NORSK POLARINSTITUTT
SKRIFTER NR. 151

OLAV ORHEIM

Glaciological investigations of Store Supphellebre, West-Norway

NORSK POLARINSTITUTT
OSLO 1970

DET KONGELIGE DEPARTEMENT FOR INDUSTRI OG HÅNDVERK

NORSK POLARINSTITUTT
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Manuscript received July 1969

Printed June 1970

A.W. BRØGGERS BOKTRYKKERI A/S - OSLO

Contents

Abstract

Glaciological studies were conducted from 1963 to 1967 on Store Supphellebre, a 12 km^2 outlet glacier from Jostedalsbreen. The glacier is in two parts: Flatbreen, extending from 1 740 to 720 m a.s.l., and Supphellebreen, a regenerated glacier extending from 320 to 60 m a.s.l. The mass balance was determined for the whole system; for Flatbreen by standard techniques, and for Supphellebreen mainly by constructing maps by terrestrial photogrammetry at a scale of 1:2 000 every spring and autumn. Three out of the four balance years were markedly positive, and during the 4-year period Store Supphellebre increased in average thickness by 1.70 m water equivalent. Glacio-meteorological investigations on Supphellebreen showed that radiation contributed only 20–30 per cent of the total heat flux to the glacier surface during the summer, the rest being contributed by conduction and latent heat of condensation. Photographs and dated moraines enabled glacier boundaries and centre-line profiles of Supphellebreen to be constructed for various times during the past 200 years; these show that the glacier shrank most rapidly after 1930. At the greatest extent of the glacier in historic time, the equilibrium line was only about 100 m below its present level of 1 350 m a.s.l.

The response time of changes in throughflow at the snout of Flatbreen to changes in its mass balance was found to be 2 to 3 years; the same value was obtained by using NYE's kinematic wave theory, and by measurements. Investigations of the internal structure of Supphellebreen showed that debris layers were buried summer surfaces, and not the result of avalanche stratification as is commonly believed.

Introduction

Store Supphellebre (61°30′N, 6°48′E), is an outlet valley glacier from Jostedalsbreen in central West-Norway (Figs. 1 and 2). Jostedalsbreen is a glacier cap (using the classification of AHLMANN 1948, p. 61), covering 473 km^2 (LIESTØL 1962a, p. 45).

As shown by the map (Fig. 3), Store Supphellebre is in two parts. The upper glacier, called "Flatbreen" locally, covers 11.8 km^2 and extends downward from 1740 to 720 m a.s.l., where it calves off a 50° rock slope and re-forms 400 m below as a 0.1 km^2 regenerated glacier.

Before this study no work had been done on the upper glacier, while the lower, owing to its easy accessibility, had been visited frequently since the early description by FORBES (1853). SEUE (1870) made the first significant observations of the glacier, including a photograph of it in 1868 or 1869, and studied the ice structures and evidence of recent advances and retreats of the glacier. REKSTAD started measurements of the position of the snout in 1899, which were repeated from three stations, usually annually, until 1960. He also studied the glacier structures (REKSTAD 1902, 1904). HAMBERG (1908, 1932) also discussed the internal structures.

Fig. 1. *Location map.*

Fig. 2. *Aerial photograph of south-western part of Jostedalsbreen. Store Supphellebre is in the right centre of the figure, with Supphellebreen, the regenerated glacier, in the bottom of the right hand valley.*

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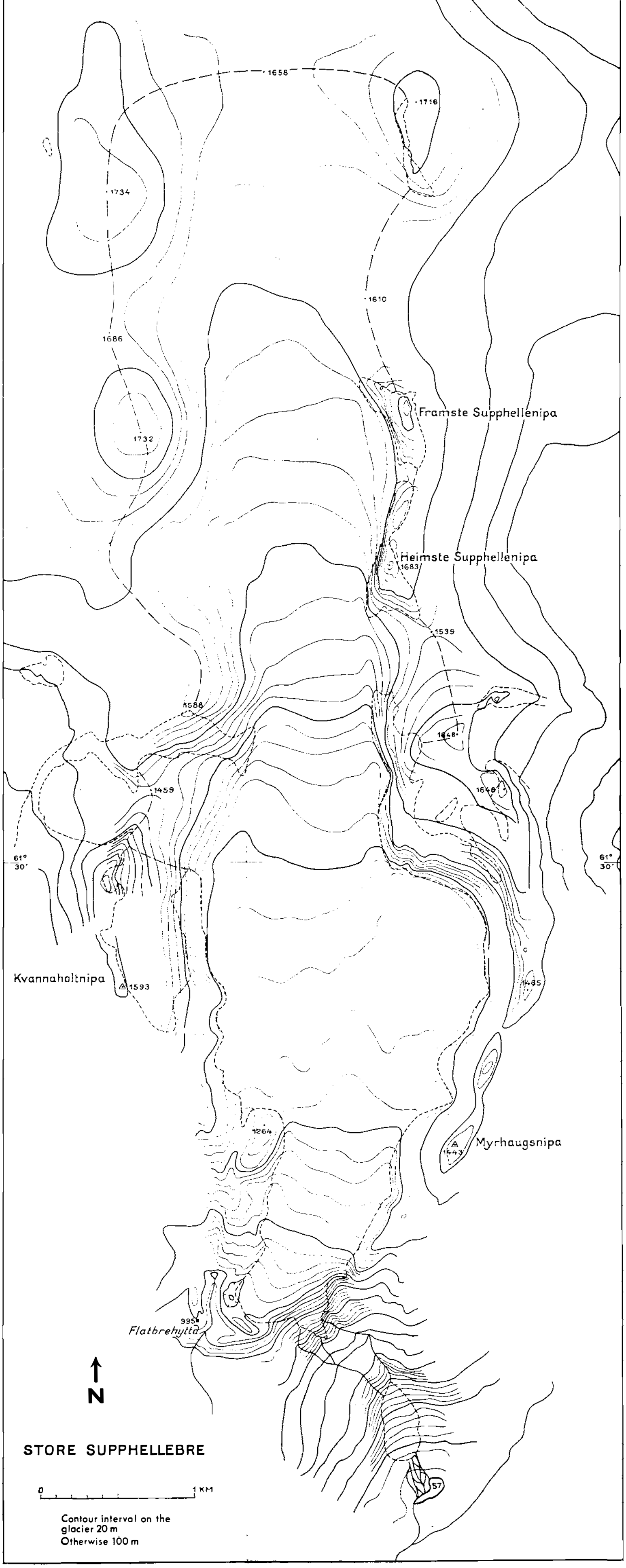

Fig. 3. *Store Supphellebre. Based on 1:50 000 map constructed by the Cartographic Survey of Norway in 1967. Short dashes, - - -, mark the glacier boundaries on land, long dashes, — — — mark the boundaries with adjacent snow fields and glaciers.*

Less significant descriptions of the glacier are found in ØYEN (1900) and BEHRMANN (1927).

The name used for the lower glacier has varied: "Supphellebreen" and "Store Supphellebre" have been most commonly employed. Locally it is called "Supphellebreen". In this work "Supphellebreen" is used for the lower glacier, "Flatbreen" for the upper, and "Store Supphellebre" for both combined.

In the following are described some of the results of studies performed on Store Supphellebre between 1963 and 1967. The discussion primarily covers the determination of the mass balance of the lower glacier, its former extent, and the much discussed ice structures. Standard mass balance techniques, such as used on Flatbreen, could not be employed on Supphellebreen because of ice avalanches. Instead, the glacier was mapped in the spring and autumn by terrestrial photogrammetry to determine the volume changes. From these and meteorological observations the areal total mass balance was determined. For a complete understanding of the processes on the lower glacier, knowledge of the conditions on the upper glacier is necessary; the first section therefore covers the mass balance determinations on Flatbreen.

Mass balance investigations on Flatbreen

The nomenclature used here is based on the proposed mass balance terms published in the Journal of Glaciology (1969, Vol. 8, (52) pp. 3–7). The mass balance on Flatbreen was determined by stratigraphic methods, whereby the ends of the winter and summer seasons at each point of the glacier are defined as the time of maximal and minimal mass, respectively, at that point. The end of the summer season is also the end of the balance year and a recognizable "summer surface" is formed at that time. The techniques in the mass balance determinations include pit stratigraphy, density measurements in the pits, with 500 cm^3 sampler, snow-depth soundings (with thin aluminium rods along sounding profiles with usually 50 m separation between the soundings), and measurements at ablation and accumulation stakes. These were 4—6 m aluminium stakes, fitted with wood extensions in the lower end to prevent independent sinking. Fig. 4 shows the distribution of pits, stakes, and sounding profiles on Flatbreen in 1966 (the 1966 balance year is the one that ends in 1966). In addition, the position of the transient equilibrium line (transient snow line in the accumulation area) was recorded at various times during the summers. This method is especially useful for obtaining balance information for inaccessible parts of the glacier. All these techniques are well known from other studies (see e.g. WALLÉN 1949, HOINKES and RUDOLPH 1962, LIESTØL 1967, ØSTREM and STANLEY 1969).

The number of snow-depth soundings, and the number of stakes in use in each of the summer seasons, are shown in Table 1. Most of the stakes survived the winter season each year and were also used as accumulation stakes.

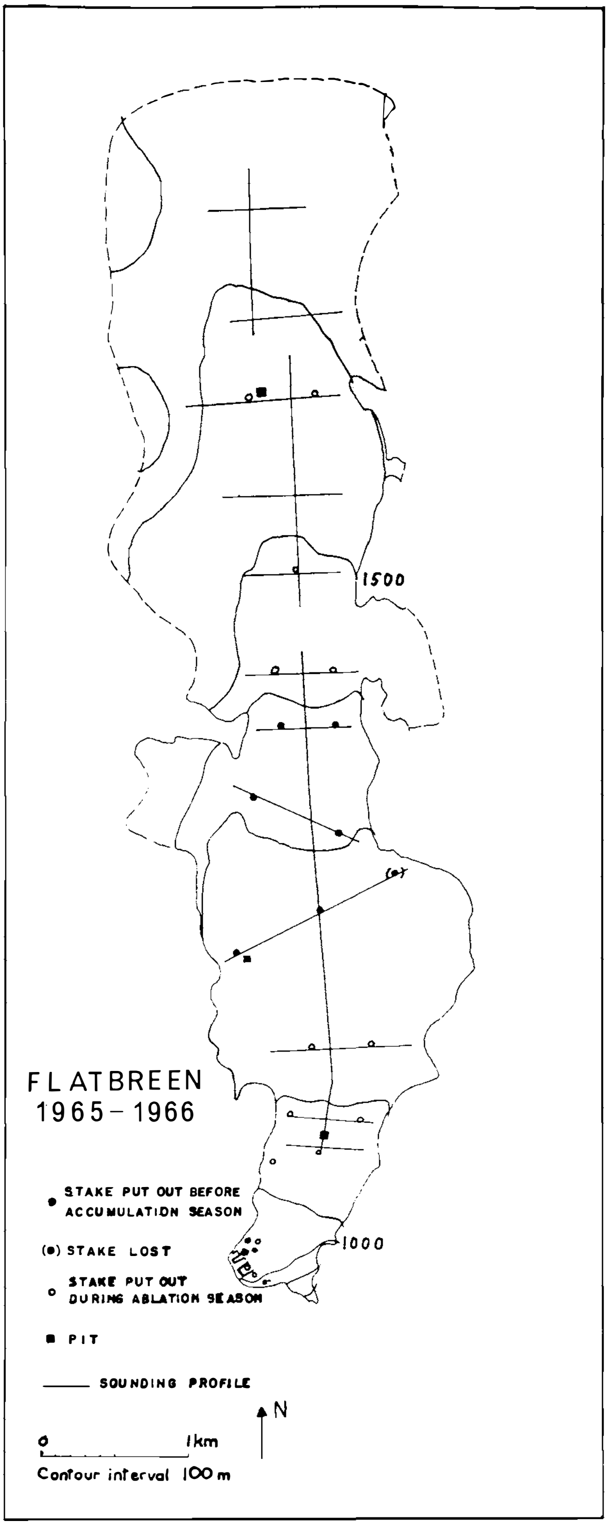

Fig. 4. *Positions of stakes, pits, and sounding profiles on Flatbreen in 1966. The distribution of stakes and pits was similar to that of 1966 in all the years; the distribution of sounding profiles varied.*

Table 1

Number of snow-depth soundings and ablation stakes, 1964—67.

	1964	1965	1966	1967
Number of soundings	121	93	280	174
Number of ablation stakes	20	22	31	24

REDUCTION OF THE FIELD DATA AND PRECISION OF THE RESULTS

Contour maps of accumulation and ablation distribution were constructed, using all the data. The areal total accumulation, C_t, and ablation, A_t, are obtained for each 100-m elevation intervals from these maps. C_t and A_t are divided by the area of the elevation interval to find the mean specific values, $\bar{c}_t$ and $\bar{a}_t$, for the intervals. The areal total net balance, B_n, is the sum of A_t and C_t (A_t is negative); similarly, the mean net balance, $\bar{b}_n$, equals $\bar{a}_t + \bar{c}_t$. All values are given as meters of water.

Generalized maps of the accumulation distribution are shown as Figs. 5—8. The ablation maps are not shown since the results of the ablation measurements from the stakes (except for those stakes that were only in operation part of the summer) are shown in the balance diagrams, Figs. 9—12. These figures also show the variations of $\bar{c}_t$, $\bar{a}_t$, $\bar{b}_n$, B_n, and S (the area distribution curve) with elevation. They are discussed further below.

Field conditions sometimes hindered the mass balance measurements, as illustrated by the varying number of soundings (Table 1); the number and distribution of measurements varied considerably during the four years. Thus, the ablation and accumulation maps were drawn making use of knowledge of the distribution in other years. This can be done with greater certainty for the ablation than for the accumulation. The ablation is fairly constant within each elevation interval, except for the glacier edges and heavily crevassed areas, which represent only a small part of the total area of Flatbreen. In every summer the ablation values have shown high internal consistency and any inter- or extrapolation in the ablation values does not seem to introduce large errors. The accumulation variations are larger and less systematic. The use of the accumulation distribution requires that it can be expected to be constant within each elevation interval. Many workers have discussed the constancy of the distribution. WALLÉN (1949, p. 540) states "... the distribution of it (the snow) seems not to change considerably provided the general weather conditions do not deviate from the normal". Similar observations are found in HOINKES and RUDOLPH (1962, p. 273), MEIER and TANGBORN (1965, p. 554), LIESTØL (1967, p. 12) and numerous others.

