VARIATIONS IN THE GLACIER MASS OF JOSTEDALSBREEN

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ABSTRACT. By comparing the recorded run-off from a precipitation district, about 55 per cent of which is covered by glaciers, to the run-off from a neighbouring district without glaciers it has been possible to determine the changes in the glacier mass of Jostedalsbreen. In the period 1900 to 1940 the annual decrease of the glacier mass was equivalent to 0·4 m. of water times the glaciated area. A close relationship is established between the change of the glacier mass and the length of one of the outflow glaciers, Briksdalsbreen. It is shown that the change in the glacier mass is related to the summer temperature and, to a minor extent, to the amount of winter snowfall.

ZUSAMMENFASSUNG. Die Änderungen in der Gletschermasse des Jostedalsbre konnten dadurch bestimmt werden, dass die aufnotierten Wasser-Abläufe in einen Niederschlag-Distrikt, der zu ungefähr 55% mit Gletschern bedeckt ist, mit den Abläufen eines benachbarten Distriktes ohne Gletscher verglichen wurden. In der Zeitspanne 1900 bis 1940 entsprach die jährliche Abnahme der Gletschermasse 0,4 m Wasser mal der vereisten Fläche. Es wurde eine enge Beziehung zwischen der Änderung der Gletschermasse und der Länge von einem der ausfliessenden Gletscher, dem Briksdalsbre, festgesetzt. Es wurde gezeigt, dass die Änderung der Gletschermasse mit der Sommertemperatur und, in geringerem Masse, mit der Menge Schnee, die im Winter fällt, zusammenhängt.

IT is well known that in the present century all glaciers which have been examined have, on average, retreated. There exist, however, no long-term measurements of the corresponding variations of the mass or volume of the glaciers. Nevertheless these are of importance in order to estimate the influence that glaciers in the precipitation area of a river may exercise upon the available water power.

In order to examine this question I have attempted some calculations of the variation of the glacier masses of certain Norwegian glaciers, and present here computations that apply to Jostedalsbreen and the results at which I have arrived. Communications dealing with this subject and also with conditions in two other glaciers in Norway have been published in *Norsk Geografisk Tidsskrift*, Vol. 8, Ht. 8, 1941, p. 273–93, and Vol. 9, Ht. 4, 1942, p. 129–57.

The computations are based on hydrological measurements undertaken by Norges Vassdrags- og Elektrisitetsvesen and on measurements of the retreat or advance of outflow glaciers which flow from the ice cap. The latter have been carried out by Bergens Museum. I have started with the assumption that the decrease in the glacier masses must have manifested itself as an addition to the run-off which precipitation alone would have caused in the same period. I have therefore computed the ratio between the run-off in glacier rivers and the run-off in neighbouring rivers in the same general locality which are *not* fed by glaciers in their precipitation district. I have assumed that variations in that ratio could serve as a basis for determining year to year variations in the decrease or increase of the mass of the glaciers. This assumption is approximately correct only if the annual precipitation in the districts under consideration varies from year to year in a similar manner relative to average conditions. Such may not always be the case, for which reason one cannot expect to determine the decrease or increase of the mass of a glacier in a single year with great accuracy, but if the computation can be carried out over a long period, the errors should in part cancel out and one should arrive at a result which should be approximately correct.

Jostedalsbreen is an ice cap in western Norway, located approximately 61° 40′ north and 7° east of Greenwich (see Fig. 1, p. 552). Its area is about 850 km.², but some of this is separated from the major part by small tracts of exposed rock. The ice cap reaches a height of about 2000 m. above sea-level. Several other glaciers are situated directly to the east and to the north of Jostedalsbreen, so that the total glacierization of this part of the country amounts to nearly 1250 km.².

