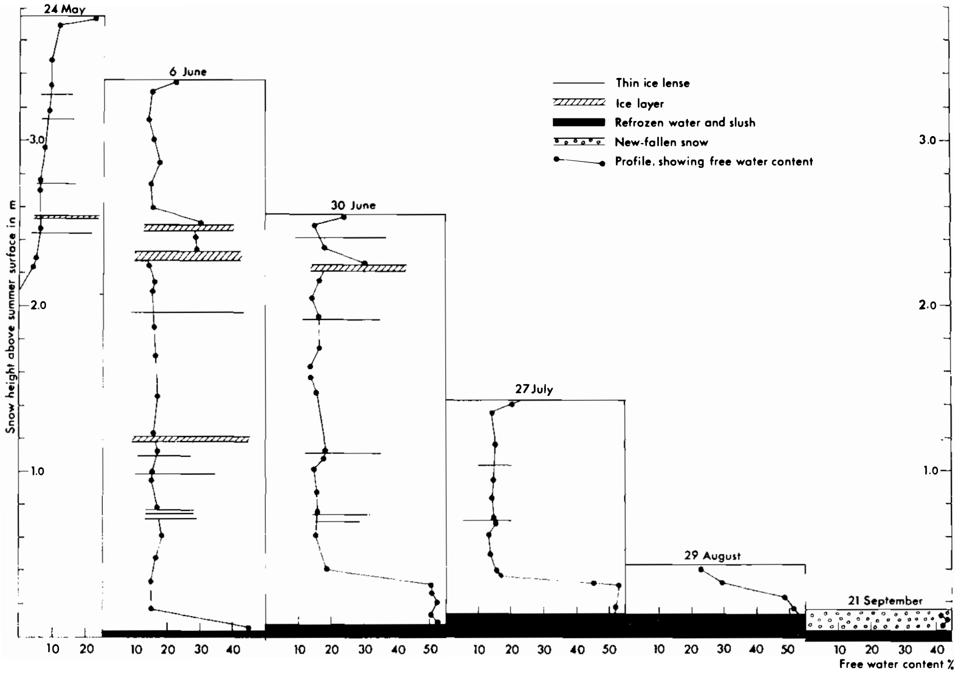


Fig. 15. *Profiles in the upper part of the glacier mass, Omnsbreen 1968, showing ice layers and free water content.*

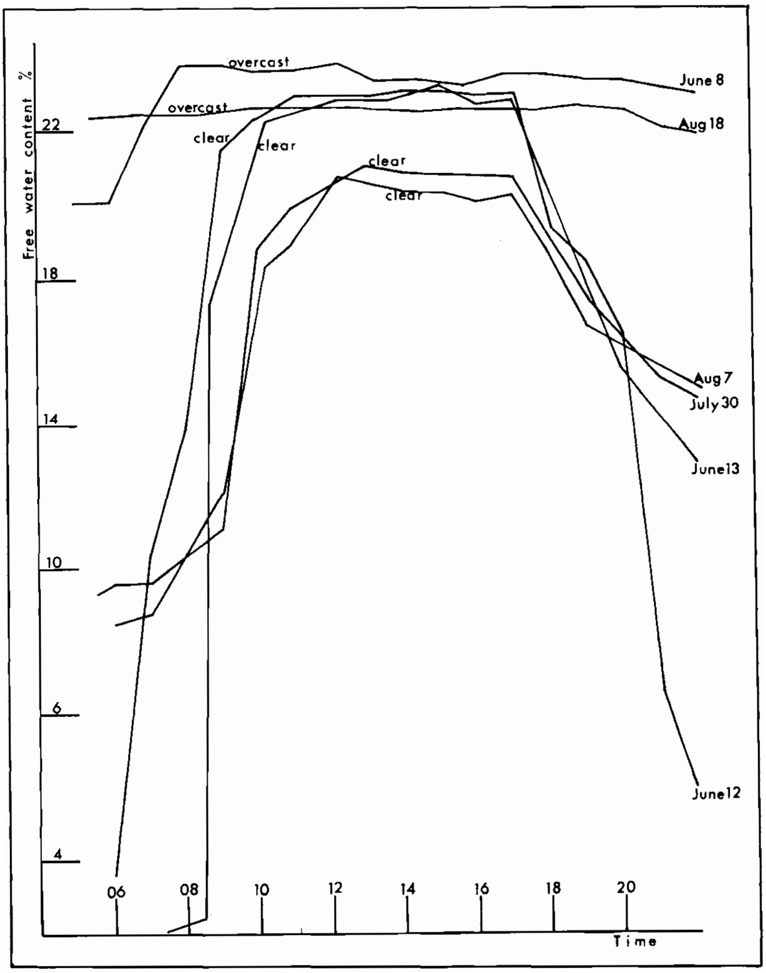


Fig. 16. *Daily variation of free water content in the uppermost 3 cm of the snow layer, Omnsbreen 1968.*

every week by measurements similar to those shown in Fig. 15 have been put into the calculation.

Corrections for free water content in ablation calculations should quantitatively be clearly stated in Tables III and IV. The density of dry snow, $\rho_{dry}$, is taken from the formula

$$\rho_{dry} = \frac{\rho_{wet} - F/_{100}}{1 - F/_{100}}$$

$\rho_{wet}$ is the density of wet snow and F the free water content given in percent of weight. As Tables III and IV confirm, the ablation becomes c. 15% less than if the free water content had not been taken into consideration. The problem will be more quantitatively discussed in connection with the heat balance investigations presented in the following chapter.

## Heat balance in the summer seasons 1968 and 1969

### THEORETICAL BASIS

Heat balance investigations have been performed and described by so many scientists that we shall just mention briefly the factors in the heat balance equation for the glacier surface:

*Incoming:*

Short-wave radiation from the sun, $I_s$.

Short-wave diffuse radiation from the sky, $I_h$.

Reflected short-wave radiation from steep mountain slopes nearby, $I_m$.

Long-wave radiation from the atmosphere, $R_i$.

Convection from the atmosphere if the temperature increases with height above the glacier surface, $Q_k$.

Condensation from the atmosphere if the water vapour pressure increases with height above the glacier surface, $Q_v$.

Rain, $Q_r$.

Conduction from the underlying glacier mass if the temperature increases with depth, $Q_b$.

*Outgoing:*

Reflected short-wave radiation, a $(I_s + I_h + I_m)$; a is the albedo.

Long-wave radiation from the glacier surface, $R_u$.

Sublimation to the atmosphere if the water vapour pressure decreases with height above the glacier surface, $-Q_v$.

Conduction to the underlying glacier mass if the temperature decreases with depth, $-Q_b$.

The energy balance equation then takes the form:

$$80\ H = \alpha(I_s + I_h + I_m) - (R_u - R_i) + Q_k \pm Q_v \pm Q_b \pm Q_r.$$

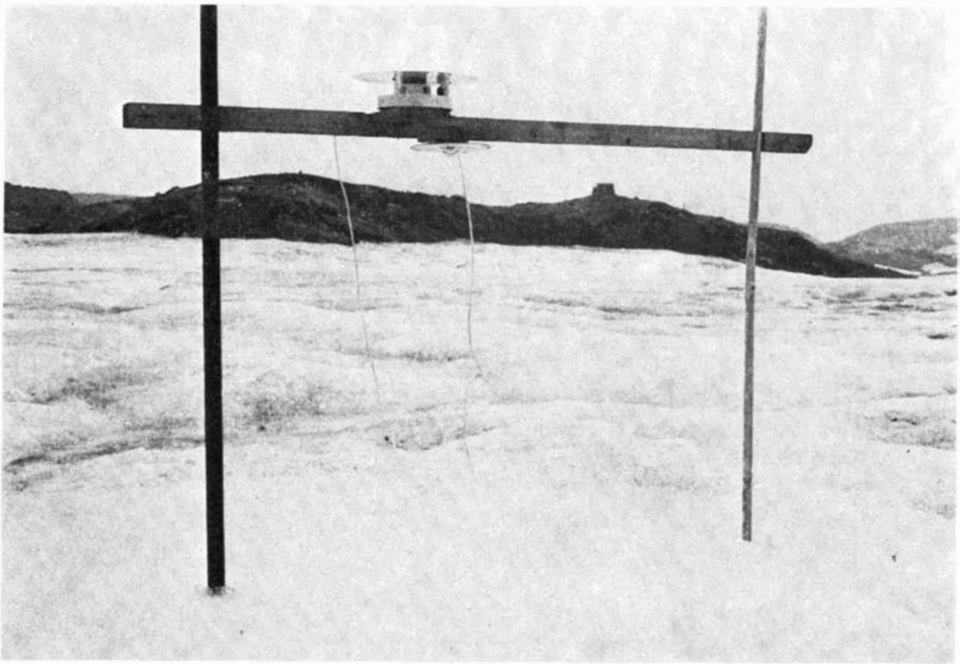


Fig. 17. *Two Moll-Gorczynski pyranometers mounted on a special frame erected on Omnsbreen. Two cables go to recording instruments in the hut visible in the background.*

Fig. 18. *Standard hut, containing one thermohygrograph and the usual meteorological thermometers, fixed at 170 cm above the glacier surface during the whole summer by the aid of a pillar arrangement of steel rods and planks.*

In the equation, H signifies the mass of melted glacier material and $\alpha$ ($=1-a$) is the absorption coefficient for short-wave radiation.

The energy supply caused by the earth's heat, by internal friction, and by meltwater streaming through holes and crevasses is probably insignificant, for Omnsbreen perhaps enough to melt about 1 g/cm$^2$ yearly. This energy exchange is consequently not taken into consideration.

Meteorological parameters for use in the heat balance calculations were recorded on Omnsbreen from 3 June to 8 September in 1968 as well as in 1969. For measuring the short-wave radiation balance, two Moll-Gorczynski pyranometers were erected, as shown in Fig. 17. The long-wave radiation balance had to be estimated, because no complete balance-meter was available. The formula presented by HOINKES and UNTERSTEINER (1952, p. 119) and later found satisfactory when examining energy exchange on glaciers in southern Norway (LIESTØL 1967, p. 19) is employed also in the present calculations:

$$R_c = R_u - R_i = R_o \left[1 - k \left(\frac{c}{10}\right)^2\right]$$

$R_o$ expresses the long-wave radiation balance for clear sky; k is a so-called cloud constant, stipulated to 1.4, and c signifies the cloud cover given in scale 1—10.