The accumulation distribution of Flatbreen is primarily determined by the wind conditions during (and shortly after) precipitation. Deflation of settled snow is not common because winds are generally light. As on the other glaciers in West-Norway, most precipitation on Flatbreen falls from cyclones moving from

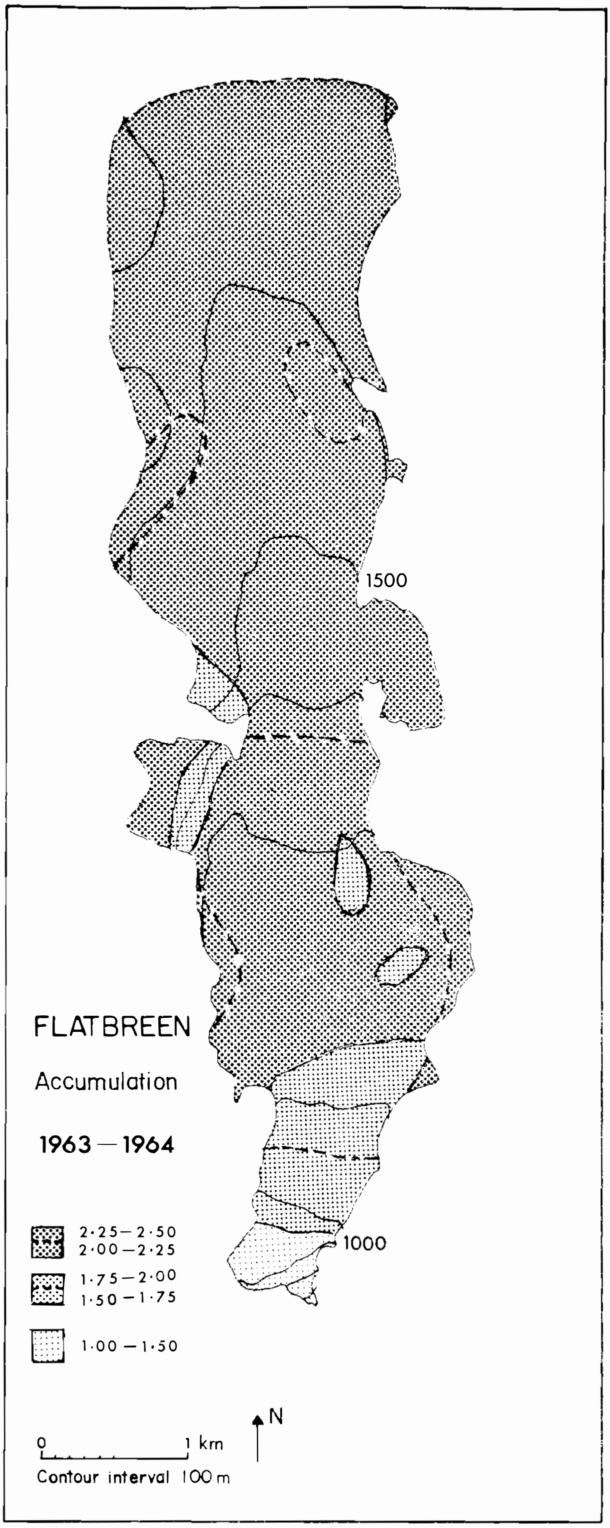

Fig. 5. *Accumulation map for Flatbreen in 1964 (values in m water).*

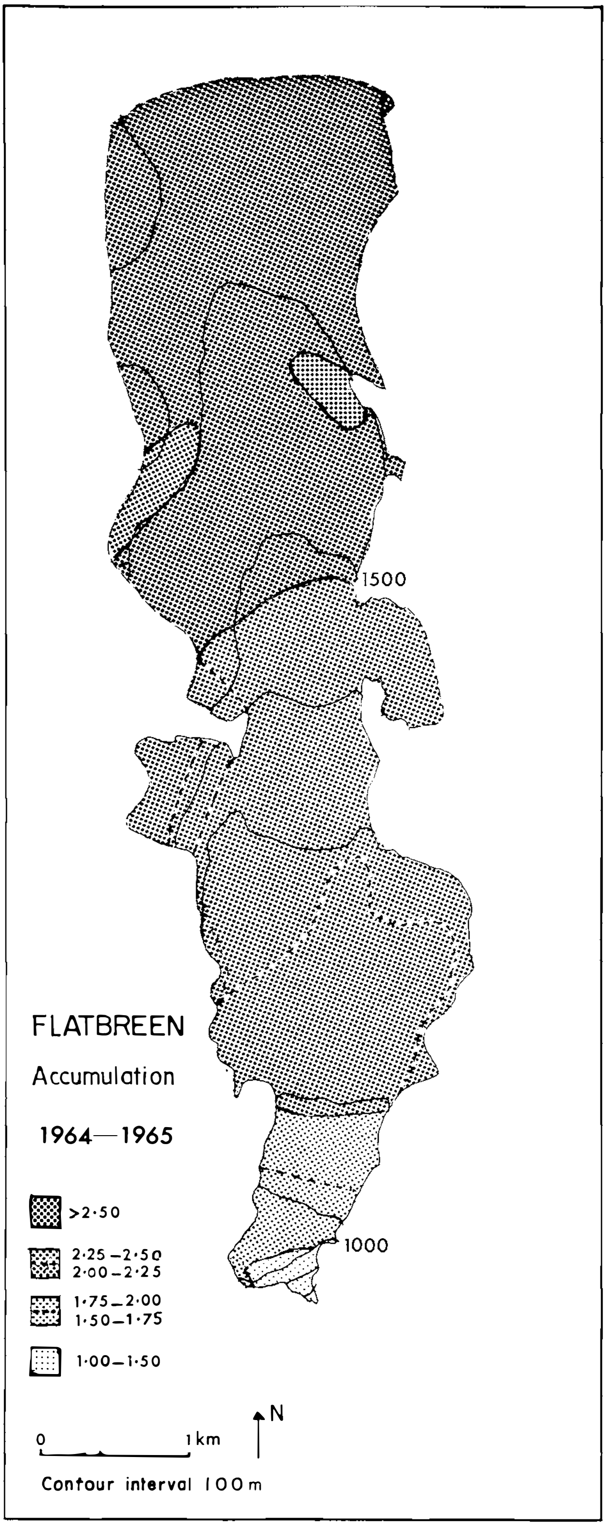

Fig. 6. *Accumulation map for Flatbreen in 1965 (values in m water).*

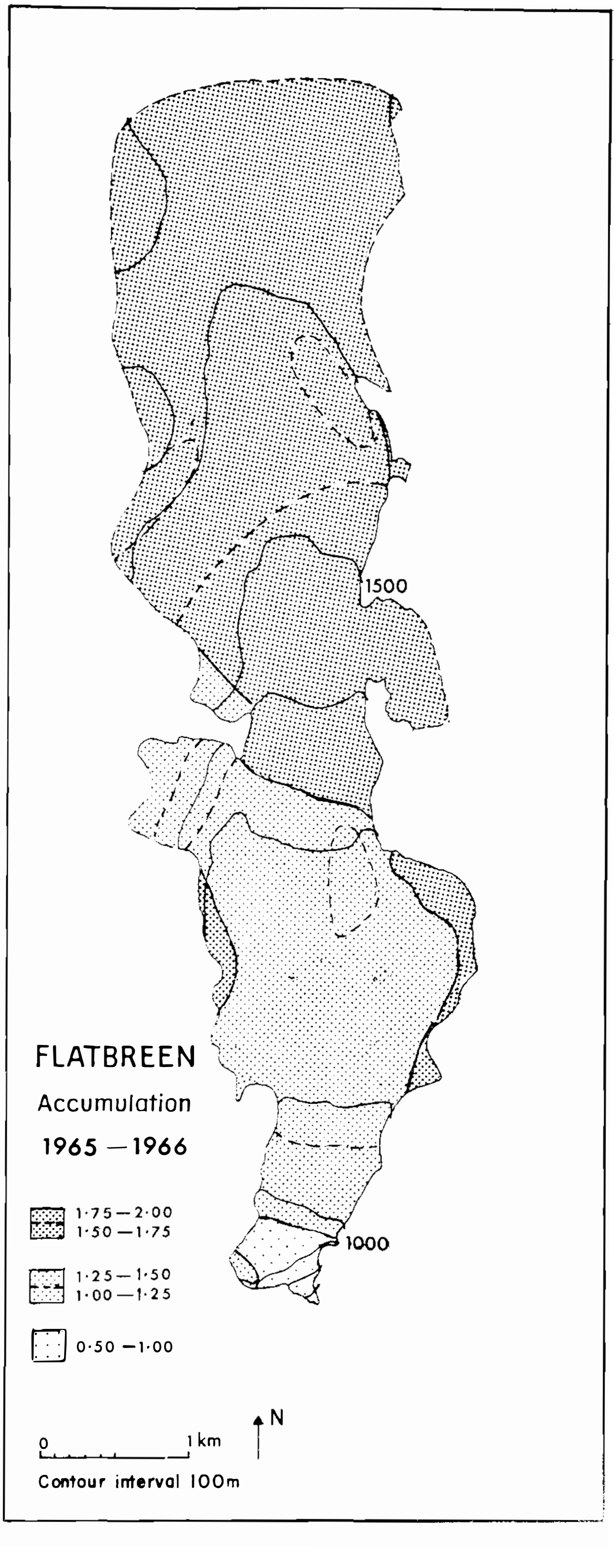

Fig. 7. *Accumulation map for Flatbreen in 1966 (values in m water).*

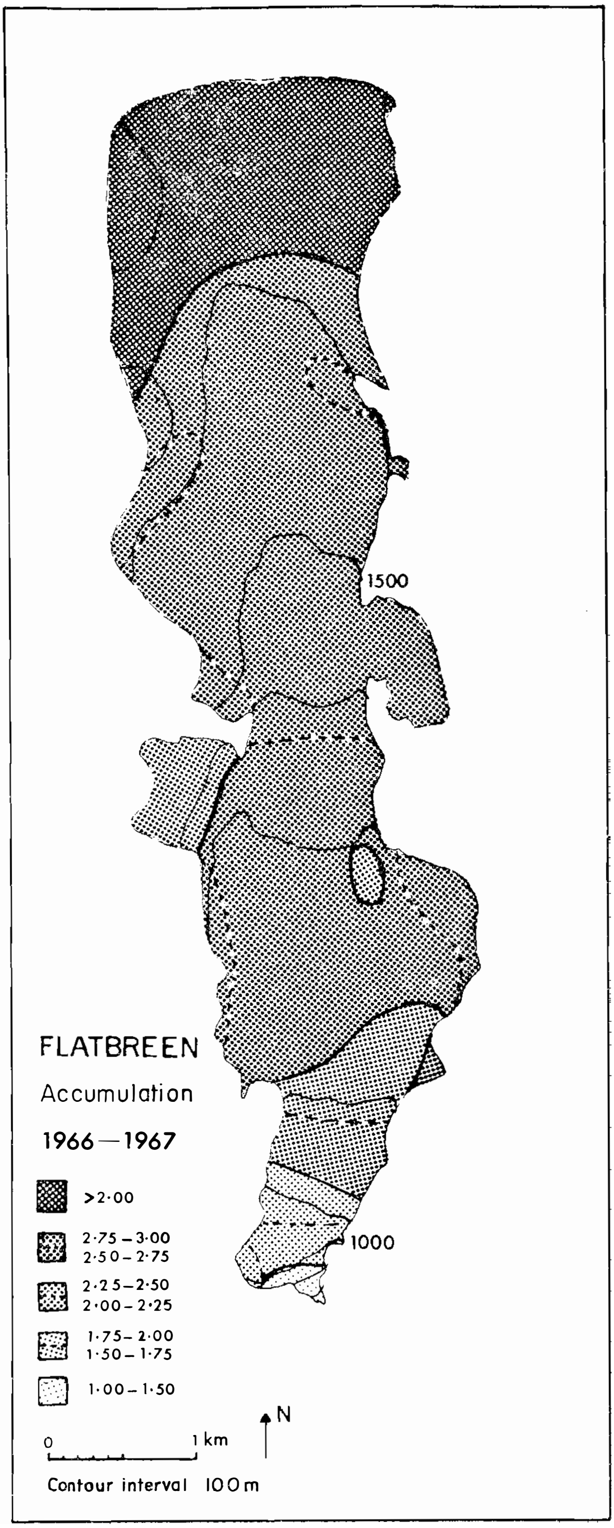

Fig. 8. *Accumulation map for Flatbreen in 1967 (values in m water).*

the west. The accumulation maps of the three nearest glaciers in West-Norway (Ålfotbreen, Nigardsbreen, and Hardangerjøkulen) which have been studied by the Hydrological Division, Norwegian Water Resources and Electricity Board (NVE), have been compared for the four years in question. (The maps are published in PYTTE and ØSTREM 1965, PYTTE and LIESTØL 1966, PYTTE 1967, ØSTREM and PYTTE 1968.) Only minor accumulation pattern variations within each elevation interval were found for each of these glaciers in the years 1964—1967. Similarly, no large variations were found in the accumulation distribution for Flatbreen where sounding profiles for separate years overlapped. Thus there is reason to believe that the wind conditions during precipitation were relatively similar during the winters of each of these four years, and that the accumulation distribution within each elevation interval obtained in one year could be applied to other years.

There are two difficulties inherent in this approach.

(1) Since the accumulation distribution is expected to be similar each year, measurements that indicate deviations from this may not be given full consideration in the drawing of the maps. With care this can probably be avoided.

(2) Even if the accumulation distribution is fairly constant within each elevation interval, the slopes of the curve of accumulation versus elevation ($\bar{c}_t/z$) may differ. Therefore it is necessary that the accumulation measurements cover all the elevation intervals of the glacier. Field conditions prevented soundings on Flatbreen above 1 400 m a.s.l. in 1965, and the shape of the average $\bar{c}_t/z$ curve for the other years was used for the accumulation determinations for the upper 300 m. MEIER (1962, p. 259) states that the balance curves for different years have similar shapes and can usually be superposed by a shift parallel to the balance axis. MEIER and TANGBORN (1965, p. 557) present seven balance curves, six of which could be superposed on the others by addition of a fixed balance value. Similar results have been obtained in the mass balance studies on Norwegian glaciers. That the shape of the balance curves are usually constant, implies that the shape of the accumulation (and ablation) curve is usually constant. Alternatively, the accumulation and ablation could both decrease or increase by equal amounts to change the shape of these curves but not of the balance curve. This will not normally take place, however, since the ablation and accumulation are highly dependent upon each other, especially in the ablation area. Here time of exposure of the ice surface with low albedo (and therefore increased rate of ablation) will vary inversely with the amount of accumulation, so that high accumulation gives low ablation and vice versa. Thus, when no variations exist in the balance curve, the accumulation curve can be expected to be constant. MEIER and TANGBORN's (op. cit.) anomalous balance curve deviates mainly for the lower part of the glacier. This is where the deviation would be most likely on Flatbreen. The shape of the $\bar{c}_t/z$ curve for 1965 does not deviate from the other years for the area below 1 400 m a.s.l., however. Thus it is believed that the errors resulting from extrapolating the $\bar{c}_t/z$ curve to the upper part is within acceptable limits.

The validity of mass balance values obtained by a study such as that on Flatbreen depends mainly upon knowledge of four factors: (1) how close (in time and amount) the winter balance determinations were to the maximum winter balance,

(2) the extent of refreezing of meltwater, (3) the extent of en- and subglacial melting, and (4) winter ablation and summer accumulation when total accumulation and ablation values are wanted. These factors are discussed below.

(1). Flatbreen was frequently visited during the spring, when the start of run-off and thus the summer season was evaluated in the pits. An excellent control on the pit results was further provided by a glacier dammed lake, which emptied every autumn and did not refill until run-off started from the glacier in spring. The measured winter balances are therefore considered to be close to the true values.