On the basis of the preceding considerations I have attempted to determine the variations in the glacier mass of that part of Jostedalsbreen from which the run-off feeds two rivers in Nordfjord, namely Oldeelva and Loelva. For the period beginning 1900 when the run-off measurements

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were started, I have compared the sums of the annual run-off values from the lakes—Oldevatn and Lovatn—to the corresponding sums of run-off from Hornindalsvatn (see Fig. 1). There are no glaciers worth mentioning in the precipitation district of Hornindalsvatn, but in some years snow drifts may persist at higher levels although in other years they will melt away. However, the same conditions also apply to the precipitation district of the glacier rivers, so that there should be no appreciable error if this feature is disregarded. The precipitation districts have the same relationship to the direction of the wind during the principal precipitations; therefore, the variations in annual precipitation in the two districts can be expected to be similar.

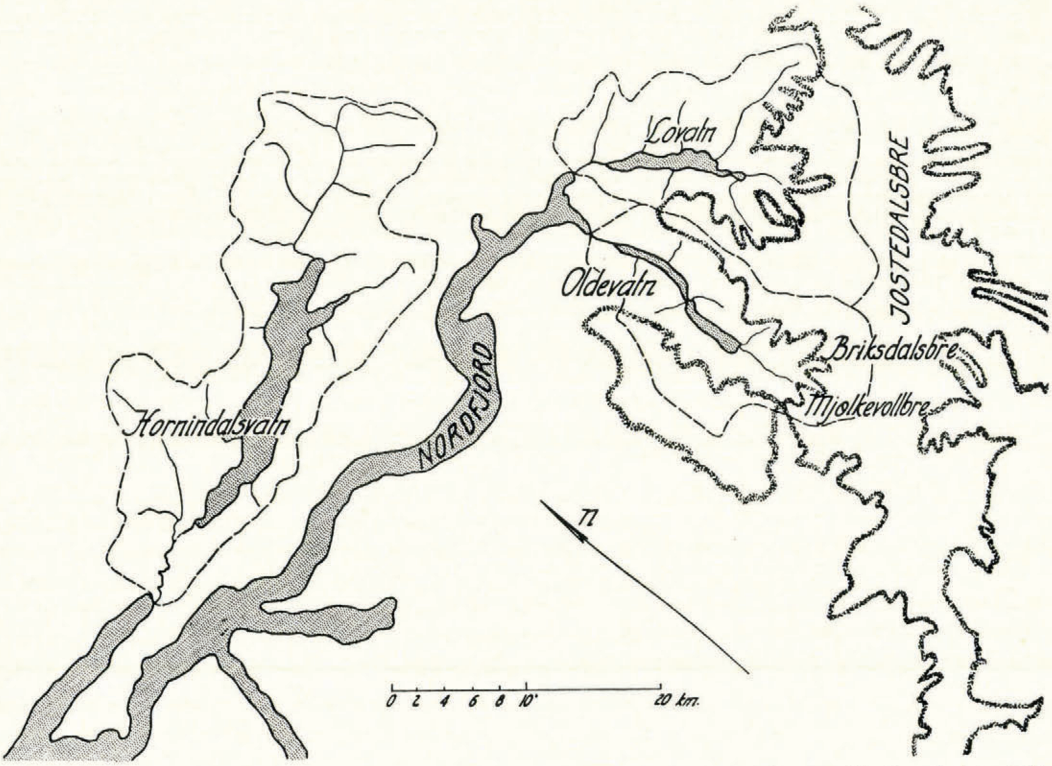

Fig. 1. The precipitation districts of the lakes Oldevatn, Lovatn and Hornindalsvatn. The broad, dotted line indicates the limits of Jostedalsbreen

According to the available maps which, however, are old and inaccurate, the precipitation district of Oldeelva at the point where it flows out of Oldevatn is about 210 km.^{2}, of which about an area of 101 km.^{2} is covered by glaciers. When flowing from Lovatn Loelva has a precipitation district of about 260 km.^{2}, of which 158 km.^{2} are covered by glacier. Thus these two rivers have a total precipitation district of 470 km.^{2}, of which 259 km.^{2} or 55 per cent are covered by glaciers. At the point where Eidselva flows out of Hornindalsvatn it has a precipitation district of about 375 km.^{2}.

