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OLAV LIESTØL

STORBREEN GLACIER IN JOTUNHEIMEN, NORWAY

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ÅRBØKER

Årbok 1960. 1962. Kr. 13.20.
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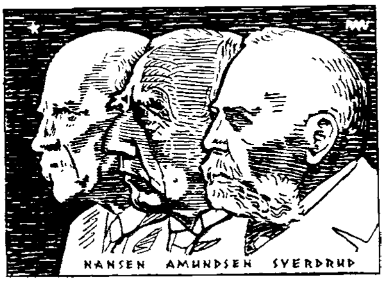

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Contents

Abstract

This report is a review of the work carried out by the author on Storbreen during the period 1949 to 1965. These investigations have included measurements of accumulation, ablation and mass balance. The results of these measurements are shown in Table II and Fig. 21. An attempt has also been made to calculate the mass balance for earlier years from the records of the neighbouring meteorological stations.

It has been possible to test the accuracy of these calculations and measurements for Storbreen on the basis of volume calculations from accurate photogrammetric maps. Table V compares the calculated and directly observed (from maps) changes in volume. The agreement between these is good and is indeed much better than could be hoped for considering the accuracy of the measurements made.

Glacio-meteorological measurements have also been taken. The results from the summer of 1955 show that radiation accounted for 54%, convection for 32%, and condensation for 14% of the ablation.

The calculated values of mass balance have also been compared with the length variation of different glaciers. One finds relatively good agreement here, also as shown in Fig. 24.

The height of the firnline is discussed in relation to the mass balance and exposition. The map in Fig. 29 shows the heights in Jotunheimen and Sør-Norge.

The surface speed of the glacier is shown together with the streamlines in Fig. 35, and a detailed picture of a stake movement is given in Fig. 36.

The last chapter deals with some measurements of sediment load. The results show the high degree to which sediment load is dependent on the discharge during the days preceding the measurements as well as the time of the measurements.

Introduction

In 1948 Norsk Polarinstitutt took over all routine glacier investigations in Norway. In the Jotunheimen area ADOLF HOEL and WERNER WERENSKIOLD had been conducting the glaciological work in previous years. Among other tasks special investigations were carried out on the flow and ablation of Hellstugubreen (Hellstugu glacier). The plan adopted by the author was that of proceeding with a closer examination of *one* glacier. In consultation with Professor W. WERENSKIOLD, Geographical Institute of Universitetet i Oslo, and Mr. H. KLÆBOE, Vassdragsvesenet, Storbreen (Storbreen glacier) in Leirdalen, West Jotunheimen, was selected.

Storbreen has many advantages as an object of closer examination: The area is of a moderate size and is easily accessible from a road passing at a distance of 2 km from the snout of the glacier. The drainage area of the glacier river has also sharp and well defined limits with a high percentage of ice-covered ground. This is of great importance when measuring the run-off. An unfavourable aspect is the uneven surface of the glacier, complicating the accumulation and ablation measurements.

Previous glaciological investigations on Storbreen

No glaciological work had been carried out in this area until P. A. Øyen began his research of the glaciers in 1891. He concentrated his investigations on the fluctuations of the glacier snout. To this effect, he had small cairns built at convenient places in front of the glaciers, and measured the distance to the ice with a tapeline along a fixed direction indicated by a secondary cairn. Øyen began his measurements on Storbreen in 1902, when two cairns were erected and marked by crosses cut in a stone. During the first years measurements were made along lines from both cairns, the one intersecting the centre of the tongue, the other c. 100 m farther north on the side. Øyen's work was suspended in 1912 for lack of funds. In 1933 W. Werenskiold resumed the measurements, but now only from the lateral cairn. The result of this work and the survey of the glacier will be dealt with in later chapters. Both Øyen and Werenskiold studied the outstanding moraines in front of the glacier, and Werenskiold in 1936 also made a special map of the area.

Physical setting

The glacier Storbreen is situated in the western part of Jotunheimen, on the eastern slope of the Smørstabb massif (c. 8°20′E, 61°35′N). The glacier covers an area of 5.42 km^2 (1963) with fairly well defined borders. The intake area of the glacier river at the water gauge, c. 200 m below the glacier snout, is 8.0 km^2, giving an ice-cover of 68%. (See Fig. 1.)

Though not typical, Storbreen has to be classified as a short valley glacier or a composite cirque glacier. The map (see folder) and the area distribution curve give a good view of the morphology. In its upper part the glacier is bordered by steep cirque walls, except where the pass to Leirbreen results in a smooth transition to the terrain farther west. A subglacial ridge divides the glacier into two well defined parts, an upper one and a lower. The three small rock islands, shown on the map, project from this ridge. The undulating surface indicates a rather shallow ice sheet, especially in the central part. The ice is probably thickest in the even south-eastern area, but so far no direct soundings have been made.

The glacier bedrock consists mainly of Jotun-norite. It is in part heavily folded and pressed, and varies much in colour and structure from place to place. Small areas with peridotite are also found, easily recognizable by their rusty brown, weathered surfaces. Outstanding pegmatite veins are seen in the cirque walls below Kniven and Smørstabbtind.

Survey

The first map covering the Storbreen area dates from 1849 and 1851, when the map sheets "Kart over Christians Amt" (Maps of the county of Christian) on the scale of 1:200 000 were published. They are most inaccurate and without close accordance to the terrain. In 1874 a better topographic map, the so-called "rektangelkart", on the scale of 1:100 000, with 100 ft contour intervals, appeared.

Fig. 1. *Aerial photo of Storbreen, August 12, 1955. In the background to the right the Fannaråki mountain and glacier, left the Horrung massif.* Photo: B. LUNCKE.

This map covers only the lower part of Storbreen, and its accuracy is not sufficient for a closer study of the state of the glacier. No survey was then made until 1936, when Norges Geografiske Oppmåling had a stereo-photogrammetric map made on the scale of 1:50 000, with 30 m contour intervals. This is a modern and accurate map, based on terrestrial photograms. A section of the map is presented in Fig. 3. The same year Professor W. WERENSKIOLD made a detailed survey, by means of tachymetric methods, of the moraines in front of the glacier. As a starting point for the survey a few station markers were used. These signals have also been used for the subsequent extended mapping. The first special and detailed map of the glacier appeared in 1940. W. SOLHEIM, then topographer at Norges Svalbard- og Ishavsundersøkelser, fixed a number of trigonometric points and linked them to the main grid of Norges Geografiske Oppmåling. At the same time stereo-photograms were taken from the three station lines. The station line on Sauhø, a ridge on the east side of Leirdalen opposite Storbreen, gives an excellent view of nearly the whole of the glacier and the moraines in front of it. The map covering the greater part of the glacier, excluding the upper firn field,

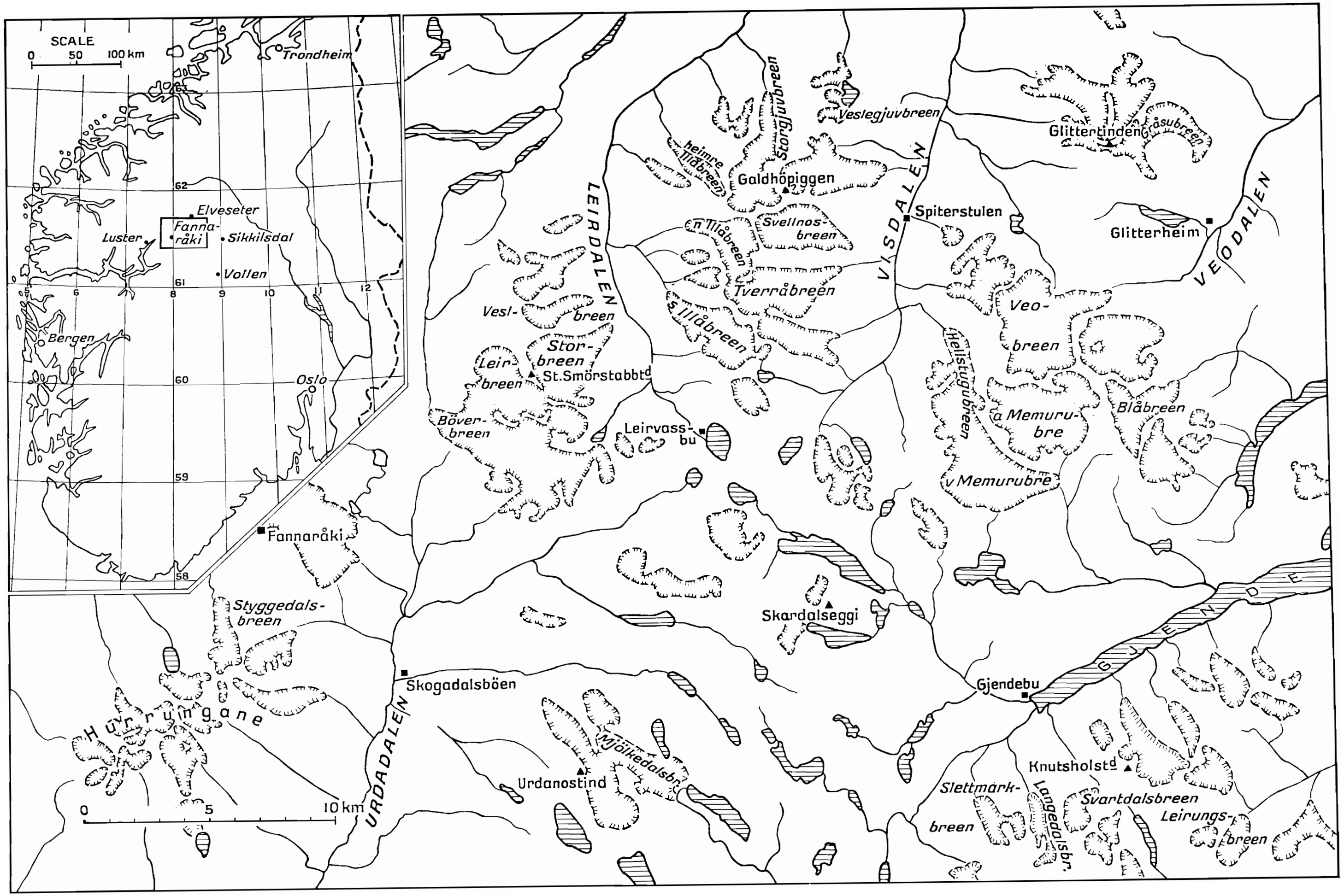

Fig. 2. *Map of the Jotunheimen area.*

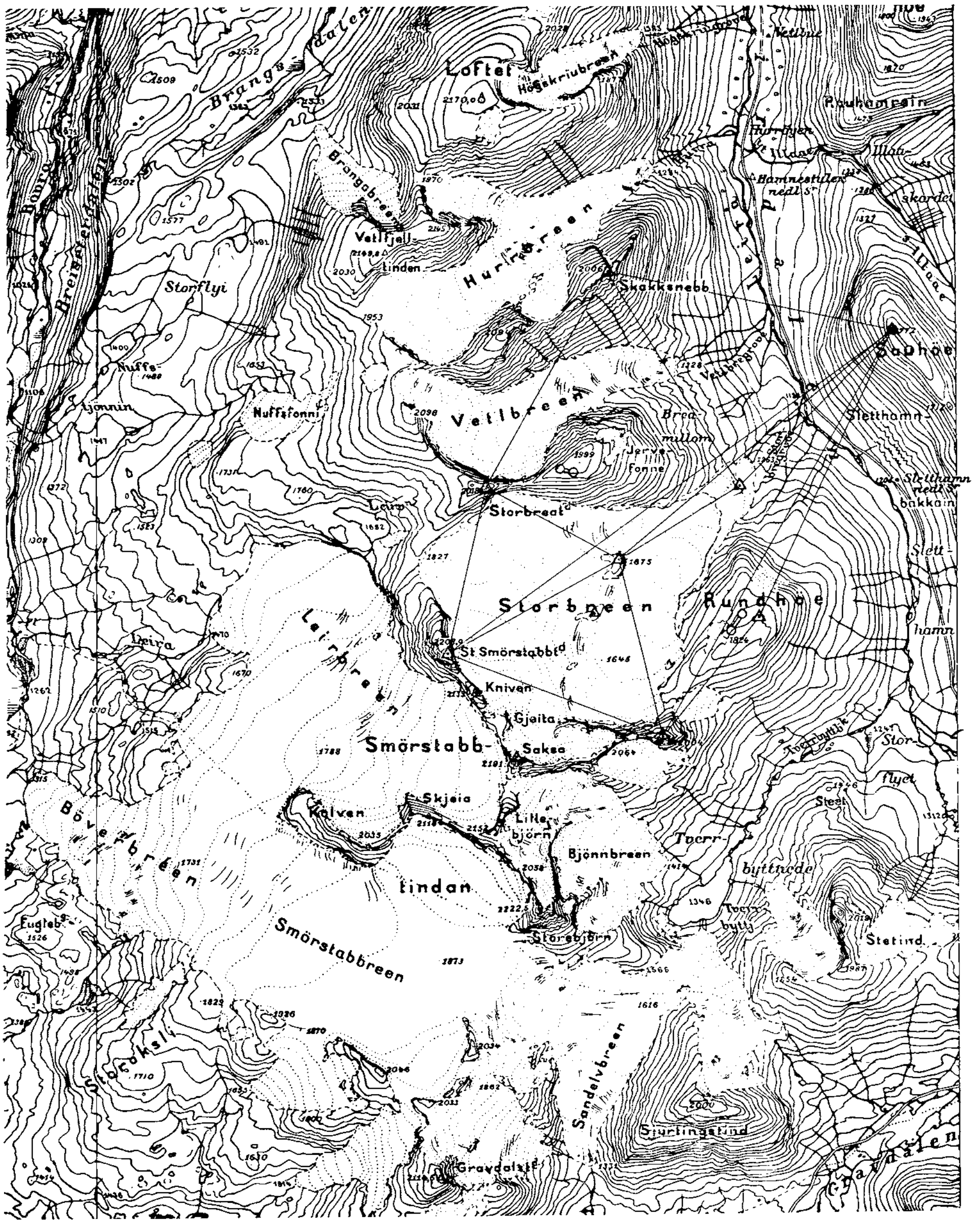

Fig. 3. *Section of map made by Norges geografiske oppmåling in 1936 with 30 m contour intervals. The map scale in the figure is c. 1:78 000.*

was plotted by the stereoautograph of the Norges Geografiske Oppmåling, on the scale of 1:10 000, with 10 m contour intervals. A special map covering the moraines was plotted on the scale of 1:2 000.

In 1949, Norsk Polarinstitutt took over the glaciological work in Jotunheimen, and in 1951 and 1955 new photogrammetric maps on the scale of 1:10 000 were made by the author. The map of 1951 is enclosed in the folder of this publication.

When using stereo-photogrammetry in the mapping of glaciers, one will always meet with difficulties in connection with the snow-covered areas. The white, even surface with few details gives little or no significant stereoscopic impression. Different types of plates have been tried in the survey of Storbreen to find an emulsion that accentuates the possible differences in colour and albedo. The results of these experiments have not been encouraging. Infra-red plates with dark red filter were used. They gave higher contrast, but had the drawback that the emulsion was too coarse-grained. Most photograms were taken with the conventional Perutz Topo-Platte, which due to its high resolving power seems to give the best results. It was experienced that the weather conditions prevailing when the photograms were taken are of great importance. Conditions when radiation plays a minor part in the ablation are most favourable: that is, in overcast, warm weather, when the snow and ice surfaces are rather soaked with water.

As a rule it is necessary to survey parts of the glacier by tachymetry in addition to photogrammetric plotting. This was the procedure used on Storbreen in 1949 and 1951.

In August 1955 aerial photographs of Storbreen were taken for the first time. By means of these, parts of the glacier were plotted. The white, even surface of last winter's snow, however, made it impossible to plot a complete map.

Since 1949 the margin of the glacier tongue has been surveyed every year by means of tachymeter, in order to find possible fluctuations. Fig. 3 shows the trig-points used in the survey of Storbreen. The positions of the poles drilled in the ice are also determined every year from some of the most favourable trig-stations along the glacier.

Accumulation

To give a complete and detailed picture of the accumulation in the course of a budget year, a continuous series of observations are needed. This will, however, require much work and can hardly be accomplished in practice. Accordingly, the investigation of accumulation on Storbreen follows a somewhat simpler procedure in actual fact. The depth of winter snow on the glacier is measured in spring, just before the ablation normally starts, that is, in the first week of May. About 90% of the total accumulation is then measured. Accumulation after that time and till the end of the budget year is calculated from precipitation and temperature figures recorded at the nearest meteorological stations, viz. Luster, Elveseter, and Fannaråki.

The depth of the snow is measured by a collapsible aluminium rod, which is driven through the snow layer down to the last autumn's glacier surface. Below the firn line, where solid ice forms the old surface, the depth is easily found. But in the firn area, where the rod, after having penetrated last winter's layer, reaches the firn surface, the transition from new to old snow is less sharp and not so easily felt. Hard crusts from thaws in the autumn will often cause stronger resistance than the old firn surface. It is therefore necessary to check the depth, from place to place, by the laborious digging of pits. In recent years core drills have been used with success both for measuring depth and density. A control is obtained where the measuring stakes are long enough to project above the snow. The fact that the relative distance between the crust layers is constant over large areas, is also of use in calculating the depth.

The soundings are made along fixed lines crossing the glacier and distributed as uniformly as possible. In the heavily crevassed areas no reliable measurement can be obtained, because the snow will blow and sink into the crevasses. The areas are, however, small in proportion to the whole glacier. An estimate of the snow mass here will, therefore, not affect the reliability of the calculation of the whole volume. Up to 600 points have been used in selected years, but from experience, a system of 300 depth measurements (on an average c. 60 per km^2) has proved to be satisfactory for the construction of accumulation maps.

The measurement of the snow accumulation could be made still simpler by measuring the snow depth and density at one or two localities only.

On the smooth, flat SE part of the glacier at c. 1600 m a.s.l. the snow has a very even distribution. The same is the case on the plateau NE of Store Smørstabbtind. Measurements at the former place, which is situated just below the firn line, should therefore represent the whole glacier quite well. The diagram (Fig. 4) shows registrations at this place in relation to the average for the whole glacier. All the measurements are made in the beginning of May. The surplus accumulation after this date is therefore not included in this diagram.

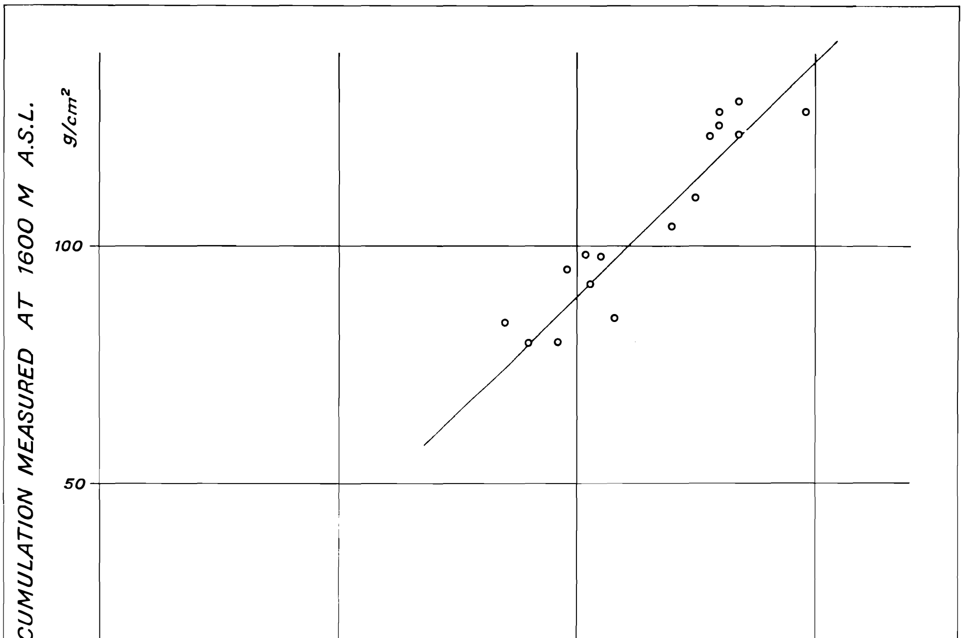

Fig. 4. *The registration of accumulation at the flat part of the glacier at 1600 m a.s.l. in relation to the whole glacier.*

As may be seen, the correlation is quite good. The maximum difference induced by measuring the accumulation at this place only, never exceeds ±15 g/cm², and the average difference is c. ±5 g/cm².

By extending the measurements to the upper plateau mentioned, still better results are obtained. The error made by using the 1600 m level only, is mainly due to precipitation falling early in the autumn. This precipitation may fall as rain in the lower part and as snow in the upper part.

Measurement on glaciers that are exposed to precipitation mainly from one direction, and thus have the same accumulation pattern from year to year, may be simplified in this way. The assumption is, however, that measurements in a sufficient number of years covering the whole glacier are available. In this way a representative place could be chosen and the correlation to the whole glacier computed.

The specific gravity of the snow is determined by weighing samples of known volumes cut out from pits. A cylindrical gauge of 500 cm³ and 10 cm long is driven down vertically through the snow along the side of the pit wall. Thus the mean specific gravity for every 10 cm can be determined. A spring balance is used for the weighing.

The number of pits dug varies from one year to another, depending on the homogenity of the snow. In 1953, e.g., there was very little variation in the density from the upper to the lower part of the glacier, and consequently only three pits were dug.

Inconnection with the density measurements, temperature and snow quality in the profile are studied. The measurements of temperature are essential for calculation of the refreezing of meltwater in the snow layers in spring. (Figs. 5 and 6.)

Each sounding, converted into terms of water content, is plotted on a map, and lines of equal accumulation drawn. By means of a planimeter the area within each line is found, and the total volume is then easily calculated.