(2) and (3). The mass balance measurements on Flatbreen were carried out on a few meter thick surface layer. Thus to obtain the complete balance for the glacier the measured balance must be corrected for any balance changes taking place below the surface layer. Refreezing of meltwater took place, in spring, until the glacier warmed to 0°C. The refreezing in the surface layer, including the formation of superimposed ice, was observed as a density increase and was included in the measured balance. The annual refreezing below the surface layer was between 0.03 and 0.06 m. These values were derived by temperature considerations, as discussed by LIESTØL (1967, p. 13–16), and by comparison with other glaciers in West-Norway.

The annual en- and subglacial ablation was estimated as 0.04 m. This is based on calculations of the frictional heat liberated, as well as assuming a geothermal heat flux of 40 cal cm^{-2} yr^{-1}.

(4). Except for possibly a short autumn period, a strong winter cold wave exists in Flatbreen, preventing run-off from any short-term surface melting. The winter ablation is therefore believed insignificant. This is not the case with the summer accumulation. This was especially large in 1964 (>0.20 m), but it was also significant in 1965 and 1967. However, because the summer balance was observed frequently and for long periods continuously, it is believed that a major part of the summer accumulation was measured. The uncertainties in the summer accumulation affect the precision of the ablation and accumulation values markedly only for 1964.

In addition to the above factors which affect the validity of the field data, the precision of the final mass balance values will depend upon the accuracy of the area determination of the glacier, and the density (in time and space) of the measurements. Because the calving terminus of Flatbreen has had constant position during the period, the only uncertainties in ascertaining the area are in determining the glacier divide. This is well marked by the contours, however, and the probable error in the area determination is below 1 per cent of the total area.

The relation between density of measurements and final precision will vary from glacier to glacier and can only be evaluated approximately. This is because the reduction of the field data to the form of accumulation and ablation maps involves using information about the distribution pattern from other years. The precision of this can only be set by personal judgement and will vary with the extent of personal knowledge. (See e. g. LA CHAPELLE 1962, p. 287). Another important factor, which can only be evaluated after a large number of measurements, is how even the distribution is. There are few changes in slope on Flatbreen, and the distribution variations of accumulation and ablation, compared to most other valley glaciers in Norway, are small. From the above it is clear that different studies may have very different relations between density of measurements and estimated precision. For example SCHYTT (1962, p. 281) gives a precision of 10 per cent with about 120 accumulation measurements per km^2, while WALLÉN (1949, p. 540) gives the same precision with 10 accumulation measurements per km^2.

In Table 2 the estimated standard errors in the mass balance values for the whole glacier are given to the nearest 0.05 m. Annual estimated standard errors vary considerably, mainly due to variations in measurement density, but the extent of summer accumulation, poor sounding conditions, and late measurements of winter balance also affect the errors. The balance values have smaller errors than the accumulation and ablation values for two reasons. Firstly, the uncertainties in the summer accumulation (and to a smaller extent the winter ablation) lower the precision of the accumulation and ablation values, but not the balance. Secondly, the balance was measured at many points on the glacier where the accumulation and ablation were not measured separately. This was the case, for example, when the position of the transient equilibrium was recorded, and when stakes that had been buried at the time of the winter balance measurements, but reappeared later in the summer, were measured. The balance at the end of the summer season was also measured at some places in the accumulation area by digging down to the past year's summer surface. This again improves the precision of the balance values more than that of the ablation and accumulation values.

Table 2

Mean values and estimated standard errors for accumulation, ablation, and net balance on Flatbreen in the years 1963–67. (Ablation by avalanching not included.)

	1964	1965	1966	1967
Accumulation (m)	2.22 ± 0.35	2.34 ± 0.35	1.64 ± 0.10	2.75 ± 0.20
Ablation (m)	-1.41 ± 0.30	-1.65 ± 0.20	-2.31 ± 0.10	-1.38 ± 0.20
Balance (m)	0.81 ± 0.20	0.69 ± 0.20	-0.67 ± 0.10	1.37 ± 0.15

The results for each 100 m in interval for the four years are represented graphically in Figs. 9–12.

Mass balance investigations on Supphellebreen

Supphellebreen extends from about 300 to 60 m a.s.l. The ice avalanches from Flatbreen make field work on Supphellebreen impossible during most of the year. Only during a three-months-long summer period are the avalanches on the glacier not a danger. The infrequency of avalanches during the summer is mainly due to the large summer melting at the calving front of Flatbreen, which, except

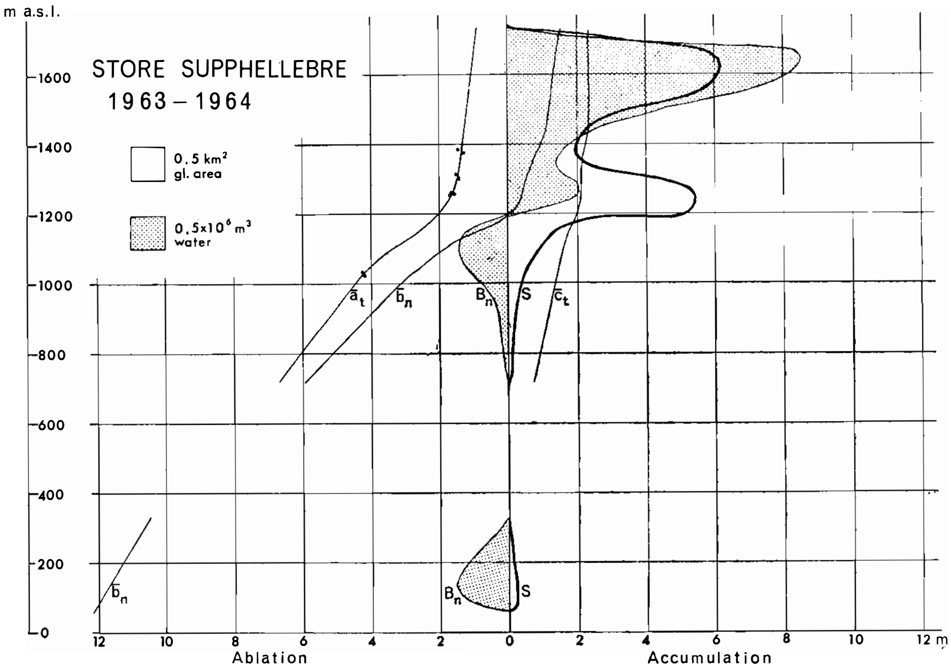

Fig. 9. *Variation with elevation of accumulation, ablation, net balance, and area distribution for Store Supphellebre in 1964.*

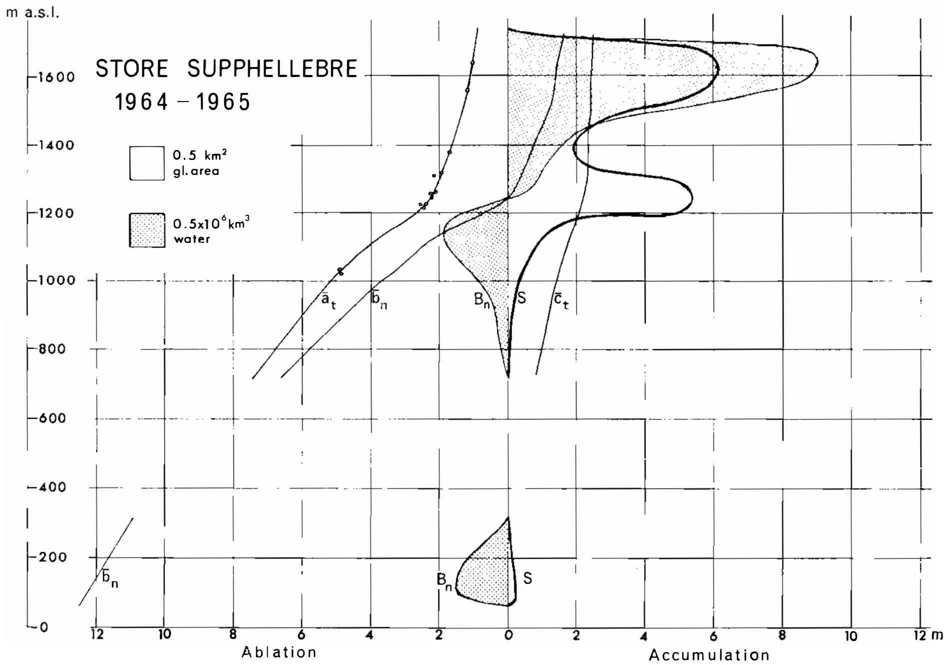

Fig. 10. *Variation with elevation of accumulation, ablation, net balance, and area distribution for Store Supphellebre in 1965.*

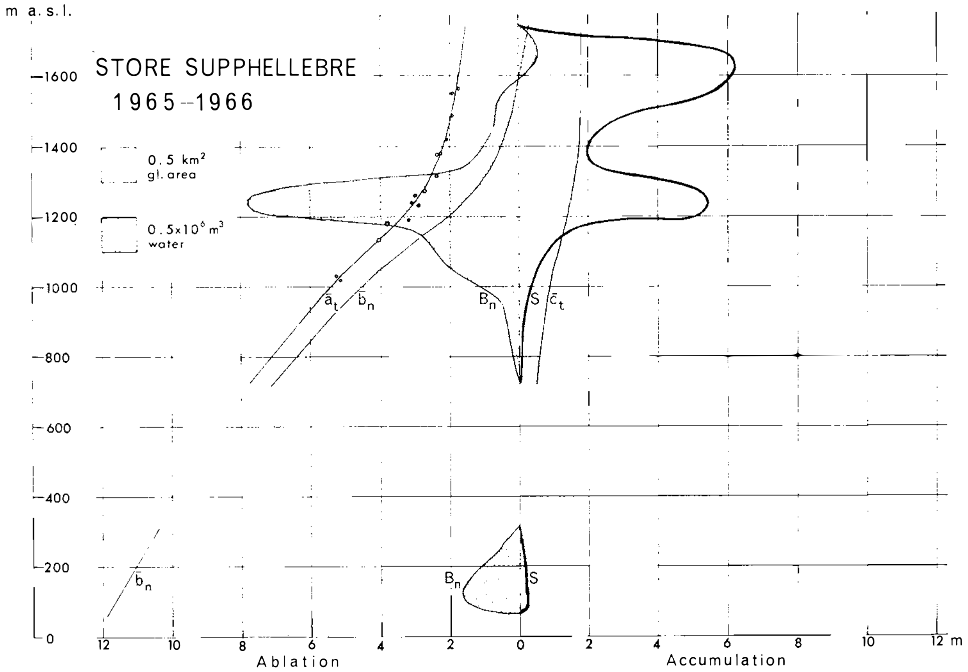

Fig. 11. *Variation with elevation of accumulation, ablation, net balance, and area distribution for Store Supphellebre in 1966.*

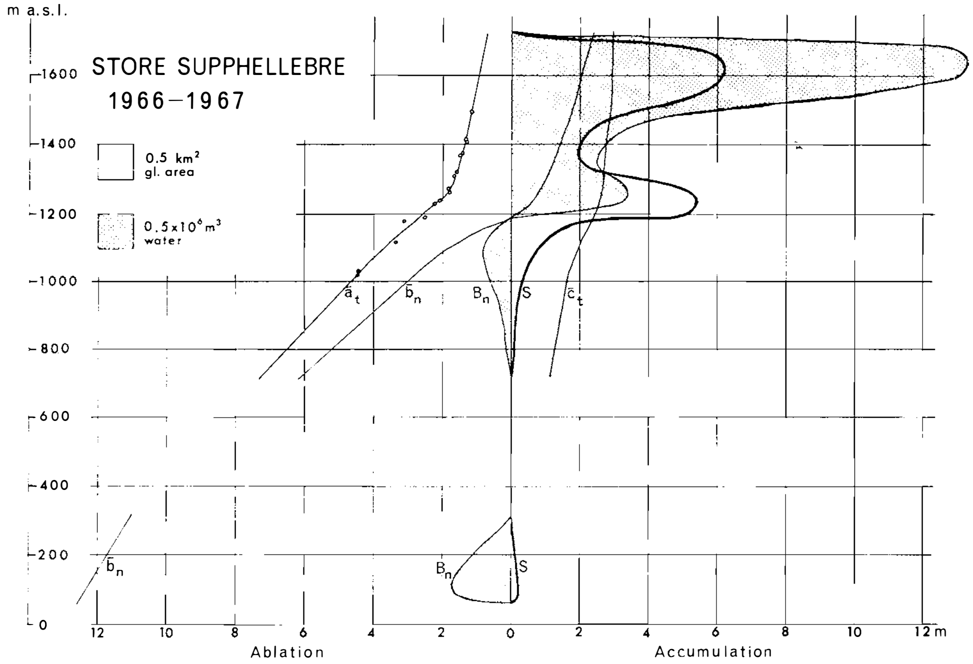

Fig. 12. *Variation with elevation of accumulation, ablation, net balance, and area distribution for Store Supphellebre in 1967.*

for cold periods, is of the same order as the throughflow at the front. Also, the river from Flatbreen opens a deep gully under Supphellebreen in the summer and the occasional avalanches usually follow this gully. The limitations on the field work made techniques different from those used on Flatbreen necessary. Supphellebreen was instead mapped to the scale of 1:2 000 by terrestrial photogrammetry every spring and autumn (in mid-June and in September/October) between 1964 and 1967. Volume changes were determined from successive maps. The areal total accumulation and ablation were determined from the volume changes, meteorological observations and some ablation stake measurements.

MAP PRODUCTION AND DETERMINATION OF VOLUME CHANGES

Mapping by terrestrial photogrammetry is well known, cf. HALLERT (1960). The area to be mapped is photographed stereoscopically from two stations. To find suitable stations can often be difficult, but this presented no problem on Supphellebreen, where excellent locations for the two stations were found on the 1930 moraine (Fig. 20).

The maps were constructed in an Orel-Zeiss Stereoautograph at Norsk Polarinstitutt in 1967. Each stereoimage was fitted to the control points in the horizontal plane. The models for 1966 and 1967 fitted very well, whereas those for 1964 and 1965 showed small scalar deviations.

Fig. 13 shows two of the seven maps constructed. The two control points are shown; the base is off the reproduced map.

Some of the maps contain small areas without contours and with the glacier limits dashed. These are parts which could be seen on only one of the plates. These areas are always very small compared with the total glacier area.

The accuracy of the maps has been evaluated by comparing contoured areas of exposed ground on the different maps. The correspondence is very good. The random human error has been evaluated by repeated drawing of the same contours. It is believed not to exceed 0.5 m, and is considerably less on the average. No systematic error has been detected.

The volume changes of a glacier can be determined from two maps by several techniques. Three which are commonly employed are:

(1) Longitudinal elevation profiles of the glacier in fixed planimetric positions are computed and the changes in the profiles are used to calculate the volume change. This method was not adequate on Supphellebreen, where large variations of glacier area with time make the method difficult to apply, and where the avalanche distribution is so uneven that a limited number of profiles would not give adequate precision to the vertical height changes.

