CONTRIBUTION TO THE PHYSICS OF GLACIERS: *A paper read at the Afternoon Meeting of the Society on 8 April 1935, by*

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GLACIOLOGY is not only important for our knowledge of present-day glaciers, but is also essential for the proper understanding of the nature and activity of glaciers existing in the Ice Ages.

The investigations, of whose results I now have the honour to speak, began in 1920 in Jotunheim, the central high mountain district in southern Norway, and were continued more especially during the summers of 1923–25 on the small Styggedal glacier. In the summer of 1931 I was the leader of the Swedish-Norwegian Arctic Expedition to North-East Land and the surrounding waters, and in the summer of 1934 I accompanied Professor H. U. Sverdrup, when we both acted as leaders of the Norwegian-Swedish Spitsbergen Expedition. Both these expeditions were made possible by grants from the Swedish Government and the Norwegian Parliament. They were carried out absolutely according to programme and by the united efforts of the Swedish and Norwegian members. The general outlines of the 1931 expedition and most of its results are published in the *Geografiska Annaler*.[1] A review of the expedition will be found in the *Geographical Journal*.[2]

The expedition of 1934[3] undertook a more concentrated glaciological-meteorological programme than the former, and had a Swedish and a Norwegian assistant as well as the two leaders. Our headquarters were on Isachsen's Plateau, a large firn-field in lat. 79° 9′ N., long. 12° 56′ E., and 850 m. above sea-level. Here we carried out the greater part of our investigations. Besides this I devoted myself to the Fourteenth of July Glacier, which goes down to Cross Bay on the west coast of Spitsbergen. We reached this glacier as early as June 19 without having seen any pack-ice in the sea. On the journey up to the plateau, which we reached on June 23, with 17 dogs and 3 sledges, I erected 22 bamboo stakes, each $2\frac{1}{2}$ m. long, and put flags and numbers on each. During the summer these stakes were to serve as gauges for measuring the melting of the snow and ice and as signals for determining the movement of the glacier. The day after our arrival at our headquarters the sledge-drivers returned with 15 dogs to the coast and the Norwegian coalmine Longyearbyen; and they fetched us again on August 18. During our 53 days' sojourn on the plateau my assistant and I made two journeys down and up the Fourteenth of July Glacier with some light equipment specially constructed for this purpose, and this was drawn by the two dogs left with us. On the way back to the coast on August 18 the gauges were measured for the fourth and last time. On August 27 we were again in Bergen without having seen any pack-ice at all in the sea around Spitsbergen.

[1] "Scientific Results of the Swedish-Norwegian Arctic Expedition." Parts I–X (vol. i), *Geografiska Annaler* 1933. Part XI, *Geografiska Annaler* 1934. Part XIII (Vascular Plants from Northern Svalbard), Skrifter om Svalbard og Ishavet n:r 62, Oslo 1934. Part XII (Oceanography) will be published in *Geofysiske Publikasjoner* (Bergen) 1935.

[2] May 1934, pp. 420–425.

[3] The results will be published in *Geografiska Annaler* (Stockholm) and in *Geofysiske Publikasjoner* (Bergen) in 1935 and 1936.

As the Oxford Expedition in 1924 had already established, the plateaus of North-East Land are covered with typical glacier-caps. These are divided into three parts: the South Ice, the East Ice, and the West Ice. They belong to the group of glaciers which are geomorphologically characterized by extending in a continuous sheet in which the ice moves outwards in all directions. They differ from continental glaciers or inland ices in that they cover smaller areas. The second group of glaciers is characterized as confined to a more or less marked path which directs the main movement of the ice. Valley glaciers, trans-section glaciers, circus glaciers, and wall-sided glaciers belong to this group, as well as tongues afloat. As a third group I will include the movable masses of ice and firn, which spread in large or small cake-like sheets over the level ground at the foot of high glaciated regions. These glaciers, piedmont glaciers and foot-glaciers as well as shelf-ice, are not independent.