In the upper part of the glacier a higher percentage of the precipitation will fall as snow, causing a greater accumulation in this area. The difference is, however, not too pronounced. The downward transportation by the prevailing westerly wind is not inconsiderable.

Compared with the icefree terrain of the surroundings, the distribution of snow on the glacier is relatively even. But, as might be expected, it is evident that the snow is blown from the convex to the concave parts. In Fig. 7 a profile is drawn from Smørstabbtind eastwards showing the distribution of snow in the spring 1954, when a special detailed investigation was made along this line. This effect also appears clearly on the accumulation maps. The maps also indicate an area in the northwest part of the glacier, with less accumulation. This is certainly caused by wind funnelling through the pass and sweeping the snow farther down. The transport of snow by wind and avalanches from unglaciated ground surrounding the glacier is small. But the high accumulation figures in lee of the mountain sides show that locally the effect is considerable.

In a year with balanced or negative budget the superimposed ice in the ablation area is removed by melting. The refrozen meltwater in the firn area is also partly removed. But the ice formed below the following autumn

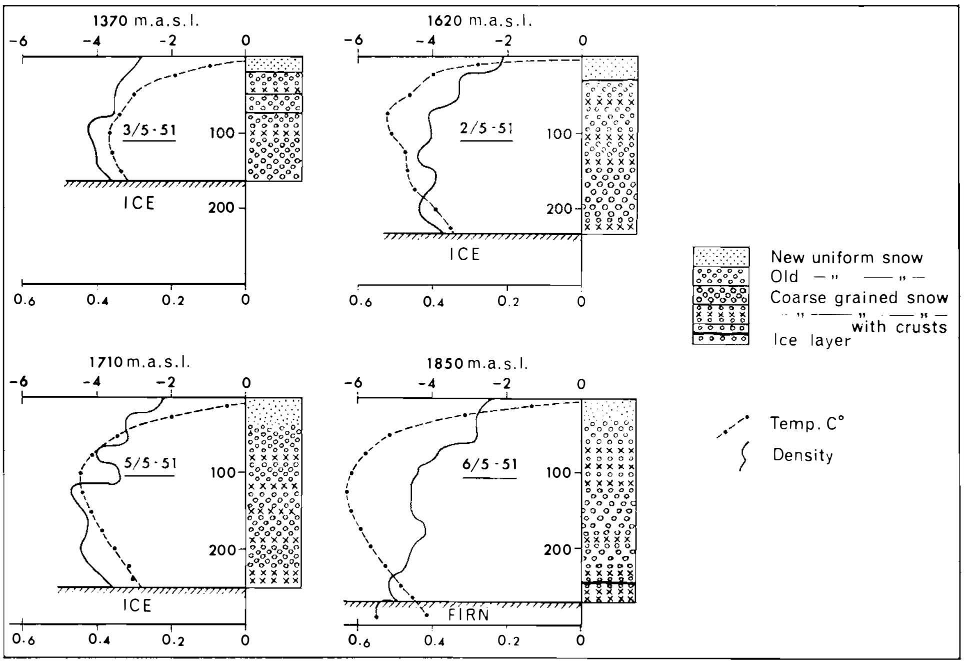

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Fig. 5. *Temperature, density and snow quality profiles observed in pits at different heights on Storbreen in the beginning of May 1951.*

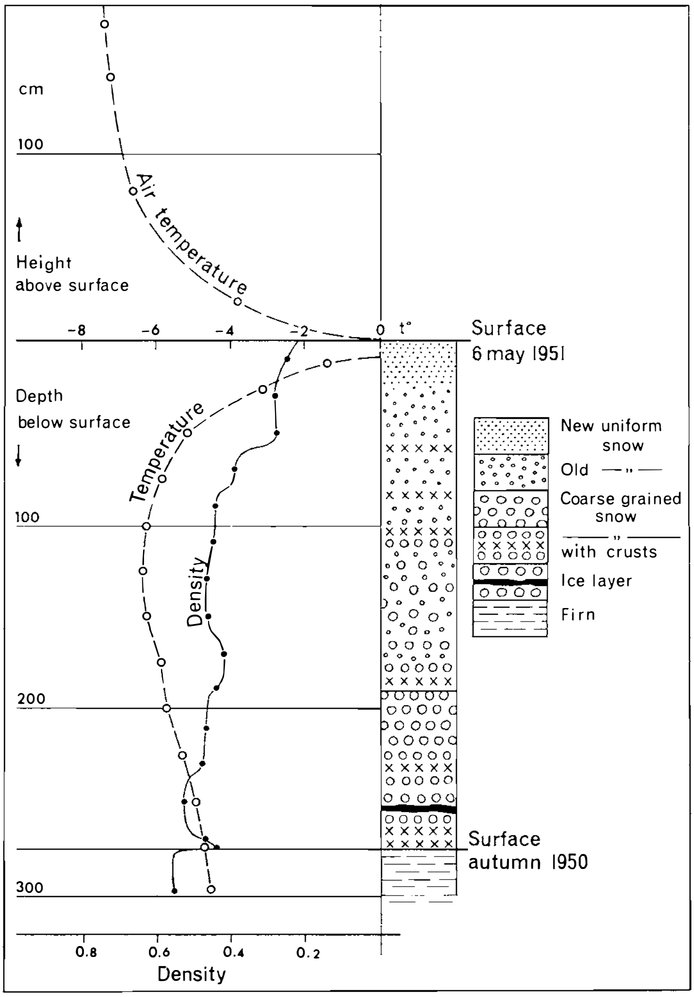

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Fig. 6. *Density, snow quality and temperature registered in a pit at 1850 m height. It represents a typical clear day situation with low air temperature (-8°C). The radiation is warming the snow surface to melting point. A thin surface layer is cooled to a temperature below melting point by evaporation.*

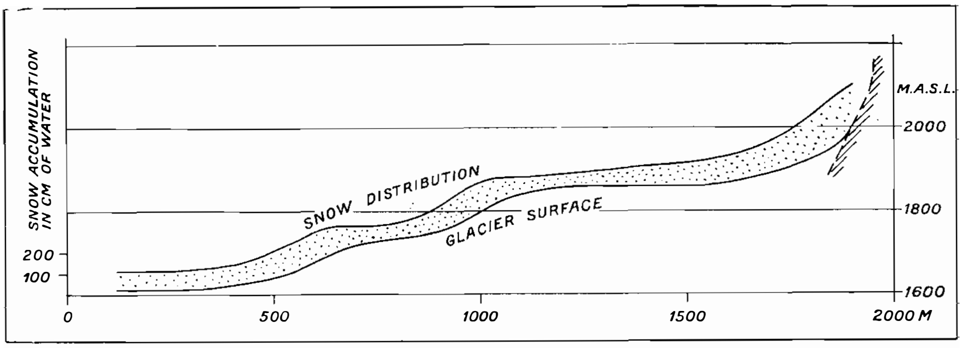

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Fig. 7. *Vertical profile from Smørstabbtind eastwards showing the distribution of snow in spring 1954.*

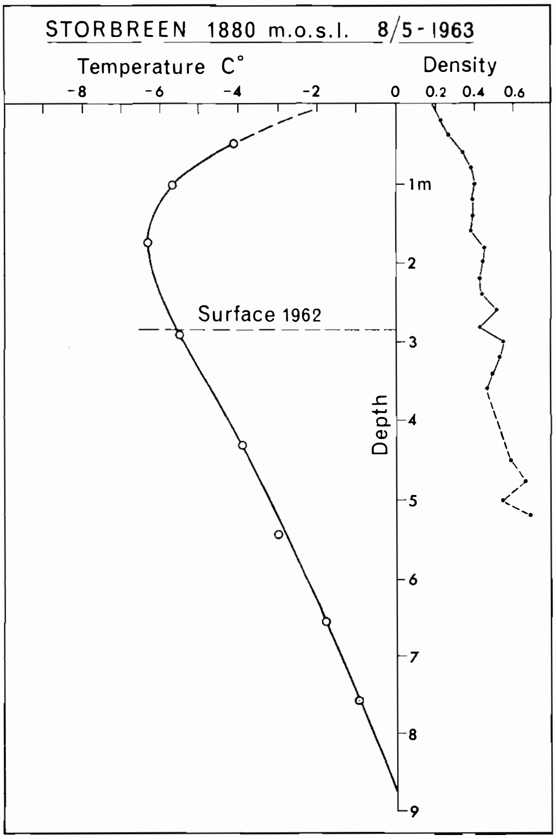

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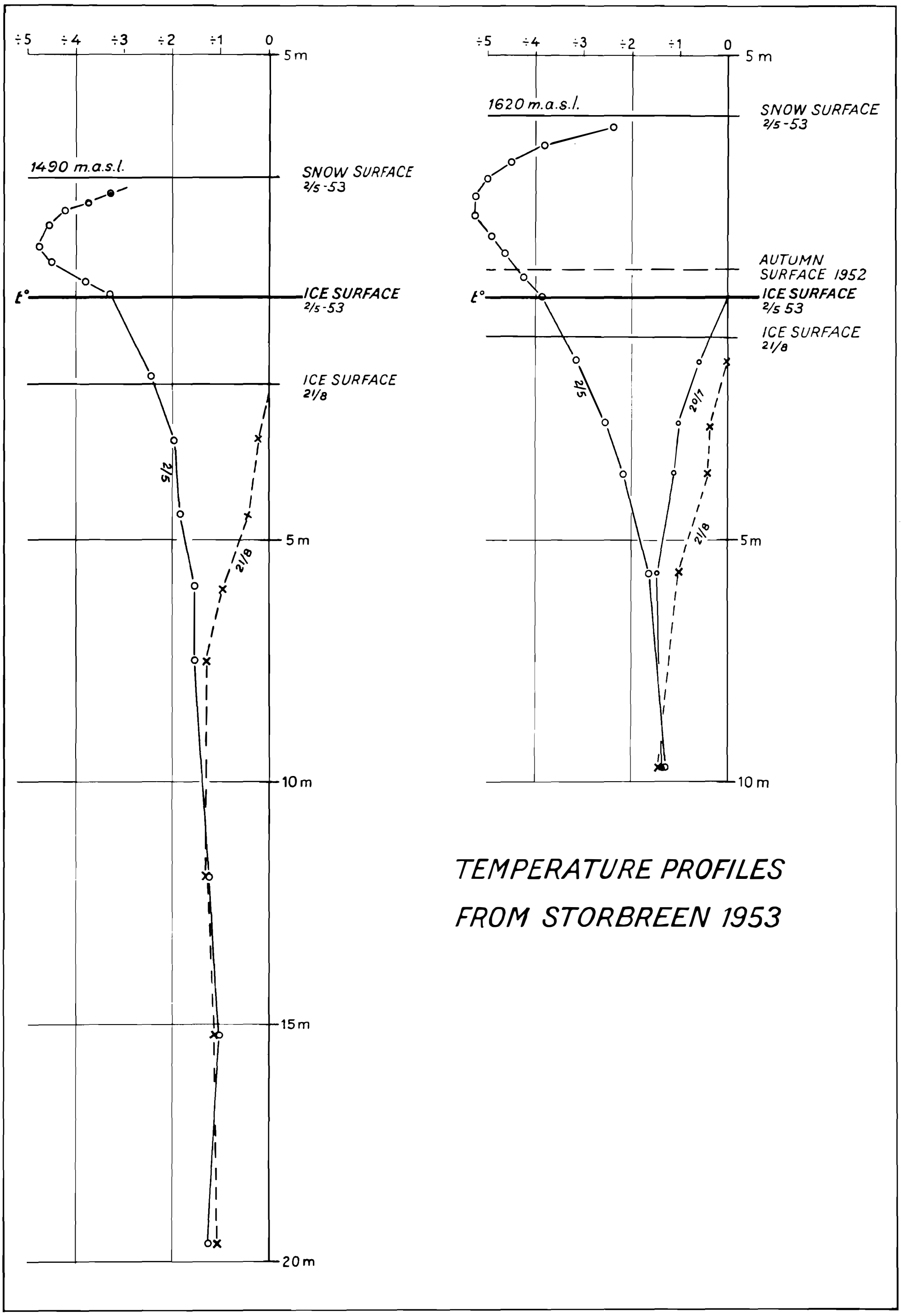
Fig. 8. *Temperature and density profile used for calculation of refrozen meltwater in the firn area.*

surface remains as a part of the net accumulation. On an average 8 to 10 cm of water equivalent is added to the total accumulation and c. 4 cm remains in the net accumulation figures. These figures have been calculated from density and temperature measurements in the snow and ice for most of the 15 years of investigation on Storbreen. Fig. 9 gives an example of the temperature registration in the ablation area in 1953. In the previous year holes were drilled at 1490 and 1620 m a.s.l. down to 20 and 8 m below the ice surface. The temperature recordings were obtained by thermistores placed at intervals from the top to the bottom of the holes. At 1620 m a.s.l. temperature readings were taken on 2/5, 20/7, and


÷5
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5 m
1490 m.a.s.l.
SNOW SURFACE 2/5-53
t°
ICE SURFACE 2/5-53
ICE SURFACE 21/8
2/5
21/8
5 m
10 m
15 m
20 m
1620 m.a.s.l.
AUTUMN SURFACE 1952
20/7
TEMPERATURE PROFILES
FROM STORBREEN 1953

Fig. 9.

21/8. Melting started just after 2/5, and by 20/7 the snow depth had shrunk to c. 30 cm. In the same time the superimposed ice increased to c. 14 cm, which is the mean of 3 stake measurements immediately around the hole. In the same period it is calculated that c. 410 cal/cm³ are taken from the meltwater to form superimposed ice. This gives $\frac{410}{80} = 5.1$ gr of ice, and with a density for the overlying snow of 0.56, c. 15.0 cm of superimposed ice will form. This agrees well with the observed value. The higher figure obtained by calculation may be the result of the meltwater content when the snow density was measured.

Ablation

Ablation is measured mainly by observing how the snow surface sinks in relation to stakes drilled down into the ice. Different types of stakes have been used. On the ice of the lower part of the glacier canes were used for the most part in the first years. These have the advantage that they never break, but they are extremely difficult to see and find again. They also have the disadvantage for winter observations of accumulation, that they do not stick up above the surface. During the first 5 years of research on the upper part of the glacier, bamboo stakes were used, some with a diameter of 4 cm, and some of 6 cm. In using these, no sinking of the stakes were observed. After 1956 there was a change to steel and aluminium poles. Stake diameters were of 25–40 mm, with a metal thickness from 1.5 to 3.5 mm. The first aluminium stakes were of a very soft quality, and they suffered from the disadvantage of being bent over repeatedly by the weight of snow. With the use of these stakes, precautions must be taken to prevent their sinking into the snow. The usual method is to fix to the lower part of the stake a plate on which it can rest. However, this necessitates the digging of a hole for each stake, and has the disadvantage of disturbing the snow stratification. The sinking also becomes negligible if the lower part of the stake is extended by a wooden dowel with more or less the same diameter as the stake itself. The wood can also be split at the lower end, so that when it is driven down, it is forced outwards, so forming a larger surface area. For the drilling down of the stakes, an auger with saw-teeth is used. The depth to which the stakes are inserted varies according to the ablation at that particular place. On the lowest parts of the glacier, it is necessary to drill to a depth of c. 5 m, while those near the firn line have not required re-drilling at all for many years. The frequent re-drilling of the stakes easily introduces an error into ablation readings. Moreover, an error will easily occur in deciding the velosity of the glacier. To prevent this, a series of wires was drilled into the glacier. With the help of a hot water drill these were sunk to 20 m. In order to find the wires more easily, a tetrahedral frame, which stood on the ice surface, was fixed to their upper ends. In addition, ordinary stakes were inserted, which could be used for accumulation measurement. With the help of the wires, a continuous measurement of ablation is obtained over several years. A period of c. 4 years is reckoned where ablation is greatest.

In the calculation of ablation, the specific gravity of the ice is set at 0.9, while the specific gravity of the snow during the ablation season keeps surprisingly

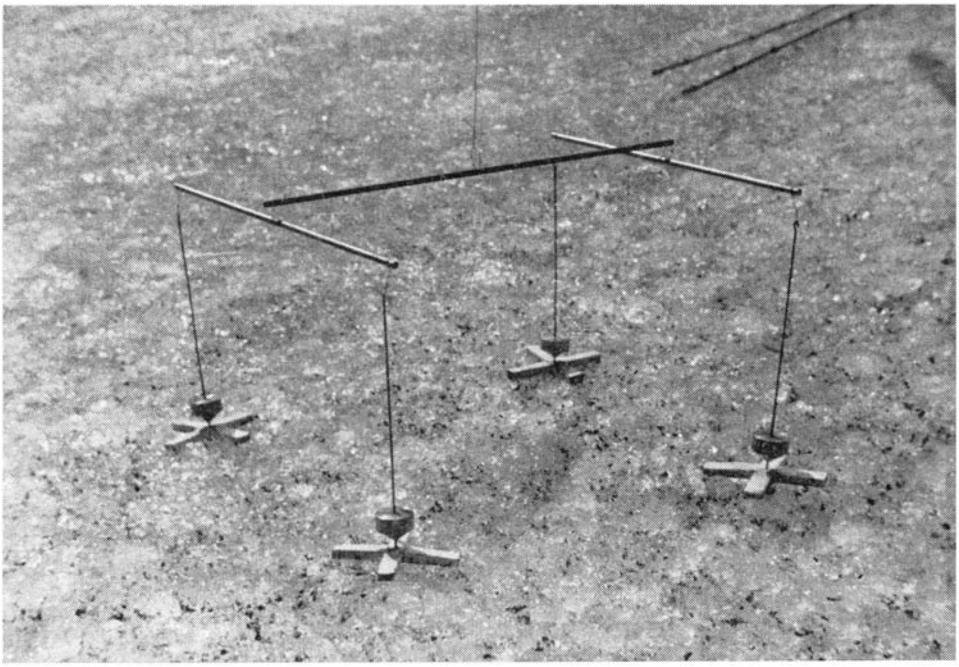

Fig. 10. *The photo shows the floats of the ablatograph which was used to record ablation during the summer of 1955. The record gives a mean of the ablation at the four plastic floats.*

constant with an average of 0.52. The following will occur at the beginning of the ablation season: The first meltwater will form ice in the snow layers downwards, and later the meltwater will be absorbed in the snow. The quantity absorbed will vary somewhat, and will be dependent upon the snow structure. Calorimetric measurements of water content have been made on Storbreen, and show some variations. At the end of the season it fluctuates about 10%. The water in the remaining snow will freeze in the course of the autumn, such that there is no necessity to consider it in the calculation of the total regime. However, if it is necessary to know the amount of ablation during a shorter period in summer, this water content will be significant, and the specific gravity of the snow must be reduced with a requisite percentage of water.

The internal ablation, i.e.: the effect of the earth's heat, internal friction, and friction of meltwater generated through holes and crevasses, is difficult to observe, and must, therefore, be calculated. This amount is very small, and lower than the degree of error in the other ablation observations. The effect of friction at the sole of Storbreen is without any special significance, but on larger and faster moving glaciers the ablation at certain places can be calculated to rise by 20–30 cm/year.

To obtain better knowledge of ablation and the controlling meteorological factors, special and more detailed measurements were undertaken in 1955, and later also in 1957 and 1965. In 1955 a small meteorological station was erected at 1600 m a.s.l. It was equipped with a radiation measuring instrument (actinograph), a thermograph, a hygrograph, and an ablatograph. The last was used for continuous

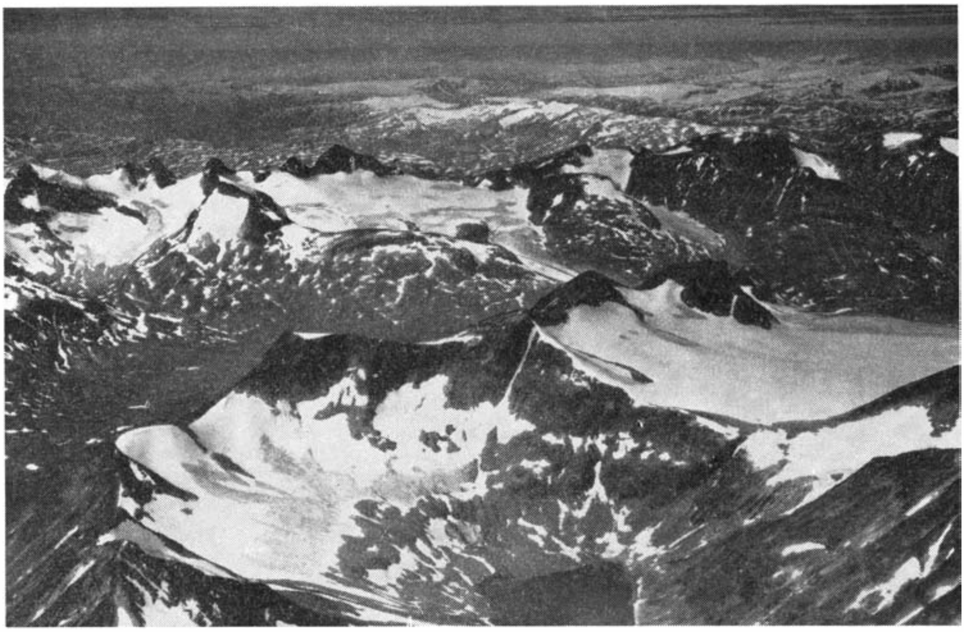

Fig. 11. *Aerial photography of part of western Jotunheimen with Storbreen in the centre; Jostedalsbreen in the far background.*

recording of ablation. The type is the same as that described in the 'Journal of Glaciology', Vol. 2, No. 16, pp. 431–432. In 1955, the measurements were begun at the end of June, and continued until the beginning of September. In this way over 80% of the ablation was registered. Wind observations were undertaken as often as possible at as many heights as possible. The measurements were made with an ordinary hand anemometer, which was placed on stakes up to a height of 5 m. The snow and ice albedos were measured with an actinometer, which was also used for the calibration of the actinograph. The glacier's albedo was mapped twice in the course of the season. The maps are based partly on actinograph measurements, and partly upon photographs of the glacier surface. The latter was done in order to obtain a more detailed picture of the variations. For the registering of temperature and humidity it is important that the instruments always stand at the same height. This is most difficult to ensure on a glacier, where the instruments are mounted on stakes drilled into the ice. As the glacier surface sinks with ablation, the instruments become continuously higher. Attempts have been made to correct this by adjusting the heights of the instruments. However, this is a difficult task, when the readings are continually upset by the adjustment, especially when it concerns the ablatograph. Errors in temperature and humidity observations over a snow surface also arise when radiation is high. It is difficult to obtain an effective shading without hindering the air circulation around the instrument at the same time. In the first 10 days of continuous observations in 1955, there was also an error in the clock of the thermohygrograph, which rendered these measurements very problematic.