(2) The volume changes are determined by placing transparencies of the maps together and drawing lines through like intersections of the contours (LIESTØL 1962b, p. 197). Areas of known vertical changes are thus determined, and consequently the total volume change. In this method area changes with time are not a problem, but it is not suitable for Supphellebreen because the variations in height between some of the maps were close to one contour (10 m), so that intersections

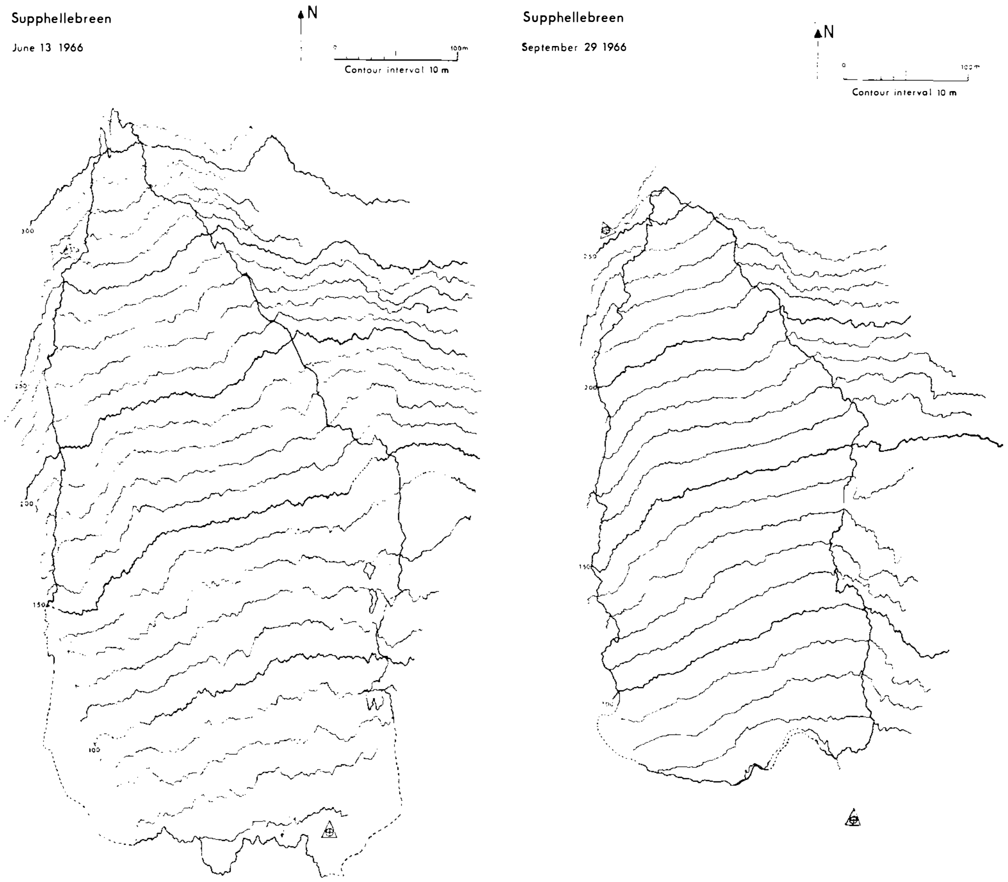

Fig. 13. *Maps of two stages of Supphellebreen in 1966. Original maps, at a scale of 1:2 000, were constructed by terrestrial photogrammetry. Triangles with circles show the two control points for the model; base line is off of the reproduced maps. Areas without contours and with dashed glacier limits are areas that could be seen on only one of the plates. The contours are dashed where shading effects or other difficulties caused uncertainties.*

between the contours were few and an inadequate reproduction of the volume change would be obtained.

(3) The transparencies are placed together and the areas between the same contour on the two maps are measured out to the circumference of the glacier of largest extent (FINSTERWALDER 1954). If the areas determined for two successive contours are F_1 and F_2; the volume change, Δv, between the contours is found from

$$\Delta v = (\Delta F_1 + \Delta F_2)\ \Delta h/2,$$

where Δh is the contour interval.

The total volume change between the two maps, V, is determined as

$$V = \sum \Delta v \qquad \text{(FINSTERWALDER 1954, p. 308).}$$

FINSTERWALDER's method is the best suited of the three described for Supphellebreen, and could be used for determination of the total volume change, V.

It does not allow for determination of the volume changes, Δv, between the contours, since the basic assumption in FINSTERWALDER's method, that the slope changes between the maps are small, does not hold for Supphellebreen, and introduces significant error in the values for Δv. Thus a fourth method was used which gave essentially the same values for V as FINSTERWALDER's, but was more precise for Δv.

Hysographic curves were determined for two successive maps of the same area, i.e., the area formed by the circumference of the glacier of largest extent. These curves were drawn in the same diagram and the area between them was measured (Fig. 14). This then gives V. The same principle was used for the determination of the volume changes between the contours, Δv, by successively constructing hypsographic curves for the same area on the two maps, the boundary now being delimited by the circumference and successive contours of the glacier of largest extent. The area between two such hypsographic curves then becomes the volume change between the contours (Fig. 14).

The final standard error in the determination of the volume changes of the glacier between two successive maps is estimated to be about 3 per cent of the volume change.

DETERMINATION OF ABLATION FROM VOLUME CHANGES

The amounts of snowfall and ice avalanches onto the lower glacier in the periods between the spring and autumn maps are negligible. The volume change is thus due to ablation, and when the density of the melted mass is known, the total ablation can be calculated in water equivalents.

It was not possible to conduct comprehensive density measurements on Supphellebreen because the glacier surface was a heterogeneous ice conglomerate. The surface consisted mostly of powdered ice with a mean density of 0.69 g cm^{-3} and partly of larger ice blocks, up to several cubic meters, with a density close

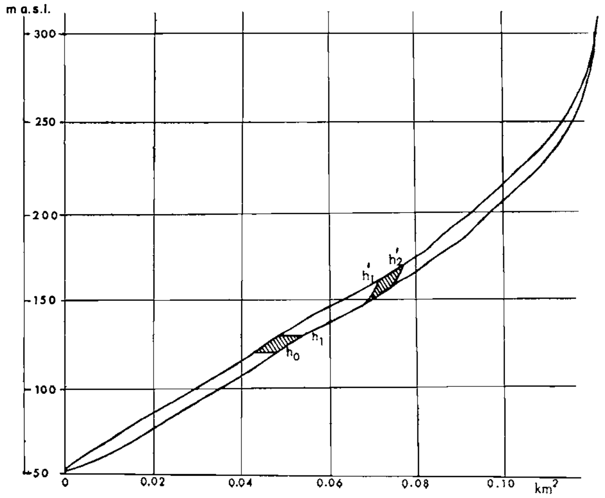

Fig. 14. *Hypsographic curves of Supphellebreen determined from successive maps and drawn on the same diagram. The total area between the curves is the total volume change between the maps, the small shaded elements illustrate the different results obtained from* FINSTERWALDER's *method (between* h_0 *and* h_1*) and the presently used method (between* h'_1 *and* h'_2*) for determining the volume changes of each contour interval.*

to 0.9 g cm^{-3}. The density increased at depth, but it was not possible to dig deep pits. The deepest pit studied was about 1.5 m. From estimation of the ratio of fines to blocks on the surface and from observations in the pits, the density of the melted mass has been set at 0.8 g cm^{-3} with an estimated standard error of ± 0.05 g cm^{-3}. In none of the years were density increases due to compaction detected, nor were any significant density variations observed from year to year. That no settling was observed was probably due to the timing of the spring measurements, as they were conducted in June each year at the time the photographs were taken. Melting takes place before this time and any settling had probably been mainly completed by June.

The errors in the density cause a main part of the error of the total ablation values, since they are larger than the volume errors. For the relative difference between the years the density errors are probably of little significance since the field measurements indicate that the density varies little from year to year.

The ablation for the periods between the spring and autumn maps is given in Table 3.

Table 3

Ablation at Supphellebreen as determined from the maps.

Period	Glacier area in June (km^2)	Areal total ablation, A (10^6 m^3)	Mean ablation, ā (m)
June 7–Sept. 11, 1965	0.121	–0.87	–7.19
June 13–Sept. 28, 1966	0.124	–0.88	–7.12
June 13–Oct. 16, 1967	0.138	–1.24	–8.97

The mean ablation, ā, is determined from the total ablation in the period, A, divided by the glacier area in June. This is not strictly correct, as it attributes the same ablation to the marginal zone, which becomes ice-free during the summer, as to the rest of the glacier. Ablation proceeds for a shorter time in the marginal zone than in the rest of the glacier, however the ablation rate concurrently is higher in the marginal zone. This is partly because this zone has more dirt cover and lower albedo than the central part, and partly because the long-wave radiation and higher air temperatures from the surrounding rock have a larger influence here. These factors (of shorter time and greater ablation rate) seem to cancel out to a large extent so that the ablation in the marginal zone approximates that of the central part. The mean values for different years will be comparable in any case, since the area of this zone represents about the same proportion of the total glacier area each year.

ABLATION DETERMINED BY METEOROLOGICAL OBSERVATIONS

The ablation determined from the maps is not the total annual ablation. The summer season, which is defined for Supphellebreen as the period in which mass loss by ablation exceeds that of mass gain by snowfall, is longer than the avalanche-free period. Melting and avalanching take place concurrently in spring (April–June) and in autumn (October–November). The sum of ablation in these periods is less than the summer ablation, but it is still very important, and must be determined.

In the following, ablation will be considered for air temperatures above 0°C; an expression degree-day is therefore introduced, which is zero for any 24-hour day with mean temperature, T, below 0°C. When T is above zero, the degree-day of the day is equal to the mean temperature. For a period of n days the total degree-days, D, will then be

$$D = \sum_{i=1}^{n} T_i \ , \qquad \begin{array}{l} T_i = T_i \text{ for } T_i > 0°C \\ T_i = 0 \text{ for } T_i \leq 0°C \end{array}$$

The air temperature was measured continuously from July 1964 to December 1966 (with the exception of 3–4 winter months with the temperatures constantly well below 0°C) at a screened thermograph 1.5 m above ground, 100 m from the snout of the glacier. A consistent linear relationship was observed between the ablation in the summer (both for shorter periods as measured by the ablation stakes, and for the whole summer as determined from the maps) and the number of degree-days in the same periods; i.e.

$$a = k \sum_{i=1}^{n} T_i \quad \text{or} \quad a = k \times D$$

The relationship for 1965 and 1966, the two summers for which complete temperature measurements at the glacier exist, is shown in Table 4. The variations in k are so small (6%) that it seems reasonable to consider k constant.

Table 4
The mean ablation per degree-day at Supphellebreen.

Period	$\bar{a}$ (m)	Degree-days, D (°C d)	k (10^{-3} m °C^{-1} d^{-1})
June 7–Sept. 11, 1965	7.19	1 104	6.5
June 13–Sept. 28, 1966	7.12	1 161	6.1

The short-term measurements show essentially the same value for k. Such linear relationship, but with different k, also has been reported by other workers, e.g. LIESTØL (1967, p. 34–36), SCHYTT (1955, p. 46; 1964, p. 277).

If this linear relationship between the degree-days and ablation can be expected to hold true for the spring and autumn periods, the ablation in these periods can be calculated from the temperature measurements. The above relationship is empirical, and it is not obvious *a priori* that it should be true for any climatic conditions. To evaluate its validity for Supphellebreen the heat balance of the glacier surface must be examined.

The heat balance of the glacier surface can be expressed as (SVERDRUP 1935, p. 146):

$$80\ H = \alpha I - R \pm Q_a \pm Q_s \pm 600\ F \qquad (1)$$

where H is the total ablation in cm water,

α is equal to $1 - A$, where A is the albedo,

I is the incoming short-wave radiation,

R is the long-wave radiation balance (outgoing – incoming),

Q_a is the heat flux by conduction and convection to/from the air,

Q_s is the heat flux by conduction and convection to/from the subsurface ice, and

F is the condensed or evaporated water in grams.

Heat flux to the surface is considered positive.

In addition to the factors in Eq. (1) there can also be heat flux by rain. This is negligible on Supphellebreen, because the amount of precipitation in the summer is of the order of 500 mm; at a mean temperature of 10°C (which is considered an upper limit for the average temperature of the rain) this would only cause melting of 0.06 m of ice.

Equation (1) can be simplified for Supphellebreen in the summer season without significant loss of precision. The glacier can be considered isothermal at 0°C and Q_s can be ignored. The ablation in periods of air temperature below 0°C is negligible. Occurrences of positive heat flux are rare in the periods of negative air temperatures; in those periods the insolation at the glacier is small because the surrounding mountains shade the glacier at low solar elevations. Thus Q_a is only considered for periods with air temperature above 0°C; Q_a is then always positive. Similarly, because of high relative humidity, the air water vapour pressure will be normally greater than that of the ice in the periods of air temperature greater than 0°C; F is then generally positive.

Q_a can for present purposes be considered proportional to the temperature gradient with height. In the summer season the ice surface is at constant temperature, thus Q_a will be proportional to the air temperature at a given level. Because Supphellebreen is in an area of maritime climate, with near constant high relative humidity in the summer season, it can be expected that the amount of water vapour in the air is approximately proportional to the air temperature. Furthermore, from other heat flux studies on Scandinavian glaciers (WALLÉN 1949, LIESTØL 1967) it is known that the latent heat flux is less important than the sensible heat flux. The sum of the sensible and latent heat fluxes can therefore be considered as approximately proportional to the air temperature, and Eq. (1) can be rewritten as:

$$80\ H = \alpha I - R + KT \qquad (2)$$

where K is a proportionality constant.

T is the temperature at the thermograph level.

The expression for the radiative heat flux, and in particular αI, is not directly related to the air temperature. Thus the right hand side of Eq. (2) will be more

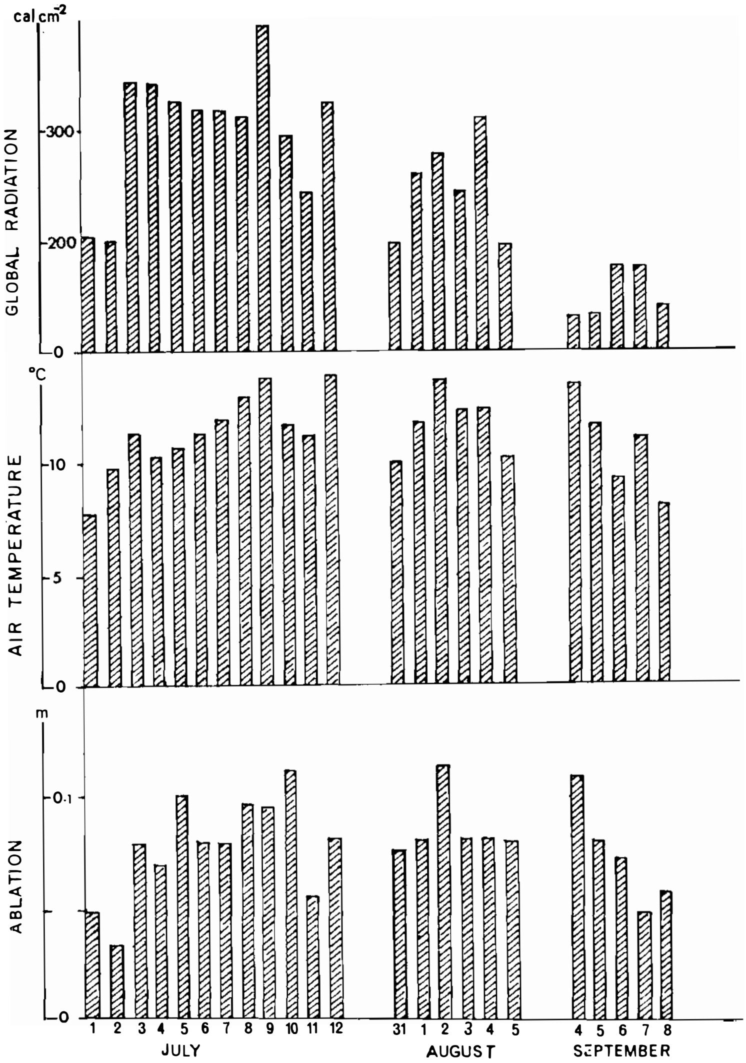

Fig. 15. *Daily incoming short-wave radiation, mean daily air temperature at screen level, and daily ablation measured by stakes at Supphellebreen for three selected summer periods of 1965.*

linearly related to air temperature the smaller the relative importance of $\alpha I - R$ compared with KT.