When computing the annual run-off I have used the period from 1 October in one year to 30 September in the next, because I have assumed that after 1 October no melting of the glaciers takes place.

In the years 1900–40 the total run-off in the glacier rivers was 40,564 million m.^{3}, and the

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run-off from Hornindalsvatn was 29,865 millions m.³. The ratio between these figures is 1·358. The decrease or increase of the glacier masses in the single years, over and above the average decrease from 1900 to 1940, has been taken as the difference between the run-off in glacier rivers and the run-off from Hornindalsvatn times 1·358. This difference represents the total change. In order to find the variations expressed in metres of water, the difference has been divided by the glacierized area.

In this computation it has been assumed that if in a single year the decrease of the glacier equals the average decrease from 1900 to 1940, then the annual values of run-off in the glacier rivers and the run-off from Hornindalsvatn stand in the same relationship to each other as the sums of run-off for the entire period. It would have been better first to have corrected the run-off in the glacier rivers by subtracting the average annual decrease of the glacier masses, but this could not be done because this figure was not known. Corrections which were undertaken afterwards showed that the more refined procedure was of no practical importance to the determination of the total decrease in the entire period.

The upper curve in Fig. 2 (p. 555) shows the sums of the deviations starting from 1 October 1900 expressed as metres of water. The curve begins at 0 and ends at 0 because it represents only deviations from the average decrease. The lower curves in Fig. 2 indicate the changes in the position of the fronts of the two glaciers, Mjølkevollbreen and Briksdalsbreen, referred to their position in 1900.

From the curves in Fig. 2 it will be seen that the advance or retreat of the outflow glaciers occurs rather consistently four years after their computed increase or decrease. Thus it takes four years before a change in the glacier mass appears as a change in the position of the fronts of the outflow glaciers. This indicates that the length of these glaciers is more influenced by the transport of material from the higher-lying ice cap than by greater or less melting of the outflow glaciers in single years. It appears that the thickness of the glacier mass four years in advance determines the length of the outflow glaciers at any given time.

From the two curves which show the positions of the glacier fronts I next read off the various dates at which one of the outflow glaciers was of the same length. Four years prior to that date the glacier mass should have had the same thickness. From the curve for Briksdalsbreen, for instance, it will be seen that the glacier was of equal length in 1917 and in 1932. The glacier mass should, therefore, have had the same thickness in 1913 and in 1928. In 1928 the curve for the variations in the glacier mass relative to the average decrease from 1900–40 (upper curve in Fig. 2) lies 6 m. above the position in 1930. This means that during the 15 years the glacier mass has, on average, decreased by 0·40 m. a year. In this manner I examined conditions at various dates, and the average value of the decrease proved to be equal to the above, that is, equal to 0·40 m. a year.

The run-off which in the 40 years from 1900 to 1940 should result from the decrease in the glacier mass should then be $0{\cdot}4 \times 259$ km.$^2 \times 40$ years, or 4144 million m.³. Therefore the run-off due to precipitation should equal 40,546 minus 4144, or 36,402 million m.³. In the final computation of the change in the glacier mass I have used this run-off, and the ratio between the run-off in the glacier rivers after subtracting the contribution from the glaciers and the run-off from Hornindalsvatn, i.e. 36,402/29,865. The result of this computation is shown in Fig. 3 (p. 555). Fig. 4 (p. 556) gives a graphic presentation for each year of the location of the front of Briksdalsbreen in relation to the computed glacier mass four years earlier. The smoothed curve in this figure has been computed by the least squares' method. It will be seen that the position of the glacier front closely follows the computed glacier mass.

Below Briksdalsbreen there is situated an end moraine which marks the point reached by this outflow glacier at the time of the great advance that took place in the first half of the eighteenth century. The smoothed curve has been extended to this end moraine in order to obtain an estimate

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of the thickness of the glacier in about the year 1744. It cannot be expected that the curve will apply with great accuracy because the outflow glacier extended beyond the region for which the curve has been computed. Its accuracy must depend upon the shape of the valley which lies below the point reached by the glacier in 1900 and also on possible additions from other parts of the ice cap. The latter possibility appears, however, to be very remote. According to the graph the glacier must have been about 60 m. (expressed as water) thicker in 1744 than it is now. This value cannot be considered accurate, but it probably represents a fair expression of how much Jostedalsbreen has decreased during the last 200 years.