Measurements and calculations of this type have been made round the world.

It has been found that the most important factors are radiation, convection, condensation, sublimation, and to a certain degree, melting by rain. Of these, radiation, convection, and condensation are the most important.

The radiation balance on a glacier surface is determined by the difference between the in-coming and the out-going radiation. The former consists of direct radiation, diffuse cloud radiation, reflected radiation from the snow-covered surroundings, and long-wave radiation from the atmosphere. A little long-wave radiation is derived in certain places from steep mountain sides, which have been warmed by the sun. The out-going radiation is composed of the long-wave variety, and reflected solar and cloud radiation. This last depends to a high degree upon the albedo of the surface. The global radiation, which is the sum of direct solar and cloud radiation, was measured in the present case by a Rubitsch actinograph. The albedo was measured at certain intervals by a Moll-Gorszynski actinometer. Values for the in-coming, short-wave radiation can thus be obtained directly. When it concerns long-wave radiation, the case is more difficult. There was unfortunately no instrument available for the direct measurement of the long-wave radiation balance. Calculations were therefore necessary. After later observations with a balance-meter on Hardangerjøkulen in the summer of 1965, the formula for the long-wave radiation balance, used by HOINKES and UNTERSTEINER (1952), appeared to be very suitable. Both height and position are so similar on Storbreen and Hardangerjøkulen that findings on one glacier can be safely applied to the other.

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

Here R_0 is determined at 0.085 cal. cm^{-2} min^{-1}. The cloud constant k is 1.4. This gives positive values for high cloud density, 9 and 10 (approx.). In July, there were two days, the 16th and 17th, with a positive balance. The cloud height was about 2 000 m, which is the same as that of the meteorological station at Fannaråki, 15 km away. It could be assumed, therefore, that the temperature in the lower surface of the cloud cover agreed with the temperature at that station. The temperature on these days fluctuated between +3.6 and -0.3, with an average of +1.3°C, and should give positive values for the long-wave radiation balance, as the formula shows. It is assumed that the glacier surface had a temperature of 0°C the whole time. Freezing on the glacier would certainly occur on clear nights, and this was, in fact, observed several times. However, it has little importance in the calculation of ablation. The long-wave radiation operates 24 hours a day, while short-wave radiation is important only after sunrise. In the calculations it was often difficult to state the correct cloud cover. To remedy this, supporting diagrams from the Rubitsch actinograph and observations from the meteorological station at Fannaråki were used.

With respect to the calculation of convection and condensation, the conditions are much more difficult, especially owing to periods when wind observations were lacking. These were taken as often and at as many height intervals as possible. However, it was impossible to make regular observations. The wind observations at Fannaråki are not quite suitable because the glacier is differently exposed, and also because there is a pronounced "Gletscherwind", especially on days with good weather. The calculations of convection and condensation for certain periods must therefore be accepted with reservation.

The energy supplied by convection and condensation is calculated respectively from the formulae:

$$Q_k = Cp \cdot As \cdot \frac{d\theta}{dz} \text{ t cal} \cdot cm^{-2}$$

$$Q_v = 600 \text{ As} \cdot \frac{0.623}{P} \cdot \frac{d\theta}{dz} \text{ t cal} \cdot cm^{-2}$$

Here cp=0.24, which is the specific heat of air at constant pressure. As, is the "Austausch" coefficient for thermally stable atmospheric behaviour. $\frac{d\theta}{dz}$ is the potential temperature gradient, e the moisture vapour pressure, and t the time in seconds.

The calculation of As also caused great difficulty, since only one anemometer was available. Therefore the wind speed at different heights could never be taken simultaneously.

Sublimation was recorded on 25 days. But it is obvious that sublimation also took place at short intervals on other days.

It has been mentioned earlier that the ablation was recorded automatically with an ablatograph. To convert the values to g/cm^2, snow density measurements had to be taken continually. The variations, however, were small, from 0.51 to 0.55 on the old snow. The water content of the snow had always to be considered. On days with strong in-coming radiation it was necessary to correct for the small melting of the ablatograph floats in the snow. This never exceeded 5 mm.

Table I, p. 21, shows the most important data for the ablation calculations.

In the table, the heat balance is calculated for the area around the station. Calculations for the whole glacier are made only for periods of 10 days. In the calculations of the contribution of radiation, in this case, account must be taken of the variations in albedo with time and place. Furthermore, the slope of the glacier relative to the sun must also be considered. In order to reduce complications, an average gradient is used for the whole glacier. The result was almost the same as for the station: radiation accounts for c. 54%, convection for c. 32%, and condensation for c. 14%.

On Storbreen the ablation season lasts from about 1st June to the middle of September, so the observation series of 1955 does not cover the whole period, but that part of the ablation season when melting was at its highest. That is to say c. 80% of the total ablation was recorded. In comparison with results from other areas the figures appear quite reasonable. The nearest observations of these ablation factors are from northern Sweden. There WALLÉN (1949), arrived at about the same figures as those for Storbreen. Several studies have been made in the Alps, especially by Professor HOINKES (1953). Here, the contribution of radiation reaches appreciably higher values, i.e.: over 80%, but this is only for very short periods; so, when taking account of the whole length of the ablation season, one must assume that correct percentage can vary somewhat. This is also

Table I.

	Date	Albedo	Global R.	Global R. absorbed	Long w R. balance	Total R. balance	Convection	Condensation	Sublimation	Total energy	Computed melting g/cm²	Ablatograph
			Cal / cm² / d								g / cm²	
JULY	6	58	405	168	— 10	158	45	25		228	2.85	3.2
	7	»	427	179	— 13	166	62	36		264	3.30	2.6
	8	57	712	306	—115	191	113	60		364	4.55	4.7
	9	»	732	315	—120	195	120	68	35	383	4.74	4.7
	10	»	730	314	—120	194	140	55	30	389	4.85	4.2
	11	59	725	297	—115	182	135	70		387	4.84	4.0
	12	»	690	283	— 80	203	95	45		343	4.29	4.7
	13	57	482	207	— 10	197	105	50		352	4.40	4.2
	14	»	490	211	— 40	171	95	58		324	4.06	4.3
	15	55	367	165	— 10	155	40	20		215	2.69	2.5
	16	»	294	132	+ 22	154	40	28		222	2.78	1.5
	17	54	300	108	+ 12	120	25	10		155	1.94	1.5
	18	65	480	168	— 40	128	0	0		128	1.60	0.5
	19	64	402	141	— 10	148	0	0		148	1.85	0.5
	20	62	460	175	— 95	80	48	28		156	1.95	2.5
	21	58	516	217	— 80	137	65	33		235	2.94	3.2
	22	»	660	277	—120	157	95	58		310	3.88	3.7
	23	»	582	244	— 95	149	98	33	22	280	3.47	4.0
	24	»	685	288	—120	168	128	5	39	301	3.76	4.2
	25	57	685	295	—120	175	138	12	40	325	4.06	4.1
	26	»	685	295	—120	175	150	28	52	353	4.33	3.7
	27	»	682	293	—120	173	168	42	35	382	4.73	4.4
	28	»	680	292	—120	172	152	58	20	382	4.75	4.2
	29	»	660	284	—120	164	145	52	12	361	4.49	4.0
	30	»	650	280	—115	175	125	58		358	4.48	3.7
	31	»	280	120	+ 10	130	58	38		226	2.83	2.7
AUGUST	1	»	252	108	+ 10	118	90	55		263	3.29	2.8
	2	»	528	227	— 90	137	48	20	12	205	2.54	2.5
	3	55	486	219	— 75	144	72	35	20	251	3.11	2.0
	4	»	366	165	— 35	130	75	35		240	3.00	2.5
	5	»	180	81	+ 15	96	160	75		331	4.14	3.4
	6	»	306	138	— 20	118	65	40		223	2.79	2.9
	7	»	259	116	0	116	35	20		171	2.14	1.7
	8	53	325	152	— 25	127	50	0	20	177	2.28	1.4
	9	45	264	145	— 35	110	80	95		235	2.93	2.8

	Date	Albedo	Global R.	Global R. absorbed	Long w R. balance	Total R. balance	Convection	Condensation	Sublimation	Total energy	Computed melting g/cm²	Ablatograph
			Cal / cm² / d								g /cm²	
AUGUST	10	43	450	256	— 55	201	105	55		361	4.50	3.5
	11	40	408	245	— 30	215	85	35	30	335	4.23	3.2
	12	38	450	279	— 35	244	110	30	35	384	4.75	3.4
	13	»	355	220	— 20	200	120	55	10	375	4.68	3.5
	14	»	366	227	— 25	202	125	65		392	4.90	3.9
	15	»	396	246	— 40	206	100	10		316	3.95	3.3
	16	38	288	179	— 30	159	95	45		299	3.74	3.5
	17	»	396	245	— 80	165	122	72		359	4.48	3.8
	18	»	108	65	+ 20	85	88	46		222	2.77	2.4
	19	»	348	216	— 60	176	65	10	30	251	3.18	2.2
	20	»	162	101	+ 15	116	113	60		292	3.65	3.1
	21	40	492	295	—120	175	85	35	25	293	3.68	3.3
	22	»	426	255	— 90	165	83	25	40	273	3.21	2.5
	23	»	426	255	— 90	165	23	15	10	203	2.53	2.2
	24	38	470	292	—110	182	102	30	30	314	3.92	3.6
	25	40	474	284	—120	164	118	78		360	4.50	3.8
	26	»	342	205	— 50	155	145	65		365	4.56	5.8
	27	»	235	141	— 10	131	107	72		310	3.87	4.1
	28	»	469	282	—115	147	45	10	20	202	2.53	2.1
	29	38	409	253	— 80	153	50	30	5	233	2.91	2.2
	30	36	193	124	+ 20	144	122	67		333	4.16	4.5
	31	40	72	47	+ 20	67	70	33		170	2.13	1.8
SEPTEMBER	1	38	325	202	— 40	162	15	5		182	2.28	0.8
	2	60	126	50	+ 10	60	8	5		73	91	0.4
	3	»	265	106	— 10	96	11	4		110	1.37	1.1
	4	50	253	126	— 20	106	16	8		130	1.62	1.4
	5	36	108	69	+ 15	84	28	8	10	120	1.49	1.6
	6	»	103	66	+ 10	76	48	25		149	1.86	2.4
	7	»	403	257	— 80	177	45	0	25	222	2.79	2.4
	8	»	476	304	—110	194	69	20	15	283	3.52	2.0
						9795	5358	2303	622	17456		
		Ice melted gr/cm²				122	67	29	1	218.2		205.3
		Ice melted %				55.8	30.6	13.2	0.4	100.0		94

Fig. 12. *Lower part of Storbreen with Leirdalen valley to the right and Hestbrepiggene in the background.*

confirmed by AMBACH and HOINKES (1963) and WENDLER (1964). The last author found that 66% of the whole ablation in the snow area and 61% in the ice area were caused by radiation. Results from polar areas are also available, but these are not easily comparable with those from Storbreen. Some measurements have been made in Iceland, and in 1936 a good deal of work was done on Vatnajøkul. On the lower parts of the glacier the contribution of convection was the greatest. This is due to the high temperatures found in such low areas, and to the typically oceanic climate. The same tendencies can be expected in Norway westwards to the coast.

The measurements described here could have been improved considerably by the use of a balance-meter. The great uncertainty in determining the cloud cover and temperature at higher levels would thus have been avoided. A recording anemometer which could measure wind speed at different levels would also have improved the results greatly. As stated above, the wind on a glacier is a very local phenomenon and, therefore, one cannot use observations from nearby meteorological stations. One should also have recording instruments for temperature and humidity at several levels, since the gradients are difficult to calculate, especially in situations with a "Gletcherwind".

Regime

The activity of a glacier and its reaction upon meteorological factors are best studied by making up its "material balance" or regime. That is the sum of total accumulation and ablation volume during one accumulation and ablation season or a budget year. The regime is positive when, during a budget year, the accumulation volume is higher than the ablation. The glacier is in equilibrium when the volumes are equal, otherwise the regime is negative. The definition of a budget year is somewhat difficult. The budget year begins when accumulation surpasses ablation, and lasts to a moment in the subsequent year when the same conditions is obtained. The length of a budget year will thus be varying from place to place and from year to year, depending on the height above sea level and on meteorological conditions. One year will also, in this way of considering a budget year, overlap the other, and begin and end at different dates at different heights.

On Storbreen, at the firn limit, the budget year normally begins in the middle of September, at the snout about 14 days later, and in the upper firn area 14 days earlier.

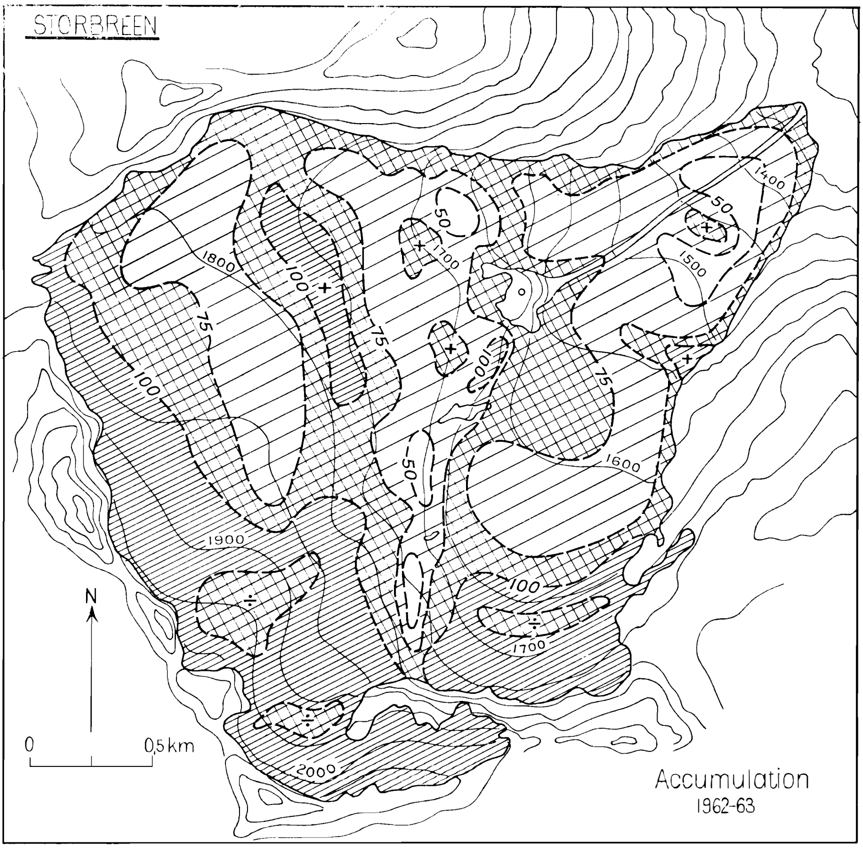

Fig. 13. *Accumulation map of Storbreen glacier in the budget year 1962–63.*

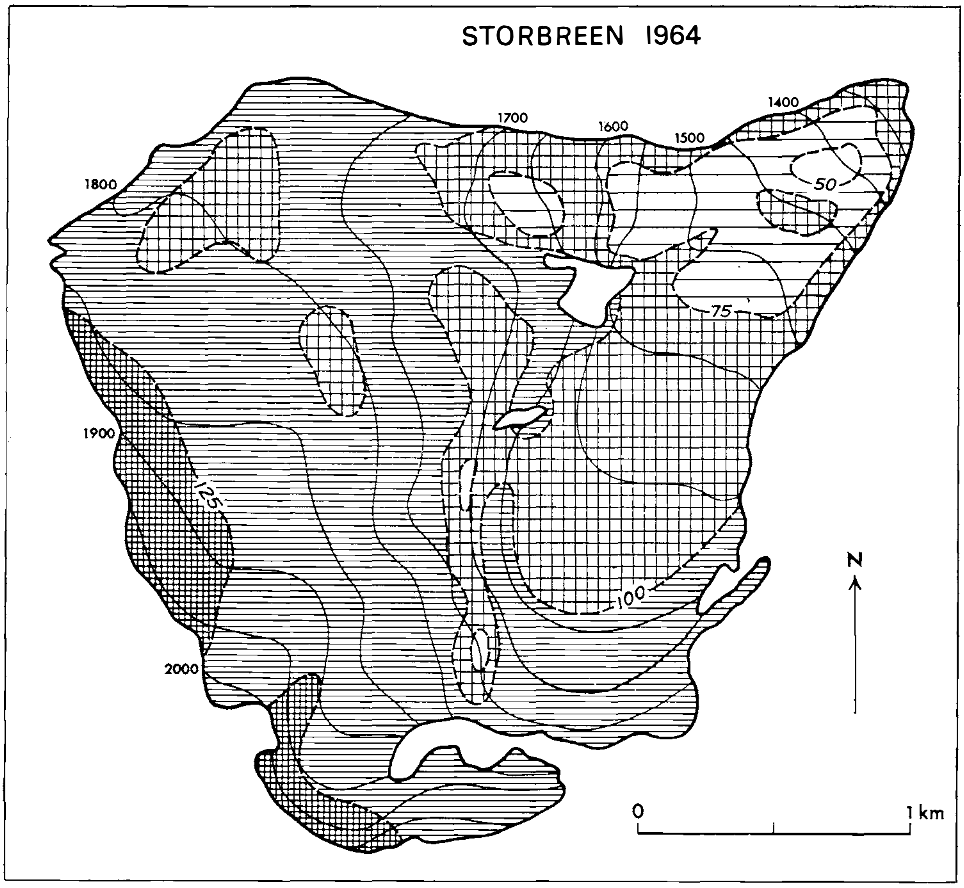

Fig. 14. *Accumulation map of Storbreen glacier in the budget year 1963–64.*

For practical reasons it would be of great advantage if the end of the budget year could be fixed at a certain date. This, however, would be unnatural in extreme years, when ablation ends very late, or accumulation begins early. For Storbreen, therefore, it has been decided not to choose any particular date for the close of the budget year. As mentioned in the chapters on ablation and accumulation, it is very difficult to obtain the total ablation. In order to measure it, one would have to have an observer on the glacier for the whole year. In practice this has been impossible. In certain years measurements of ablation could have been carried out during the greater part of the ablation season, but spring and autumn have always been difficult times. There is always the possibility of snowfall which melts away again, and which are not recorded at all. Approximations for these volumes can be determined by calculation, and this has been done for each year on Storbreen. Therefore, the figures given below show the total accumulation. In addition to the short descriptions of the individual budget years, certain special years have been chosen and expressed graphically. Furthermore, there are maps showing the distribution of accumulation for a number of years.

The individual budget years are described below:

1948–49

No direct measurements were made of the accumulation before ablation began. The accumulation volume had therefore to be calculated from observations of the remaining snow layer in early summer and from meteorological observations at the surrounding meteorological stations. The precipitation was highly above normal throughout western Norway and the central mountain regions, causing the largest accumulation volume registered during the 16 years of investigation, and probably the largest in this century.

The ablation in the summer of 1949 was also above normal, but could not compensate for the preceding winter's high accumulation volume. The result was therefore a positive balance at the end of the budget year.

1949–50

Accumulation was measured between 1st and 9th May. On the snout the ablation had already started, but the meltwater was still deposited in the snow or refrozen on the ice surface below. To find the depth of the snow, 360 soundings were made, and in ten pits gravity, structure and temperature were investigated. With the calculated addition of snow that fell after direct measurements had been made, the accumulation volume totalled $8.20.10^6$ ton or 152 g/cm^2.

In the ablation period the glacier was visited only once, viz. in the last week of August. This was also a little too late to prevent some of the stakes at the lower part to melt out.

1950–51

The accumulation measured in early May totalled $6.30.10^6$ ton, which is well below normal.

In the course of the summer the glacier was visited at the beginning of July, and later at the end of August and beginning of September. The summer was rainy, with temperatures a little below normal. Owing to the low accumulation volume the regime came out with a negative balance of –54 g/cm^2.

1951–52

The $7.90.10^6$ ton accumulated this year was a little above normal. The bulk of the accumulation came in mid-winter, especially in December, when the meteorological station Fannaråki registered 227 mm.

The summer of 1952 was even more rainy and colder than 1951. The temperature at Fannaråki during the period 1/5–30/9 was 1.73°C below the last 20 years' average. The result was a positive material balance of +31 g/cm^2.

1952–53

The accumulation period set in early, at the firn limit about 1/9. But the winter was rather dry, resulting in an accumulation volume $7.30.10^6$ ton, which is near the average for the seven years investigated. Owing to the extremely warm June, 4.9°C above normal, ablation had surpassed last winter's accumulation as early as about the middle of July. The rest of the summer was, however, rather cold and rainy, with temperatures below normal. The result was a deficit of –85 g/cm^2.

1953–54

Precipitation was low throughout the winter, causing a low accumulation volume.