A Robitzsch bimetallic actinograph was placed near the glacier, in 1965, to investigate the importance of the radiative flux. The instrument recorded the incoming radiation of wavelengths between 0.36 and 2.0 μ, i. e. practically all the short-wave global radiation, I. The instrument was calibrated shortly before it was taken into the field, and as the value of the night-time (zero) line did not show any variations during the summer, I was determined with adequate accuracy. Concurrently with the radiation measurements, the daily ablation at Supphellebreen was measured at four wooden stakes at 70 m a.s.l., and the air temperature was recorded on the thermograph. This was at 55 m a.s.l., the same elevation as the actinograph, but slightly further from the glacier. (Fig. 20.)

Daily variations in ablation, air temperature, and incoming short-wave radiation are given in Fig. 15. It is apparent that the incoming radiation is of less importance to the ablation than the air temperature. This is further demonstrated by the following considerations.

In Eq. (2) the heat transfer to the surface is known from measurements of the vertical ablation, H. (The well-known difficulties caused by density changes in relating surface lowering to true ablation for short periods and small amounts of ablation (see e.g. MÜLLER and KEELER 1969) do not introduce significant errors because the daily ablation is large). Thus if the radiative heat flux can be evaluated, its contribution to the ablation can be determined.

It was not feasible to measure the albedo of the surface of Supphellebreen. However, since numerous studies are in fair agreement of the albedo of snow and ice, it seems reasonable to make use of published values. For the periods in question the following values have been accepted.

Period	Albedo (A)
July 1–12	0.5
July 31–August 5	0.35
September 4–8	0.2

The long-wave radiation balance must next be calculated. This has previously been done in Scandinavia for Kårsaglaciären (WALLÉN 1949) and for Storbreen (LIESTØL 1967). Calculations from their data give a mean daily balance of –79 cal cm^{-2} (80 days), and –53 cm^{-2} (65 days) respectively. The long-wave radiation balance is probably less negative for Supphellebreen than for these glaciers, which are both at higher elevations and are more freely exposed than Supphellebreen. However, it is unlikely that it would be positive over periods of months.

In Table 5, R is chosen as 0 to give a maximum reasonable value for the expression $\alpha I - R$. The importance of the radiative heat flux in the total ablation can now be estimated.

Table 5

The share of the radiation flux in the total heat flux at Supphellebreen.

Period (in 1965)	α (1–A)	I (cal cm^{-2})	αI (cal cm^{-2})	H (cm)	80 H (cal cm^{-2})	αI/80 H (%)
July 1–12	0.5	4 820	2 410	93.7	7 496	32
July 31–Aug. 5	0.65	1 720	1.118	53.1	4 248	26
Sept. 4–8	0.8	410	408	36.9	2 952	14

The values are approximate, but unreasonable values of A and R must be chosen to make large changes in the result. If the long-wave radiation balance, for example, was changed to – 40 cal cm^{-2} d^{-1}, the percentage values for $\alpha I - R$ for the three periods would decrease by 6 to 7 per cent, and if the albedo for each of the periods was reduced by 0.1 the percentages would increase by 7, 4 and 2 per cent respectively. Most likely the percentage values are too high rather than too low. The contribution of the radiation flux to the total heat flux is much smaller than for previously measured glaciers in Scandinavia: Kårsaglaciären, 59% (Wallén 1949, p. 631); Storbreen, 56% (Liestøl 1967, p. 21). That the contribution of the radiation flux is small, increases the theoretical justification for the observed linear relationship between ablation and air temperature above 0°C. As expected, the contribution of the radiation flux decreases during the summer. Because the value of the proportionality factor in the relationship between ablation and air temperature probably would vary as the contribution by radiative heat flux varied, the proportionality factor may not be the same for the spring and autumn periods, and not equal to that determined for the summer period. However, it is the sum of the ablation in these periods each year which is required, and because the decrease in contribution of radiation flux during the summer season is regular, the deviations from the determined proportionality constant can be expected to cancel out. The ablation for the spring and autumn periods is thus determined as

$$\bar{a} = D \times 6.3 \times 10^{-3}\,\mathrm{m}, \qquad (3)$$

where D is the number of degree-days as before,

The constant is the mean of the proportionality factors determined for 1965 and 1966.

No temperature records exist at Supphellebreen for the first part of the 1964 summer season or for 1967. However, regular measurements are made at the meteorological station at Skarestad, 4 km downvalley at about 10 m a.s.l. Fig. 16 shows that the correlation between air temperature at Skarestad and at Supphellebreen is very good for the summer season. For the above-mentioned periods the number of degree-days have therefore been determined from the temperature measurements at Skarestad using a correction factor, varying during the summer, determined from the meteorological observations at both stations. The ablation in these periods is then determined from Eq. (3) as before. For 1964 the whole ablation is calculated from the temperature data. For the other years only the spring and autumn ablation is calculated this way.

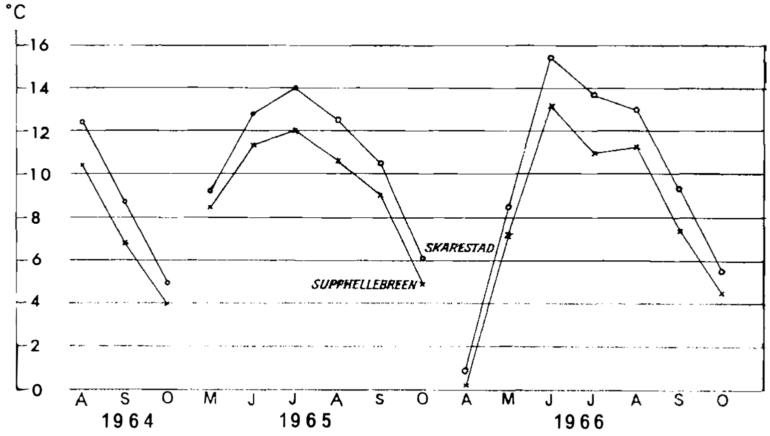

Fig. 16. *Comparison of monthly mean air temperatures at Skarestad at the mouth of the Supphelle valley (upper curves), with those at Supphellebreen (lower curves).*

Table 6

Mass balance for Store Supphellebre, Flatbreen, and Supphellebreen from 1964 to 1967.

Bal-ance Year	Store Supphellebre							Flatbreen							Supphellebreen						
	Area	Accumulation		Ablation		Balance		Area	Accumulation		Ablation		Balance		Area	Accumulation		Ablation		Balance	
	S (km^2)	C_t (10^6m^3)	$\bar{c}_t$ (m)	A_t (10^6m^3)	$\bar{a}_t$ (m)	B_n (10^6m^3)	$\bar{b}_n$ (m)	S (km^2)	C_t (10^6m^3)	$\bar{c}_t$ (m)	A_t (10^6m^3)	$\bar{a}_t$ (m)	B_n (10^6m^3)	$\bar{b}_n$ (m)	S (km^2)	C_t (10^6m^3)	$\bar{c}_t$ (m)	A_t (10^6m^3)	$\bar{a}_t$ (m)	B_n (10^6m^3)	$\bar{b}_n$ (m)
1964	11.967	26.27	2.20	-17.90	-1.50	8.37	0.70	11.852	26.27	2.22					0.115			-1.22	-10.65		
1965	11.973	27.72	2.32	-21.02	-1.76	6.70	0.56	11.852	27.72	2.34	-21.15	-1.79	6.57	0.55	0.121	1.62	13.39	-1.49	-12.32	0.13	1.07
1966	11.976	19.47	1.63	-28.74	-2.40	-9.27	-0.77	11.852	19.47	1.64	-28.62	-2.41	-9.15	-0.77	0.124	1.29	10.44	-1.41	-11.37	-0.12	-0.93
1967	11.990	32.58	2.72	-18.04	-1.50	14.54	1.22	11.852	32.58	2.75	-18.34	-1.55	14.24	1.20	0.138	1.97	14.26	-1.67	-12.08	0.30	2.18

DETERMINATION OF THE ACCUMULATION

The accumulation on Supphellebreen is determined in the same manner as the ablation. The volume changes between the autumn and the spring maps are determined by the hypsographic method described above. This volume change is the difference between total accumulation and the ablation in the period between the maps; the ablation in each period is calculated from the number of degree-days in the period and Eq. (3). This is then added to the volume change to give total accumulation. As no stereo-photographs were taken in autumn 1963, the accumulation during the 1963–1964 winter cannot be determined.

Table 6 shows the total accumulation, ablation, and net balance for Supphellebreen for the four years.

Mass balance of Store Supphellebre

The avalanche mass from Flatbreen to Supphellebreen does not enter into the mass balance values for the two combined, because this mass does not leave the system. To determine the mass balance for Store Supphellebre the surface mass balance for Flatbreen (i.e. the mass balance without the avalanches) must be determined, and the mass balance of Supphellebreen apart from the avalanches. The surface mass balance of Flatbreen is known. The ablation for Supphellebreen is known, but not the accumulation apart from the avalanches, i.e. the winter snowfall. Because this cannot be separated from the avalanches, it cannot be measured. In front of the glacier the winter snowfall totals about 0.25–0.5 m yr^{-1}; it is likely to be larger on Supphellebreen because of snow accumulation by avalanches from the mountainsides in spring, but it probably does not exceed 1 m yr^{-1}.

Any avalanche mass that leaves the system is an ablation loss, and must be included. This applies to the occasional summer avalanches after the gully has formed under Supphellebreen. Again the amount cannot be measured, but it is unlikely to exceed 10 per cent of the yearly avalanche total. Such an amount would correspond to about 1 m (of water) evenly distributed over Supphellebreen. Because these two unknowns, the winter snowfall and the avalanche mass lost, are probably of similar magnitude and have opposite effects, they have been discounted. No large errors in the mass balance of Store Supphellebre can result from this; an error of 1 m in the mass balance values of Supphellebreen will introduce an error of only 1 per cent in the mass balance values of Store Supphellebre.

Figs. 9—12 represent graphically the mass balance of Store Supphellebre, the balance (i.e. the ablation) of Supphellebreen is shown, with the slope of the line based on the slope determined in 1965. Knowing the avalanche mass from Flatbreen, the complete mass balance of Flatbreen can also be calculated. The mass balance of Store Supphellebre, Flatbreen and Supphellebreen are shown in Table 6. The final errors in the determination of ablation and avalanche mass for Supphellebreen are estimated to be 10 per cent. This increases the error in the mass balance values for Store Supphellebre by 1 per cent, and the error in the ablation of Flatbreen by the same amount. This increase in errors is so small that the much larger, estimated standard errors for the surface mass balance of Flatbreen, given in Table 2, can be considered as the estimated standard errors in the mass balance of Store Supphellebre and Flatbreen in Table 6. The estimated standard errors in the mass balance of Supphellebreen are (as stated above) 10 per cent.

MASS BALANCE OF STORE SUPPHELLEBRE IN AN EQUILIBRIUM YEAR

Inspection of the balance diagrams for Flatbreen (upper part of Figs. 9—12) reveal that the shapes of the balance curves do not show large variations from year to year, and as discussed earlier the curves can be approximately superposed by shifting them parallel to the balance axis (i.e. "horizontally"). This means that the conditions between the years vary so that the balance changes by an amount which is constant with height. This effect can be used to determine the balance curve for Store Supphellebre in an equilibrium year. Based on the four years of studies the average surface mass balance curve for Flatbreen, $<b_n>$, is determined. This curve is then shifted parallel to the balance axis so that the balance becomes positive and equal to the mean balance (avalanches not included) on Supphellebreen in the four years. This balance curve, Fig. 17, is then the balance curve for Store Supphellebre in an equilibrium year, with the size of Supphellebreen equal to its average dimension of the four years.

The mean equilibrium line is the elevation at which the balance is zero, 1 350 m a.s.l.

A form of "normal" values for the accumulation and ablation can be determined

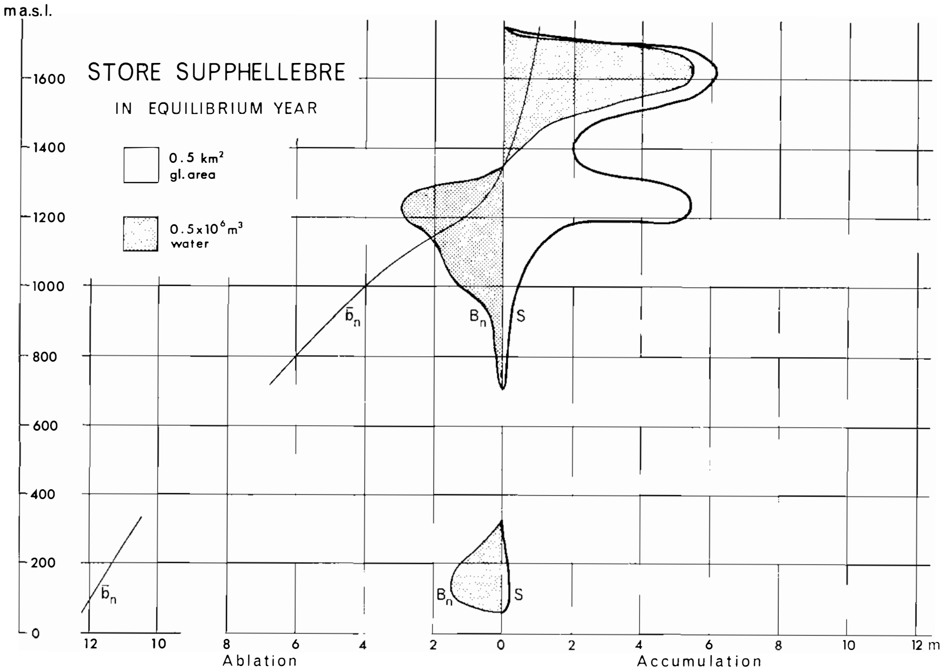

Fig. 17. *Variation with elevation of net balance for Store Supphellebre in an equilibrium year.*

if the assumption is made that the deviations from equilibrium in the four years result equally from deviation in the accumulation as in the ablation. The mean of the absolute values of the accumulation and ablation in the four years is determined. For Store Supphellebre this is 2.01 m, and is considered to be the value of accumulation and ablation in a "normal" equilibrium year. The values for the surface mass balance of Flatbreen are: accumulation 2.03 m (the increase in specific value is due to the smaller area of Flatbreen compared with Store Supphellebre), ablation 1.89 m. The ablation at Supphellebreen is equal to 0.12 m evenly distributed over Store Supphellebre.