In connection with these computations I have endeavoured to ascertain to what extent these results are related to the fairly well-known meteorological factors which influence the melting of glaciers. Decrease or increase of the glacier mass depends on the one hand on melting by addition of heat and on the other hand by accumulation in the form of snow or hoar deposits.

The following processes convey heat to the glacier:

1. Incoming radiation. Incoming radiation is only of importance during summer because in winter it is not strong enough to cause melting. The amount of radiation depends on the altitude of the sun and the cloud cover, but is independent of the air temperature.

2. Convection of heat from the air. If the air temperature is above 0° C. convection increases with increasing air temperature and wind velocity.

3. Condensation of water vapour on the surface of the glacier.

4. Precipitation in the form of warm rain, but this source is probably unimportant under the temperature conditions existing on Jostedalsbreen.

5. Conduction of heat from the interior of the earth, but this source has been neglected.

Summer evaporation may deprive the glacier of some heat, but the loss must be unimportant on an ice cap like Jostedalsbreen, where there is no foehn.

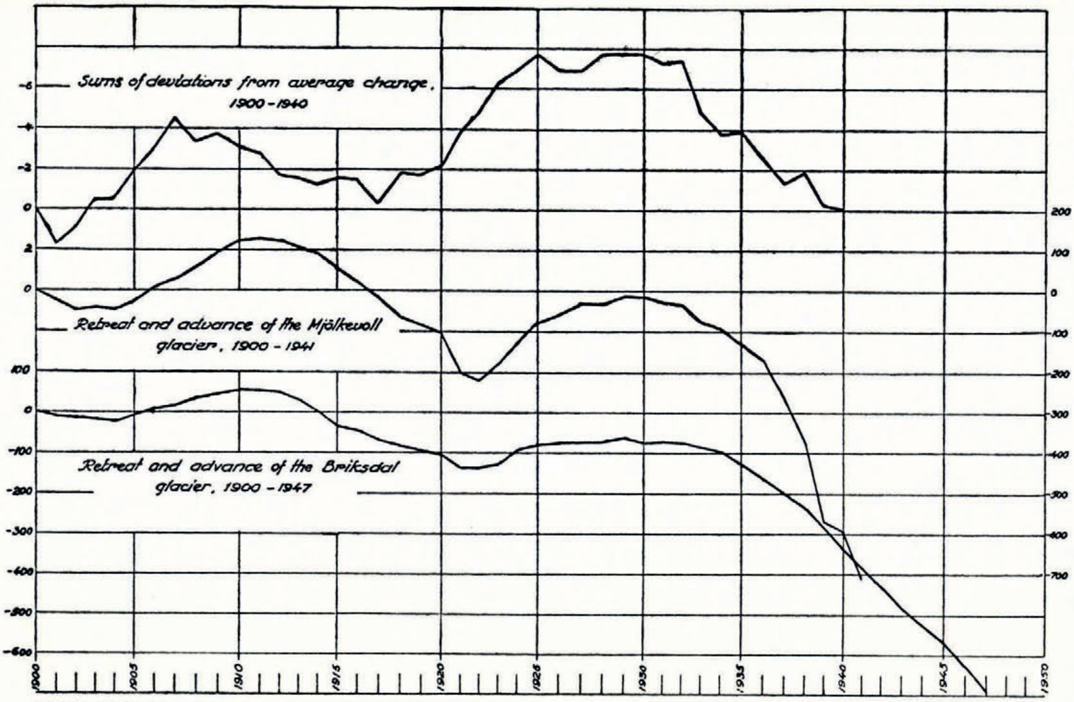
The heat gain must first melt the snow and ice which correspond to the precipitation that has fallen on the glacier as snow or hoar during the year. When this has taken place, further melting will reduce the glacier.