The summer temperature was normal, but owing to the low accumulation the deficit was as large as –77 g/cm².

1954–55

From the beginning of the accumulation period, starting simultaneously all over the glacier, till the measurements were initiated, no thawing or extraordinary weather conditions occurred. Accordingly, the snow was exceptionally homogeneous from the snout to the top. The accumulation was a little above normal.

The ablation season set in late. No meltwater had passed the limnigraph until the middle of June. The rest of the summer was, however, warm and dry, resulting in a deficit of -49 g/cm².

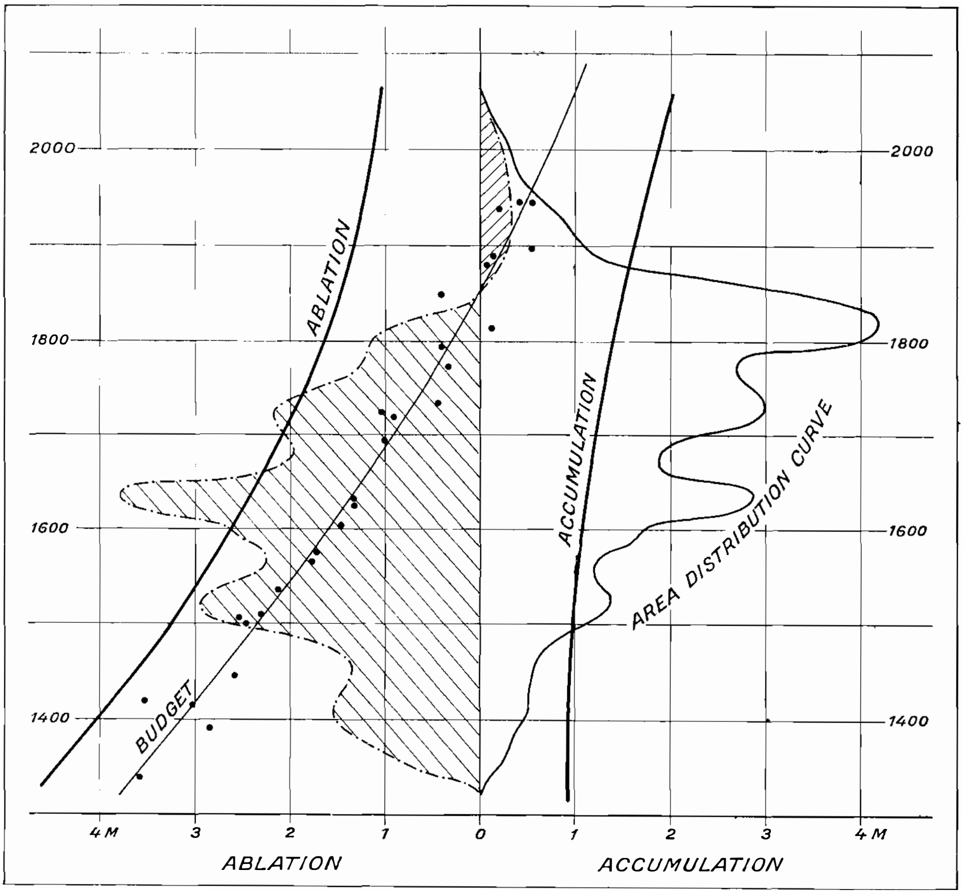

Fig. 15. *The regime of Storbreen glacier in the year 1952–53. The curves represent accumulation, ablation and the variation in the glacier mass balance with height. The shaded area represents the volume of increase and decrease of the glacier during the budget year.*

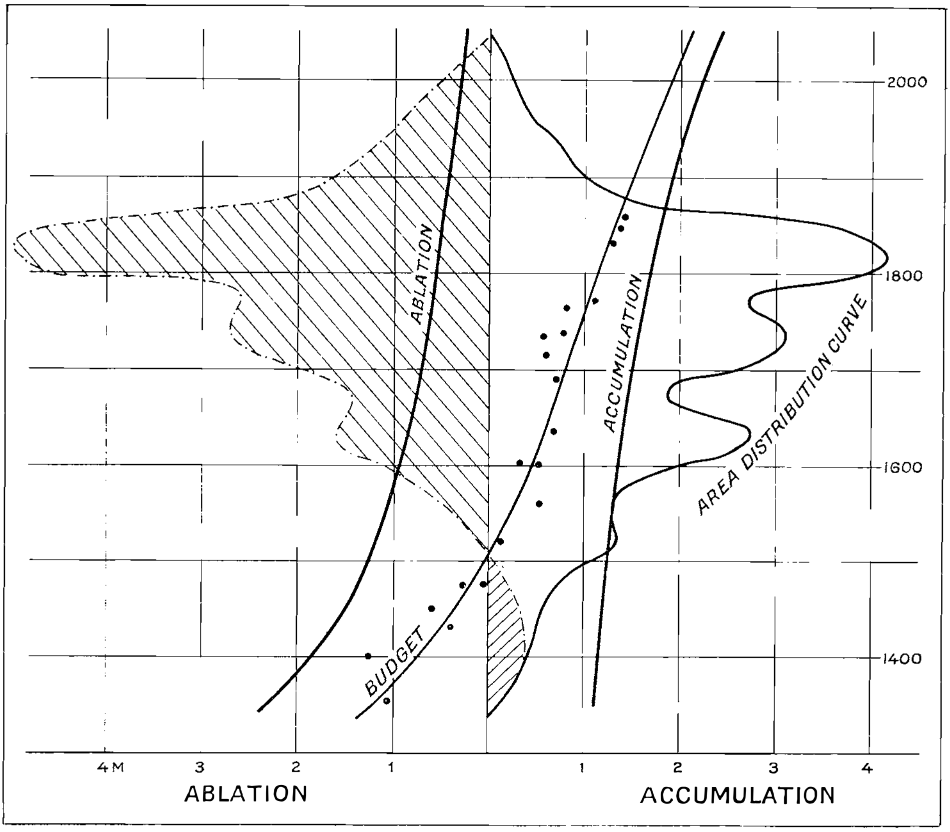

Fig. 16. *The regime of Storbreen in the budget year 1961–62.*

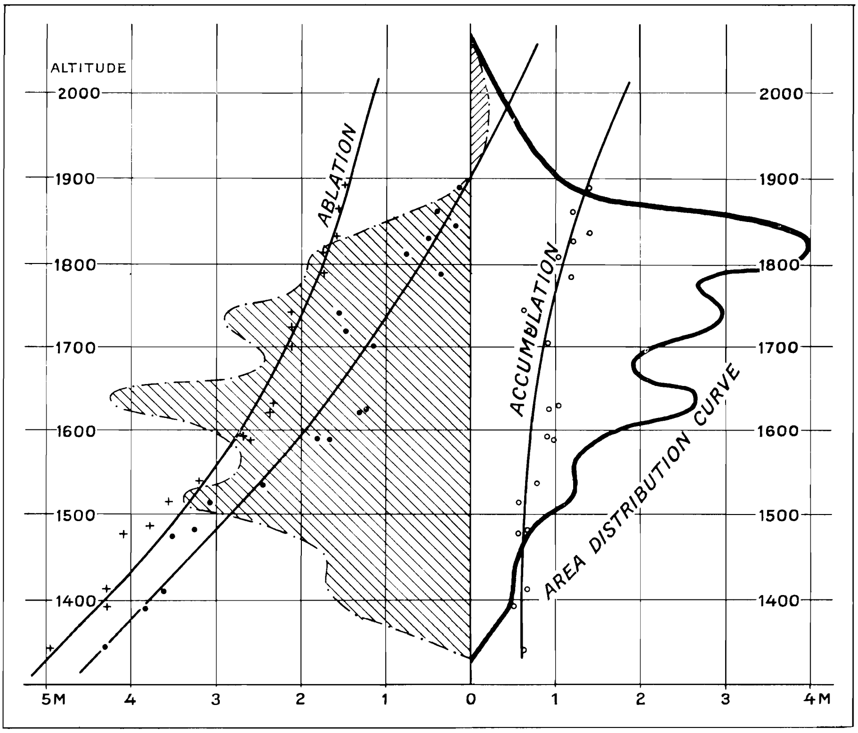

Fig. 17. *The regime of Storbreen in the budget year 1962–63.*

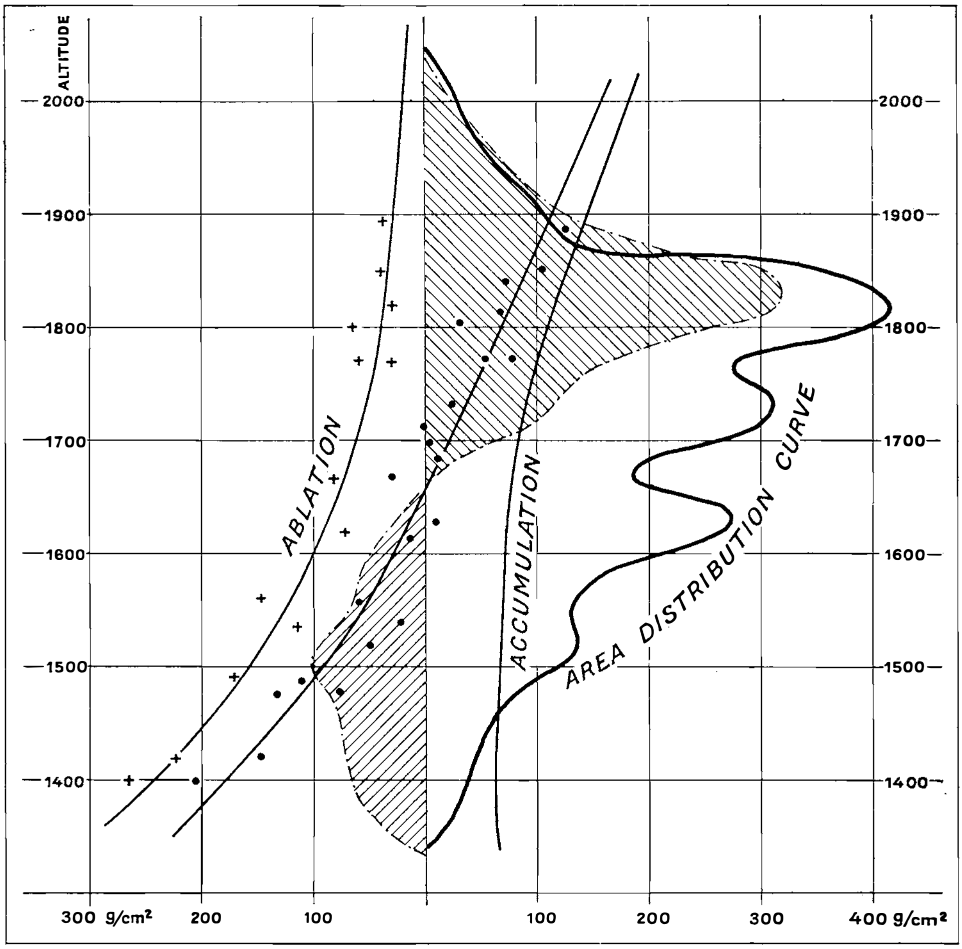

Fig. 18. *The regime of Storbreen in the budget year 1963–64.*

1955–56

At the upper part of the glacier accumulation set in about September 10th. At the snout ablation persisted till the end of the month. Most of the precipitation came before mid-winter (c. 70% above normal). But the rest of the season was dry, except for May and early June. The part of the accumulation to be calculated for the months May and June, and added to the direct measurements of 97 cm, was as high as 34 cm, giving a total of 131 cm.

Owing to the wet and cold summer, 1° below average for the summer months, the ablation was also below average. The result was a negative balance of -17 g/cm^2.

1956–57

The accumulation during this year was a little above normal. This was due principally to an unusually large precipitation in January, which provided c. 30% of the total accumulation. The summer was quite rainy and cold, and this resulted in a small surplus for the glacier.

1957–58

About 80% of the total accumulation fell during the autumn. A certain amount also occurred in May and June, which were very cold this year. July was also cold, but an unusually warm September, which was 4.1°C above normal, changed the regime from a positive to a weak negative balance.

1958–59

The accumulation was far below normal. A warm, dry summer caused the greatest ablation hitherto measured. The result was a large deficiency, 128 g/cm^2, which was also the highest negative regime measured so far.

1959–60

In eastern Norway the precipitation during the accumulation season was about 50% above normal, while in western Norway it was 50% below normal. The measurements on Storbreen showed a deficiency of 35%, relative to the

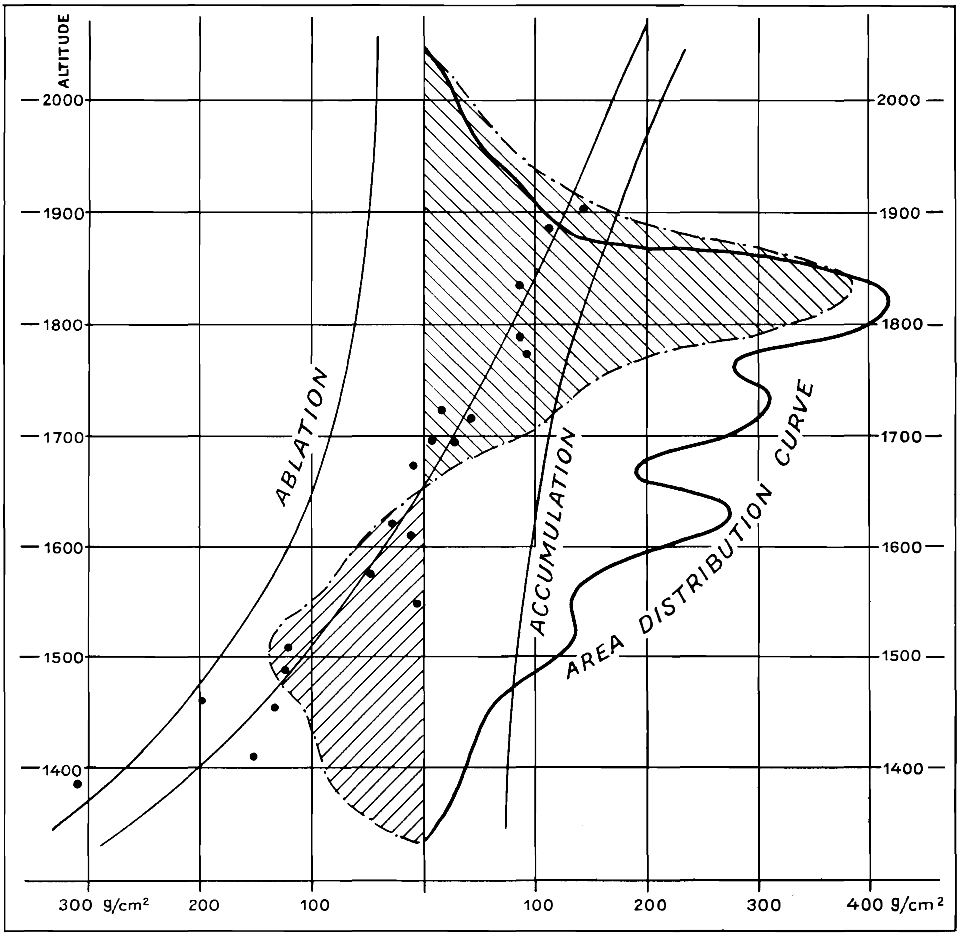

Fig. 19. *The regime of Storbreen in the budget year 1964–65.*

calculated normal year. This shows clearly how Storbreen is influenced by the weather conditions in west Norway. The summer was wet but warm, and the result was the next largest negative budget so far measured.

1960–61

The autumn, which normally provides the greatest part of the accumulation, was very dry this year, and the result of the measurements in spring showed a deficiency with respect to normal. The ablation was around the normal, but the result was a negative balance of –52 g/cm^2, owing to the low accumulation.

1961–62

The accumulation season began very late, and the measurements in May showed it to be 15 g/cm^2 below normal, but, owing to the extremely cold summer, the accumulation continued more or less throughout the whole summer half of the year. For the same reason, the ablation was far below normal, only 82 cm. The result for the year, therefore, was a surplus of 72 g/cm^2, which was the highest increase hitherto measured.

1962–63

The winter was very dry, and the accumulation reached no more than 96 cm, which was the lowest measured. The summer was wet, but mild. The ablation was therefore above normal, and this, with the unusually low accumulation, resulted in a deficiency of 118 g/cm^2.

1963–64

The winter was similar to the previous one, very dry, especially during the later part which had practically no precipitation. The summer, however, was very cold, such that a great part of the precipitation during the ablation season fell as snow in the highest areas. The temperature for the period 1/5–30/9 lay 1.2°C below normal. The result was an ablation far below the average, namely 95 g/cm^2. The positive balance was 21 g/cm^2.

1964–65

The winter precipitation was about the normal, and just as in the previous year, the accumulation continued through the summer, as a result of the low temperature, which was 0.4°C below normal. The ablation was 120 g/cm^2. For the first time, two consecutive years had a positive balance, although the surplus was no more than 34 g/cm^2.

From the figures showing the regime of Storbreen for some of the individual years (Figs. 15–19) it can be seen that the curve representing the variation of the specific budget b with height is not linear. The gradient $\frac{db}{dz}$ decreases with increasing height on most glaciers. In the figures mentioned, the curve is smoothed in relation to the observed values. With a sufficient number of observations it would be

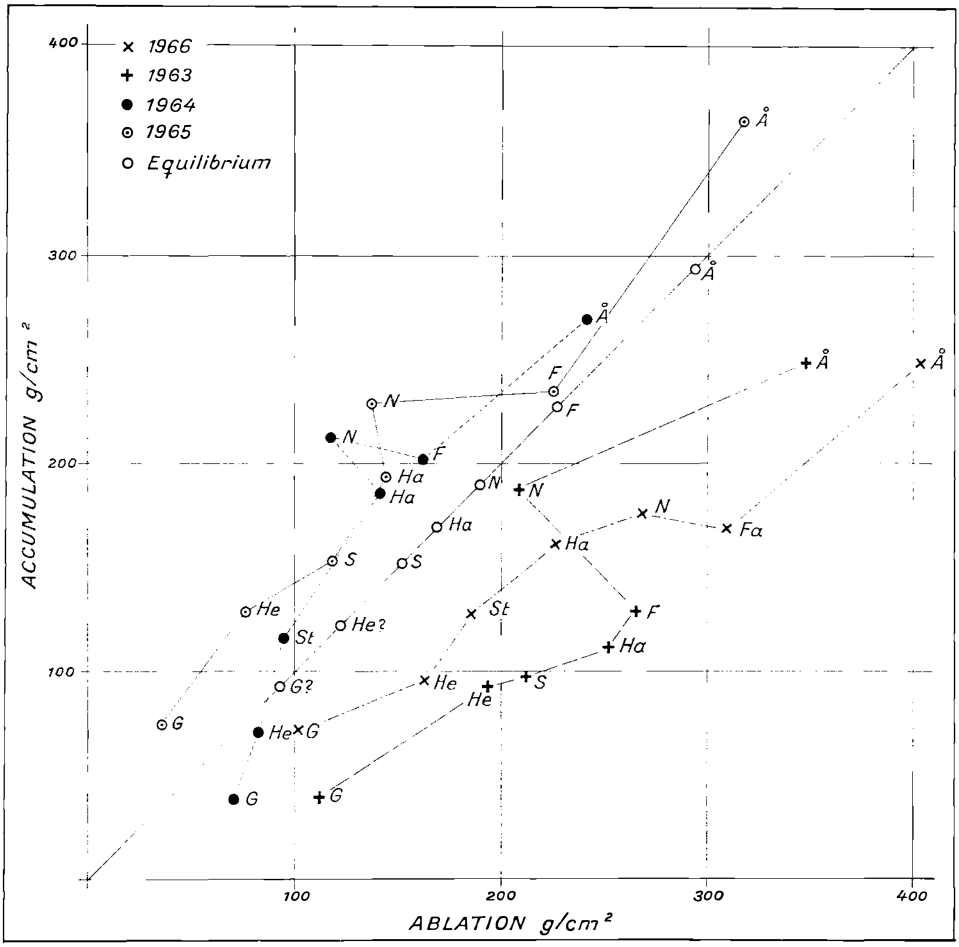

Fig. 20. *The diagram shows the regime of Storbreen in four years in relation to other glaciers in southern Norway. The diagonal represents the conditions when the glaciers are in equilibrium and have a normal regime. S = Storbreen, Ha = Hardangerjøkulen, Å = Ålfotbreen, N = Nigardsbreen, He = Hellstugubreen, G = Gåsbreen, and F = Folgefonni. The last five glaciers are measured by Norges Vassdrags- og Elektrisitetsvesen.*

possible to draw a correct and continuous curve, which, however, would certainly be irregular.