An interesting comparison can be made between the variations in the accumulation values determined for Flatbreen, and the variations from a meteorological normal (for the period 1901–1930) calculated by The Norwegian Meteorological Institute which publishes maps of the variations in snow accumulation for all of Norway. The maps are based on the precipitation observations at the permanent meteorological stations, and are calculated using a model such that the proportional variations in the amount of precipitation in an area follow that of the nearby meteorological stations (usually groups of four or five stations are used for each area), and that the amount of precipitation that falls as snow can be calculated from the temperature observations and a chosen lapse rate. Maps of snow accumulation as percentages of normal for elevations in 400 m intervals up to 1 200 m a.s.l. are published for the last days of the months January to April. In addition, values for the variations in snow accumulation of an area are calculated on request for the elevations 1 600 and 2 000 m a.s.l., for the whole winter season.

The mean of the values from 1 200 m from the map of April 30, and 1 600 m a.s.l. for the whole winter season, ought to compare closely with the variations in the winter balance for Flatbreen, because the main part of the glacier is between 1 200 and 1 600 m a.s.l., and because April 30 is close to the end of the winter season at 1 200 m a.s.l. The small summer accumulation has been subtracted from the total accumulation to give the winter balance and the percentage variations of the winter balance from the "normal" value of 2.03 m have been computed. The values for 1 200 and 1 600 m a.s.l. have been determined by A. JAKHELLN (personal communication) and the means of these are given in Table 7. For 1967 only the values for 1 200 are available, and these (as well as those for previous years for comparison), are therefore given.

Table 7

Percentage variations in snow accumulation determined by meteorological calculations and determined from this mass balance study.

	1964	1965	1966	1967
Map for 1 200 m a.s.l.	90%	108%	63%	122%
Mean of maps for 1 200 and 1 600 m a.s.l.	96%	110%	81%	—
Mass balance study	99%	110%	81%	135%

The very good correspondence indicates that both procedures are valid, and that the "normal" value calculated from the mass balance study is possibly close to the long-term meteorological normal.

Fig. 18 shows that for the four years a linear relationship exists between the mass balance measured at the three stakes at 1 260 m a.s.l. and the mass balance of Store Supphellebre. More than four years of measurements are necessary to ascertain whether this linear relationship is of general validity for Store Supphellebre. The stakes are in an elevation interval that represents a quarter of the total area, however, and they will probably never be completely unrepresentative of the mass balance of Store Supphellebre. As the stakes are situated near the equilibrium line, they can be expected to survive for many years with little attention (they are about 3–4 m into the glacier) and can thus be used as indicators of the mass balance when the mass balance investigations are reduced in scope.

Special investigations on Supphellebreen

ABLATION, EMERGENCE VELOCITY, AND GLACIER THICKNESS

The surface volume change, Δv, has been determined for each contour interval from the maps of Supphellebreen for 1965, by the hypsographic method described earlier. From the volume change the surface lowering has been calculated by dividing the volume by the area of each contour interval measured in June. The

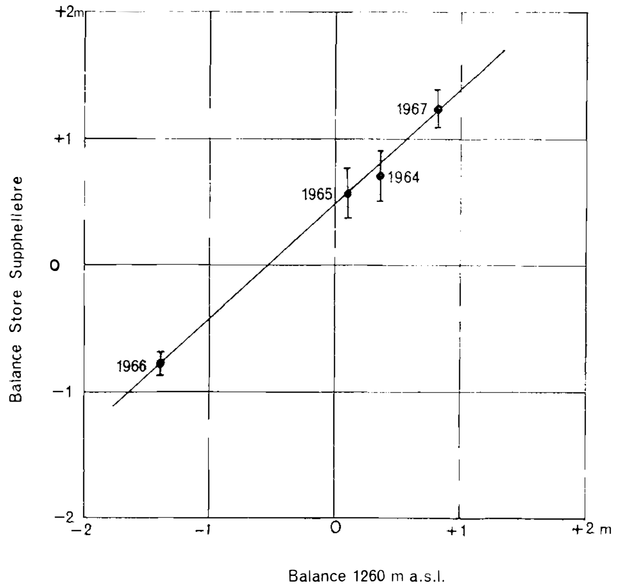

Fig. 18. *Relation, for the four years, between net balance measured for Store Supphellebre, and net balance measured at the stakes at elevations of 1 260 m a.s.l. The vertical lines at each point equal the estimated standard errors in the balance values for Store Supphellebre.*

variation with elevation of the measured volume change and the surface lowering, and also the calculated values of ablation, are given in Fig. 19. The values for ablation are calculated on the assumption that the ablation decreases linearly with elevation. This is an assumption which on most glaciers is not fulfilled, mainly owing to variations in albedo, slope, and wind strength with elevation. However, at Supphellebreen the glacier surface is of uniform consistency, and no systematic variations of albedo with elevation are apparent, the slope is constant with elevation, and the glacier is so small that the wind conditions are not expected to vary with elevation. The assumption is therefore believed reasonable. Ablation at the centre of gravity of the glacier area is then equal to the mean ablation for the glacier. This ablation was 7.19 m in the period between the maps, and the elevation of the centre of gravity was 145 m a.s.l. In the same period the ablation was measured at four stakes (that showed high internal consistency) at 70 m a.s.l., the average ablation was 7.67 m. The straight line in Fig. 19 is drawn using these two sets of values. (The ablation curve is theoretical below 70 m a.s.l., since this part of the glacier became ice-free during the summer.) The total ablation of each contour interval is determined by multiplying the specific ablation with the area in June of each interval.

The difference between the ablation and the surface lowering curve (Fig. 19) is the emergence velocity of the glacier. Since the ablation is uncertain, only the order of magnitude of the emergence velocity can be determined from the curves; it varies from $+2$ m yr^{-1} at 75 m a.s.l. to —6 m yr^{-1} at 285 m a.s.l. The emergence velocity seems to decrease towards the head of the glacier. The surface lowering curve is unreliable here, however, as the volume changes are here so small as to be of the same order as the working precision in the determination of the volume changes.

The ice discharge through any cross-section of the glacier can be calculated

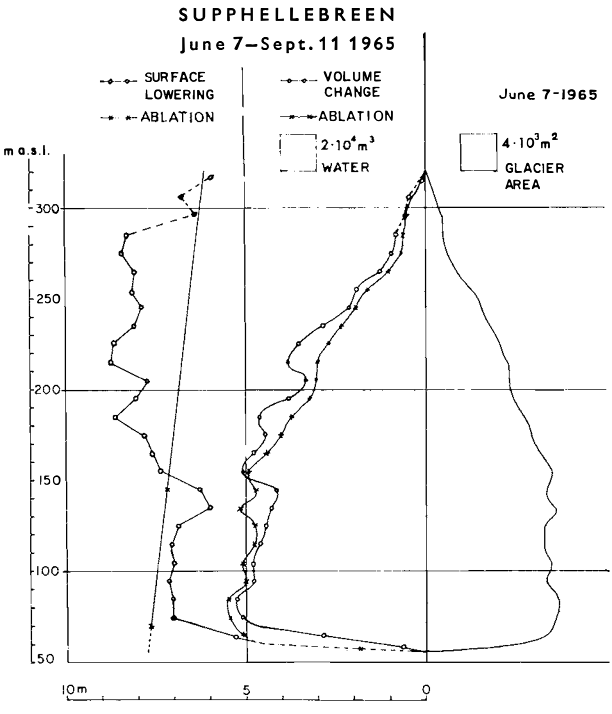

Fig. 19. *Variation with elevation of surface lowering, and volume change from June 7 to September 11, 1965, as determined from the maps, and of specific and total ablation in the same period as determined from ablation studies. The area distribution curve for Supphellebreen in June 7, 1965, is shown. The difference between the ablation and the surface lowering curves show the emergence velocity of the glacier.*

from the emergence velocities, and if the average (over both depth and width) of the cross-section velocity is known, the mean thickness of the glacier can be determined. The uncertainties in the ablation values (and in mean velocity) prevent detailed thickness analysis. However, the order of magnitude of the glacier thickness at the equilibrium line has been determined. The difference between the volume change measured on the maps and the ablation is determined for the glacier above and below the equilibrium line (150 m a.s.l., the elevation at which the emergence velocity is zero), as 6.4×10^6 m^3 and 6.0×10^6 m^3 respectively. Because any changes in density due to settling are believed small, the volumes should be approximately equal, and the difference is probably mainly due to working imprecisions in the planimetry. The mean, 6.2×10^6 m^3, is taken as the throughflow under the equilibrium line. No velocity measurements exist exactly at the equilibrium line, and none at depth anywhere in the glacier, but three velocity measurements (for periods from 2 months to one year) exist at elevations between 70 and 90 m a.s.l. These show values from 0.01 m d^{-1} to 0.05 m d^{-1}; from these, and knowledge of the velocity distribution with depth at similar glaciers (in particular Vesl-Skautbreen, McCall 1960), the mean cross-sectional velocity at the equilibrium line has been taken as 0.06 m d^{-1}. (More sophisticated analysis is unwarranted since the value for the throughflow is approximate.) Using a mean ice density of 0.9 g cm^{-3} the cross-sectional area is determined as 10^6 m^2. The glacier width at the equilibrium line is 270 m; thus the mean ice thickness at the equilibrium line is 4×10 m. Assuming a channel profile that is a continuation of the mountainsides flattened out at the bottom, the maximum depth is about 7×10 m.

CHANGE IN DIMENSIONS OF SUPPHELLEBREEN IN HISTORIC TIME

Access to Supphellebreen is easy and it has been visited frequently since the middle of the last century. As a result, an unusual number of photographs of the glacier are available. (A selection of these, covering every decade from the 1860's to the 1960's, with the exception of the 1870's, is given in ORHEIM, unpublished). These photographs, in conjunction with observations on the moraine system in front of Supphellebreen, have been used to reconstruct the former dimensions of the glacier. The elevation of characteristic morphologic features that were recognizable both in the photographs and in the 1: 50 000 map (contour interval 20 m) of the area (constructed in 1967), were determined from the map. From this the elevation of the head of the glacier was determined for the years 1868 (the alleged 1868 photograph may have been taken in 1869), 1899, and 1930, with an estimated error in the absolute values of ±20—30 m, in the relative elevation differences between the different years of ±10—20 m. The position of the terminus of the glacier could not be determined from the photographs; in 1868 it is not shown, and in those for 1899 and 1930 there are no recognizable morphologic features to assist in position determinations. The position has instead been determined from the moraines. In Fig. 20 the centreline of the glacier has been drawn, and along this line the positions of the moraines have been precisely determined. Of the moraines shown, the positions of the moraines for 1930 and c. 1750 are accurate because they can be located on the 1967 map. The positions of the other moraines have been measured along the line to about ± 20 m. The data of the 1930 moraine is accurate to within one year. The date of the outer moraine is approximate, but that the greatest extent of Supphellebreen in historic time was near the middle of the 18th century, is known from the records of the farms in the Supphelle valley. REKSTAD's observations in 1899 (REKSTAD 1902, p. 13), when he stood at the glacier edge and measured the distances to the moraines in front of the glacier, show that the glacier front in 1899 was near the position of the moraine marked "1910 (?)" in Fig. 20. The glacier extent in 1868 is not known for certain, but comparison with FÆGRI's observations (FÆGRI 1933, p. 16 and 55) from Nigardsbreen (another outlet glacier from Jostedalsbreen), strongly indicate that the large moraine marked "1850, 1870" in Fig. 20 shows the glacier position in about 1870, the same year that a large moraine was formed by Nigardsbreen. Thus as near as possible the glacier position in 1868 is determined.

The other dates in Fig. 20 are based on comparison with the moraines of Nigardsbreen, and are approximate. The dashed lines indicating the glacier margins at the various times are also approximate; they are based partly on photographs, and partly on the marginal moraines. The latter become difficult to distinguish towards the head of the glacier, and are only approximately located.

The reconstructed centre-line profiles for the glacier in 1750, 1868, 1899, and 1930 are shown in Fig. 21, the central parts of the profiles are determined from the photographs and are approximate. Also shown are the profiles in 1965 based on the terrestrial-photogrammetry maps. The thinning of the glacier is seen to be especially large between 1930 and 1965. From the measurements of the posi-

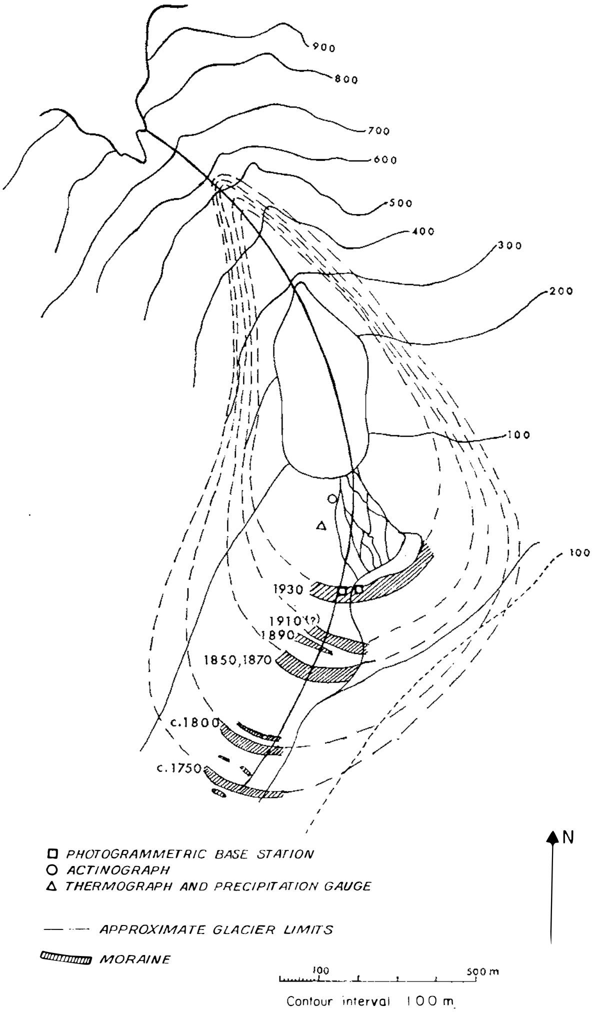

Fig. 20. *Map of Supphellebreen area (based on the 1 : 50 000 map constructed in 1967) showing locations of photogrammetric stations, actinograph, thermograph, and precipitation gauge. Moraines accurately determined are shaded; where approximate they are dashed. The dashed lines also mark the approximate glacier limits at the various times indicated by the dates on the moraines. The 100 m a.s.l. contour on the east side is based on older and less accurate maps of the district and is approximate.*

tion of the snout, which were discontinued in 1960, and the present study, the glacier is known to have had its smallest extent since 1750 between 1960 and 1963. All photographs and measurements show that the snout of Flatbreen has had a constant elevation of about 720 m a.s.l. To join Flatbreen in 1750, Supphellebreen must have reached to this elevation, but it is clear (see the estimated 1750-profile, Fig. 21) that the glacier cannot have been joined with Flatbreen without extending considerably further downvalley. Supphellebreen has thus been a regenerated glacier throughout historic time.