The available observations furnish no basis for computing the gain of heat by radiation. Similarly no observations are available for determining the gain of heat by condensation of water vapour. Air temperatures on the glacier have not been recorded, but temperature measurements for lower localities are available, and from these one can estimate the year to year variations in the summer temperature on the glacier. No wind observations on the glacier have been made.

There are also no observations of the amount of precipitation that has fallen as snow on the glacier during the year, but precipitation has been measured at lower localities in the vicinity, and on the basis of this and the run-off measurements one can estimate the precipitation on the glaciers.

Of the meteorological factors it is thus only summer temperatures and precipitation in the form of snow which can be used for comparison with the changes in the glacier mass. One cannot expect to find any fixed relation between these meteorological factors and the computed glacier change in single years because the incoming radiation, which is an important factor, does not vary as the temperature. Furthermore, the summer temperature on the glacier will not always vary as much as the temperature at a station in the valley because the vertical temperature gradient varies with the humidity of the air and is greater in a dry summer than in a wet one. The winter precipitation may also not be in step with that measured at stations in the valleys. On an average for a number of years one may, however, expect to find a relationship between the variations in glacier mass on the one hand and the variations in summer temperature and snow precipitation on the other.

By using the run-off measurements and the computed decrease of the glacier mass it is found that the precipitation on the glacier must have been 1·13 times the sum of precipitation on the two nearest stations, namely Opstryn and Briksdal. It is not possible to determine how much of this



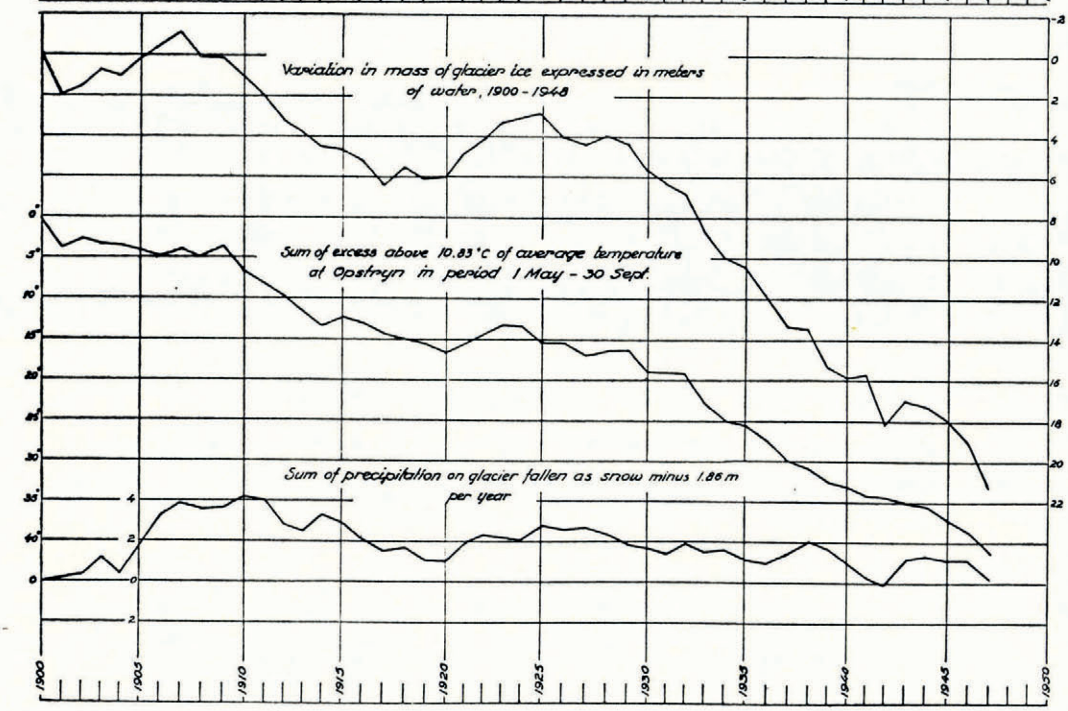


Fig. 2 (*above*). *Sums of differences in run-off from glacierized and glacier-free areas, taken as deviations from total change from* 1900 *to* 1940 *and expressed as metres of change in thickness of glacier mass. Changes in the locations of the fronts of the glacier arms, Mjølkevollbre and Briksdalsbre.*