In addition to the radiation measuring instruments, a complete meteorological station was erected on a horizontal part of the glacier surface c. 1540 m a.s.l. Wind speed was recorded in three heights above the glacier surface (20, 45, and 170 cm). Temperature and relative humidity were registered by thermohygrographs in heights of 10 cm and 170 cm. Stands, the principle of which is shown in Fig. 18, arranged the instruments quite satisfactorily in the planned positions. Both temperature and humidity recordings were controlled by an Assmann psychrometer and by thermometers mounted in the standard hut. Ninety-eight special measurements of the mean wind force in periods of 15 minutes entailed that the distribution laws given by WALLÉN (1948, p. 599) were used in the heat balance calculations concerning convection, condensation, and sublimation. The theoretical considerations based upon the direct measurements on Omnsbreen gave the following expressions:

$$\text{Convection,} \quad Q_k = 2.8 \cdot \frac{\theta_{170} \cdot u_{170}}{n_\theta \cdot 170^{(1/n_\theta + 1/n_u)}}$$

$$\text{Condensation,} \quad Q_v = 6.5 \cdot \frac{(e_{170} - 4.58) \cdot u_{170}}{n_\theta \cdot 170^{(1/n_\theta + 1/n_u)}}$$

$$\text{Sublimation,} \quad -Q_v = 7.3 \cdot \frac{(e_{170} - 4.58) \cdot u_{170}}{n_\theta \cdot 170^{(1/n_\theta + 1/n_u)}}$$

The symbols $u_{170}$, $\theta_{170}$, and $e_{170}$ express wind velosity, temperature, and water vapour pressure respectively, measured 170 cm above the glacier surface. To find the exponential factors, $n_\theta$ and $n_u$, the previous mentioned wind speed measure-

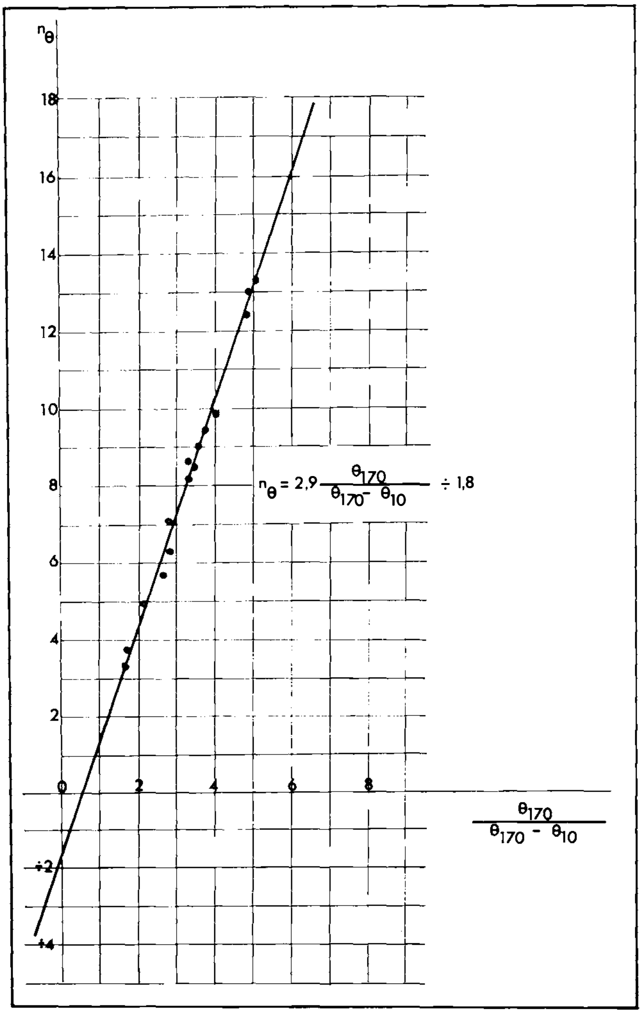


Fig. 19. *The diagram is used to get values for* $n_\theta$ *in the formulae for convection, condensation and sublimation when temperatures at 10 cm and 170 cm heights above the glacier surface are measured.*

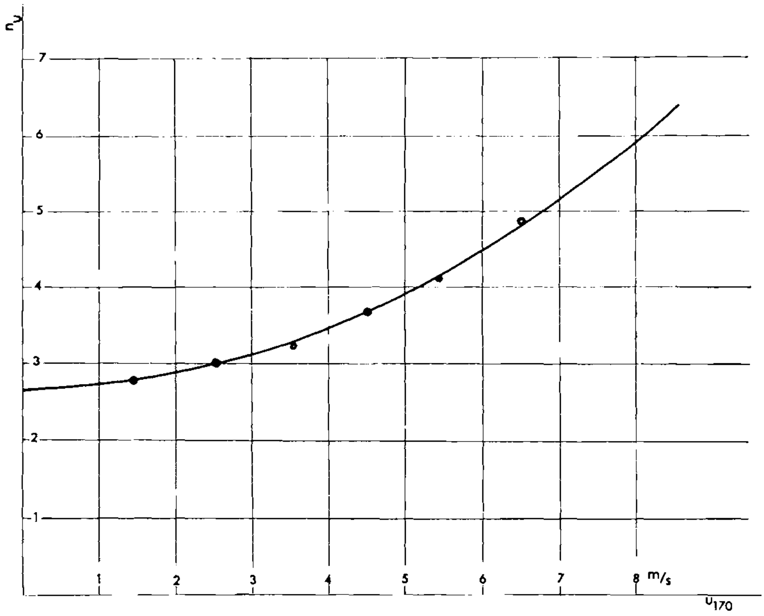


Fig. 20. *Relation between the measured wind velocity at 170 cm above the glacier surface,* $u_{170}$, *and the factor* $n_u$ *in the formulae for convection and condensation/sublimation.*

ments were used together with numerous registrations of the temperature at different heights above the glacier surface. The results of these investigations are shown in Figs. 19 and 20.

When $u_{170}$, $\theta_{170}$, and $e_{170}$ are all recorded directly, and $n_u$ and $n_\theta$ are picked out of Figs. 19 and 20, the calculations of convection, condensation, and sublimation should be justified. The expressions given above will find the energy in cal/cm$^2$ for one day.

The energy supported by rain is found by the formula

$$Q_r = \frac{r}{10} t_r \ \text{cal/cm}^2$$

where r expresses the rainfall in mm and $t_r$ the temperature of the raindrops, here using the temperature written by the thermograph at the height of 170 cm above the glacier surface during rainfall. The precipitation was recorded in Standard recorders.

As the measurements on Omnsbreen were performed when the temperature of the winter-snow layer was 0°C throughout, and the temperature gradient in the glacier ice was insignificant in late summer, the factor $\pm Q_b$ is ignored.

## RESULTS

In Tables III and IV the daily values of ablation factors plus calculated and recorded ablation are listed. At the end of each table the totals of the respective factors are given together with the corresponding values for the ablation factor's relative role in the melting process.

Probably the most interesting results taken from the tables are those concerning the relative contributions of the ablation factors:

1) In the period 3 June – 8 September 1968, the calculated ablation amounts to 237.5 g/cm$^2$. Of this, 49.6% was caused by radiation, 34.2% by convection, and 15.7% by condensation. Only 0.4% is attributed to rain and 0.1% to sublimation.

2) In the corresponding period in 1969, the calculated ablation amounts to 310.4 g/cm$^2$. Radiation accounts for 54.6%, convection for 31.0%, and condensation for 14.0%. Rain causes 0.3% and sublimation 0.1%, approximately.

The daily discrepancy between calculated and observed ablation is on the average c. 10% of the measured ablation. It should be noted that the well known difficulties, caused by density changes in relating surface lowering to true ablation for short periods, do not introduce significant errors either in 1968 or in 1969 because the daily ablation is relatively large, the daily mean values are c. 2.3 g/cm$^2$ and c. 3.1 g/cm$^2$ respectively. The close agreement of the calculated and the registered total ablation may indicate that WALLÉN's adapted formulae and the arrangement on Omnsbreen have proved useful, although the nearly merging values in 1969 (310.4 g/cm$^2$ and 311.8 g/cm$^2$) may be attributed to coincidence. The present examination, however, has too few accurate measurements to justify any definite decision concerning exponential contra logarithmic based formulae for the distribution of wind, temperature, and vapour pressure in the atmosphere close to the glacier surface. Publications presented earlier, discussing the energy exchange between the atmosphere and the glacier surface, have used different formulae to describe the vertical distribution of the meteorological parameters. A thorough discussion concerning the meteorological parameters over melting ice surfaces has been made by GRAINGER and LISTER (1966, pp. 91–105) but any final conclusion in the form of general laws do not exist today.

For a nearly flat glacier, such as Omnsbreen, without a marked firn area, the role of albedo has to be emphasized. The mean albedo was 6% lower in 1969 compared with 1968, causing an ablation difference of c. 30 g/cm$^2$ or c. 13% of the ablation in the actual period of 1968. As Tables III and IV show, the summer surface (ice nearly all over the glacier) was exposed around 21 July in 1969, while snow covered the whole glacier during the investigation period in 1968.

The 1677 cal/cm$^2$ higher value of heat supplied by convection and condensation in 1969 relative to the value in 1968 expresses, together with the 4142 cal/cm$^2$ higher radiative income in 1969, the extremely unfavourable conditions for the glacier during the summer of 1969; the summer of 1968 should be classified climatically as warm and sunny, with mean temperature 1–2 degrees above normal. It was especially in August 1969 that the warm weather caused catastrophic ablation, from Table IV calculated to a daily mean of c. 3.9 g/cm$^2$ (normal ablation in August is c. 2.3 g/cm$^2$ per day). In order to give more visual information about the ablation conditions in the summers of 1968 and 1969, the meteorological parameters are drawn in Figs. 21 and 23 respectively. In Figs. 22 and 24 the weekly ablation is pictured graphically. These illustrations clearly demonstrate the shifting ablation conditions from one day/period to another, and should illustrate what is said above quite well.

Figs. 22 and 24 should be illustrative also as a warning against drawing conclusions about the relative role of ablation factors for a glacier if based upon short-term measurements. Table V presents the calculated values per week concerning the relative role of the 5 factors involved. All values are given as a percent. The most extreme case is the difference of 33% in relative radiation contribution (and corresponding differences in the convection and condensation values) which arose between the periods 24 June–30 June and 1 July–7 July in 1969. The expected diminishing role of radiation after the summer solstice is not marked, especially in 1969. The calculated values in the period 17–23 June compared with the period 2–8 September in 1969 should emphasize the conclusion.

To calculate the correct ablation for snow mass for shorter periods in the course of the summer, from 18% of mass in early summer to c. 12% in late summer, the values obtained by measuring depth and density must be subtracted. If not, the mass of the already melted snow, which is equal to the free water content, will be involved. On normal summer days in the Omnsbreen district an energy amount c. 40 cal/cm$^2$ too high will be calculated if the free water content is omitted.