THE RESPONSE OF SUPPHELLEBREEN TO CHANGES IN THE MASS BALANCE OF FLATBREEN

General climatic considerations suggest that the longer the summer season, the smaller the proportional variations in the summer ablation because the likelihood of consistent deviations in meteorological parameters (of which air temperature

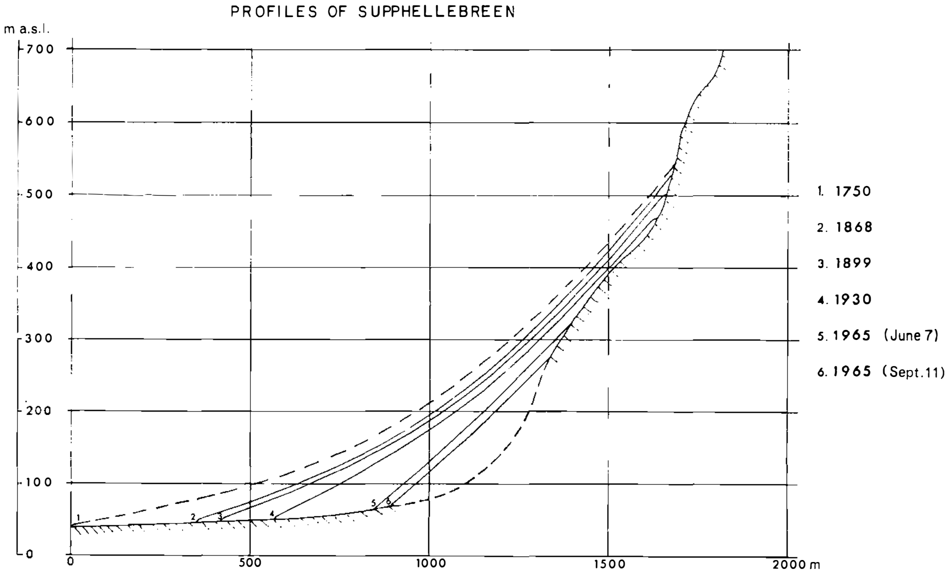

Fig. 21. *Profiles of Supphellebreen at various times during the past two hundred years. Profiles are based on photographs and moraines*; *the profile of 1750 is tentative. Vertical exaggeration 2 ×.*

is the most important) becomes less with increased length of the time interval. The above considerations are borne out by comparison of the results from Supphellebreen and Flatbreen (Table 2 and 7); the proportional variations in the ablation, $\bar{a}_t$, are much larger for the latter (with summer seasons of about 4 months) than for the former (summer season about 7 months). The variations in the mass balance of Supphellebreen can thus be expected to depend mainly on variations in accumulation, i.e. in the avalanche mass from Flatbreen, as Table 7 confirms for 1964—1967. Since Supphellebreen is only 1 per cent of the area of Flatbreen, changes in the mass balance of Supphellebreen become very sensitive indicators of variations in the throughflow at the snout of Flatbreen caused by changes in its mass balance.

The time taken for a change in the mass balance at Flatbreen to be expressed as a change in throughflow at the calving snout can be evaluated in three ways: (1) by theoretical considerations, (2) by comparison of the variations in the values for throughflow and the mass balance of Flatbreen, and (3) by comparison with Briksdalsbreen, a similar glacier for which the time lag has been determined.

(1) Theoretical evaluations of the response time.

Theoretical considerations of the response of a glacier to changes in mass balance, Nye (1960, 1963a, 1963b) indicate that changes in the mass balance are propagated downglacier as a kinematic wave with a speed of about $4u_s$, where u_s is the surface velocity. (The same order of speeds for the kinematic wave was deduced by Weertman (1958).) Without diffusion this traveling wave would cause an unstable increase in glacier thickness in the area of compressive strain. Diffusion dampens the wave and prevents short-period changes from reaching the snout of the glacier in the form of a wave. In Nye's model the upper half of the glacier is considered to be under extending strain, the lower half under compressing strain. Nye designates these to correspond to the accumulation and ablation areas respectively. The time taken for the maximum change in throughflow as a result of a single pulsatory change in mass balance (as for example from adding a constant mass to the whole glacier) to reach the snout is the time taken for the kinematic wave to move to the snout from this half-way point of the glacier, where the strain and the mass balance change sign (Nye 1963a, p. 448). Supphellebreen does not fit Nye's simple model, because the strain and the mass balance do not change sign at the same location. Furthermore the strain and the velocity conditions are highly complicated and deviate markedly from Nye's model in the ablation area because of the icefall and the calving snout. No strain measurements exist for Flatbreen, and the model cannot be adjusted to fit the conditions on it.

However, the order of magnitude of the time lapses between changes in the mass balance, expressed as changes in the throughflow at the snout, can probably be determined. This is done in the following two cases, by (a) taking the starting point of the kinematic wave as the point at which the strain becomes compressive, and (b) taking the starting point at the equilibrium line in the years 1964 and 1965.

(a) From the crevasse distribution the strain becomes compressive below about 1 320 m a.s.l. (The strain seems to be of varying sign below 1 200 m a.s.l. At the top of the icefall (1 000 m a.s.l.) it is probably strongly extensive.) The mean surface flowrate below 1 320 m a.s.l. (averaged over the glacier length) is about 200 m yr^{-1}. (Measured velocity ranges from a minimum of 40 m yr^{-1} at 1 260 m a.s.l. to 400 m yr^{-1} at 1 000 m a.s.l.; insufficient data are available for the heavily crevassed areas to permit exact calculation of the mean velocity.) The distance from the snout to the start of the compressive zone is 3.4 km. A kinematic wave of velocity 800 m yr^{-1} would thus travel this distance in 4 years.

(b) The equilibrium line in 1964 and 1965 (these being the two years within the period 1964—1967 when conditions seem to have affected the throughflow at the calving snout) was about 1 200 m a.s.l. A kinematic wave resulting from these two positive years would travel the 1.7 km to the snout in about 2 years. (The mean velocity for this section of the glacier is taken as 250 m yr^{-1}.)

Diffusion may prevent the kinematic wave from reaching the snout, and this must be evaluated for the two cases. Again, the deviations between Nye's model and the actual conditions make any conclusion tentative. The average "penetration distance" (metres) of the kinematic wave is approximately (Nye 1960, p. 579):

$$0.5\, u_s^2 \tan\alpha\, \tau/h_0,$$

where u_s is the surface flow rate (m yr^{-1})
α is the surface slope
τ is the period of the change in mass balance, (yr)
h_0 is the glacier thickness (m).

For the glacier below 1 320 m a.s.l., (a), tan α equals 0.2. The mean ice thickness is estimated as 50 m. For a cycle of one positive and one negative year, the kinematic wave would be attenuated over 300 m. For a cycle of two positive and two negative years, the kinematic wave would reach about 1 200 m downglacier before attenuation.

For the region below 1 200 m a.s.l., (b), tan α is 0.3, the ice thickness is taken as 50 m. For the first cycle, the kinematic wave would travel about 800 m; for the second about 3 000 m.

The above calculations indicate that the effect of two positive years may well be expressed by an increased throughflow at the snout, while it seems less likely that the throughflow at the snout should be affected by the kinematic wave from a single year of positive or negative mass balance. Nevertheless, the limitations of the model must be remembered. Also of importance is the fact that the diffusion will only affect the travelling wave when the changes in throughflow cause slope changes large enough to affect the shear stresses throughout the thickness of the glacier (NYE 1960, p. 579). Any smaller changes in the throughflow will move as kinematic waves without attenuation, and will be able to affect the measured throughflow at the snout.

(2) Comparison between the variations in the throughflow at the snout of Flatbreen, and the mass balance of Flatbreen.

The variations in mass balance from 1964 to 1967 of Store Supphellebre, and of Flatbreen alone, have followed those of the other measured glaciers in South-Norway. (See for example LIESTØL 1969, Fig. 5, p. 190.) Unpublished data for 1968 indicate that the variations are still parallel. In the years before 1964, the mass balance of measured glaciers in South-Norway was strongly negative in 1963, and strongly positive in 1962. Before that, with the exception of one very slightly positive balance in 1957, there were a series of mainly strongly negative years back to 1953. The snout of Supphellebreen retreated throughout the 1950's, and as mentioned previously, Supphellebreen had its smallest extent in historic time between 1960 and 1963. Between autumn 1963 and autumn 1964 the snout of Supphellebreen advanced, but no value for the throughflow is available. The response of the snout of Supphellebreen to changes in the throughflow is almost immediate (all the avalanches reach far down onto the glacier, and many reach the snout). A correlation is strongly indicated between the first marked positive balance year in a decade, 1962, and the first recorded advance of Supphellebreen in the same period, 1964. However, because the position of the snout from 1961—1963 is not known, the advance may have started before 1964. In the three years from 1964 to 1967 the throughflow from Flatbreen, as measured on Supphellebreen, was 1.62, 1.29, and 1.97×10^6 m^3. Comparison between these values and the mass balance of Flatbreen, which is presumed negative in 1963, and was measured (Table 2) as positive in 1964 and 1965, negative in 1966, and positive in 1967, indicates that the lower throughflow in 1966 was a result of the negative mass balance in 1963, and the very marked increase in throughflow in 1967 was caused by the two positive years 1964 and 1965. These results thus closely agree with the two to four year time lapse between mass balance changes and throughflow changes established in (1) by use of NYE's analytical results. However, the simple correlation is complicated because the throughflow each year is also affected by the conditions of that year: the amount of mass that calves off Flatbreen in a year will depend upon the mass balance of the calving mass during the year. Inspection of Figs. 9—12 show that the mass balance of the lower part of Flatbreen was similar in the years 1964, 1965 and 1967, but was considerably more negative in 1966. It seems likely that the low value for the throughflow in 1966 was probably partly caused by this negative balance. Because the balance for the other years is similar, the variations in throughflow in those years were probably only to a minor extent caused by this effect. It thus seems well established that the very marked increases in throughflow in 1967, compared with both 1966 and 1965, was the effect of a kinematic wave caused by the two successive positive years.

(3) An indirect confirmation of the above results can be found from the studies by ROGSTAD (1941, 1951) of Briksdalsbreen, another outlet glacier from Jostedalsbreen that has dimensions similar to Store Supphellebre; the measurements of their frontal positions show that the two glaciers behave similarly. ROGSTAD (1941, p. 277) found that for the period 1900 to 1940 the time between a mass balance change on Briksdalsbreen and the corresponding change in position of the snout was 4 years. (ROGSTAD did not measure the mass balance, but determined the variations in the mass balance by comparing the variations in run-off between areas without glaciers with run-off from Briksdalsbreen.) Briksdalsbreen is smaller now, and LIESTØL (personal communication) considers the time lag at present to be nearer to three years.

The conclusions are that the changes in mass balance of Flatbreen are recorded on Supphellebreen after two to three years, and that a marked change in mass balance will affect the throughflow at the snout of Flatbreen even if the change only lasts for a single year. Data from the continuing measurements should enable a more complete test of NYE's theory to be made in the future.

There was considerable change in total mass of Supphellebreen in the period of the measurements. From October 1964 to October 1967 the glacier area increased by 20 per cent, and the mass increased by 0.31×10^6 m^3 (water), corresponding to 3.5 m distributed over the area of the glacier in October 1967 (0.089 km^2). The mass change (i.e. the volume change multiplied by the density) was determined both by adding the mass changes between the seven successive maps, and by direct determination of the mass change between the map from October 1964 and that for October 1967. Both procedures gave the same value for the mass change, confirming that the imprecisions in determining the volume change by the hypsographic method are small.

The mass balance of Store Supphellebre (as well as that of practically all other glaciers in South-Norway) was markedly positive in three out of the four years of this study. Unpublished data show that Store Supphellebre and the other glaciers also in 1968 were strongly positive. In the four years of this study the mass of Store Supphellebre increased by 20.34×10^6 m^3 (Table 7), corresponding to 1.70 m distributed over the glacier. Most of this mass increase took place on Flatbreen in 1967, and has therefore not yet affected Supphellebreen. If all the excess mass was avalanched onto Supphellebreen, it would increase the thickness of the glacier of present area by about 170 m. This is unrealistic value, but it illustrates how sensitive Supphellebreen is to changes in mass balance of Flatbreen. In view of the possibilities of such changes in mass balance affecting the throughflow, the large changes in dimension of Supphellebreen in historic time (Figs. 20 and 21) are understandable; these are believed to be caused only to a minor extent by changes in the ablation at Supphellebreen.

When the series of recent positive balance years are considered, it is clear that at least temporarily the consistent reduction in size of the glaciers that took place in the decades from 1930 to 1960 has been reversed. It is interesting to speculate how much longer Supphellebreen would have lasted had not the trend reversed. If the equilibrium line rose to 1 380 m a.s.l., that is, only 30 m above the elevation of the steady state equilibrium line calculated for Store Supphellebre at present, the mass balance of Flatbreen would have been zero, and no excess mass would be available for avalanching. The reduction in throughflow would take place after 2—3 years, although it would be a much larger number of years before the throughflow stopped completely. If no avalanches arrived at Supphellebreen, it would, with present ablation and snowfall, and using the previously calculated value for the approximate thickness, disappear in about 5 years. Altogether, if the equilibrium line had continued its historic rise (see below) to reach and average around 1 380 m a.s.l. in the 1960's, Supphellebreen would probably have disappeared sometime between 1970 and 1975.