These irregularities are due mainly to uneven accumulation, which is itself due to transport by wind, and unevenesses in relief. The curve for the variation of ablation with height is smoother, as should be the case theoretically. As mentioned earlier, the ablation is determined in the main by three factors, radiation, convection, and condensation. Radiation is, so to speak, constant with height. When the importance of wind is ignored, the effect of convection, and to some extent also the condensation, depends upon the temperature, which is in turn dependent upon the height above sea level. Thus follows this approximation:

$$\frac{da}{dz} = K \frac{dt}{dz}$$

Here a is ablation, t the temperature, and K a constant. When the thermal

Table II

Year	Accumulation g/cm²	Ablation g/cm²	Budget g/cm²	Temp. Luster 1/5–30/9
1948–49	228	208	+ 20	10.98
1949–50	152	181	— 29	10.22
1950–51	113	167	— 54	10.02
1951–52	144	113	+ 31	8.68
1952–53	140	125	— 85	11.68
1953–54	121	198	— 77	10.68
1954–55	157	206	— 49	10.46
1955–56	131	148	— 17	9.60
1956–57	142	137	+ 5	9.28
1957–58	154	162	— 8	10.08
1958–59	107	235	—128	11.10
1959–60	98	207	—109	11.38
1960–61	110	162	— 52	10.04
1961–62	154	82	+ 72	9.04
1962–63	96	214	—118	11.24
1963–64	116	95	+ 21	9.02
1964–65	154	120	+ 34	10.28
Mean	136	168	— 32	10.21

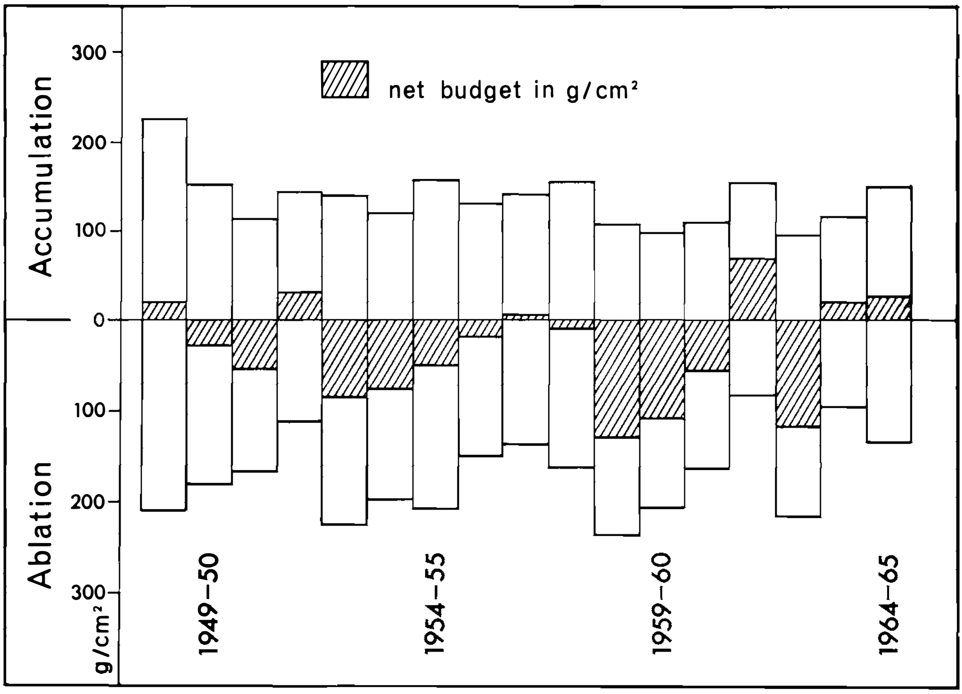

Fig. 21. *Diagram showing regime observations at Storbreen 1949–65.*

gradient is nearly constant within the height intervals discussed here, the variation of the ablation with height should be approximately linear. We know, however, that this is far from being the case, and the reasons are several. Firstly, convection is to a high degree dependent on the wind strength, and that, on the average, is not equal over the whole glacier. On warm, clear days, when the ablation is greatest, a "Gletcherwind" occurs. This is non-existent on the upper parts of the glacier, but is very strong and constant on the lower parts. Furthermore, R is not constant in so much as the albedo varies. There is a distinct difference between snow-covered and ice areas. One finds, therefore, a considerable decrease in the absorbed radiation on passing the firn line. However, in the course of the ablation season this line will gradually retreat upwards to the climatic snow-line, which is normally reached at the end of the season. The result is a gradually decreasing effect of radiation up to the firn line, after which, however, it should remain more or less constant. During the ablation season, snowfall in the upper regions, which has not been recorded, will have a similar effect upon the ablation. The result is that the ablation gradient $\frac{da}{dz}$ decreases relatively rapidly with height up to the firn line, and afterwards remain more constant.

Variations in climate and the regime

Direct observations of regime date back to 1949 only. That is, measurements of variations in length are available as far back as 1901. There is a seeming connection between variations in length and the regime on most of the glaciers investigated. It takes some few years, however, for the outcome to make its appearance, and only pronounced continuous climatic variations are generally to be recorded.

The 17 years dealt with in this paper supply the material for establishing a connection between meteorological data from the nearby situated meteorological stations and the regime of the glacier.

There are two predominant factors determining the life of the glacier: precipitation during winter and summer temperature.

According to the earlier descriptions of glacial-meteorological research on Storbreen, radiation should play the greatest part in ablation. Now, however, there are no direct observations of solar radiation at the nearest meteorological stations in the area. What we have are observations of temperature, cloud cover and humidity, together with wind strength. Nevertheless, there is a good correlation between temperature and radiation, such that, using temperature alone, quite a good correlation with ablation can be obtained. When the wind variations are ignored, convection will be nearly proportional to the temperature. Furthermore, condensation will also be dependent upon and well correlated with the temperature.

The meteorological stations used for the calculation of the average temperature on Storbreen are the following: Fannaråki, Luster, and Elveseter. These stations are considered to be the most representative for this glacier area. Fannaråki lies 1.5 km and Luster 37 km WSW of Storbreen, while Elveseter lies about 16 km to the NW. The station Fannaråki lies at 2062 m, Luster at 484 m, and Elveseter at 674 m above sea level. The equilibrium line on Storbreen normally lies at 1690 m a.s.l. The height differences, therefore, between the firn line and the three stations, Fannaråki, Luster, and Elveseter are 372 m, 1206 m, and 1016 m respectively. Thus, Fannaråki, in terms of height differences, lies nearer than the other stations. The Meteorological Institute in Norway in its description of the stations has referred to Luster as fairly satisfactory. The station is situated on an exposed ledge high on the side of Luster Fjord, and should therefore not be influenced by inversion, and especially not by local warming effects. It should then be representative for a larger surrounding area. Elveseter is not described as a particularly good station, since it lies in a narrow valley and experiences some shading effects. Furthermore, in the winter half of the year, one has to reckon with a certain amount of inversion. The temperature observations at Fannaråki have been described by ODD EIDE (1942), who made some comparisons between Fannaråki and the free atmosphere over Kjeller. It was found that the summer temperature at Fannaråki was about 2°C lower than that over Kjeller at the same height. This could be due to a certain amount of compression around the peak, and to some out-going radiation. However, comparing Fannaråki with the surrounding stations and using the normal temperature gradient for the summer months, it can be concluded that Fannaråki is quite as representative as the other stations round about, and does not differ significantly from the ordinary trend in its observed temperatures. Since Fannaråki, as mentioned above, lies nearer to Storbreen both in horizontal distance and height, one is justified in giving its observations double weight.

Using the arithmetic mean of the temperature observations at the three stations, with those from Fannaråki weighed double, a temperature can be obtained corresponding to a height of 1320 m. To obtain the temperature at the firn line at 1690 m, the above temperature must be reduced to this height by using the daily temperature gradients for the different months. In Table I the temperature for the firn line is calculated for the summer months of the years 1949 to 1964. The calculations are made for the months May to September. Some ablation can also occur in October, but this is of such small significance that it is not considered here. In the lowest line of the table the sum of the degree-days is calculated from the corresponding temperatures. Among the temperatures recorded for the summer months can be found a number of negative values which affect the mean. These temperatures ought not to be included, as they have no importance in ablation. An unusually cold May will thus lower the whole average, giving an unrepresentative summer temperature. It would be natural, therefore, to use only the positive temperatures. This would, however, constitute a very large task; one would have to go through the tables for each day, and preferably for each observation, taking out those observations which were above zero. But a near approximation can be obtained by representing the monthly mean graphically and measuring by planimeter the area between the temperature curve and the zero line. By this means a good deal of the minus temperature effects at the beginning and the end of the period can be eliminated. Thus, the sum of all the positive temperatures is obtained. In the literature one often finds

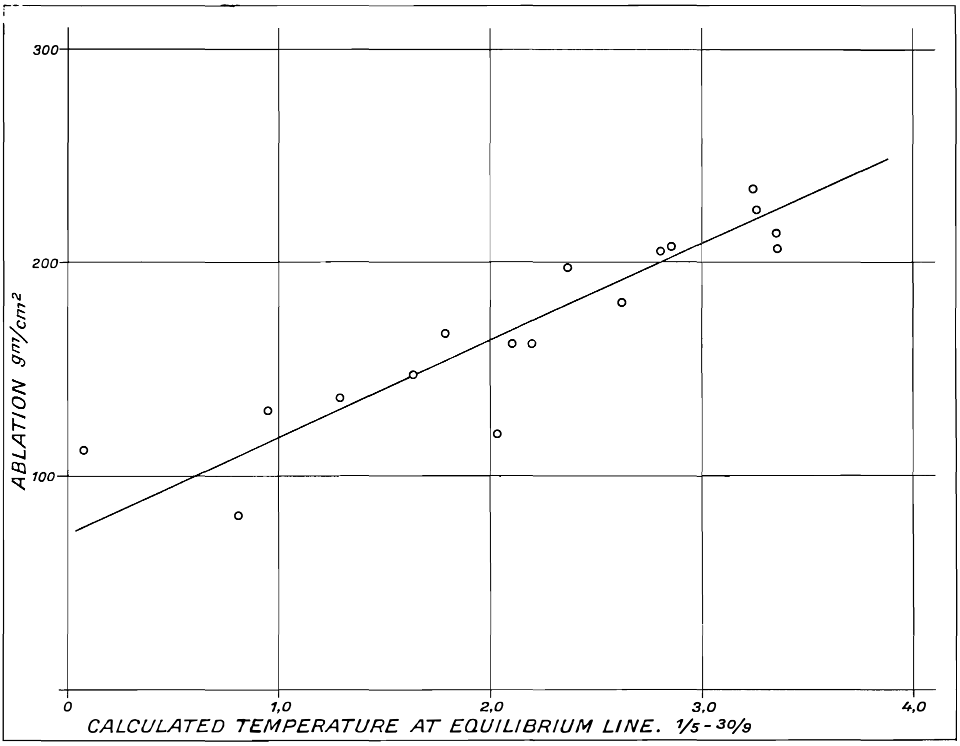

Fig. 22. *Relation between ablation at Storbreen and calculated summer temperature at firn line.*

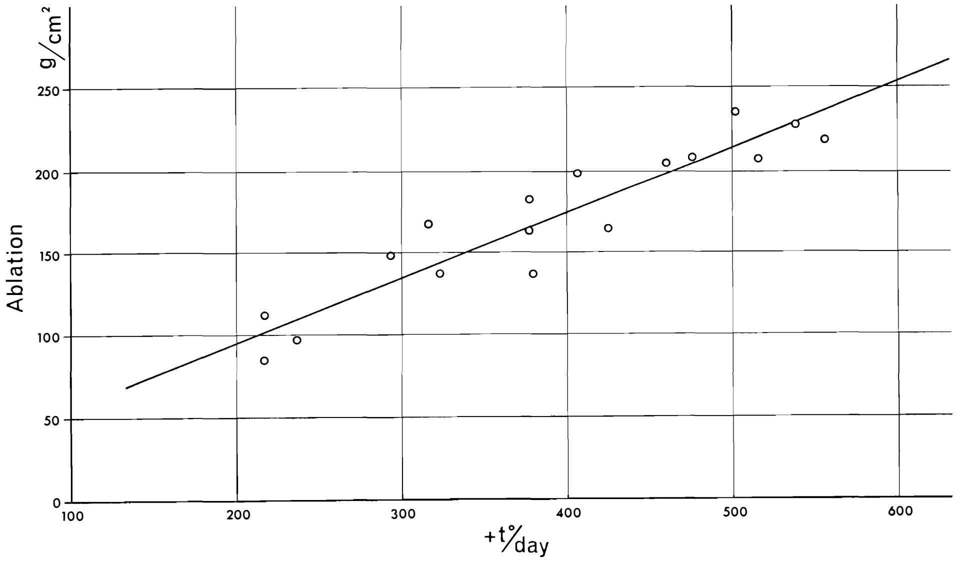

Fig. 23. *The correlationship between ablation on Storbreen and "temperature degree days" calculated from temperature observations from the stations Elveseter, Luster and Fannaråki for the years 1949–65.*

the expression "degree-day", which is an expression for these positive temperatures. One degree-day should therefore be one degree multiplied by one day. If the mean temperature for one day is, e. g. 5°, such a day will represent 5 degree-days. As can be seen from Fig. 23, the degree-days give a better correlation with ablation than does temperature alone. The difference is, however, not so great as to prohibit the use of temperature in the calculation of ablation.

As mentioned before, there are cloud cover observations from the three stations employed here. These are, however, very unreliable, and are based upon personal judgements. Over a high mountain area, such as this, the cloud cover will be highly variable, often with fog on the higher parts. In consequence therefore, no attempt has been made to arrive at the weight which should be given to cloud observations in the calculation in order to arrive, eventually, at still better values for ablation.

The good correlation to be found here gives a basis for the calculation of ablation backwards in time. The observations at Elveseter and Fannaråki do not extend further back than 1935 and 1932 respectively. One is therefore reduced to using only the station at Luster, where there are observations as far back as 1900. To go still further back in time, one must use observations from Bergen. The correlation between this last station and Storbreen is not so good as for

Table IV

Calculated temperature at firn line on Storbreen 1690 m above sea level

	1949	1950	1951	1952	1953	1954	1955	1956
May	—0.92	—0.65	—0.87	—3.25	—0.38	+1.40	—3.25	—1.43
June	+2.68	+1.98	+1.82	+0.23	+7.28	+2.80	+1.25	+1.17
July	+4.78	+4.20	+2.47	+3.38	+4.70	+4.28	+7.93	+4.98
Aug.	+2.95	+4.93	+4.23	+2.53	+3.53	+4.15	+6.85	+1.80
Sept.	+4.15	—0.28	+1.30	—2.50	+0.78	—0.78	+1.28	+1.45
mean	2.86	2.03	1.79	0.08	3.27	2.37	2.81	1.64
+t°.day	476	376	315	216	538	406	448	294

	1957	1958	1959	1960	1961	1962	1963	1964
May	—2.25	—3.40	+0.60	+1.25	—0.88	—2.18	+0.75	—0.05
June	+0.93	+2.73	+3.25	+4.85	+2.88	+0.45	+5.70	+1.20
July	+5.20	+4.05	+6.40	+4.35	+4.28	+4.63	+4.80	+2.60
Aug.	+3.80	+3.78	+4.90	+5.05	+2.73	+1.73	+4.75	+2.95
Sept.	—1.40	+3.43	+1.15	+1.35	+2.03	—0.60	+0.63	—0.13
Mean	1.29	2.11	3.25	3.37	2.20	0.81	3.36	1.31
+t°.day	320	425	502	518	378	218	556	238

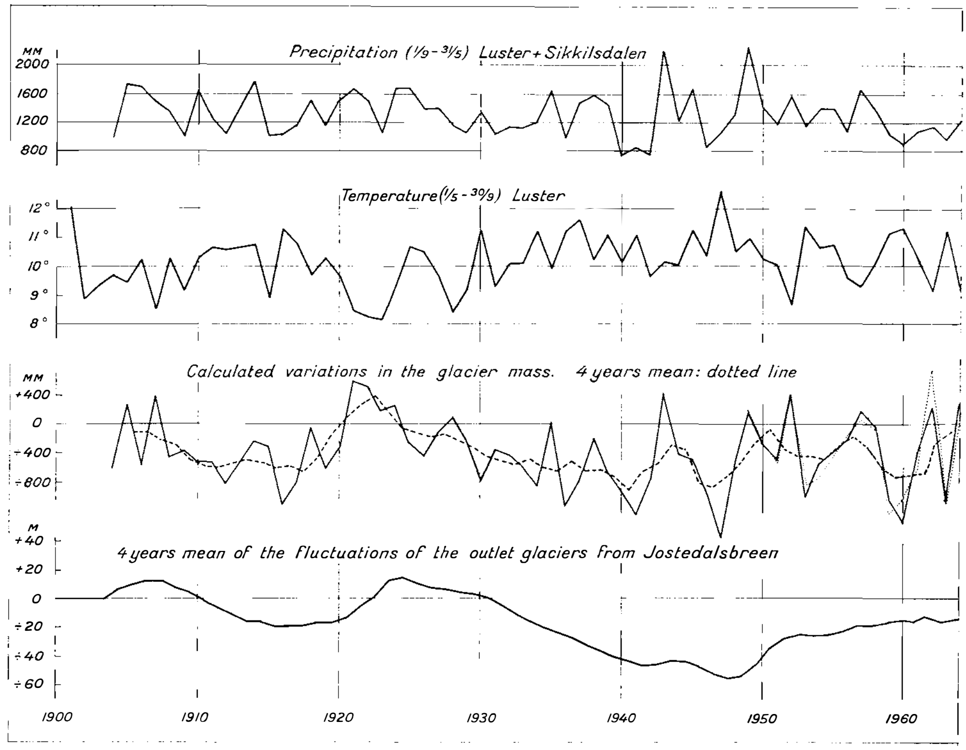

Fig. 24. *Calculated and observed variations in Storbreen's budget. The observed portion, covering the years 1949–64, is represented by the dotted line. As the Luster meteorological station lies halfway between Storbreen and Jostedalsbreen, the calculated balance should also be reasonably representative for the latter. A curve of the lenght variation of its outlet glaciers is therefore given at the bottom of the figure. Note the good agreement between the four years mean of observed length variations and calculated balance, taking into account a four year lag.*

Luster, but, nevertheless, it gives a very good basis for calculations of ablation on Storbreen.

The calculations of accumulation is not as simple as those for ablation. Storbreen lies on a watershed, and will receive precipitation from both east and west. The correlation, therefore, between observations of precipitation and the surrounding stations will not be particularly good. The Meteorological Institute in Norway has undertaken correlation calculations of the precipitation at different stations in the country. These show that there is an unusually good correlation within the different parts of the country. Over the greater part of West-Norway the correlation coefficient is over 0.95. On the other hand, the correlation between East- and West-Norway is negative for most stations. For the region near the watershed it is about zero. But calculations indicate that the high mountain areas near the watershed have a higher influence from west.

In Fig. 24 the accumulation on Storbreen is compared with that at the stations of Sikkilsdalen and Luster.. If the measurements on Storbreen are compared with those in Bergen, for example, the correlation is almost quite as good. One could, therefore, have used any station one chose in the whole of West-Norway. Since

Table III. Calculated mass balance based on data from Bergen 1816–1962

Year	Precip. 1/9–1/5 Bergen	Accumulation Storbreen	Temperature Bergen 1/5–1/10	Abl.calc. Storbreen	Mass balance Storbreen
1816	No observations. The mean precipitation 1861–1962 used.	No observations. The mean precipitation 1861–1962 used.	1160	112	+ 26
17			1238	156	— 18
18			1294	188	— 50
19			1352	221	— 83
1820			1208	139	— 1
21			1246	160	— 22
22			1238	156	— 18
23			1162	113	+ 25
24			1286	184	— 46
25			1324	205	— 67
26			1318	202	— 64
27			1240	157	— 19
28			1346	218	— 80
29			1244	159	— 21
1830			1254	165	— 27
31			1394	245	—107
32			1230	152	— 14
33			1262	170	— 32
34			1334	211	— 73
35			1194	131	+ 7
36			1026	35	+103
37			1126	92	+ 46
38			1124	91	+ 47
39			1126	92	+ 46
1840			1126	92	+ 46
41			1192	130	+ 8
42			1324	206	— 68
43			1286	184	— 46
44			1188	128	+ 10
45			1236	155	— 17
46			1418	259	—121
47			1196	132	+ 6
48			1162	113	+ 25
49			1146	104	+ 34
1850			1178	122	+ 16
51			1084	68	+ 70
52			1414	257	—119
53			1288	184	— 46
54			1260	169	— 31
55			1234	154	— 16
56			1126	92	+ 46
57			1340	214	— 76
58			1354	222	— 84
59			1280	180	— 42
1860			1186	126	+ 12
61			1262	170	— 32
62	907	81	1260	169	— 88
63	1616	144	1146	104	+ 40
64	1771	158	1158	110	+ 48
65	1035	92	1264	171	— 79
66	1119	100	1272	176	— 76
67	1440	128	1170	117	+ 11
68	1590	142	1302	193	— 51
69	983	88	1072	61	+ 27
1870	1211	108	1192	130	— 22
71	896	80	1234	154	— 74
72	1162	103	1314	200	— 97
73	1160	103	1238	156	— 53
74	1803	161	1168	116	+ 45
75	1337	119	1007	25	+ 94
76	918	82	1216	144	— 62
77	638	57	1098	76	— 19
78	1295	115	1258	168	— 53
79	631	56	1250	164	—108
1880	1558	139	1292	187	— 48
81	946	84	1162	113	— 29
82	1536	137	1324	205	— 68
83	721	64	1007	25	+ 39
84	1306	116	1274	177	— 61
85	1402	125	1078	65	+ 60
86	1475	131	1134	97	+ 34
87	1547	138	1160	112	+ 26
88	1740	155	1196	132	+ 23