# Table III

*Energy and ablation account, Omnsbreen 1968*

| Date | Global radiation cal/cm$^2$ | Albedo % | Absorbed global radiation cal/cm$^2$ | Long-wave radiation cal/cm$^2$ | Radiation balance cal/cm$^2$ | Convection cal/cm$^2$ | Condensation cal/cm$^2$ | Sublimation cal/cm$^2$ | Rain cal/cm$^2$ | Calculated heat supply cal/cm$^2$ | Calculated ablation g/cm$^2$ | Ablatograph registration cm | Density of wet snow g/cm$^2$ | Free water content % | Ablation registered g/cm$^2$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | JUNE | | | | | | | | | |
| 3 | 601 | 67 | 198 | −104 | 94 | 92 | 52 | | | 238 | 2.98 | 6.5 | 0.54 | 17 | 2.9 | |
| 4 | 342 | 68 | 109 | − 48 | 61 | 86 | 46 | | | 193 | 2.41 | 5.0 | 0.55 | 17 | 2.3 | |
| 5 | 274 | 67 | 90 | − 8 | 82 | 79 | 47 | | 3 | 211 | 2.63 | 5.7 | 0.55 | 17 | 2.6 | |
| 6 | 279 | 66 | 94 | + 5 | 99 | 57 | 3 | | 5 | 164 | 2.05 | 4.6 | 0.55 | 17 | 2.1 | |
| 7 | 340 | 66 | 116 | − 28 | 88 | 0 | 0 | 5 | | 88 | 1.10 | 6.2 | 0.55 | 17 | 1.2 | |
| 8 | 295 | 67 | 98 | − 5 | 103 | 2 | 9 | | 1 | 115 | 1.44 | 2.8 | 0.55 | 17 | 1.3 | |
| 9 | 436 | 66 | 148 | − 68 | 80 | 16 | 7 | | 1 | 104 | 1.30 | 2.8 | 0.55 | 17 | 1.3 | |
| 10 | 302 | 66 | 103 | − 88 | 15 | 10 | 0 | | | 25 | 0.31 | 1.1 | 0.55 | 17 | 0.5 | |
| 11 | 537 | 66 | 183 | −112 | 71 | 49 | 4 | 6 | | 124 | 1.55 | 3.3 | 0.55 | 17 | 1.5 | |
| 12 | 786 | 64 | 283 | −120 | 163 | 52 | 31 | 22 | | 246 | 3.08 | 7.2 | 0.55 | 17 | 3.3 | |
| 13 | 794 | 64 | 286 | −121 | 165 | 48 | 20 | 16 | | 233 | 2.92 | 5.9 | 0.56 | 17 | 2.8 | |
| 14 | 764 | 64 | 275 | −120 | 155 | 99 | 23 | 20 | | 277 | 3.47 | 7.6 | 0.56 | 18 | 3.5 | |
| 15 | 628 | 64 | 226 | −118 | 108 | 78 | 17 | 12 | | 203 | 2.54 | 5.2 | 0.56 | 18 | 2.4 | |
| 16 | 798 | 64 | 287 | −121 | 166 | 86 | 16 | 8 | | 268 | 3.36 | 6.7 | 0.56 | 18 | 3.1 | |
| 17 | 649 | 63 | 240 | −111 | 129 | 91 | 31 | 10 | | 251 | 3.14 | 6.3 | 0.56 | 18 | 2.9 | |
| 18 | 411 | 65 | 144 | − 46 | 98 | 86 | 38 | | 1 | 223 | 2.79 | 5.6 | 0.56 | 18 | 2.6 | |
| 19 | 312 | 64 | 112 | − 11 | 101 | 59 | 24 | | 2 | 186 | 2.20 | 5.4 | 0.56 | 18 | 2.5 | |
| 20 | 306 | 64 | 110 | + 3 | 113 | 88 | 45 | | 2 | 248 | 3.10 | 7.4 | 0.56 | 18 | 3.4 | |
| 21 | 307 | 63 | 114 | − 43 | 71 | 35 | 26 | | 2 | 134 | 1.68 | 3.5 | 0.55 | 17 | 1.6 | |
| 22 | 355 | 64 | 131 | − 80 | 51 | 29 | 17 | | 3 | 100 | 1.25 | 2.4 | 0.55 | 17 | 1.1 | |
| 23 | 298 | 65 | 104 | + 4 | 108 | 31 | 34 | | 1 | 174 | 2.18 | 5.2 | 0.55 | 17 | 2.4 | |
| 24 | 381 | 64 | 134 | − 14 | 123 | 48 | 46 | | 1 | 218 | 2.73 | 5.4 | 0.55 | 17 | 2.5 | |
| 25 | 447 | 64 | 161 | − 63 | 107 | 44 | 60 | | 4 | 215 | 2.69 | 6.1 | 0.55 | 17 | 2.8 | |
| 26 | 300 | 64 | 108 | + 17 | 125 | 52 | 44 | | 6 | 227 | 2.84 | 6.1 | 0.55 | 17 | 2.8 | |
| 27 | 310 | 63 | 114 | − 19 | 95 | 42 | 30 | | 3 | 170 | 2.13 | 4.3 | 0.55 | 17 | 2.0 | |
| 28 | 292 | 64 | 105 | + 2 | 113 | 29 | 5 | | 1 | 148 | 1.85 | 3.5 | 0.55 | 17 | 1.6 | |
| 29 | 329 | 64 | 118 | − 52 | 66 | 14 | 3 | | | 83 | 1.04 | 2.2 | 0.55 | 17 | 1.0 | |
| 30 | 408 | 63 | 151 | − 66 | 85 | 24 | 11 | | | 120 | 1.50 | 3.0 | 0.55 | 17 | 1.4 | |
| | | | | | | | JULY | | | | | | | | | |
| 1 | 428 | 62 | 163 | − 26 | 137 | 60 | 51 | | | 248 | 3.10 | 6.7 | 0.55 | 17 | 3.1 | |
| 2 | 412 | 62 | 157 | − 63 | 94 | 104 | 51 | | 1 | 250 | 3.13 | 6.5 | 0.55 | 17 | 3.0 | |
| 3 | 692 | 63 | 256 | −110 | 146 | 138 | 72 | | | 356 | 4.45 | 10.4 | 0.55 | 17 | 4.8 | |
| 4 | 317 | 63 | 117 | − 38 | 79 | 87 | 58 | | 1 | 225 | 2.82 | 5.0 | 0.55 | 17 | 2.7 | |
| 5 | 293 | 63 | 108 | + 19 | 127 | 82 | 47 | | 1 | 257 | 3.22 | 7.4 | 0.54 | 15 | 3.4 | |
| 6 | 295 | 62 | 112 | + 16 | 128 | 47 | 53 | | 1 | 229 | 2.86 | 5.9 | 0.54 | 15 | 2.7 | |
| 7 | 310 | 62 | 118 | − 47 | 71 | 40 | 10 | | | 121 | 1.52 | 3.3 | 0.54 | 15 | 1.5 | |
| 8 | 254 | 61 | 99 | + 20 | 119 | 78 | 41 | | 2 | 240 | 3.00 | 6.3 | 0.54 | 15 | 2.9 | |
| 9 | 267 | 61 | 104 | + 19 | 123 | 67 | 27 | | 2 | 219 | 2.74 | 7.1 | 0.54 | 14 | 3.3 | |
| 10 | 263 | 60 | 105 | + 15 | 120 | 42 | 12 | | 3 | 177 | 2.22 | 4.7 | 0.54 | 14 | 2.2 | |
| 11 | 302 | 59 | 124 | − 37 | 87 | 54 | 31 | | | 172 | 2.15 | 4.7 | 0.55 | 15 | 2.2 | |
| 12 | 258 | 60 | 103 | + 13 | 116 | 53 | 18 | | | 187 | 2.34 | 5.1 | 0.55 | 15 | 2.4 | |
| 13 | 351 | 59 | 144 | − 56 | 88 | 65 | 32 | | | 185 | 2.32 | 4.7 | 0.56 | 16 | 2.2 | |
| 14 | 661 | 59 | 271 | −104 | 167 | 42 | 17 | | | 226 | 2.83 | 5.9 | 0.56 | 16 | 2.8 | |
| 15 | 520 | 59 | 213 | − 82 | 131 | 88 | 46 | | | 265 | 3.31 | 6.9 | 0.56 | 16 | 3.3 | |
| 16 | 431 | 59 | 177 | − 80 | 97 | 122 | 72 | | | 291 | 3.65 | 7.1 | 0.56 | 16 | 3.4 | |
| 17 | 490 | 58 | 206 | − 96 | 110 | 103 | 46 | 15 | | 259 | 2.24 | 5.7 | 0.56 | 16 | 2.7 | |
| 18 | 338 | 59 | 139 | − 48 | 92 | 88 | 27 | | | 206 | 2.59 | 5.3 | 0.56 | 16 | 2.5 | |
| 19 | 384 | 60 | 154 | − 82 | 75 | 85 | 39 | | | 199 | 2.49 | 5.1 | 0.56 | 16 | 2.4 | |
| 20 | 501 | 60 | 200 | − 95 | 105 | 74 | 13 | 10 | | 192 | 2.40 | 5.3 | 0.56 | 15 | 2.5 | |
| 21 | 558 | 59 | 229 | − 98 | 131 | 74 | 18 | | | 223 | 2.79 | 6.2 | 0.56 | 15 | 2.9 | |
| 22 | 593 | 59 | 243 | −101 | 142 | 67 | 20 | | | 229 | 2.74 | 5.7 | 0.56 | 16 | 2.7 | |
| 23 | 392 | 59 | 161 | − 97 | 64 | 72 | 17 | | | 153 | 1.79 | 3.6 | 0.56 | 15 | 1.7 | |
| 24 | 380 | 59 | 156 | − 46 | 110 | 34 | 37 | | | 181 | 2.27 | 4.8 | 0.56 | 14 | 2.3 | |
| 25 | 406 | 59 | 166 | − 87 | 79 | 58 | 24 | | | 161 | 1.89 | 3.7 | 0.56 | 14 | 1.8 | |
| 26 | 422 | 58 | 177 | − 99 | 78 | 89 | 28 | | | 195 | 2.44 | 4.8 | 0.56 | 14 | 2.3 | |
| 27 | 508 | 56 | 224 | −102 | 122 | 69 | 14 | | | 205 | 2.56 | 5.2 | 0.56 | 14 | 2.5 | |
| 28 | 517 | 57 | 222 | −109 | 113 | 29 | 3 | | | 145 | 1.82 | 3.8 | 0.56 | 15 | 1.8 | |
| 29 | 402 | 58 | 169 | − 82 | 87 | 90 | 27 | | | 204 | 2.55 | 4.8 | 0.56 | 15 | 2.3 | |
| 30 | 711 | 58 | 299 | −120 | 179 | 108 | 42 | | | 329 | 4.11 | 8.7 | 0.56 | 15 | 4.2 | |
| 31 | 258 | 57 | 111 | + 1 | 112 | 47 | 30 | | | 189 | 2.36 | 2.9 | 0.56 | 15 | 1.5 | |