ELEVATION OF THE EQUILIBRIUM LINE OF STORE SUPPHELLEBRE IN HISTORIC TIME

NYE (1963b) has shown how the yearly mass balance of a glacier may be calculated from observations of the snout position of the glacier. His theory has not been fully tested, but even if it should be found to give an acceptable numerical reconstruction of the mass balance, it is still limited to the period for which snout observations exist. For Norway, such observations go back to about 1900. The changes in climate and of mass balance, expressed as variations in the height of the equilibrium line, may be found for any period, by the following approach. Assuming steady-state conditions, and a known shape of the balance curve, the height of the equilibrium line of any glacier can be found for any period for which the area distribution of the glacier is known by locating the balance curve so that the total balance, B_n, of the glacier is zero.. Because the past dimensions of a glacier usually can be fairly well determined from marginal moraines, and because a reasonable shape of the balance curve can in most cases be found from present studies, such a method would seem to offer an excellent opportunity for climatic reconstructions. This is not the case, however, because the critical assumption of steady-state is seldom fulfilled for any length of time. If an attempt is made to circumvent this difficulty by evaluating the response time of the glacier, a new and generally insurmountable problem is encountered, because as soon as the dimensions of the glacier change, the response time changes in a manner which can not be predicted accurately. Thus the response of the glacier with different dimensions cannot be evaluated. Store Supphellebre is unusual in that here the difficulties can be overcome. In the preceding section it has been shown that the response time of Supphellebreen to changes in the mass balance of Flatbreen is about two to three years, and the response is so sensitive that even a single year's variation in mass balance may be felt as increased throughflow at Flatbreen and movement of the snout of Supphellebreen. Even at its largest extent in historic time the area of Supphellebreen (Table 8) was only 8 per cent of the area of Flatbreen, and it is therefore believed that the response of Supphellebreen at all times must have been very sensitive to changes in the mass balance of Flatbreen. Thus any equilibrium line determined must be close to the actual equilibrium line at the time, since large deviations would have affected the snout position. That the response of Store Supphellebre was not markedly slower in earlier times, can be claimed with high certainty: Flatbreen has not changed its snout position at any photographed time since 1868, and most likely never in historic time, because this is completely controlled by the abrupt change in bedrock slope. Because the surface slope for the lower part of Flatbreen is strongly dependent upon the bed slope, any large changes there are unlikely. The changes in dimensions of Supphellebreen do not seem to markedly increase the response time. All available evidence (descriptions, photographs, and the absence of ogives on Supphellebreen (see below)) indicate that the avalanches from Flatbreen always have swept over most of the glacier, causing a large amount of the mass to be brought immediately to the lower part of Supphellebreen even when it was much larger. It is thus concluded that Supphellebreen offers an unusually good opportunity for avoiding the steady-state errors usually inherent in any reconstruction of the mass balance from known glacier dimensions. The other errors in the reconstruction, from assumptions about the net balance curves and the elevation of the surface of the glacier, are much less critical, since errors here only affect the value of the final result, but do not invalidate the method (which large deviations from steady-state might). The net balance curve determined for Flatbreen have then been moved parallel to the balance axis until it gave Flatbreen a positive balance equal in magnitude to the negative balance of Supphellebreen. (Avalanches discounted.) The elevation at which the balance was zero is given in Table 8.

Table 8

Area and balance of Supphellebreen and height of the equilibrium line of Store Supphellebre at various occasions throughout historic time.

Time of formation of moraine	Area of Supphellebreen (km^2)	Balance, b_n, at centre of gravity of Supphellebreen (m^2)	Total net balance, B_n of Supphellebreen (10^6 m^3)	Elevation of equilibrium line of Store Supphellebre (m a.s.l.)
ca. 1750	0.92	–10	–9.2	1 240
ca. 1800	0.75	–10	–7.5	1 250
1850 and 1870	0.52	–10	–5.2	1 265
1910	0.42	–10	–4.2	1 280
1930	0.30	–10	–3.0	1 300
1964–1967	0.12	–12	–1.4	1 350

The magnitude of the net balance of the centre of gravity of Supphellebreen has been taken as 90 per cent of the balance for 1964—1967 (–11 m) at that elevation. (Approximately 190 m a.s.l. for all the years before 1964.) This very approximate correction of 10 percent is because the summer temperature (and therefore ablation) was probably slightly lower during these years than at present. (See for example LIESTØL 1967, Table III, p. 38, showing variations in summer temperature of Bergen since 1816.) The estimated standard errors in both the area and the net balance of Supphellebreen are 20 per cent, giving a standard error in the volumes in Table 8 of about 30 per cent. This introduces a standard error of only 10–20 metres in the elevation of the equilibrium line, however. Thus the values of the elevation of the equilibrium line are believed to give good indications of the size of the climatic variations at various times of glacier advance or standstill. Because these values must represent the average climatic conditions over only a few years before the advance or stand-still, the position of the glacier is unlikely at any time to have been the result of long-term changes. (The exception to this is of course the first build-up, which requires a long time; after this, however, the movement of position of the glacier snout is considered to be a reflection of short-term changes. Because the values only give the elevation of the equilibrium line at times of glacier advance or standstill, they do not reflect average conditions during the historic period.) If the elevation changes were caused by temperature alone, the results indicate that the air temperature was about 0.7°C lower in 1750 than at present. No comparable estimates of the elevation of the equilibrium line in historic time exist for Norway. LIESTØL (1963, p. 138) calculated from somewhat similar considerations that the equilibrium line was 200 m lower for a late Pleistocene advance (10 000 yr(?) before present) of Hardangerjøkulen. An uncertain area distribution curve, as well as difficulties introduced by lack of knowledge of the response time, made his calculations approximate. Despite this his result compares well with those from Store Supphellebre, which indicate that even a small change in mass balance gives a large variation of the glacier snout. This also accords with the theoretical results of NYE (1960). In the 1750 advance the glaciers in Norway reached their largest extent in historic time. The results show that this was the result of the lowering of the mean equilibrium line relative to present by only about 100 m. (That the values for Store Supphellebre are representative for a larger area is concluded from the fact that the variations in elevation of the equilibrium line and the measured mass balance of the glacier have been in step with all other measured glaciers in South-Norway since this study was initiated.)

CHARLESWORTH (1957, p. 147, 151, and 646) cites estimates of the elevation of the snow line within the past two hundred years from various parts of the world. Most of the estimates are 100 to 200 m below present snow-line elevation, agreeing well with the values for Store Supphellebre. However, the very approximate nature of these estimates must be emphasized; none of them were based on comprehensive mass balance studies such as those reported here, and because of varying definitions and calculations of the elevation of the snowline, the estimates of the lowering vary considerably. For example, variations from 50 to 500 m have been reported from the Alps (CHARLESWORTH, op. cit.). MERCER (1961) estimates that the firn limit on various glaciers in Alaska has risen from 75 to 450 m since the recent glacier maximum. His approach is similar to that described here, but he assumes the shape of the balance curve based on studies from other glaciers. The comprehensive mass balance investigations in Norway and elsewhere during the last decade have shown that the balance curves vary widely for different areas, and for this reason his results must be considered approximate.

Although MERCER's method is an improvement of most earlier studies, it is still not adequate for accurate equilibrium line determinations, which must depend upon both comprehensive mass balance investigations in the field and evaluation of the response time and steady-state conditions of the glacier. Only from such studies will it be possible to decide whether the past variations in elevation of the equilibrium line, and thus climate, have been different for various parts of the world.

INTERNAL STRUCTURES OF SUPPHELLEBREEN

Supphellebreen is one of the best known regenerated glaciers (see for example CHARLESWORTH 1957, p. 92); its internal structures were in particular discussed in older literature (SEUE 1870; REKSTAD 1904; HAMBERG 1908, 1932; BEHRMAN 1927). Two types of structures have been described: (a) blue-and-white layers, and (b) debris layers. During this study the solid ice of Supphellebreen was generally not exposed because of the positive mass balance, but in autumn 1966 most of the glacier snout was free of avalanche material, and the structures were there observed in a few open crevasses. Both types of layers were found to dip gently up-glacier and towards the centre line of the glacier. They seemed discordant, although this is a tentative conclusion as no single exposures showed the two types meeting or crossing. The exposures were inadequate to determine the spatial distribution of the layers in the glacier, but from older photographs and descriptions it is clear that at least the debris layers formed a trough-structure transverse to the glacier.

The blue-and-white layers consist of about 0.5 to 4-cm-thick discontinuous blue layers of bubble-free ice, in a ground mass of white bubbly ice. At the junction of two crevasses the layers were seen to be discs generally 20 to 200 cm in diameter. Hamberg (1908, p. 4) suggests that these layers are a reflection of the heterogeneous nature of the ice accumulation, the blue layers being formed by the ice-blocks being flattened at depth, while the white ice is compressed from the broken-up ice. This explanation seems reasonable in view of the above observations of the blue layers lying as discs. (Blue layers are easily formed from percolating meltwater, and may also form by secondary processes within the ice, for example possibly by the migration of air from "soft" to "hard" ice (MEIER 1960, p. 60), or under high pressures, possibly by regelation (SHUMSKII 1958, p. 247); conceivably the blue layers in Supphellebreen may have been formed in more than one manner.)

The debris layers, mostly about 1—3 cm thick, consist of both fine and coarse material. REKSTAD (1904, p. 78) proposed that one debris layer was formed after each avalanche, by the avalanche mass being sorted by density so that the debris was deposited at the bottom of the avalanche layer. Hess (1904, p. 175, quoting E. Richter) and Behrmann (1927, p. 139) also believed that the debris layers in Supphellebreen were a result of the stratification due to successive avalanches. That such an observation is incorrect is suggested by the following observations at Supphellebreen. The vertical separation of the debris-layers is on the order of 1 m, which is approximately 100 times the average vertical thickness of a single avalanche. The thickness of the debris layers is also far too large by the same order of magnitude to correspond to the mass of debris brought in a single avalanche. The misinterpretation by these authors is probably because they visited Supphellebreen in the summer, when the avalanches are few. From the present study the number of ice avalanches onto Supphellebreen in the winter is estimated to be in the order of several thousand (approximately one every hour), making the above hypothesis untenable. The debris layers are believed to be summer (ablation) surfaces that have been buried in the upper part of the glacier and have reappeared in the lower. As Fig. 22 shows, the upper surface of the glacier becomes very dirty during late summer, both by debris melting out from the ice below and from dust blowing onto the glacier, and this surface contrasts sharply with the newly arrived fresh ice. It seems highly unlikely that conditions affecting the formation of the debris layers were different in previous times; that the debris layers also then were buried summer surfaces is supported by the observation of Seue (1870, p. 41) that there seemed to be a debris layer for each year; he did not draw the correct conclusions from this, however. That conditions have not changed is furthermore supported by the observations of Hamberg. He visited the glacier on October 2, 1905, when the several avalanches took place. Hamberg (1932, p. 77) writes that the regular structure of Supphellebreen cannot have been formed by stratification by the irregular avalanches as believed by Rekstad and others. However, Hamberg was unable to offer satisfactory explanation for the debris layers.

There are no ogives on Supphellebreen at present; this is not surprising as the glacier is now so short that avalanches sweep over its entire length. In some of the photographs from last century there are faint signs of wave-forms on the surface, but in none of them can ogives be recognized with certainty. Because none of the earlier observers, who were generally very perceptive, describe any such surface features, no marked ogive system can ever have existed on Supphellebreen since 1868. From existing theories (see for example Nye 1958) ogives would be expected to start at a point if there is a pulsatory arrival of mass, or pulsatory variation in pressure at that point. Because both these conditions would be fulfilled if the main part of the avalanche mass was deposited at the head of Supphellebreen, the majority of the avalanche mass must have reached far down the glacier at all times since 1868.

Acknowledgments

The encouragement of Professor Hans Holtedahl of the Institute of Geology, University of Bergen, and of Dr. Kåre Utaaker, who provided the meteoro-

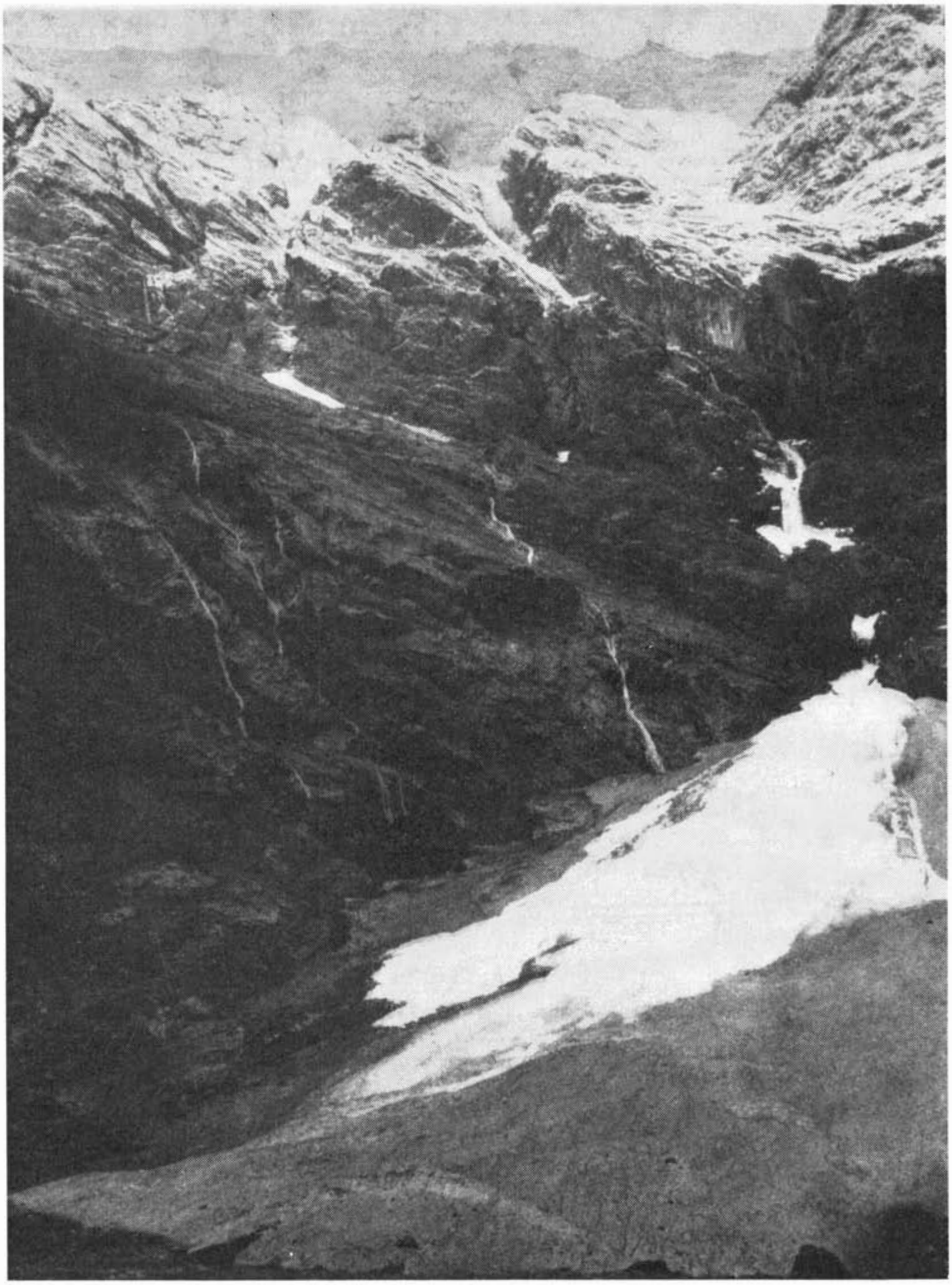

Fig. 22. *Supphellebreen on October 18, 1967. The surface of the glacier was exceptionally dirty this year, because Flatbreen during 1966–1967 increased in size and started eroding previously deposited marginal moraines, thus bringing down increased amounts of debris. The 1967–1968 avalanche season on Supphellebreen started about a week before this picture was taken; the difference between the freshly arrived ice and the summer surface is very noticeable.*

logical instruments from the Institute of Geophysics, University of Bergen, is much appreciated.

The writer is very grateful for discussions with RANDI PYTTE, and especially OLAV LIESTØL, who offered many helpful and valuable comments; and to the members of the Institute of Polar Studies who provided assistance with the preparation of this manuscript.

Among the numerous willing field assistants, my brother ALV ORHEIM, and ANDERS ØYGARD, who also provided free use of his hut at Flatbreen for the period of this study, deserve particular mention.

Financial support for the field studies was provided by the Institute of Geology, University of Bergen, and by Norsk Polarinstitutt.

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