Year	Precip. 1/9–1/5 Bergen	Accumulation Storbrcen	Temperature Bergen 1/5–1/10	Abl.calc. Storbreen	Mass balance Storbreen
89	1446	129	1242	159	— 30
1890	1133	101	1244	160	— 59
91	1445	129	1266	172	— 43
92	1369	122	1062	56	+ 66
93	1389	124	1226	149	— 25
94	1607	143	1224	148	— 5
95	837	74	1296	189	—115
96	1623	145	1226	149	— 4
97	1194	106	1224	148	— 42
98	1807	161	1124	91	+ 70
99	1763	157	1178	122	+ 35
1900	1413	126	1196	132	— 6
01	1593	142	1358	225	— 83
02	1602	143	1072	61	+ 82
03	1535	137	1166	115	+ 22
04	1142	102	1192	130	— 28
05	1667	148	1236	155	— 7
06	1644	146	1244	159	— 13
07	1489	133	1066	58	+ 75
08	1357	121	1212	141	— 20
09	1196	106	1086	69	+ 37
1910	1618	144	1322	204	— 60
11	1385	123	1288	184	— 61
12	1327	118	1222	147	— 29
13	1650	147	1232	153	— 6
14	1948	174	1286	184	— 10
15	1264	113	1102	78	+ 35
16	1036	92	1156	110	— 18
17	1247	111	1298	190	— 79
18	2287	204	1166	115	+ 89
19	1377	123	1172	118	+ 5
1920	2274	203	1230	152	+ 51
21	1881	168	1078	65	+103
22	1757	157	1088	70	+ 87
23	1332	119	1028	36	+ 83
24	1786	159	1198	133	+ 26
25	1824	163	1342	216	— 53
26	1314	117	1288	184	— 67
27	1813	162	1210	140	+ 22
28	1168	104	1074	62	+ 42
29	1395	125	1146	104	+ 21
1930	1894	169	1376	236	— 67
31	1459	130	1170	117	+ 13
32	1512	135	1250	163	— 28
33	1736	155	1440	272	—117
34	1454	130	1322	204	— 74
35	1903	170	1238	156	+ 14
36	1173	105	1378	236	—131
37	1369	123	1346	218	— 95
38	1846	165	1248	162	— 3
39	1833	164	1342	215	— 51
1940	938	84	1224	148	— 64
41	1020	91	1306	195	—104
42	1034	92	1194	131	— 39
43	2303	205	1258	168	+ 37
44	1616	144	1250	163	— 19
45	1541	138	1354	222	— 84
46	1378	123	1318	202	— 79
47	1241	111	1468	288	—177
48	1543	138	1286	184	— 46
49	2504	224	1302	193	+ 31
1950	1784	159	1338	213	— 54
51	1372	122	1262	170	— 48
52	1514	135	1132	96	+ 39
53	1379	123	1360	226	—103
54	1737	155	1296	189	— 34
55	1675	150	1300	192	— 42
56	1523	136	1228	150	— 14
57	1712	153	1182	124	+ 29
58	1761	157	1298	190	— 33
59	1359	121	1306	196	— 75
1960	970	87	1346	218	—131
61	1104	99	1256	166	— 67
62	1570	140	1148	105	+ 35

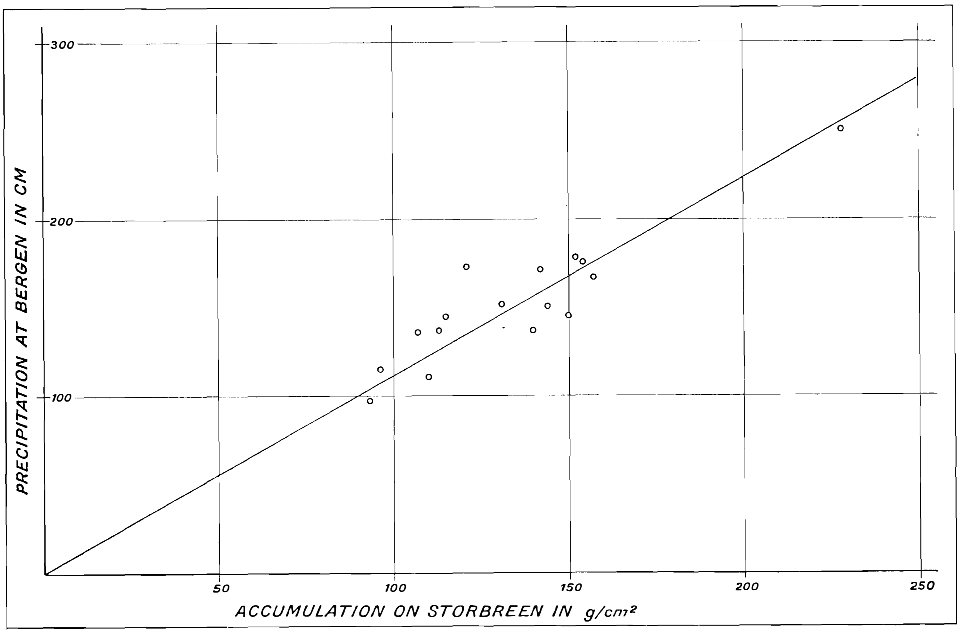

Fig. 25. *The diagram shows the relation between the winter precipitation (1/9–31/5) in Bergen and the accumulation on Storbreen. The point to the top right dates from the Winter of 1948–49, when accumulation was exceptionally great.*

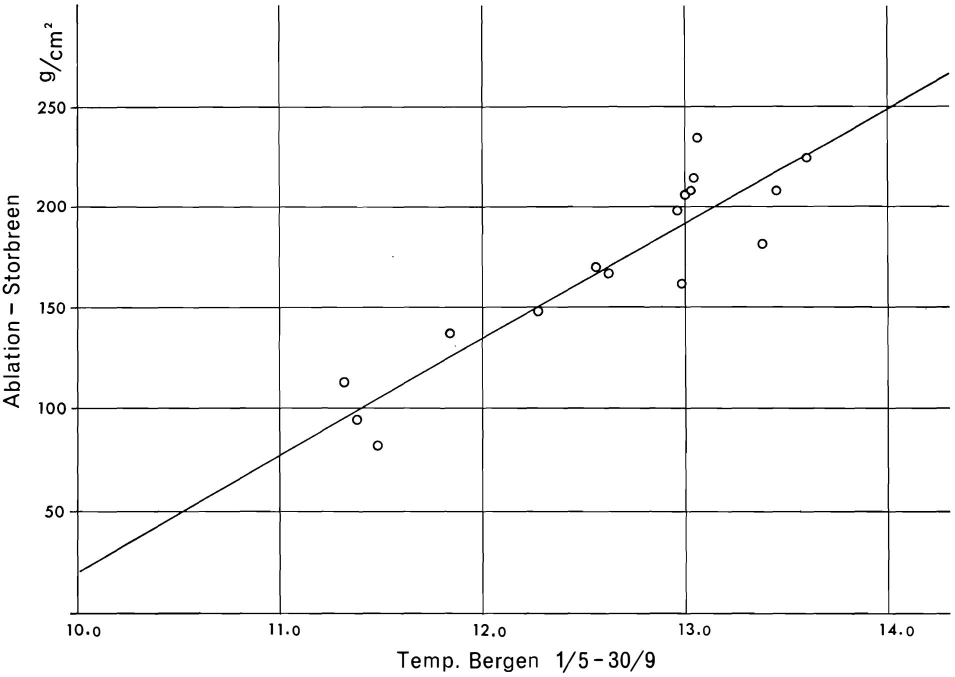

Fig. 26. *The correlationship between summer temperature in Bergen and the ablation on Storbreen during the years from 1949 to 1964.*

Bergen has observations over a very long period, it is natural to use that station. The calculations backwards in time are therefore based on the measurements in Bergen.

In Table III both accumulation and ablation are arranged according to these calculations. The resulting values in the last column represent the variations in the glacier mass for the individual years.

To obtain a check on these calculations, some research has been done on the total volumetric change of Storbreen. As stated before, there exists a very accurate photogrammetric map from 1936. The map covers the whole of the glacier, and so far over the essential parts that it can be used to calculate the retreat of the glacier from that time until the present day. There are also stereophotogrammetric maps from 1942 and 1951, and after that, trigonometrical stake observations. Table V shows the relationship between the calculated and the directly observed changes in the volume of the glacier measured on the maps. It can be seen that the agreement is unusually good, and better than could be hoped with the accuracy with which the measurements can be made. There is thus reason to believe that it ought to be possible to extrapolate these calculations backwards in time, and that they very nearly give the correct material balance for the glacier.

Table V

Volume changes on Storbreen

	1936–40	1940–51	1936–51
Measured on the map	—240 g/cm^2	—630 g/cm^2	—870 g/cm^2
Calculated mass balance	—237 »	—677 »	—914 »

The calculations which are presented here, and which are based on observations from Bergen and Luster, should also be applicable to other glacier areas within the region. From the outflows of Jostedalsbreen we have continuous observations of the positions of the glacier snouts since about 1900. It is interesting, in view of this, to compare the variations of the snout with those of the glacier's volume. There will naturally be a certain time-lag, such that it will take a few years before an excessive mass in the upper areas of the glacier expresses itself down the snout, where the measurements are taken. The short steep glacier tongues from Jostedalsbreen can react quicker than those which are larger and flatter, as is to be expected. The best series of observations is from Briksdalsbreen in Olden. Measurements have been made there continuously since 1900. The time-lag there is c. four years. In Fig. 24 a comparison is made between the glacier's volume, calculated from Luster, and the variations in the length of some of the outflows of Jostedalsbreen. If the observation for each year is used, the picture becomes confused. Here, it has been decided to take a mean over a four year period. The curves produced show a very good correlation between changes in the glacier volume and changes in length. Even small variations in the volume find expression in variations in the glacier's length.

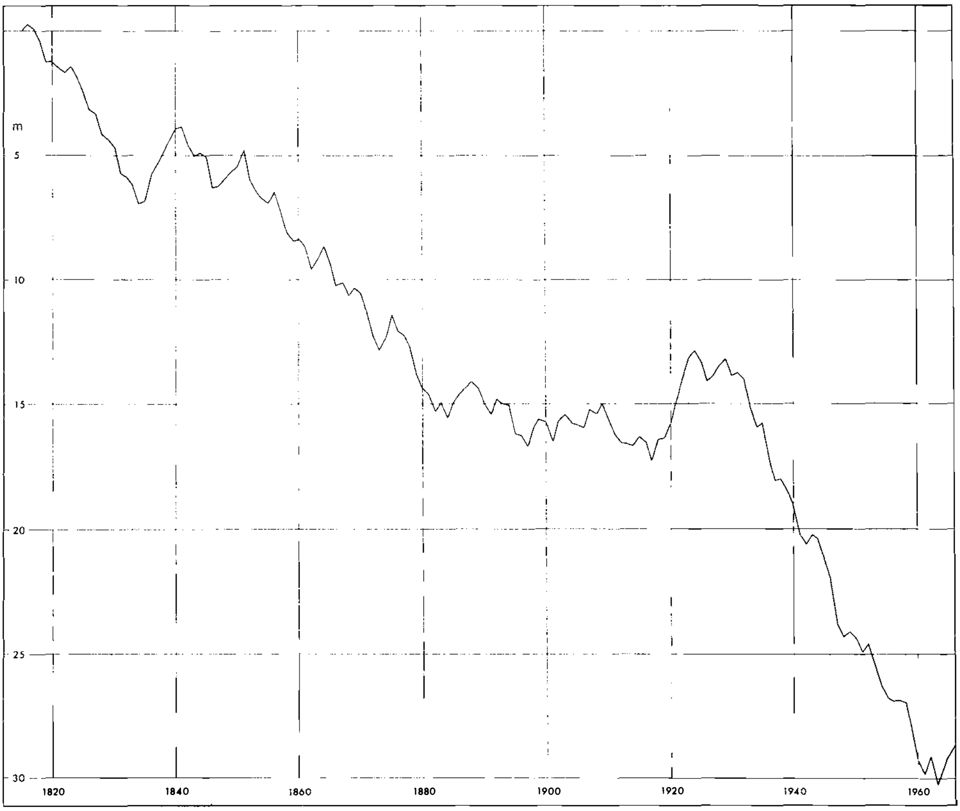

Fig. 27. *Change in Storbreen's mass calculated from observations of temperature and precipitation in Bergen. For the years before 1862, only temperature observations were used in the calculations.*

The firn line

In general, the snow line, in the truest sense of the word, should be that height at which ablation and accumulation balance each other. Owing to the uneven accumulation caused by terrain and wind, an average snow line must be used over a reasonably large area. It therefore becomes a matter of definition as to where one should place such a line. G. HOLMSEN (1916) developed a method in which he made use of the hypsographic curve. The entire area of glaciers and snow-fields is measured on a map, and the height corresponding to this area is found on the hypsographic curve. In other words, one assumes that all the snow areas which are measured in the region and represented by the hypsographic curve are evenly distributed from the top and downwards. The lower edge represents the snow line.

The above definition are of a more general application. So far as it concerns glaciers, the situation is simple. But the snow line, or the 'firn line' which is more usually used in connection with glaciers, are also concepts which are defined in different ways.

Terms like temporary, climatological, equilibrium, steady-state equilibrium line, and several others have been used. The expression temporary snow line or firn line has been used in slightly different manners. It usually means the height to which the winter snow melts away by a certain date. The expression has also been used to mean the highest limit of the winter snow for the individual years, in contrast to the climatological snow line, which is the average over several years.

The definition of the climatological line is not easy, however. It is dependent upon the period of time chosen. A 30 year period, as used by the meteorologists will be the most natural choice. However, the difficulty is that there are scarcely any glaciers on which the height of the snow line has been observed for a 30 year period. The question is further complicated by the long period of time required by a glacier to adjust its areal and height distribution to a new climate. The climatological line, based on say a 30 year period, will therefore not correspond to a steady-state line for the same period. It will be shown later that the average snow line for the period 1931 to 1960 lies c. 100 m higher than a line which would keep the glacier in equilibrium, i.e. the steady-state equilibrium line.

Some of the same problems occur with the definition of the limit of glaciation. This is usually defined as the minimum height which a mountain must have for the formation of permanent ice. This limit will lie higher than the snow line, over which there must be a certain area so that glaciers can exist.

The glaciers' sluggish adjustment to climatic changes also enters the problem. The glaciation limit measured today lies far below that which would be obtained after the glaciers had adjusted themselves to the climate of the period 1931–1960 for example. Many of the present day glaciers are in fact relics from the climate of the eighteenth century.

Commonly one thinks of the firn line as synonymous with the equilibrium line. However, below the line separating ice and snow at the end of the ablation season occurs an area with 'superimposed' ice, which, definition-wise, must belong to the accumulation zone (SCHYTT 1949). This area is important, especially on sub-polar glaciers, for example in Spitsbergen, where the vertical interval is over 50 metres between the equilibrium line and the lower margin of the snow. On the glaciers of West-Norway in the maritime region, however, the interval is insignificant. On Storbreen it is about 10 metres on an average.

If the net material balance is a linear function of the height, an expression for the height of the firn line can be obtained quite simply. Let the material balance at an arbitrary place on the glacier be called 'b' and the height above sea level be 'Z'. Over the firn line then 'b' is positive, below negative, and at the firn line $b = 0$. One can therefore write:

$$b = k(Z - Z_f),$$

where k is a constant and Z_f is the height of the firn line above sea level.

Let the total area of the glacier be 'A' and the increase or decrease of the glacier's total mass be 'M', then:

$$\int n \, dA = M$$

If the glacier is stationary, then:

$$\int n \, dA = 0$$

Substituting for n:

$$\int k(Z - Z_f) \, dA = 0$$

$$Z_f = \frac{\int Z dA}{A}$$

This is to say that the snow line goes through the centre of gravity of the glacier surface measured on a map or on the hypsographic curve for the glacier. In reality, the conditions are not so simple. The value of k is not constant, but is a function of accumulation and ablation, which does not change in a linear fashion with height above sea level. Normally $k = \frac{db}{dZ}$ will decreease with the height, so the that firn line comes below the actual centre of gravity of the glacier. On a glacier with more or less normal areal distribution with height, the accumulation area will therefore be larger than the ablation area. BRÜCKNER found that this relationship between the two areas $\frac{Ac}{Aa}$ was fairly constant, and that for the Alps the ratio was about 3 to 1. He used this to determine the height of the snow line over larger areas by taking from a map the height which fulfilled that condition. It is apparent, however, that there are wide variations both with the climatic conditions and the form of the glacier. On Murraybreen in Spitsbergen the relationship was inverted to 1 to 3. AHLMANN (1927) has also found great variations,

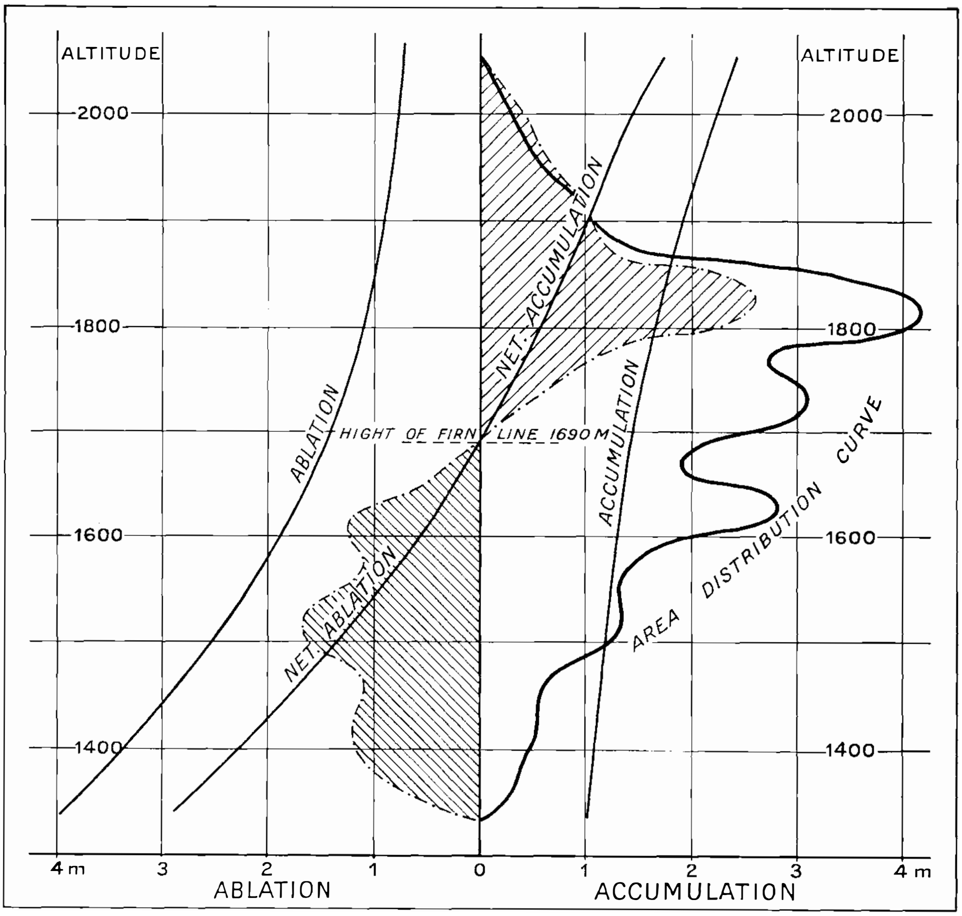

Fig. 28. *Computed regime of Storbreen in a year with equilibrium and "normal" mass blance.*

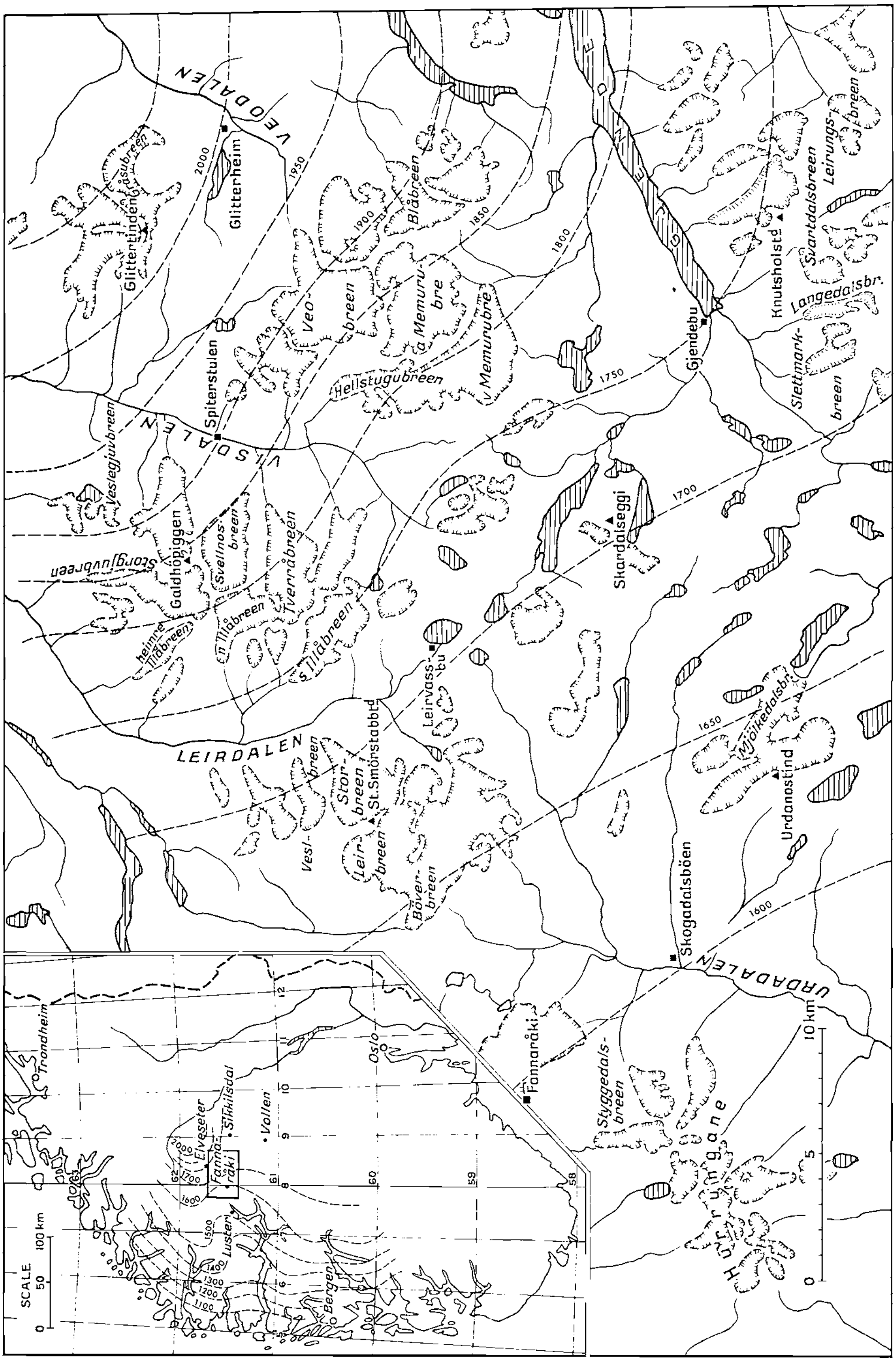

Fig. 29. *Map of the height of the equilibirum line for Jotunheimen and a part of southern Norway.*

among others in the Hurung massif, where he discovered variations from 2 to 1, to 0.6 to 1. On Storbreen the ratio is 1.6 to 1. This last figure is calculated on the basis of Fig. 28, which shows the relations, such as they would be in one year, with a normal balance in material budget. The curve for the variation in material balance with height in Fig. 28 concerns Storbreen, but this could be extended as an approximation for the whole of Jotunheimen. Fig. 29 shows the map for the height of the equilibrium line in Jotunheimen. The heights are determined for a series of glaciers in the same manner as for Storbreen, using the hypsographic curve for each single glacier together with the curve for the material balance. The map does not show the average height at the temporary equilibrium line in the last years, but a height corresponding to that for the glaciers (with the size that they had in 1960) when in steady-state condition. It will correspond with a sort of average year when the glaciers neither increase nor decrease.