| Date | Global radiation cal/cm² | Albedo % | Absorbed global radiation cal/cm² | Long-wave radiation cal/cm² | Radiation balance cal/cm² | Convection cal/cm² | Condensation cal/cm² | Sublimation cal/cm² | Rain cal/cm² | Calculated heat supply cal/cm² | Calculated ablation g/cm² | Ablatograph registration cm | Density of wet snow g/cm² | Free water content % | Ablation registered g/cm² | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | AUGUST | | | | | | | | | |
| 1 | 404 | 59 | 166 | – 91 | 75 | 42 | 34 | | | 151 | 1.89 | 3.8 | 0.55 | 15 | 1.8 | |
| 2 | 366 | 59 | 150 | – 89 | 62 | 86 | 30 | | | 177 | 2.21 | 4.7 | 0.55 | 15 | 2.2 | |
| 3 | 600 | 58 | 252 | –120 | 132 | 70 | 17 | | | 219 | 2.74 | 6.3 | 0.55 | 15 | 2.9 | |
| 4 | 588 | 58 | 247 | –120 | 127 | 56 | 10 | | | 193 | 2.41 | 5.3 | 0.55 | 15 | 2.5 | |
| 5 | 398 | 58 | 167 | – 56 | 111 | 89 | 32 | | | 232 | 2.90 | 5.4 | 0.55 | 14 | 2.6 | |
| 6 | 383 | 57 | 165 | – 97 | 68 | 56 | 26 | | | 150 | 1.89 | 3.7 | 0.55 | 14 | 1.8 | |
| 7 | 607 | 58 | 255 | –121 | 134 | 74 | 8 | | | 216 | 2.70 | 5.7 | 0.55 | 15 | 2.7 | |
| 8 | 430 | 58 | 181 | –108 | 73 | 104 | 39 | | | 216 | 2.70 | 5.5 | 0.55 | 15 | 2.6 | |
| 9 | 481 | 57 | 207 | –116 | 91 | 98 | 14 | | | 203 | 2.54 | 5.3 | 0.55 | 15 | 2.5 | |
| 10 | 394 | 58 | 165 | –104 | 61 | 73 | 34 | | | 168 | 2.10 | 4.9 | 0.55 | 16 | 2.3 | |
| 11 | 461 | 59 | 189 | –106 | 83 | 70 | 31 | | | 184 | 2.55 | 5.2 | 0.55 | 16 | 2.4 | |
| 12 | 242 | 59 | 99 | – 38 | 61 | 44 | 35 | | | 140 | 1.75 | 3.7 | 0.55 | 16 | 1.7 | |
| 13 | 418 | 59 | 171 | – 81 | 90 | 36 | 24 | | 4 | 154 | 1.93 | 4.9 | 0.55 | 15 | 2.3 | |
| 14 | 409 | 58 | 172 | – 69 | 103 | 34 | 20 | | | 157 | 1.96 | 3.6 | 0.55 | 15 | 1.7 | |
| 15 | 351 | 58 | 147 | – 60 | 87 | 21 | 11 | | 1 | 120 | 1.50 | 2.9 | 0.56 | 15 | 1.4 | |
| 16 | 197 | 58 | 81 | + 8 | 89 | 7 | 6 | | | 122 | 1.53 | 3.1 | 0.56 | 16 | 1.5 | |
| 17 | 230 | 59 | 97 | – 34 | 63 | 78 | 37 | | | 178 | 1.23 | 2.9 | 0.56 | 16 | 1.4 | |
| 18 | 166 | 58 | 68 | + 6 | 74 | 64 | 56 | | 3 | 197 | 2.47 | 5.0 | 0.56 | 16 | 2.4 | |
| 19 | 254 | 59 | 107 | – 37 | 70 | 78 | 48 | | | 196 | 2.45 | 5.6 | 0.56 | 15 | 2.7 | |
| 20 | 262 | 58 | 110 | – 41 | 69 | 70 | 38 | | | 177 | 2.22 | 4.4 | 0.56 | 15 | 2.1 | |
| 21 | 350 | 58 | 151 | – 68 | 83 | 81 | 53 | | 2 | 219 | 2.74 | 5.6 | 0.56 | 16 | 2.7 | Gradually increasing free water content because of relatively slow run-off. The snow depth amounts to only 50 cm |
| 22 | 297 | 57 | 125 | – 64 | 61 | 98 | 56 | | | 213 | 2.67 | 5.8 | 0.56 | 16 | 2.8 | |
| 23 | 401 | 58 | 168 | – 87 | 81 | 121 | 74 | | | 276 | 3.45 | 7.4 | 0.59 | 23 | 3.5 | |
| 24 | 407 | 58 | 175 | –108 | 67 | 116 | 47 | 5 | | 230 | 1.63 | 3.4 | 0.59 | 23 | 1.6 | |
| 25 | 435 | 57 | 187 | –110 | 77 | 148 | 19 | 7 | | 244 | 3.05 | 6.4 | 0.59 | 22 | 3.0 | |
| 26 | 478 | 57 | 206 | –120 | 86 | 118 | 22 | | | 226 | 2.83 | 5.5 | 0.59 | 23 | 2.5 | |
| 27 | 501 | 57 | 215 | –120 | 95 | 123 | 16 | | | 234 | 2.93 | 6.0 | 0.59 | 22 | 2.8 | |
| 28 | 304 | 57 | 131 | – 88 | 43 | 67 | 18 | | | 128 | 1.60 | 3.0 | 0.63 | 30 | 1.4 | |
| 29 | 457 | 57 | 197 | –117 | 80 | 62 | 38 | | 1 | 181 | 2.27 | 4.7 | 0.64 | 30 | 2.2 | |
| 30 | 414 | 58 | 174 | –119 | 55 | 56 | 11 | 8 | | 122 | 1.53 | 3.0 | 0.64 | 31 | 1.4 | |
| 31 | 71 | 58 | 30 | + 16 | 46 | 60 | 29 | | | 135 | 1.69 | 3.2 | 0.64 | 31 | 1.5 | |
| | | | | | | | SEPTEMBER | | | | | | | | | |
| 1 | 109 | 58 | 46 | + 8 | 54 | 67 | 66 | | 8 | 195 | 2.44 | 4.9 | 0.64 | 31 | 2.3 | |
| 2 | 304 | 55 | 137 | – 91 | 46 | 62 | 21 | | | 129 | 1.61 | 3.0 | 0.63 | 31 | 1.4 | |
| 3 | 263 | 56 | 116 | – 25 | 91 | 50 | 65 | | 6 | 212 | 2.65 | 5.1 | 0.63 | 30 | 2.4 | |
| 4 | 122 | 56 | 54 | + 2 | 56 | 92 | 40 | | 1 | 189 | 2.36 | 4.9 | 0.63 | 30 | 2.3 | |
| 5 | 319 | 54 | 147 | – 41 | 106 | 118 | 36 | | 1 | 261 | 3.26 | 6.6 | 0.64 | 32 | 3.1 | |
| 6 | 282 | 54 | 130 | – 40 | 90 | 41 | 58 | | 5 | 194 | 2.42 | 4.7 | 0.64 | 31 | 2.2 | |
| 7 | 471 | 52 | 226 | –117 | 109 | 42 | 18 | | | 169 | 2.11 | 4.2 | 0.64 | 31 | 2.0 | |
| 8 | 464 | 50 | 232 | –118 | 114 | 46 | 20 | | | 180 | 2.25 | 5.5 | 0.64 | 31 | 2.6 | |

3 JUNE — 8 SEPTEMBER

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 39295 | 60 | 15612 | –6187 | 9425 | 6516 | 2982 | 134 | 79 | 19002 | 237.5 | 488.3 | | | 229.3 | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Melted ice g/cm² | 117.8 | 81.5 | 37.3 | 0.2 | 1.0 | 237.5 | | | 229.3 | |
| Melted ice % | 49.6 | 34.2 | 15.7 | 0.1 | 0.4 | 100.0 | | | 96.5 | |

# Table IV

## *Energy and ablation account, Omnsbreen 1969*

| Date | Global radiation cal/cm$^2$ | Albedo % | Absorbed global radiation cal/cm$^2$ | Long-wave radiation cal/cm$^2$ | Radiation balance cal/cm$^2$ | Convection cal/cm$^2$ | Condensation cal/cm$^2$ | Sublimation cal/cm$^2$ | Rain cal/cm$^2$ | Calculated heat supply cal/cm$^2$ | Calculated ablation g/cm$^2$ | Ablatograph registration cm | Density of wet snow g/cm$^2$ | Free water content % | Ablation registered g/cm$^2$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JUNE | | | | | | | | | | | | | | | | |
| 3 | 718 | 68 | 230 | −103 | 127 | 0 | 16 | 10 | | 143 | 1.79 | 3.8 | 0.51 | 15 | 2.0 | |
| 4 | 786 | 67 | 259 | −118 | 141 | 8 | 4 | 25 | | 153 | 1.91 | 4.5 | 0.51 | 15 | 2.1 | |
| 5 | 791 | 67 | 261 | −120 | 141 | 23 | 0 | 20 | | 164 | 2.05 | 4.4 | 0.52 | 16 | 2.3 | |
| 6 | 754 | 67 | 249 | −114 | 135 | 46 | 10 | | | 191 | 2.39 | 5.0 | 0.52 | 15 | 2.4 | |
| 7 | 626 | 67 | 207 | − 92 | 115 | 29 | 16 | | | 160 | 2.00 | 4.3 | 0.52 | 16 | 2.4 | |
| 8 | 332 | 68 | 106 | + 15 | 121 | 62 | 30 | | | 259 | 3.24 | 7.4 | 0.52 | 16 | 3.4 | |
| 9 | 584 | 67 | 193 | − 72 | 121 | 126 | 45 | | | 292 | 3.65 | 8.2 | 0.52 | 15 | 3.9 | |
| 10 | 671 | 66 | 228 | −110 | 118 | 83 | 21 | | | 232 | 2.90 | 6.8 | 0.52 | 15 | 3.0 | |
| 11 | 756 | 67 | 249 | −106 | 143 | 65 | 28 | | | 236 | 2.95 | 6.5 | 0.52 | 16 | 2.8 | |
| 12 | 622 | 66 | 211 | − 60 | 151 | 49 | 15 | | | 215 | 2.69 | 5.8 | 0.53 | 16 | 2.5 | |
| 13 | 584 | 66 | 199 | − 42 | 157 | 54 | 26 | | | 237 | 2.96 | 6.7 | 0.53 | 16 | 2.8 | |
| 14 | 796 | 66 | 271 | −121 | 150 | 39 | 6 | 12 | | 195 | 2.44 | 5.0 | 0.52 | 15 | 2.2 | |
| 15 | 745 | 67 | 246 | −104 | 142 | 77 | 31 | | | 250 | 3.12 | 7.0 | 0.52 | 16 | 3.0 | |
| 16 | 723 | 65 | 253 | −115 | 138 | 141 | 69 | | | 348 | 4.35 | 9.3 | 0.52 | 16 | 4.1 | |
| 17 | 454 | 66 | 154 | − 38 | 116 | 86 | 34 | | 2 | 238 | 2.98 | 6.7 | 0.52 | 16 | 2.6 | |
| 18 | 381 | 67 | 126 | − 57 | 69 | 99 | 62 | | | 230 | 2.88 | 6.7 | 0.52 | 16 | 2.7 | |
| 19 | 608 | 66 | 207 | −100 | 107 | 101 | 39 | | | 247 | 3.09 | 6.1 | 0.56 | 13 | 3.0 | Ice layer exposed on glacier surface |
| 20 | 409 | 66 | 139 | − 38 | 101 | 129 | 90 | | 1 | 321 | 4.01 | 8.5 | 0.54 | 14 | 4.0 | |
| 21 | 408 | 66 | 139 | − 16 | 123 | 127 | 55 | | 5 | 300 | 3.75 | 7.9 | 0.52 | 15 | 3.5 | |
| 22 | 419 | 65 | 147 | − 17 | 130 | 91 | 49 | | 8 | 278 | 3.48 | 7.5 | 0.52 | 15 | 3.5 | |
| 23 | 464 | 66 | 158 | − 39 | 119 | 100 | 76 | | 6 | 301 | 3.76 | 8.4 | 0.53 | 16 | 3.6 | |
| 24 | 506 | 65 | 177 | − 47 | 130 | 129 | 74 | | | 333 | 4.16 | 9.5 | 0.52 | 16 | 4.1 | |
| 25 | 524 | 65 | 183 | − 77 | 106 | 162 | 90 | | | 358 | 4.48 | 10.9 | 0.53 | 16 | 4.2 | |
| 26 | 470 | 65 | 165 | − 60 | 105 | 92 | 68 | | 1 | 266 | 3.32 | 7.7 | 0.53 | 16 | 3.0 | |
| 27 | 341 | 65 | 123 | − 49 | 74 | 105 | 69 | | 2 | 250 | 3.13 | 7.0 | 0.52 | 15 | 2.9 | |
| 28 | 453 | 64 | 163 | − 52 | 111 | 44 | 19 | | 1 | 175 | 2.19 | 5.1 | 0.52 | 16 | 1.7 | |
| 29 | 502 | 64 | 181 | − 76 | 105 | 46 | 18 | | | 170 | 2.13 | 5.5 | 0.52 | 15 | 1.9 | |
| 30 | 335 | 64 | 121 | − 2 | 119 | 49 | 25 | | 1 | 194 | 2.43 | 5.7 | 0.52 | 15 | 2.0 | |
| JULY | | | | | | | | | | | | | | | | |
| 1 | 442 | 62 | 168 | − 13 | 155 | 65 | 19 | | | 239 | 2.99 | 6.5 | 0.53 | 16 | 2.8 | |
| 2 | 424 | 63 | 157 | − 16 | 141 | 63 | 22 | | 2 | 228 | 2.85 | 6.1 | 0.52 | 15 | 2.7 | |
| 3 | 299 | 63 | 111 | + 18 | 129 | 18 | 12 | | | 159 | 1.99 | 4.7 | 0.53 | 15 | 2.1 | |
| 4 | 294 | 63 | 109 | + 20 | 129 | 10 | 11 | | | 150 | 1.88 | 4.2 | 0.53 | 15 | 1.9 | Gradually the snow transforms into slush |
| 5 | 301 | 64 | 108 | + 20 | 128 | 0 | 0 | | | 128 | 1.60 | 4.1 | 0.54 | 18 | 1.8 | |
| 6 | 320 | 64 | 115 | + 8 | 123 | 0 | 0 | | | 123 | 1.54 | 3.2 | 0.54 | 18 | 1.4 | |
| 7 | 402 | 63 | 149 | − 38 | 111 | 51 | 16 | | | 178 | 2.23 | 5.6 | 0.53 | 16 | 2.4 | |
| 8 | 304 | 62 | 116 | + 12 | 128 | 22 | 13 | | 2 | 165 | 2.06 | 4.6 | 0.54 | 19 | 2.0 | |
| 9 | 309 | 61 | 121 | + 2 | 123 | 44 | 11 | | | 178 | 2.23 | 5.8 | 0.54 | 19 | 2.5 | |
| 10 | 327 | 60 | 131 | − 40 | 91 | 59 | 26 | | | 176 | 2.20 | 5.8 | 0.56 | 23 | 2.5 | |
| 11 | 478 | 60 | 191 | − 52 | 139 | 40 | 8 | | 1 | 188 | 2.35 | 4.8 | 0.54 | 20 | 2.0 | |
| 12 | 503 | 68 | 211 | − 54 | 157 | 32 | 20 | | | 209 | 2.61 | 6.3 | 0.54 | 21 | 2.6 | |
| 13 | 504 | 54 | 232 | − 61 | 171 | 29 | 15 | | 1 | 216 | 2.70 | 6.4 | 0.56 | 24 | 2.7 | |
| 14 | 240 | 52 | 115 | + 20 | 135 | 31 | 27 | | | 193 | 2.41 | 5.3 | 0.58 | 26 | 2.3 | |
| 15 | 413 | 50 | 207 | − 28 | 179 | 72 | 5 | | | 256 | 3.20 | 7.4 | 0.61 | 32 | 3.1 | |
| 16 | 625 | 48 | 325 | −108 | 217 | 109 | 49 | | | 375 | 4.69 | 12.0 | 0.60 | 33 | 4.0 | |
| 17 | 344 | 48 | 179 | − 11 | 168 | 72 | 39 | | 1 | 280 | 3.50 | 8.4 | 0.63 | 36 | 3.6 | |
| 18 | 208 | 58 | 87 | + 16 | 103 | 0 | 0 | | | 103 | 1.29 | 3.1 | 0.68 | 45 | 1.3 | New-fallen snow |
| 19 | 191 | 63 | 71 | + 24 | 95 | 29 | 18 | | 1 | 143 | 1.79 | 4.6 | 0.55 | 28 | 1.7 | |
| 20 | 194 | 52 | 93 | + 22 | 115 | 69 | 16 | | 1 | 203 | 2.54 | 10.0 | 0.48 | 24 | 3.2 | |
| 21 | 182 | 43 | 104 | + 24 | 128 | 70 | 46 | | 1 | 245 | 3.06 | 7.1 | 0.68 | 45 | 3.0 | |
| 22 | 175 | 43 | 100 | + 24 | 124 | 72 | 47 | | 3 | 246 | 3.08 | 7.9 | 0.68 | 45 | 3.3 | |
| 23 | 171 | 43 | 97 | + 25 | 122 | 71 | 38 | | 5 | 236 | 2.95 | 7.6 | 0.68 | 45 | 3.2 | |
| 24 | 158 | 44 | 88 | + 34 | 122 | 58 | 24 | | | 253 | 3.16 | 7.3 | 0.69 | 45 | 3.2 | |
| 25 | 623 | 42 | 361 | −114 | 247 | 41 | 13 | | | 300 | 3.76 | 8.8 | 0.69 | 47 | 3.8 | |
| 26 | 408 | 42 | 237 | − 79 | 158 | 74 | 23 | | | 255 | 3.19 | 8.3 | 0.69 | 48 | 3.4 | |
| 27 | 143 | 42 | 83 | + 24 | 107 | 84 | 59 | | 1 | 251 | 3.14 | 8.3 | 0.69 | 46 | 3.3 | |
| 28 | 186 | 42 | 108 | + 17 | 125 | 89 | 47 | | | 261 | 3.26 | 8.0 | 0.70 | 49 | 3.3 | |
| 29 | 183 | 42 | 106 | + 28 | 134 | 174 | 71 | | | 379 | 4.74 | 11.9 | 0.70 | 49 | 4.9 | |
| 30 | 154 | 43 | 88 | + 39 | 117 | 95 | 65 | | 16 | 293 | 3.66 | 4.5 | 0.87 | 15 | 3.8 | Refrozen layers formed in the present year are exposed |
| 31 | 389 | 42 | 226 | − 41 | 185 | 128 | 22 | | | 335 | 4.19 | 4.6 | 0.89 | 7 | 4.0 | |