Fig. 3 (*below*). *Comparison between variations in glacier mass,* 1900–1948, *summer temperatures and snow precipitation.*

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precipitation fell as snow, but I have assumed that it was in the solid form during the seven months October to April. From this I find that the mean annual solid precipitation on the glacier was 1860 mm. By examining how much snow and ice melted on the glacier in single years (the estimated snow precipitation plus the computed decrease or increase in the glacier mass) I find that on the average the glacier mass remained constant when the average temperature in the months May to September was 10·83° C.

In Fig. 3 (p. 555) below the curve for the decrease of the glacier mass, there is shown a second curve, which gives the sums (from 1901) of the deviations of the mean temperature at Opstryn from 10·83° C. The third curve in the same figure gives the sums (from 1900) of the deviations of the snow precipitation from 1860 mm.

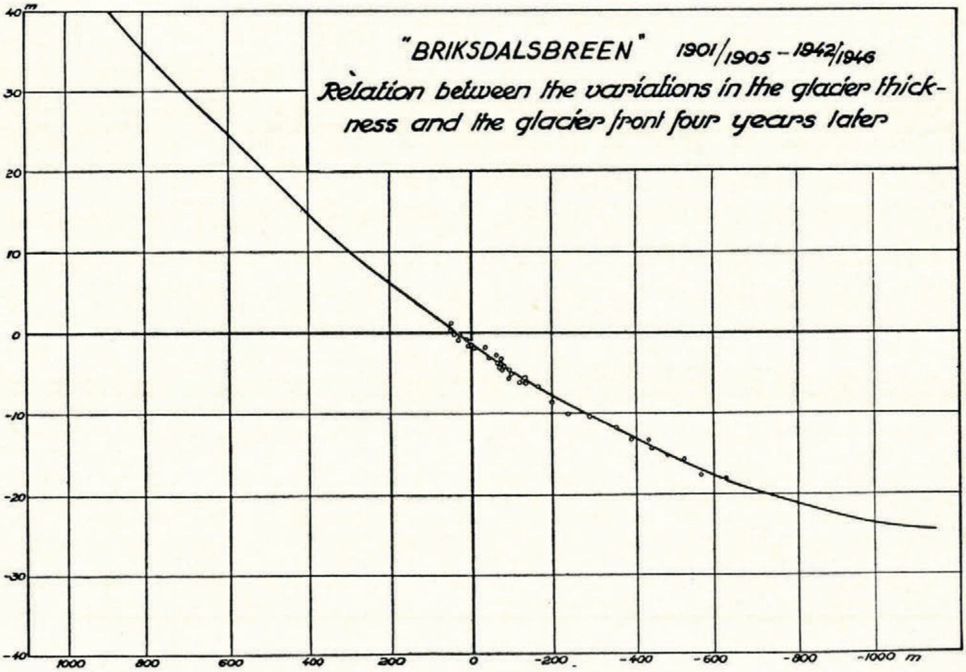

Fig. 4. Relation between variation in thickness of mass of Jostedalsbreen and position of front of Briksdaksbreen four years later. The ordinates represent deviations of ice cap thickness from the datum year of 1900 expressed in metres of water. The abscissae denote deviations in metres in the position of the glacier front referred to the same year.

It is seen that the computed variation in the glacier mass generally follows the variations in the temperature, but it is also seen that in a few cases a large amount of solid precipitation has brought about an increase in the glacier mass in spite of a high temperature. This was the case, for instance, from 1901 to 1907. Otherwise there are irregularities which may be ascribed to variations from year to year in other meteorological factors or to uncertainty in the estimate of the snow precipitation in single years.

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