On Storbreen the average height of the temporary yearly firn line between the years 1949 and 1963 has been 1765 m a.s.l., that is, as can be seen from Fig. 28, 75 m higher than that representing the axis of equilibrium for the glacier. That also is quite reasonable when, at the same time, the glacier has had a deficit of 42 cm on average.

Fig. 30 shows the relationship between the net material balance and the height of the firn line on Storbreen. The correlation is exceedingly good. Theoretically the relationship between the two quantities should not be linear, but the figure shows it to be very nearly the case, actually in the field.

It can also be seen from the figure that the highest and lowest measured values

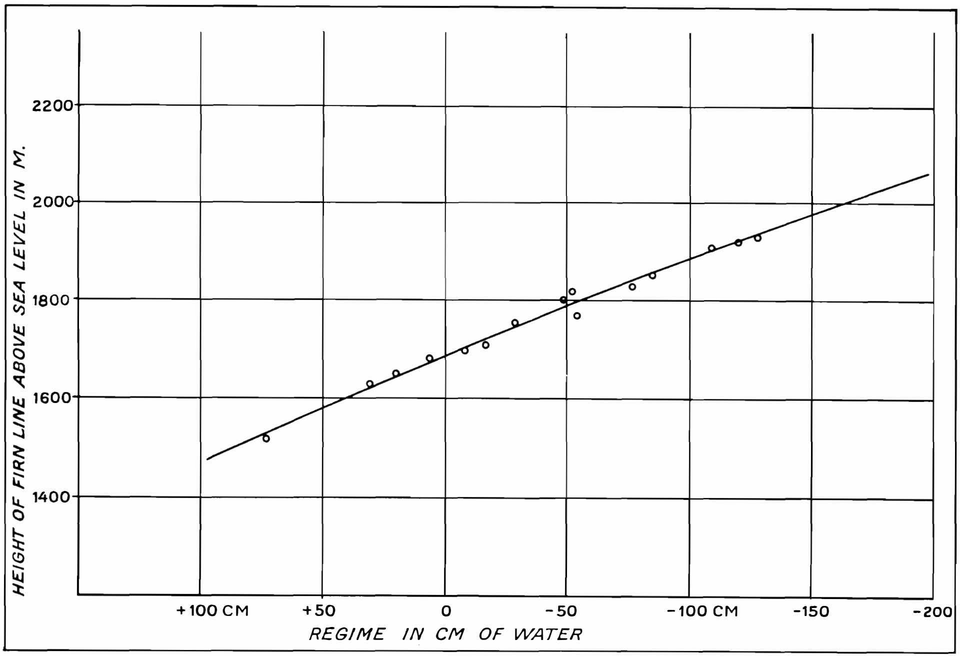

Fig. 30. *Relation between height of equilibirum line and mass balance at Storbreen glacier in the years 1949–64.*

are, respectively, 1930 m (in 1959) and 1515 m a.s.l. (in 1962.) Using the calculated values for material budget in Table III, together with Fig. 30, one finds theoretically that, in the period after the year 1900, the temporary firn line lay highest (at 2020 m) in the unusually warm and dry year of 1947. In that year a very insignificant part of the glacier – less than 1 % – would have belonged to the accumulation area. The year 1921 shows the lowest firn line, when, theoretically, it should have lain at about 1500 m. At that time the glacier reached further down, but nevertheless, only 12 % of the area belonged to the ablation zone.

In the same way, one could calculate the average height for the 30 year period 1931 to 1960. This is the same period that is used by the Meteorological Institute in Norway for the calculation of the climatological data. This shows itself to be 1785 m a.s.l., 95 m higher than the steady-state equilibrium line. This demonstrates significantly that Storbreen has not nearly adjusted itself in its areal and height distribution to the present climate.

Even the neighbouring glaciers could have very large differences in the heights of their firn lines owing to their different aspects and situation. The accumulation conditions vary; but also variations in insolation will influence the height. Therefore, the north-facing glaciers will have lower firn lines than those facing south. In the shadow cast by the usually steep north-facing corrie walls there will only occur a diffuse short-wave radiation, but also that will be reduced. Outside the shadow area the slope of the glacier surface, away from the sun, on the north-facing glaciers, will further reduce the effectiveness of the short-wave radiation. The difference in insolation on two glaciers, which face respectively north and south, can theoretically be calculated, but becomes fairly complicated when all the factors are taken into account. The difference will also depend upon how great a part is played by the direct radiation in the total ablation. On over-cast days there will be a diffuse short-wave radiation, which is the same for all situations. Moreover, the long-wave radiation balance will also be fairly similar, though the long-wave radiation from the south-facing mountain sides can locally be quite significant. A very simple calculation is used with the help of an over-simplified glacier model, from which is obtained a difference in ablation between the south-facing and the north-facing glaciers, of 15–20 %, which should correspond to a difference of about 50 m in the height of the firn line. It is here calculated with a surface slope angle of 10°, a shading corrie wall 200 m in height, a mass balance value of 150 g/cm^2, and a length of glacier of 4 km. This figure should be applicable to the central part of Jotunheimen. As the climate becomes more Atlantic, the less becomes the difference between the north- and south-facing glaciers, since the part played by radiation becomes less.

One complicating factor, as mentioned before, is the variations in accumulation, which can also be dependent upon the aspect of the glacier. In Jotunheimen the precipitation comes predominantly from the south and south-west. There could be a strong lee-current, which would give a greater accumulation on the north side of a mountain, with the lowering of the firn line accordingly. On small north-facing corrie glaciers this lee-current would have very much effect, especially if there were large wind-swept areas in the surroundings. However, there will also be very great variations in the direct precipitation owing to local orographic effects.

In the drawing of the map, Fig. 29, it was necessary to undertake a large degree of levelling out. In the Galdhøpiggen massif, for example, a much steeper gradient towards the north-east can be observed than is shown on the map. On Søndre Illåbre, for example, the firn line lies at 1740 m a.s.l., while that of the little glacier north of Juvflya on the north side of the massif lies at 1980 m. This gives a gradient of 240 m in 10 km. Here, the high mountain massif, which reduces precipitation from the south and west, is important.

A factor that must be taken into account is the distribution of precipitation throughout the year. Western areas have a greater percentage of their precipitation in the winter half of the year than do easterly, more continental regions. Accumulation in the easterly glacier area, therefore, becomes still less than the total annual precipitation would indicate, as a higher percent will fall as rain.

Fig. 29 shows a map of the firn line in South-Norway, constructed in the same way as that for Jotunheimen. The material for the maps is based upon 34 glaciers, on which steady-state equilibrium line has been determined. In order that the special local conditions of accumulation and exposure should not complicate the picture, averages have been taken.

It can be seen that the glaci-isohypses are fairly parallel with the coast, and rise in altitude inland. This phenomenon has been described and explained by several workers, A. M. HANSEN, HELLAND, REKSTAD, and AHLMANN, among others. REKSTAD correlated the height of the snow line with the temperature for the summer months. He found that the snow line lay c. 420 m lower than the 0° isothermal surface for the months May–August, but in the coastal area it was much lower. He ascribed the latter to the greater accumulation in these areas. AHLMANN (1922, 1929) made similar calculations, and found that 37% of the rise eastwards was due to rising summer temperatures, and the remaining 63% to a decrease in precipitation.

The isotherms progress relatively evenly, with an even gradient inland. The temperature alone, therefore, will cause an even tendency in the glaci-isohypses. The precipitation map, however, shows a very complicated pattern. This is due, in the first instance, to a topographic effect. One should be aware, however, of the fact that the glaciers cover the highest areas and, between them, the same great variations which are otherwise to be found in the terrain, are not to be expected. Nevertheless, it is clear that the uneven accumulation causes the unevenesses in the course of the glaci-isohypses. In a way, the glaci-isohypse map reflects the pattern of precipitation. If, therefore, one had a satisfactory precipitation map, it would be possible to construct a detailed map of the snow line, or vice versa.

Volume and marginal fluctuations

As already mentioned, the direct measurements of the position of the glacier front were initiated in 1901, when ØYEN put up his mile cairns. Measurements of previous variations are only feasible when based on the positions of the moraine ridges and through analogy with other glaciers.

Originally one had two sighting lines, one on either side of the glacier tongue.

After a few years, however, the southern line was dropped, and until today the northern line has been followed. Especially in later years the line has hit the glacier sidelong, such that the measurements have hardly been representative for the ablation on the glacier tongue throughout the time. Fig. 31 shows an uneven vertical profile along the direction line. This will also affect the representative value of the measurements, the rate of retreat depending upon the angle of inclination of the bedrock. Equalized over a number of years, these measurements will probably give an indication of the regime of the glacier.

As mentioned above, a break appears in the measurement series between 1912 and 1933. In that period an advance took place, which has left a conspicuous end moraine, probably from around 1925 to 1928, when most of the glaciers in Norway were advancing. The measurements indicate small advances around 1905–08. The moraine ridges found in about the locality where an advance is indicated by the sighting line, are therefore likely to date from a period prior to those years. (See Fig. 32.)

We have no possibility of dating the outer moraine ridges. Dealing with these, one has to conclude analogically from glaciers in West-Norway, particularly Nigardsbreen, which is fairly well investigated (Fægri 1933). The fact is, however, that one will have to take into account somewhat diverging conditions when dealing with an outlet from a glacier cap and a smaller valley glacier in the central mountain region. There are, however, for the period from which fairly reliable measurements are available, good correlation between the outlets from Jostedalsbreen and the glaciers in Jotunheimen. One is, accordingly, justified in supposing the outermost moraines to be expressive of the advance during the 1740-years.

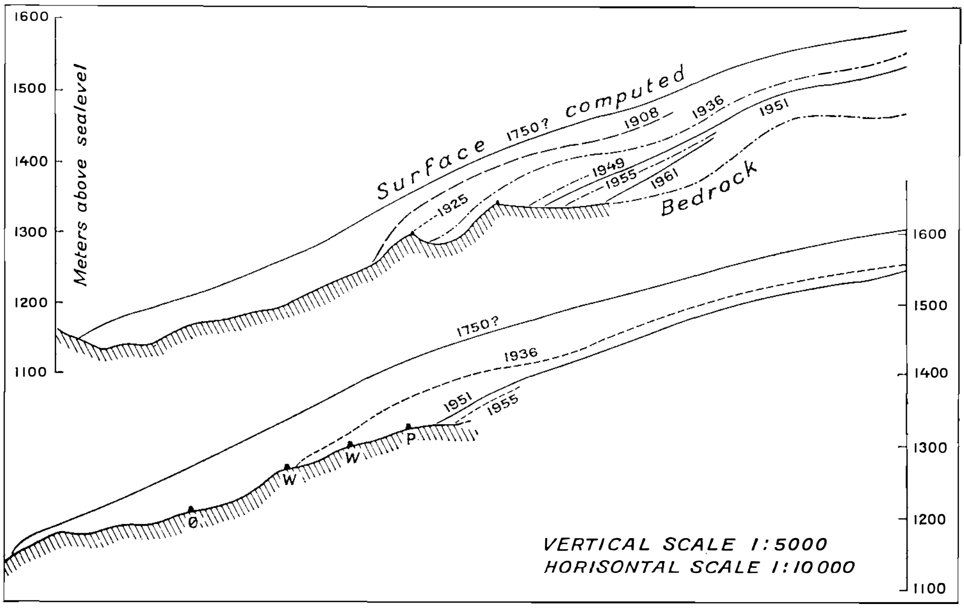

Fig. 31. *Vertical profile of the glacier tongue of Storbreen. The upper profile goes along the central part of the tongue, the lower one along the line where the length measurements are made.*

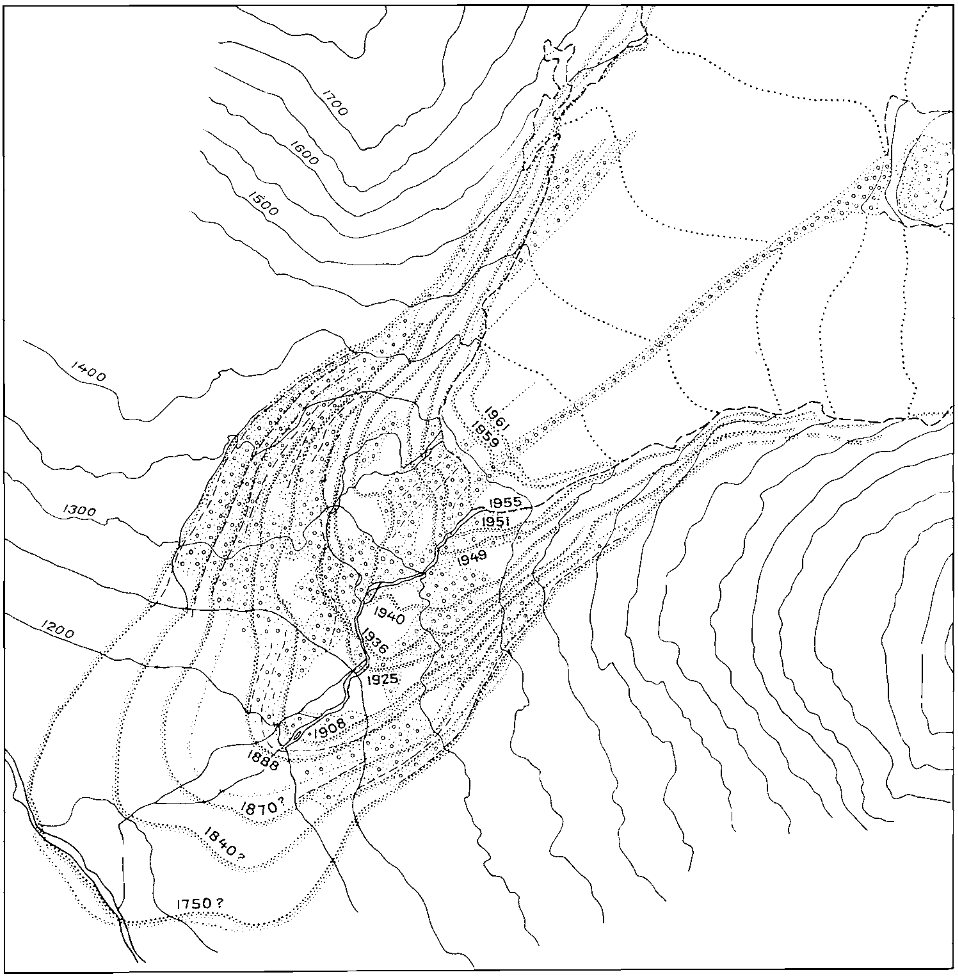

Fig. 32. *Position of the glacier front in various years. For the years since 1888, the map is based on direct observations, and for the earlier years on its similarity with Nigardsbreen where the age of presumably coinciding morainal ridges is known.*

On certain places this moraine is distinctly double, as are also a number of other glaciers in Jotunheimen. This outer ridge of the double moraine differs from the other ones through its even surface and well developed cover of humus soil and plants, in contrast to the large-blocked ridges just inside. It would seem that this moraine for an extensive period has been exposed to disintegration of a different order of magnitude than is the case with those farther in. We have, however, to take into consideration that when the glacier advanced for the first time after postglacial warm epoch, it moved in front of the disintegration and humus soil which had formed during that period. Accordingly we will find just that material in the, to all appearance, very old outer ridge.

The glacier must, some time during the period of its largest advance, have crossed Leira, but there is no sign of a damming being caused. The river has certainly had a surplus of heat, great enough to keep a tunnel open.

On the map (Fig. 32) the various moraines are indicated with statement of

Fig. 33. *The two photographs are taken from the eastern side of Leirdalen valley, and show the retreat of Storbreen from 1908 to 1951. The glacier snout has retreated c. 650 m, and the mean vertical lowering of the glacier surface is c. 10 m. Note that the glacier river has changed its course from the southern to the northern part of tongue.*

supposed age. It appears that they are joining alongside the glacier sides and become less distinct. This is partly caused by the fact that the sides are considerably steeper than the ground in front of the glacier, and partly by the gradually decreased thinning alongside the glacier tongue upwards. This last trait is of common appearance with glaciers. (See HOEL and WERENSKIOLD 1962.) A similar linear decrease would probably be found on Storbreen, but here the older survey is insufficient for the upper parts. Small variations in the upper parts appear on the photo taken in 1908, when compared with photo from the same glacier in 1955. (Fig. 33.) In the profile (Fig. 31) the surface for 1750 has been calculated according to the side moraine, 1936 and 1951 according to maps, and later to trigonometrical profiles. It is also evident to what extent the subsurface affects the topography of the surface.

The transport of material down the glacier is dependent upon the depth of the glacier and the velosity. The flow depends in turn upon depth, but to what extent is obscure. According to the classical theory, the formula for the vertical distribution of flow is

$$V = KZ^2 \sin \alpha$$

Accordingly the transport should be approximately proportional to the depth to the third power. A decrease in depth by a high amount of ablation during a number of years will, therefore, influence rather heavily the transport down the glacier.

The lower parts will not be supplied with a sufficiency of material to balance ablation, whereas the accumulation area initially will not lose to the same extent as before. The result is an increasing reduction of the glacier area from the top downward. For some time even an increase in the firn area may take place. That condition will, however, not be a stable one, and theoretically a periodic variation in the transport should be expected. The result is a more extensive fluctuation in the glacier tongue and decrease upward.

A map of the glacier surface under its maximum extent has been calculated. From this map one is enabled to calculate the total decrease in the glacier volume until present time (1965). It appears that the glacier has decreased $190 \,.\, 10^6$ m^3. Considering a present average depth of about 75 m, a present glacier volume of $75 \times 5.4 \,.\, 10^6 = 405 \,.\, 10^6$ m^3 is obtained, meaning a loss of c. 30% of its original largest volume. This corresponds to an average decrease of about 35 m. As mentioned above (p. 7), a map was prepared in 1936. Using the same method, the decrease is found from that year up to 1955, being about $60 \,.\, 10^6$, meaning that approximately one third of the total decrease has taken place during the last 20 years.

Fig. 34. *Lateral moraines on the south side of Storbreen, c. 1200 m a.s.l. The lowest ridge dates from c. 1925–28, the highest probably from c. 1750.*

Velocity measurement

Triangulation work was carried out on Storbreen every year when the other measurements were made. However, no systematic velocity measurements have been made, other than with a few odd stakes each year. It was very difficult to obtain accurate theodolite intersections on many of the stakes, since the fixed points around the glacier are not sufficiently well placed for such measurements. However, those stakes situated on the south-eastern part of the glacier, near two nunataks, are quite well fixed by observations. Moreover, it is possible to sight a number of stakes on the upper part of the glacier from the two nunataks, i.e.: stakes No. 18, 19, 20, and partly 22. Stakes No. 26, 27, and 28 have been fixed by resection only, and the accuracy therefore is not so great. For the lowest stakes, Nos. 1 to 8, special stations have been erected along the side of the glacier. From these they were observed about three times in the course of the summer for the first five years. Intersections were made on all stakes, using from two to five stations. The accuracy of the calculated positions is, of course, much dependent on the site of the stakes relative to the observation stations. This also applies to height determination, which was very difficult for certain stations. Some angles were very steep, so that any error in the calculated position has a large effect upon the calculated height. The map, Fig. 35, shows each stake position with an arrow showing the direction of movement. The length of the arrow is proportional to the annual movement. The map also shows the horizontal projection of the flowline directions, which are calculated from the stake positions. Air photography has also been used to obtain a better picture of the flowline direction. There can be seen a definite streaming in the glacier which is mirrored in the structure of the ice. The velocity varies from a maximum of 5.9 cm/day to a few mm/day on the lowest part of the glacier where the ice stagnates. No measurements of the ice thickness have been made on Storbreen, either by gravimetry or seismic methods. Nor have thermal borings reached the bottom, so they cannot be used. It is not possible, therefore, to calculate the material transport. However, the observations of some stakes are accurate enough for the determination of the flowline directions in the vertical plane. Fig. 36 illustrates how stake No. 14 has moved in a vertical profile during that period when the observations were made. The diagrams also show the velocity, and how a point on the surface at stake 14 has moved.