| Date | Global radiation cal/cm² | Albedo % | Absorbed global radiation cal/cm² | Long-wave radiation cal/cm² | Radiation balance cal/cm² | Convection cal/cm² | Condensation cal/cm² | Sublimation cal/cm² | Rain cal/cm² | Calculated heat supply cal/cm² | Calculated ablation g/cm² | Ablatograph registration cm | Density of wet snow g/cm² | Free water content % | Ablation registered g/cm² | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AUGUST | | | | | | | | | | | | | | | | |
| 1 | 557 | 42 | 323 | −117 | 206 | 191 | 38 | | | 425 | 5.31 | 6.6 | 0.90 | 6 | 5.9 | |
| 2 | 568 | 42 | 329 | −115 | 214 | 182 | 41 | | | 437 | 5.46 | 6.5 | 0.90 | 5 | 5.8 | |
| 3 | 525 | 42 | 305 | −108 | 197 | 139 | 55 | | | 391 | 4.89 | 5.5 | 0.90 | 5 | 4.9 | |
| 4 | 596 | 42 | 346 | −120 | 226 | 123 | 21 | | | 370 | 4.63 | 4.9 | 0.90 | 3 | 4.4 | Refrozen layers formed in the previous balance year are exposed |
| 5 | 571 | 42 | 331 | −117 | 214 | 59 | 20 | | | 293 | 3.66 | 4.2 | 0.90 | 3 | 3.8 | |
| 6 | 394 | 42 | 229 | − 52 | 177 | 116 | 34 | | 1 | 328 | 4.10 | 4.9 | 0.90 | 3 | 4.4 | |
| 7 | 601 | 41 | 355 | −121 | 234 | 65 | 19 | | | 318 | 3.98 | 4.9 | 0.90 | 2 | 4.4 | |
| 8 | 598 | 41 | 353 | −121 | 232 | 112 | 10 | | | 354 | 4.43 | 5.1 | 0.90 | 2 | 4.6 | |
| 9 | 546 | 42 | 317 | −114 | 203 | 117 | 36 | | | 356 | 4.45 | 5.1 | 0.90 | 2 | 4.6 | |
| 10 | 520 | 42 | 302 | −113 | 189 | 131 | 53 | | | 373 | 4.66 | 5.3 | 0.90 | 2 | 4.8 | |
| 11 | 602 | 42 | 355 | −121 | 234 | 107 | 32 | | | 374 | 4.67 | 5.6 | 0.90 | 2 | 5.0 | |
| 12 | 566 | 41 | 334 | −120 | 214 | 95 | 45 | | | 354 | 4.43 | 4.9 | 0.90 | 2 | 4.4 | |
| 13 | 518 | 41 | 306 | −118 | 188 | 118 | 41 | | | 347 | 4.34 | 5.2 | 0.90 | 2 | 4.7 | |
| 14 | 419 | 42 | 243 | − 82 | 161 | 126 | 39 | | | 326 | 4.08 | 4.9 | 0.90 | 2 | 4.4 | |
| 15 | 401 | 42 | 233 | − 77 | 156 | 138 | 60 | | | 354 | 4.42 | 5.2 | 0.90 | 2 | 4.7 | |
| 16 | 430 | 41 | 254 | − 93 | 161 | 122 | 52 | | | 335 | 4.19 | 4.2 | 0.90 | 2 | 3.8 | |
| 17 | 472 | 41 | 278 | −110 | 168 | 129 | 23 | | | 320 | 4.00 | 4.9 | 0.90 | 2 | 4.4 | |
| 18 | 412 | 40 | 247 | − 85 | 162 | 124 | 20 | | | 306 | 3.83 | 4.0 | 0.90 | 2 | 3.6 | |
| 19 | 222 | 40 | 133 | − 38 | 95 | 97 | 51 | | 2 | 245 | 3.06 | 3.7 | 0.90 | 2 | 3.3 | |
| 20 | 409 | 41 | 241 | − 71 | 170 | 49 | 28 | | | 247 | 3.09 | 3.1 | 0.90 | 2 | 2.8 | |
| 21 | 200 | 41 | 118 | − 70 | 48 | 91 | 72 | | 1 | 212 | 2.65 | 3.2 | 0.90 | 2 | 2.9 | |
| 22 | 91 | 42 | 53 | − 5 | 48 | 89 | 58 | | | 195 | 2.44 | 2.9 | 0.90 | 2 | 2.6 | |
| 23 | 184 | 41 | 109 | − 18 | 91 | 70 | 34 | | 1 | 196 | 2.45 | 2.6 | 0.90 | 2 | 2.3 | |
| 24 | 90 | 42 | 52 | + 23 | 75 | 101 | 87 | | | 263 | 3.29 | 3.2 | 0.90 | 2 | 2.9 | |
| 25 | 53 | 42 | 31 | + 19 | 50 | 66 | 62 | | 4 | 202 | 2.53 | 2.2 | 0.90 | 2 | 2.0 | |
| 26 | 204 | 42 | 118 | − 1 | 117 | 74 | 37 | | 2 | 230 | 2.88 | 2.8 | 0.90 | 2 | 2.5 | |
| 27 | 331 | 42 | 195 | − 36 | 159 | 67 | 35 | | | 263 | 3.29 | 3.3 | 0.90 | 2 | 3.0 | |
| 28 | 335 | 41 | 201 | − 47 | 154 | 77 | 45 | | | 276 | 3.45 | 3.3 | 0.90 | 2 | 3.0 | |
| 29 | 392 | 39 | 239 | −100 | 139 | 86 | 52 | | | 277 | 3.46 | 3.4 | 0.90 | 2 | 3.0 | |
| 30 | 419 | 39 | 256 | −110 | 146 | 29 | 11 | | | 186 | 2.32 | 2.4 | 0.90 | 2 | 2.2 | |
| 31 | 184 | 41 | 112 | 0 | 112 | 83 | 62 | | | 257 | 3.21 | 3.8 | 0.90 | 2 | 3.4 | |
| SEPTEMBER | | | | | | | | | | | | | | | | |
| 1 | 112 | 41 | 66 | + 4 | 70 | 100 | 80 | | 1 | 251 | 3.14 | 3.8 | 0.90 | 2 | 3.4 | |
| 2 | 90 | 41 | 53 | + 19 | 72 | 98 | 71 | | 3 | 244 | 3.05 | 3.3 | 0.90 | 2 | 3.0 | |
| 3 | 108 | 40 | 65 | + 10 | 75 | 86 | 68 | | 2 | 231 | 2.89 | 3.2 | 0.90 | 2 | 2.9 | |
| 4 | 79 | 41 | 47 | + 23 | 70 | 86 | 50 | | 3 | 209 | 2.61 | 3.1 | 0.90 | 2 | 2.8 | |
| 5 | 203 | 40 | 122 | − 5 | 117 | 64 | 18 | | 1 | 200 | 2.50 | 2.6 | 0.90 | 2 | 2.3 | |
| 6 | 464 | 38 | 288 | −110 | 178 | 30 | 10 | 25 | | 218 | 2.73 | 2.9 | 0.90 | 2 | 2.6 | |
| 7 | 327 | 40 | 196 | − 36 | 160 | 67 | 20 | 10 | 2 | 249 | 3.11 | 3.4 | 0.90 | 2 | 3.1 | |
| 8 | 397 | 39 | 242 | − 78 | 164 | 44 | 17 | | 1 | 226 | 2.82 | 3.6 | 0.90 | 2 | 3.2 | |

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| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 39846 | 54 | 18316 | −4749 | 13567 | 7701 | 3474 | 102 | 86 | 24828 | 310.4 | 549.0 | | | 311.8 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Melted ice g/cm² | 169.6 | 96.3 | 43.4 | 0.2 | 1.1 | 310.4 | | 311.8 |
| Melted ice % | 54.6 | 31.0 | 14.0 | 0.06 | 0.34 | 100.0 | | 100.5 |

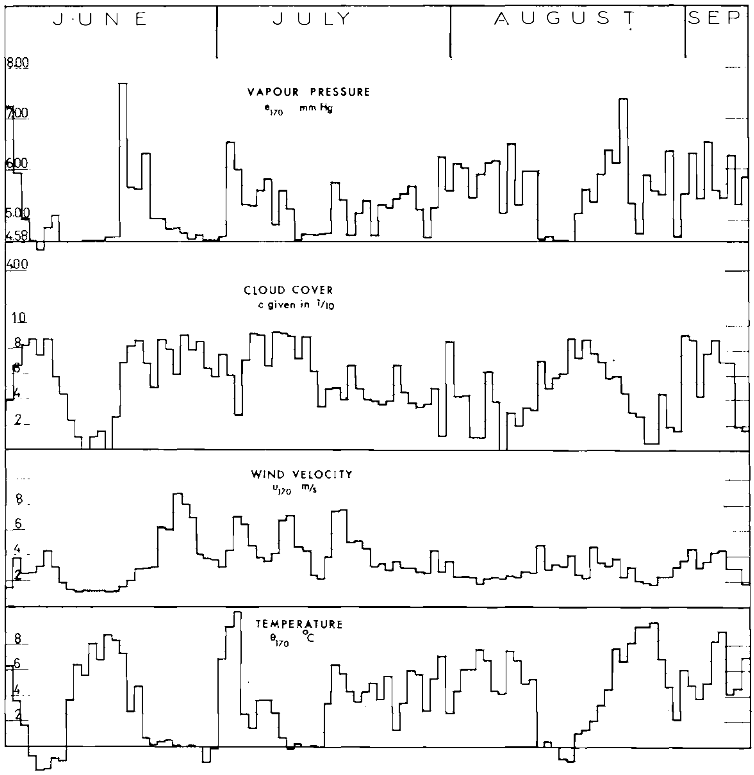

Fig. 21. *The most important meteorological parameters measured at 170 cm above the glacier surface of Omnsbreen in 1968.*

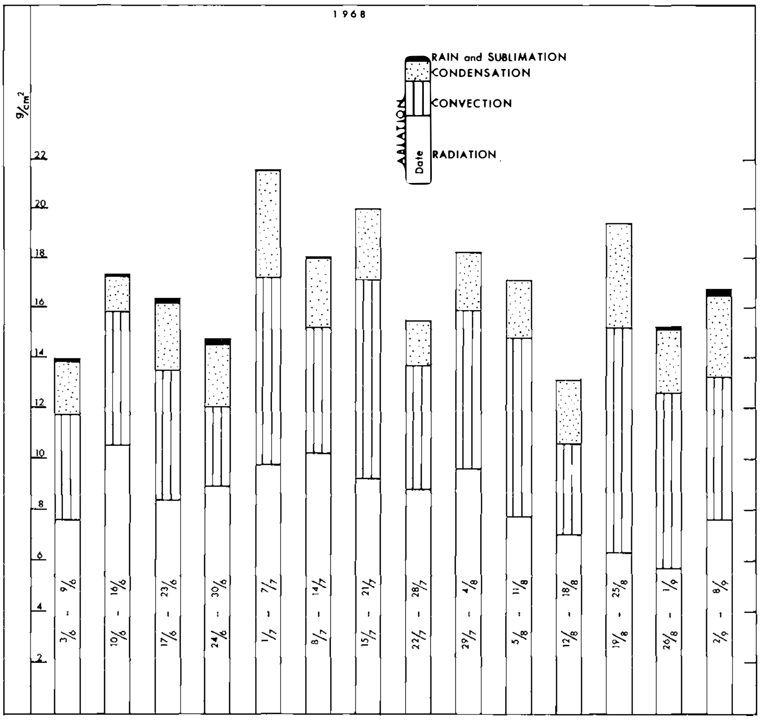

Fig. 22. *The weekly ablation and the contribution from different factors, Omnsbreen 1968.*

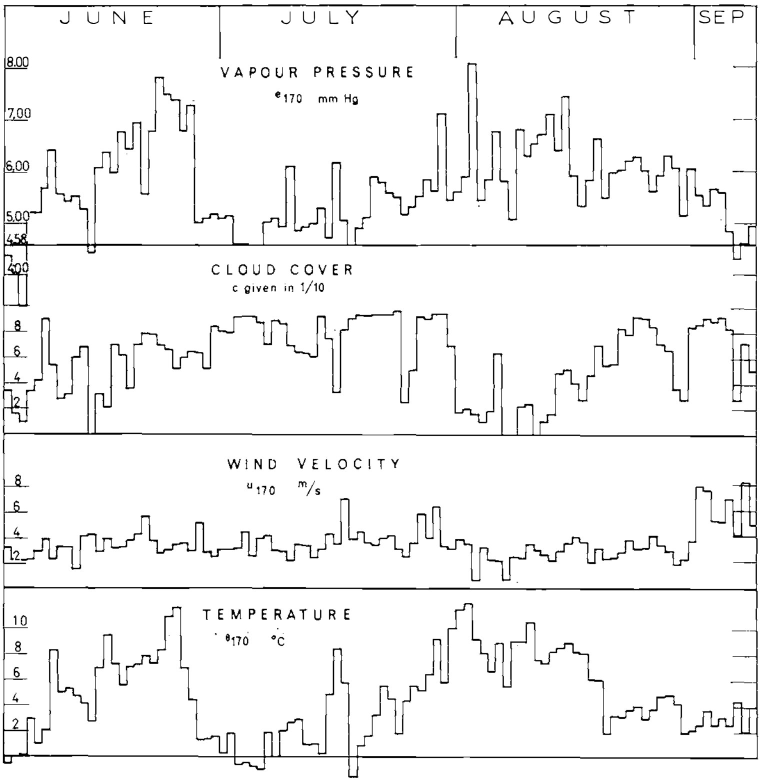

Fig. 23. *The most important meteorological parameters measured at 170 cm above the glacier surface of Omnsbreen in 1969.*

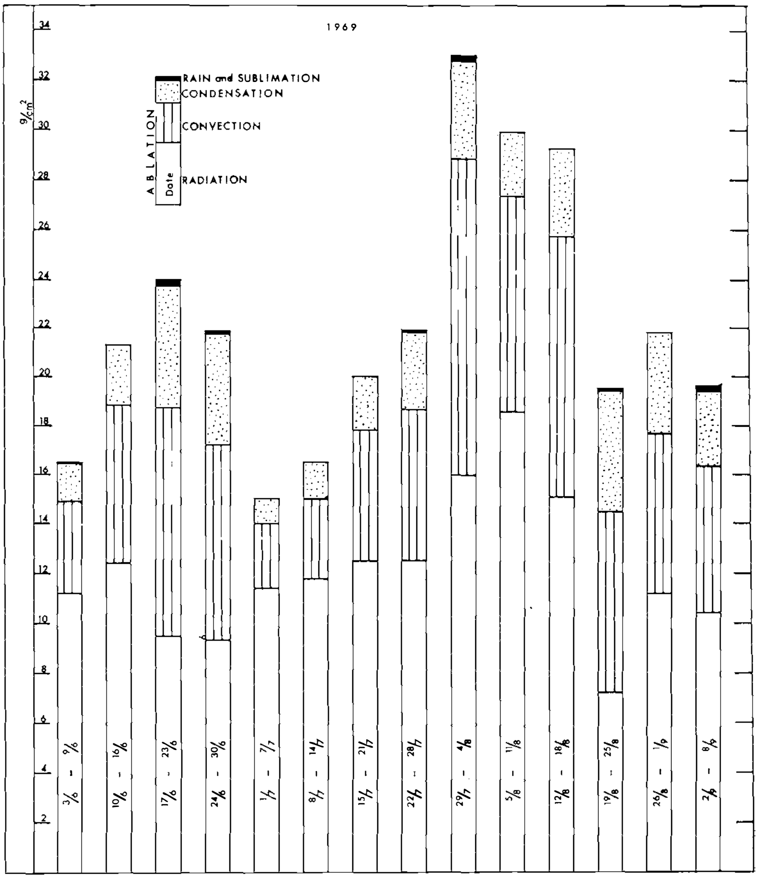

Fig. 24. *The weekly ablation and the contribution from different factors, Omnsbreen 1969.*

Table V

*Relative importance of climatic factors for the ablation on Omnsbreen. Weekly accounts during the summer season.*

| | 1968 | | | | | 1969 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Period | Radiation | Convection | Condensation | Sublimation | Rain | Radiation | Convection | Condensation | Sublimation | Rain |
| 3/6– 9/6 | 54.4 | 29.9 | 14.7 | 0.1 | 0.9 | 68.1 | 22.3 | 9.1 | 0.5 | – |
| 10/6–16/6 | 60.5 | 30.7 | 8.1 | 0.7 | – | 58.6 | 29.8 | 11.5 | 0.1 | – |
| 17/6–23/6 | 51.2 | 31.3 | 16.5 | 0.1 | 0.9 | 39.8 | 38.1 | 21.0 | – | 1.1 |
| 24/6–30/6 | 60.4 | 21.4 | 16.9 | – | 1.3 | 43.0 | 35.9 | 20.8 | – | 0.3 |
| 1/7– 7/7 | 45.2 | 34.8 | 19.8 | – | 0.2 | 76.0 | 17.2 | 6.6 | – | 0.2 |
| 8/7–14/7 | 56.5 | 27.9 | 15.1 | – | 0.5 | 71.3 | 19.4 | 9.0 | – | 0.3 |
| 15/7–21/7 | 46.2 | 39.8 | 13.8 | 0.2 | – | 62.7 | 26.3 | 10.8 | – | 0.2 |
| 22/7–28/7 | 56.0 | 32.4 | 11.6 | – | – | 57.3 | 27.9 | 14.3 | – | 0.5 |
| 29/7– 4/8 | 51.8 | 35.2 | 13.0 | – | – | 48.5 | 39.1 | 11.8 | – | 0.6 |
| 5/8–11/8 | 44.9 | 41.6 | 13.5 | – | – | 61.9 | 29.5 | 8.5 | – | 0.1 |
| 12/8–18/8 | 53.0 | 28.2 | 18.0 | – | 0.8 | 51.6 | 36.4 | 12.0 | – | – |
| 19/8–25/8 | 32.4 | 45.8 | 21.6 | 0.1 | 0.1 | 37.0 | 37.4 | 25.1 | – | 0.5 |
| 26/8– 1/9 | 37.4 | 45.3 | 16.4 | 0.1 | 0.8 | 51.3 | 29.5 | 19.0 | – | 0.2 |
| 2/9– 8/9 | 44.8 | 34.9 | 19.4 | – | 0.9 | 53.2 | 30.3 | 15.5 | 0.3 | 0.7 |
| 3/6– 8/9 | 49.6 | 34.2 | 15.7 | 0.1 | 0.4 | 54.6 | 31.0 | 14.0 | 0.06 | 0.34 |

## Special results from the heat balance investigation

### RADIATION AND CLOUD COVER

The 196 days of observation on Omnsbreen during the summers of 1968 and 1969 give a fairly satisfactory foundation for a discussion of the radiation's variation with cloud cover for different periods of the ablation season. The four period chosen are put into Fig. 25 where the global radiation for these periods is traced as functions of cloud cover.