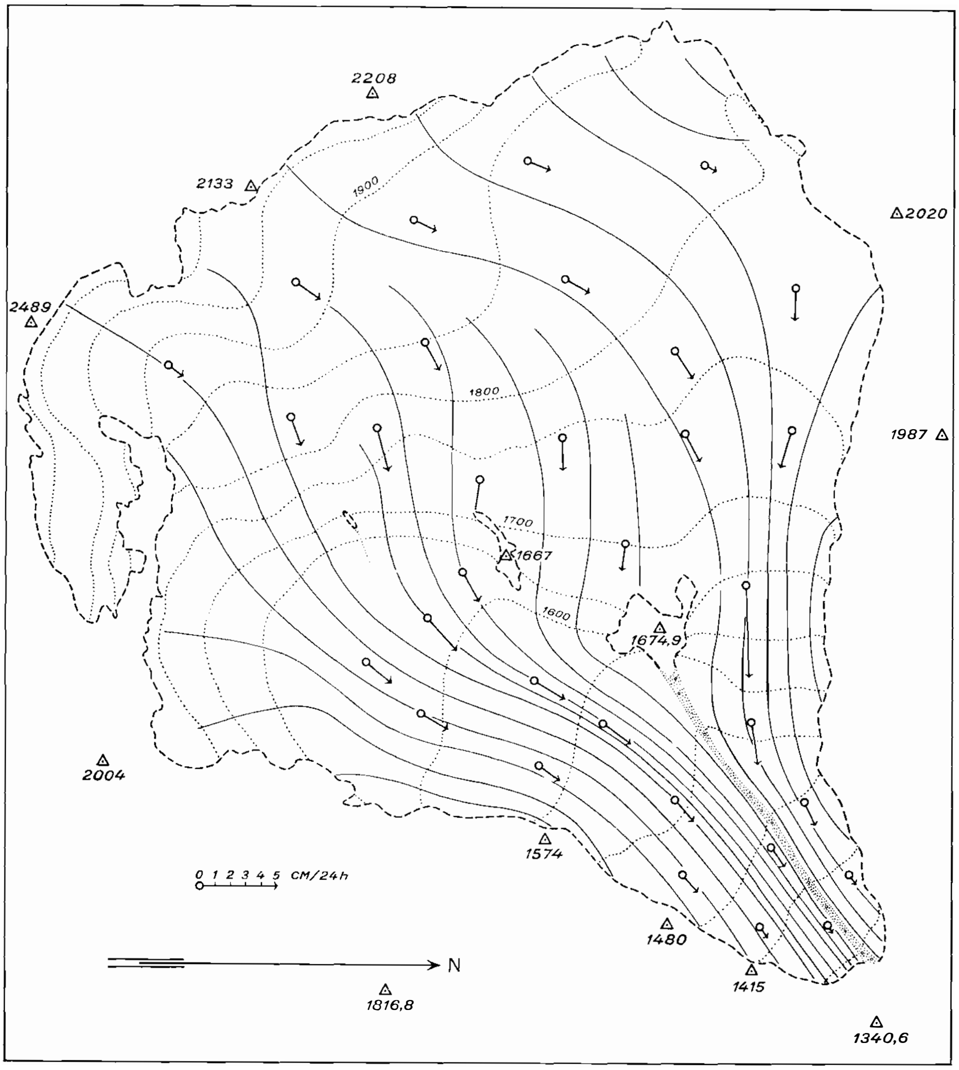

Fig. 35. *Map of the stream lines and stakes where velocity are measured. The length of the arrows represents the velocity.*

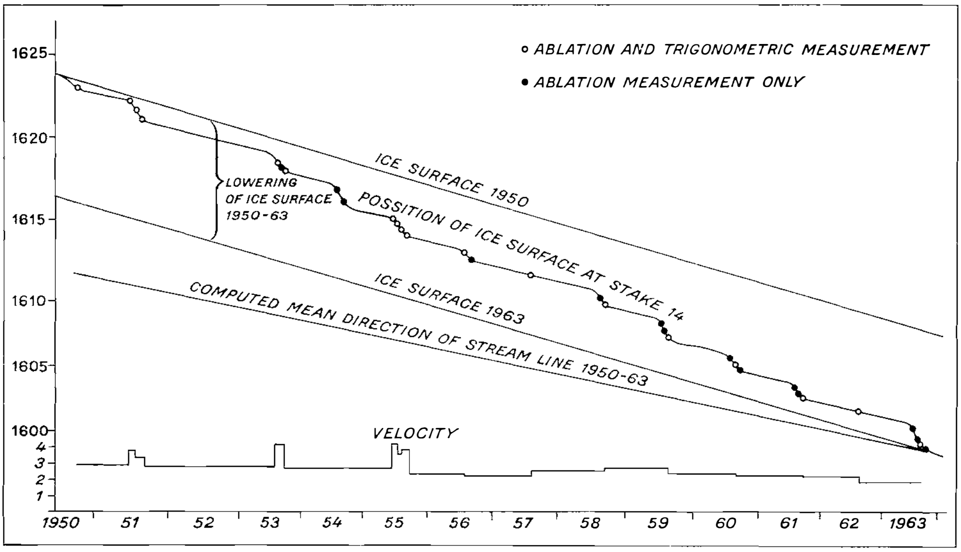

Fig. 36. *Diagram of ablation and flow at stake 14, c. 1610 m a.s.l.*

Fig. 37. *Map of the crevasse systems on Storbreen.*

As mentioned above, the velocity was measured several times during the summer of each year. Especially accurate observations were made in 1951, 1953, and 1955. During this last year the positions of most stakes were fixed in the course of the summer. It is clear from the diagram that the summer velocity is higher than the average for the rest of the year. However, Storbreen does not lend itself to any more detailed study of the variations in velocity, which is far too small for the purpose. Fig. 36 shows how the velocity of that point on the glacier has decreased with decreasing thickness of the ice. There is also an indication of an increase in velocity from 1957 to 1959, just in those years when the glacier had a slight positive budget. Presumably a wave passed down the glacier from the firn region. However, the stake pattern is too open for one to follow such a wave movement. It can be seen from Fig. 36, also, that the calculated direction of the flowline rises towards the surface, which means that the site is below the firn line and that ablation out-weighs accumulation. Had the glacier been in equilibrium, the transport would normally have counterbalanced the deficiency at this point. That was obviously not the case during these years. It will be seen that the surface has sunk c. 7 m in 13 years, and that the total ablation at stake 14 has been 12 m in this period. The downward material transport has thus managed to replenish 5 m of the 12 which were required to keep the glacier at equilibrium.

In connection with the glacier's movement, crevasse formation has also been mapped and recorded. The crevasse system in several places follows a pattern which agrees closely with the classical theories of crevasse formation. This particularly concerns the area around the largest nunatak. Fig. 37 is a map of the crevasse system. Fig. 38 is cut out from an aerial photograph taken in 1955 from the southeast toward the largest nunatak. Here, the ice flow divides about either side of the rock, and the form of the ice movement can be seen clearly from the crevasse directions.

Discharge and sediment load

In collaboration with Norges vassdrags- og elektrisitetsvesen, Norsk Polarinstitutt has made measurements of discharge in the river from Storbreen. In this connection, a water mark and a limnograph were set up about 300 m below the snout. Here, the river flows through a canyon-like section and is stopped by a small concrete dam with a V-shape. Above it a small basin has been formed, and there the limnigraph was erected. These measurements proved to be quite problematic, as the glacier river has a large material transport, and there was no clearing device above the limnigraph to remove the coarse sediment. The dam was, therefore, quickly silted up. As a result, it was only possible to obtain quite short series of reliable observations, owing to the variable conditions along the floor of the dammed section. The calibration of the water-level curve was done with the help of the so-called "salt-method". Later, the dam was improved, and new calibration curves were constructed, but the results of these measurements have not yet been calculated. It is intended to compare the measured ablation values with those for the discharge. Of course, account must be taken of rainfall and

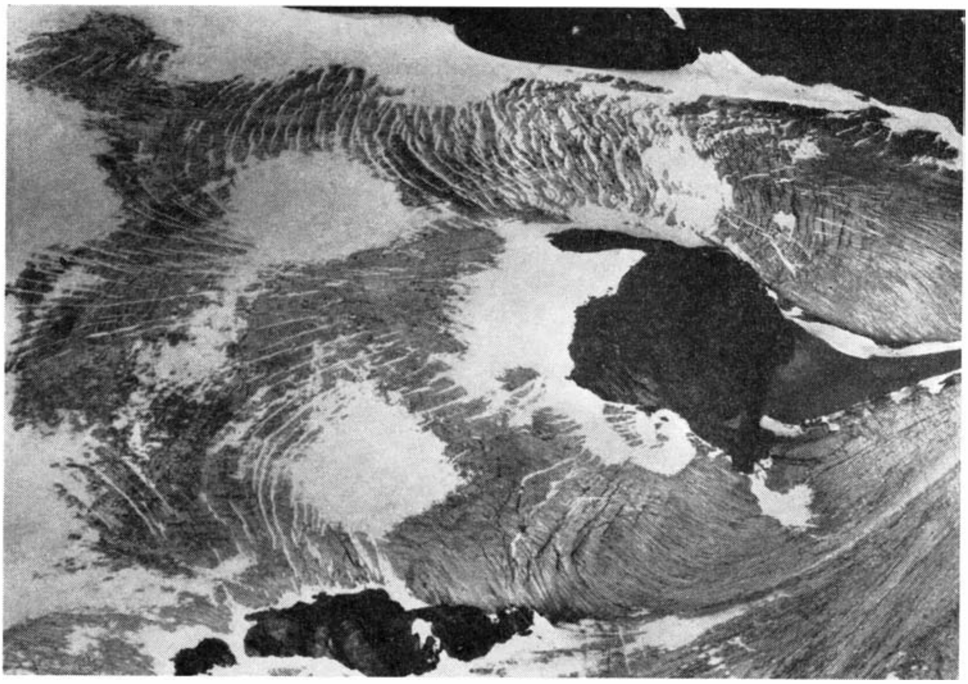

Fig. 38. *Aerial photo of the central part of Storbreen. Note the crevasse system in relation to the nunataks and flow direction*

condensation, and possible sublimation from the glacier. The mud transport by the glacier river has also been the subject of research, firstly by state hydrologist SYVER ROEN, and later by the author. The observations were taken every hour for a whole day, and once a day over a certain period. In certain years only occasional observations were made in the spring and autumn. Fig. 40 shows the equipment used. The samples were taken very simply by dipping a litre container quickly into the middle of the stream. It was necessary to be very quick in emptying the water into a filter apparatus, so that the sediment had no time to settle in the sampling container. The filter apparatus was the same the whole time. It consists of a strong container, in which the pressure can be increased above the water by pumping in air. This considerably increases the rate of filtration. Ordinary filtration is often impossible owing to clogging of the filter, so that an inordinately long time is needed to pass the water through. The filter lies up against a perforated plate which is screwed to the bottom of the container. The filters used were ordinary Schleicher and Schull no. 589, with a stated maximum pore size of 0.01 mm. A membrane filter was also used to obtain the finest fractions.

It is known from earlier experiments that the mud concentration varies greatly with both the discharge and the time of day and year when the sample is taken. The purpose of these experiments was to find whether there was any regular relationship between discharge, time, and mud concentration. As mentioned earlier, samples were therefore taken at quite short intervals throughout the

Fig. 39. *Aerial photo of the snout of Storbreen. Note the lateral moraine ridges to the left and the flooded moraine in front of the glacier.*

Fig. 40. *The photo shows the equipment which was used for the measurements of sediment load. The filter lies against a perforated plate, screwn fast to the holder to the right in the picture. After the holder becomes full of water, air is pumped in to speed up the filtering.*

day, and it was also attempted to spread some of the sampling over the whole ablation season. Fig. 41 shows the result of Syver Roen's measurements for the summer of 1951. Figs. 42 and 43 show those of the author during 1955. The samples illustrated here show the variations during a whole day. Sunny periods were chosen for the observations, when the variations in water level were closely related to the temperature, and the water level curve was displaced by a couple of hours.

The treatment of the filtrate was not the same for all samples. In his measurements, Syver Roen used to burn the paper at white heat in a platinum dish, and then weigh it. Of course this had the disadvantage that some of the material escaped as gas. The author also used this method to some extent; however, the method of weighing the paper alone, and then again with the filtrate upon it, proved to be reasonably accurate. It is necessary, however, that the paper have the same moisture content before as after. The samples were then stored at a temperature of c. 25°C in both cases, and on checking the weight, it was found that the error involved was considerably less than in the sampling and filtering.

From the figures it can be seen clearly that the mud transport increases with the water level. High water levels have high mud concentrations. On the other hand, there is no direct proportion between discharge and mud composition. It appears that the maximum mud transport does not coincide with the maximum discharge, but reaches a maximum when the water level is rising. It can be concluded, then, that mud transport is not dependent upon absolute discharge alone, but to a far greater degree upon the per cent increase of discharge per interval of time. It can be said in approximation that the mud transport is proportional to

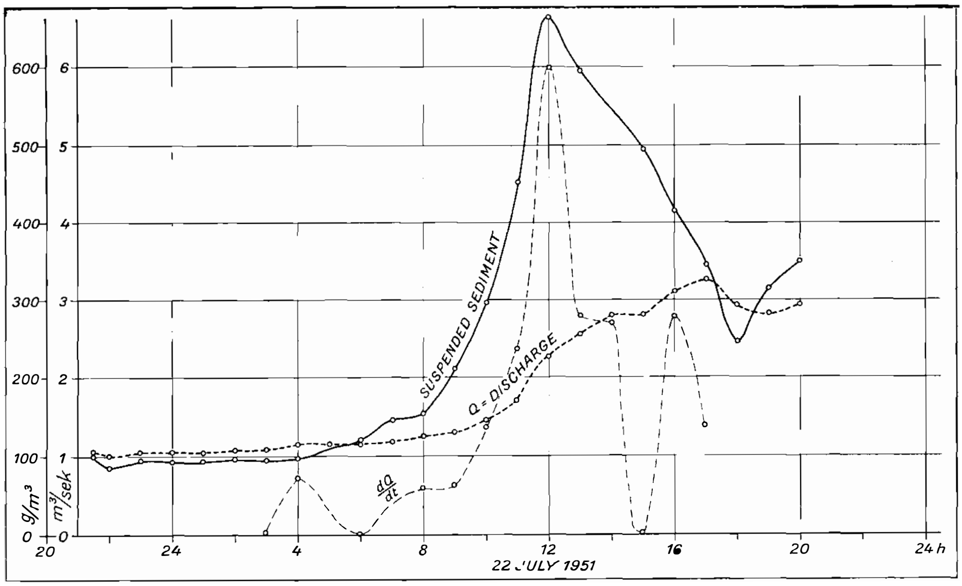

Fig. 41. *The curves show the relationship between discharge and suspended sediment during one day. Notice the good agreement between the rate of discharge* $\frac{dQ}{dt}$ *and the suspended material.*

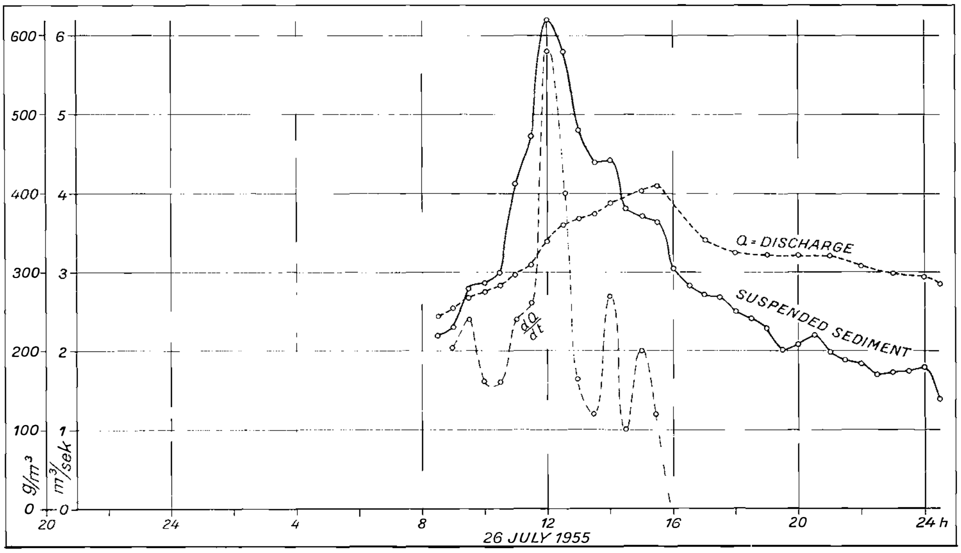

Fig. 42. *This figure is the same as the foregoing, except that the curves for July 26, 1955, are more detailed. The discharge curve is here drawn on the basis of limnigraph records.*

the differential co-efficient of the discharge. The explanation for this is quite simple. Under the glacier there is a very widespread drainage system, carrying melt-water which comes through crevasses, holes at the surface, from the glacier sides, and partly from melting beneath the glacier. The glacier constantly produces new material by grinding on its own bed. This material is collected by the streams and carried down to the glacier river. When the discharge in this drainage system increases, the water will steadily collect more material which has been produced by the glacier. There occurs, then, a large increase in the material transport when the discharge rises. When the water level is constant, the streams will collect no more material than the glacier produces at that moment, and as discharge decreases, most streams and canals will flow over areas which have been washed fairly clean. As the water level increases again, the streams are able to work with the material produced by the glacier since the last high water period. This is also applicable to ordinary rivers, but not to the same degree as to glacier rivers. It can be said, in other words, that the mud transport is not directly dependent upon the absolute discharge, but is more dependent upon the size of the new area covered by the subglacial drainage system per unit of time, and upon the rate of increase of discharge and the length of time since water has flown over the area.

The measurements of mud transport on August 25 showed these relationships clearly. The observations began that day at 07.45 hours, and the water level had already begun to rise. Both that and the mud transport rose evenly, until 11.00 hours, when there began a marked increase in mud transport relative to the discharge, which was about 3.4 m^3/sec. On examining the limnograph recordings for the preceding week, one was able to find a simple explanation. From August 21 to 25, when the measurements were made, the discharge reached no higher value than 3.4 m³/sec. When the discharge rose above this, the river had four days' erosional material to remove. In the same way, on reaching 3.6 m³/sec, it had eight days' material to remove. The afore mentioned proportion between increasing discharge per second and mud transport applies, therefore, only to periods with more or less equal fluctuations in discharge, e.g. days with clear weather and similar temperatures. This was the case with the measurement of July 26, 1955. The preceding days had clear weather, similar temperatures, and about the same discharge.

The measurement of mud transport in 1959 showed no results of special interest. Measurements were made on August 29. The temperature at the observation station was about 0°C, and the discharge was very small. With the ordinary filter paper it was impossible to record any transport.

It thus follows that the glacier's erosion is very difficult to calculate by means of mud transport measurements. A rough calculation can be attempted, however. A few mud transport measurements have been taken earlier at two glaciers in Jotunheimen. However, these were made at about midday during a period of good weather, and thus when the discharge of the glacier river was at its highest. Clearly, these are not representative measurements, and a calculation of erosion based on them will give much too high a value. Even with the rather large number of observations made at Storbreen, it is difficult to find a mean suitable for such a calculation. A rough estimate places the mud transport at c. 100 g/m³. In a normal year the run-off from the glacier should be about 8 million cubic metres. This should give a corresponding mud quantity of 800 tons. Distributed over the whole under-surface of the glacier, this gives only 0.1 mm of erosion. This is a relatively low value in comparison with other calculations of glacial erosion in Norway. REKSTAD took measurements in front of Engabreen, Svartisen, to see

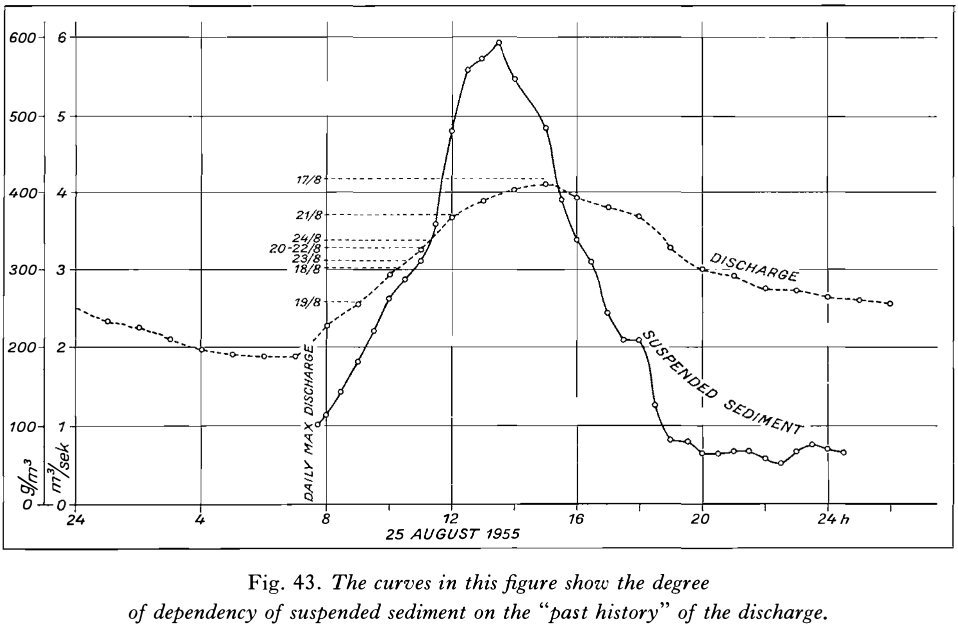

Fig. 43. *The curves in this figure show the degree of dependency of suspended sediment on the "past history" of the discharge.*

how fast a lake filled with sediment. He then calculated that the erosion distribution evenly over the whole glacier must be about 11 mm, i.e. 1000 times that found at Storbreen. However, it must be taken into account that, in ordinary mud transport measurements, the material transported along the river bed escapes measurements, and this material is certainly quite important. To measure its transport is not easy, and it is very difficult to estimate.

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