The curved lines indicate that the incoming energy for c = 10 (fully overcast) is 450—500 cal/cm$^2$/day lower than the incoming energy for c = 0 (clear sky). The displacement of the curves towards lower positions is of course due to their representing periods successively farther from summer solstice. To put this picture in a little more perspective, the curves for daily global radiation for a clear sky are given for Omnsbreen (1540 m a.s.l.) and Blindern/Oslo (94 m a.s.l.) in Fig. 26. It may be mentioned that their difference, which in mid-summer is c. 70 cal/cm$^2$/day, can be explained partly by greater amounts of dust and pollution in the Oslo air, because tropospheric absorption alone cannot be responsible for more than c. 50 cal/cm$^2$/day (found on days with northerly winds, and thereby relatively clean air, in Oslo).

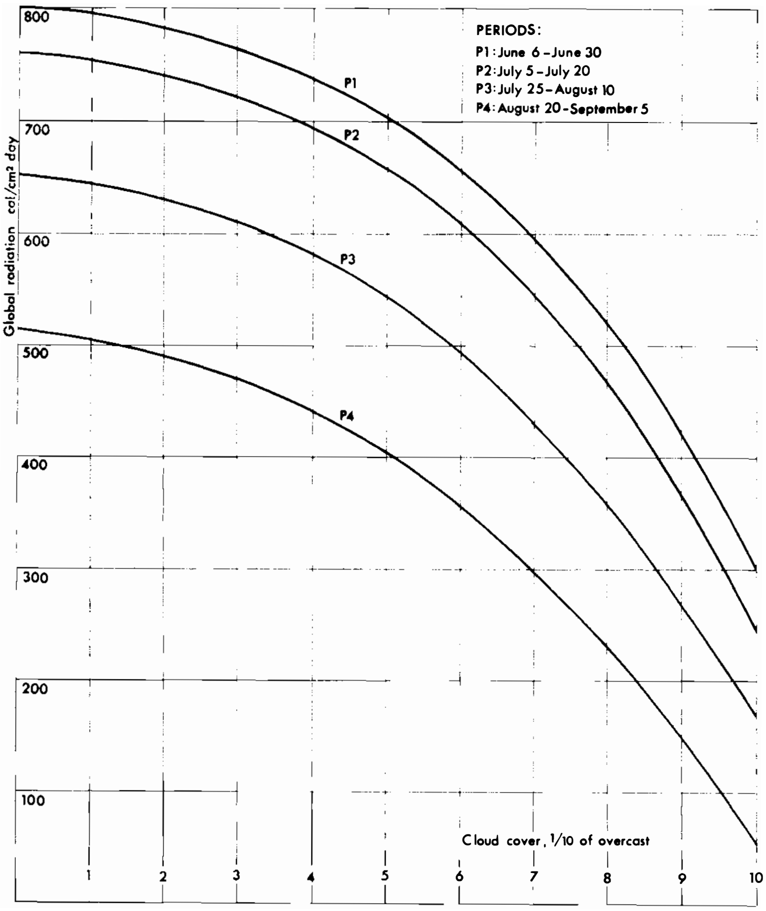

Fig. 25. *Relation between measured daily global radiation and observed daily mean cloudiness. Mean values from the registrations in 1968 and 1969 are used.*

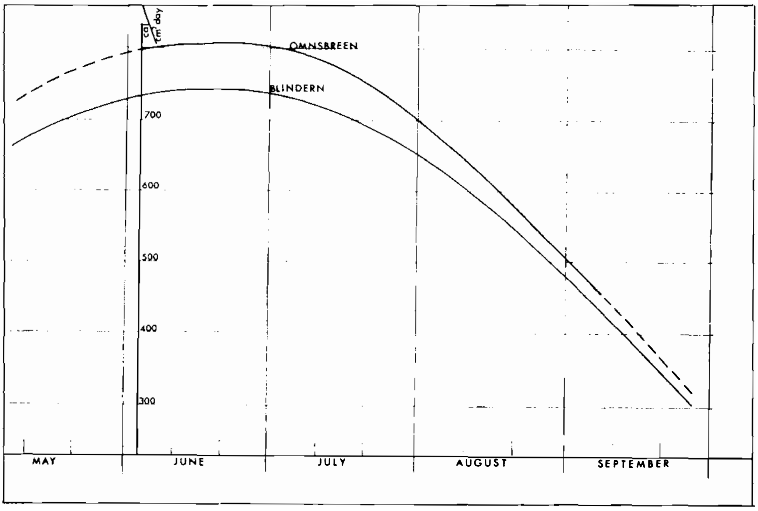

Fig. 26. *Global radiation for clear sky registered at Omnsbreen and Blindern (Oslo) during the summer period. For Omnsbreen, the mean values for 1968 and 1969 are presented; concerning Blindern, values registered from 1965 to 1969 are used as the base for the curve shown here.*

In Fig. 27 two curves are drawn, representing two different formulae for long-wave radiation balance. The thick line represents the previously used formula

$$R_c = R_0 [1 - k (\frac{c}{10})^2]$$

The corresponding resultant curves, giving the net radiation energy supply to the glacier surface in relation to cloud cover for the four periods chosen, are shown in Fig. 28 (the observed mean values of the albedo are of course incorporated).

From the calculations represented in Fig. 28 it seems that the energies absorbed for $c = 0$ and $c = 10$ early in the ablation season are nearly the same. This result is not unreasonable, because of the relatively high albedo (65—70%) and the considerable role played by long-wave radiation. In the last part of the ablation season the difference is here calculated to be c. 120 cal/cm²/day.

Another feature of the curves in Fig. 28 is that they show relatively high values for cloud cover 5—6 in the scale given. For P1 and P2 the maximum heat supply occurs by this cloudiness if the curves in Fig. 28 represent the current situation. However, diagrams recorded by the ablatograph seem to indicate that maximum ablation caused by radiation occurs when the cloud cover is about 4 (registered on days when other conditions were fairly steady). This maximum, in the first part of the summer, agrees well with the result indicated by the dotted line in Fig. 28, which is a consequence of using the formula for long-wave radiation balance given by ÅNGSTRÖM (see WALLÉN 1948, p. 499):

$$R_c = R_0(1 - k\frac{c}{10}); \quad k = 0.9 \text{ (see thin line in Fig. 27).}$$

The ÅNGSTRÖM formula, on the other hand, obviously gives too low values for the net energy supply to the glacier surface when the sky is overcast.

The investigation presented above has too few accurate global measurements for a finite conclusion to be given. In addition, it is difficult to present simple relations between long-wave radiation balance and cloud cover. The cloud thickness and height of cloud base will complicate the picture. The cloud "constant", k, should have higher values for increasing cloud cover, as discussed by PHILLIPS (see WALLÉN 1948, p. 499).

Of course, some other formulae for long-wave radiation balance could have been discussed here, for example the one given by AMBACH and HOINKES (1963, p. 28). However, when the period of investigation lasts nearly the whole summer, calculations indicate that none of the formulae mentioned entail any considerable error in the final result. Still, it is to be hoped that improved balance meters will make the above discussed problems less important.

## ALBEDO

Continual recordings of the global radiation and of the radiation reflected from the glacier surface automatically gave the albedo for the whole period of registration on Omnsbreen.

The principle features of the albedo's daily variation are shown in Fig. 29.

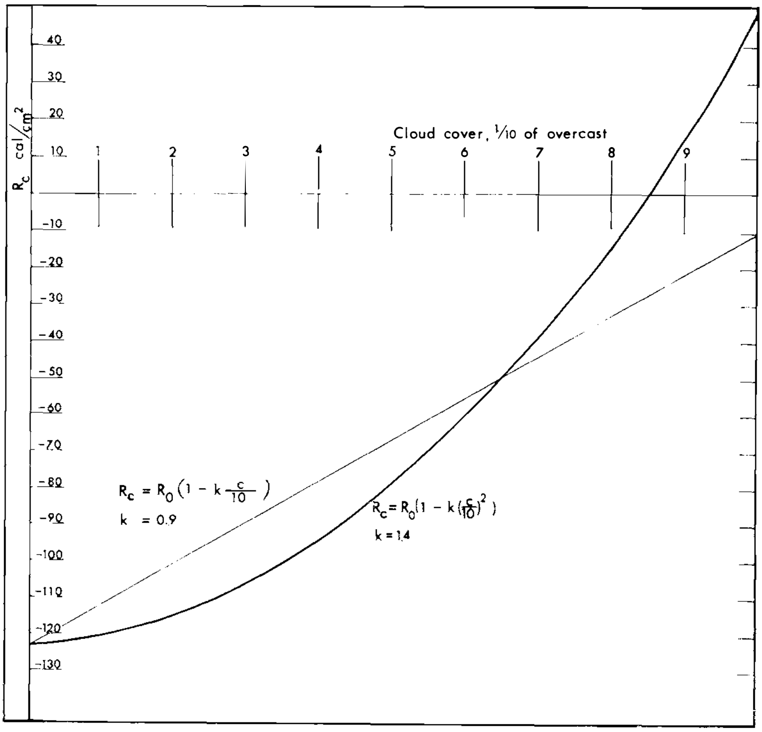

Fig. 27. *Two curves, both of which express the long-wave radiation balance: the thick line represents the formula of* Hoinkes *and* Untersteiner *and the thin line represents the* Ångström *formula.*

From the figure is worth noticing the difference of c. 18% in measured albedo between 6 a.m. and 2 p.m. on clear days in the first part of the summer season. Later, the difference becomes c. 10% (see curves for 7 August and 27 August). In overcast weather there seems to be only a slight difference.

Several previous investigations have established the features mentioned concerning the albedo's daily course (Sauberer and Dirmhirn 1952, p. 280; Hubley 1955, p. 561; Liljequist 1957, p. 89; Ambach and Hoinkes 1963, p. 28; Scheibbner and Mahringer 1968, p. 184), although the values given by the mentioned authors differ somewhat.

Concerning the causes of the mentioned phenomena, however, there exists some disagreement. For the present author the results given by Liljequist (1957, p. 89) and by Ambach and Hoinkes (1963, p. 28), indicating that the daily variations in solar altitude and spectral composition of the global radiation cause 4—5% of the albedo variation, seem to fit in well with the observations on Omnsbreen. With regard to Fig. 29, one will at 2 p.m. find a difference in albedo equal to 5% for overcast as compared with clear weather (see curves for 8 June/12 June 1968 and for 6 August/7 August 1969; the values for 4 September/27 August 1968 cannot be used in this connection because of increasing slush on the glacier surface by this time). It has to be assumed that physical properties of the glacier mass for the dates in question are fairly similar. As can be concluded from Fig. 16, the free water content shows an insignificant difference. The dates chosen are so near each other that any difference in crystal size, surface dirt cover, etc., scarcely has to be taken into account. It may also be suggested that the diffuse global radiation for overcast weather is similar in its physical behaviour to the diffuse sky radiation appearing early in the morning and late in the evening under a clear sky. As may be known, the albedo for diffuse sky radiation are a few percent higher than the albedo for direct sun radiation. Possibly some fractions of a percent have to be subtracted from the above difference of c. 5%, caused by "multiple reflection" appearing on overcast days.

For the remaining daily albedo variation the free water content seems to be the main cause. As shown in Fig. 16, the free water content in the snow layer close to the glacier surface varies considerably on clear days, while being fairly constant

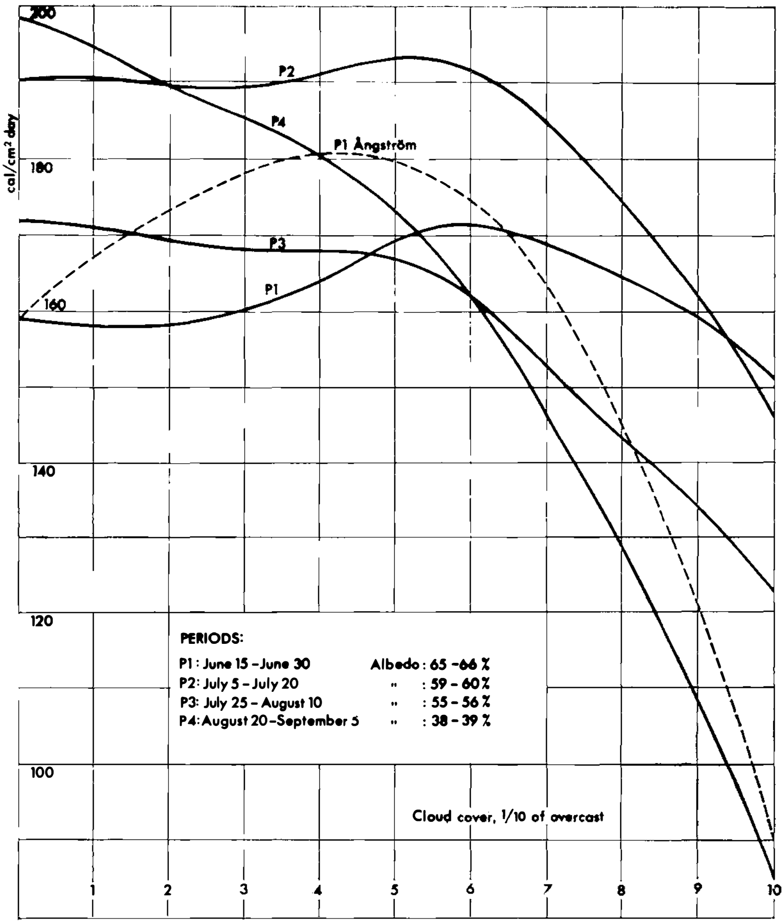

Fig. 28. *Radiant energy received by the glacier surface given as a function of cloud cover. The thick lines represent the energy resulting from use of* HOINKES *and* UNTERSTEINER'S *formula for long-wave radiation balance, the dotted line when using the* ÅNGSTRÖM *formula.*

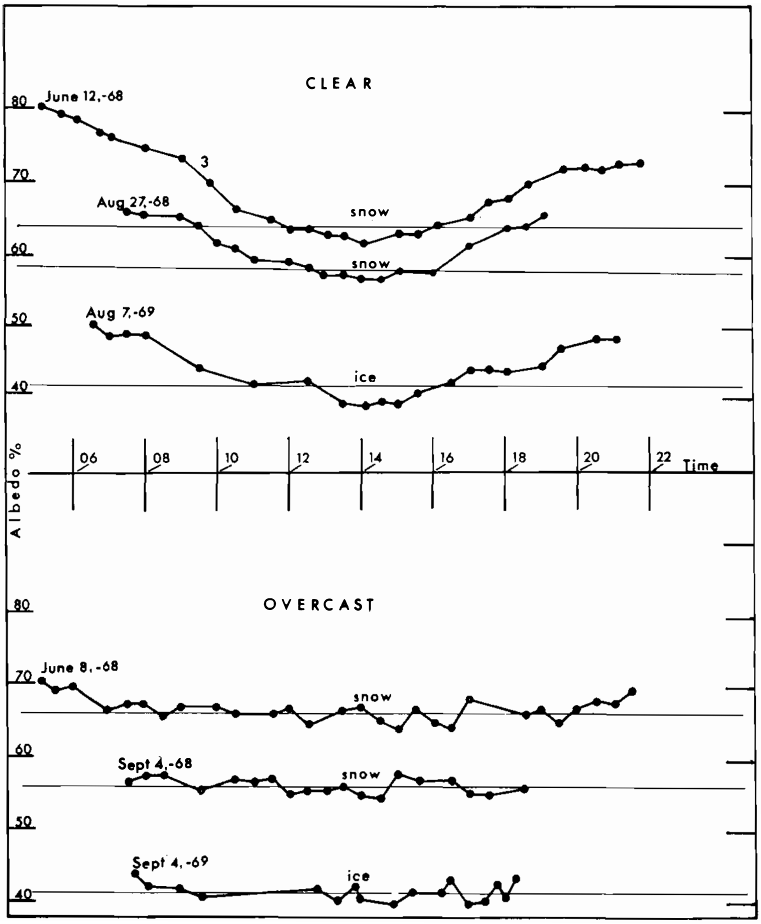

Fig. 29. *Albedo variations during clear and overcast days. The curves are based upon the direct measurements on Omnsbreen in 1968 and 1969.*

on overcast days. As is well known, water absorbs nearly all short-wave radiation energy carried by global radiation.

The decreasing albedo in the course of the summer cannot be attributed to changes in free water content (see Fig. 15 and Tables III and IV), and must be mainly caused by increasing quantities of dirt on the glacier surface together with the growth and rounding of the snow grains.

In several publications the albedo used in heat balance calculations has been determined by using an albedometer, turning it alternately toward the sky and the glacier surface. From the previous discussion it might seem clear that arbitrary choose of the measuring times may result in considerable errors in the values for radiant balance. As can be concluded from Fig. 29, the error will be most apparent if the albedo taken early in the morning is used as the representative albedo for the actual day. The curves in Fig. 29 indicate that measurements performed at 12 noon and at 4 p.m. on clear days will give satisfactory results. On overcast days the measuring times can be chosen less strictly. The best method, of course, will be to carry out several measurements during the day, for example at 11 a.m., 1 p.m., 3 p.m., and 5 p.m., thereby avoiding some of the errors resulting from secondary (short time) variations in the albedo.

## COMPARISONS WITH RESULTS FROM STUDIES OF OTHER GLACIERS

Results of heat balance studies of several glaciers around the world have been presented by PATERSON (1969, pp. 58—61). The most striking feature in PATERSON's synopsis seems to be the short field period upon which most of the results (giving the relative importance of heat source in the ablation) are based. Keeping in mind the problems discussed in connection with Table V, the difficulty of comparing the results obtained on Omnsbreen with those obtained on other glaciers can readily be appreciated. However, the ablation conditions in the Omnsbreen district are fairly similar to the conditions in western Alaska and the coastal range southwards to the Canada/USA border. This assumption is based also upon results not presented by PATERSON (see MAYO and PEWE 1963, pp. 633—643; STRETEN and WENDLER 1968, pp. 431—440). In all probability nearly the same conditions exist in the glacier areas of Iceland, excluding the extreme oceanic climate along the southern coast. Regarding the relative importance of heat sources in the ablation, results from studies in Spitsbergen (SVERDRUP 1935, pp. 145—166) and in Novaja Zemlja (CHICHOV et al. 1968) are comparable with the results obtained on Omnsbreen. These investigations were performed in a sufficiently long period of the ablation season.

More general conclusions concerning heat supply from the atmosphere to the ice and snow surface are beyond the scope of this paper, here referring to e.g. SVERDRUP (1935), AHLMANN (1953), HOINKES (1955 and 1964) and MEIER (1965).

The results of heat balance investigations previously performed in Norway are not mentioned in PATERSON's list, and it is natural to present them here. All the glaciers put into Table VI are situated in the mountain massif of southern Norway's central part. Heat balance investigations have not yet been performed on glaciers in northern Norway. In Table VI Gråsubreen is situated farthest east and Ålfotbreen farthest west.

In Table VI some of the results are based upon field work of too short duration. However, they may give a fairly satisfactory basis for a more general synopsis showing the climatic factor's relative contribution to the ablation in an east-west section in southern Norway. In Table VII meteorological data from stations situated not far from the glacier are used as supplements to the results obtained on the glaciers.

It has to be emphasized that the field work, upon which the values in Table VII are based, is far from complete. Table VII, as well as PATERSON's list, indicate that there is a definite need for heat balance studies on representative glaciers around the world. These studies should be performed simultaneously on the glacier during most of the ablation season. As a first step it might be sufficient just to separate the radiation from the other ablation factors. With the new instruments available for radiation registrations the program mentioned should not lead to any insurmountable problems. Mass balance studies are, as is well known,

## Table VI

*Relative importance of the main climatic factors for the ablation on glaciers examined in southern Norway*

| Glacier | Surface | Dates | Elev. in m | % contribution from | | | Reference |
|---|---|---|---|---|---|---|---|
| | | | | rad. | conv. | cond. | |
| Gråsubreen | snow | 12 June–18 1963 | 1975 | 98 | 2 | | Klemsdal 1970 |
| | snow/ice | 27 July–9 Aug. 1963 | | 59 | 27 | 14 | |
| Storbreen | –»– | 6 July–8 Sep. 1955 | 1600 | 54 | 32 | 14 | Liestøl 1967 |
| Skagastølsbreen | –»– | May–Sep. 1954 | 1600 | 79 | 21 | | Eriksson 1959* |
| | –»– | May–Sep. 1955 | | 66 | 34 | | |
| Omnsbreen | snow | 3 June–8 Sep. 1968 | 1540 | 50 | 34 | 16 | Messel 1971 |
| | snow/ice | 3 June–8 Sep. 1969 | | 55 | 31 | 14 | |
| Supphellebreen | ice | 1 July–12 1967 | 70 | 32 | 68 | | Orheim 1968 |
| | –»– | 31 July–5 Aug. 1967 | | 26 | 74 | | |
| | –»– | 4 Sep.–8 1967 | | 14 | 86 | | |
| Aus. Memurubre | snow/ice | 26 June-30 Aug. 1970 | 1900 | 67 | 33 | | Messel 1971** |
| Ålfotbreen | –»– | 1 June–13 Sep. 1970 | 1250 | 44 | 56 | | Messel 1971** |

* Theoretical calculations based upon meteorological data taken nearby. **Unpublished data.

## Table VII

*The ablation conditions in the principal glacier areas of southern Norway*

| Glacier area | Radiation % | Convection % | Condensation % |
|---|---|---|---|
| Jotunheimen, east | 65 | 24 | 11 |
| Jotunheimen, west | 59 | 28 | 13 |
| Jostedalsbreen, east-Finse area | 54 | 31 | 15 |
| Jostedalsbreen, west | 46 | 36 | 18 |
| The westernmost glaciers | 37 | 40 | 23 |

going on in several glacier areas around the world, and some of these areas can be considered as representative for heat balance studies. In Norway radiation registrations are planned to be carried out on Ålfotbreen and on a glacier in Jotunheimen during the following summer seasons.

A further development of the above may throw more light upon the connection between climatic fluctuations and glacier variations, as fundamentally discussed by Ahlmann (1948 and 1953) and treated by numerous authors.

## Acknowledgements

Financial and technical support for field studies and office work was provided mainly by Norsk Polarinstitutt. Important instruments were given by Geografisk Institutt at the University of Oslo and by the Norwegian Meteorological Institute.

Students in geography and meteorology assisted with great enthusiasm in the field. Valuable help was also given by the staff at Finse railway station and Finse Tourist Hut with winter observations and transport.

I should like to express my hearty thanks to OLAV LIESTØL, glaciologist at Norsk Polarinstitutt, for all the encouragement, suggestions, and criticism he offered both during the field work and with the manuscript. Discussions with VIDAR HISDAL and TORGNY E. VINJE concerning meteorological problems have been of great use. Also ELI HOLMSEN, MAGNE GALÅEN, and EINAR NETELAND deserve special mention for their respective contributions: preparing the manuscript for press, drawing most of the figures, and assistance with instrument construction and testing.

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