During my 350-km. sleigh journey across the three glacier caps, a pit about 2 m. in depth was dug at each camping place. Sections of three different types were thus exposed: one belonging to the ablation area, another to the accumulation area, and the third to a transition area between them. The firn-line, or climatological snow-line, which is of such great importance to our knowledge of glaciers, coincides with the boundary between the ablation and the transition areas. Such pits, which are very easy to make, thus rendered it possible to determine the altitude of this line without having to wait until it was revealed by the summer melt of the snow. On the North-East Land glacier-caps it was at altitudes varying from 350 to 550 m. above sea-level.

The area of the relatively best-known West Ice is about 2800 sq. km., 1600 of which are situated above the firn limit and 1200 beyond it. The thickness of the central parts of the three glacier-caps of North-East Land can hardly exceed 200 m., and they are probably 150–200 m. thick where they meet the sea.

The largest glacier-cap in Norway, the Jostedalsbrae (about 1000 sq. km.), is most likely much thinner. Over large areas the ice is certainly not more than 20 or 40 m. thick, and the topography of the surface of the ice sheet is influenced in detail by the rock surface underneath.

The object of my glaciological work has been to analyse the active physical processes, to investigate quantitatively the amount of snow, ice, and water passing through the glaciers, and on the basis of this knowledge to discuss the geophysical conditions of the existence and life of glaciers. In my opinion such investigations are absolutely necessary to acquire a more thorough knowledge of the geography of glaciers.

First of all I should like to treat ablation processes. While the amount and distribution of precipitation has long been carefully investigated and measured, ablation—by which I mean the joint result of the processes eating into the snow or ice surface, *i.e.* melting and evaporation—has not been made the object of any detailed study until the last few years. This is rather surprising, as ablation is obviously of as much importance in our knowledge of glaciers as are any other of the factors: accumulation, movement, etc., which have been closely studied ever since the first beginnings of glaciology.

Plate 1. A view of Sveanor, headquarters of the Swedish–Norwegian Arctic Expedition in 1931

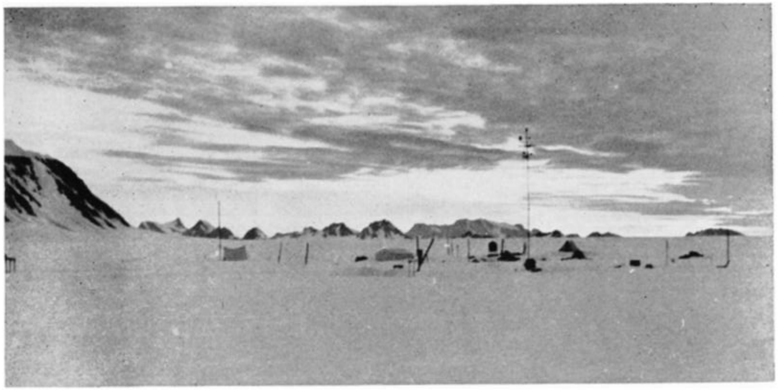


Plate 2. The headquarters of the Norwegian–Swedish Spitsbergen Expedition in 1934

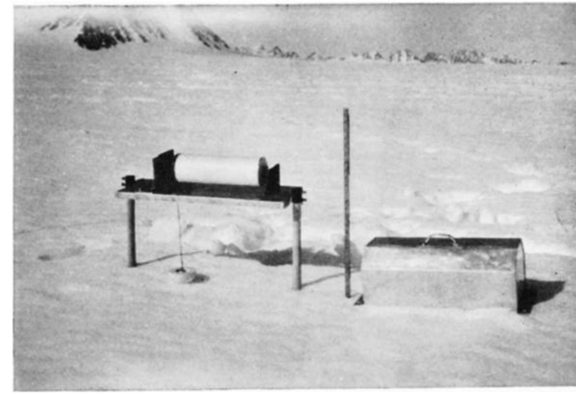


Plate 3. The ablatograph in use on Isachsen's Plateau

Plate 4. The margin of the Fourteenth of July Glacier in the fjord

For my preliminary studies[1] in the Jotunheim in lat. 60° 25′ N. and 1350 m. above sea-level I employed a first attempt at a recording instrument, an ablatograph. The amount of the ablation was determined at intervals of 8–10 hours and correlated with temperature, wind velocity, precipitation, and the values calculated of the radiation from the sun and sky. The observations covered 2515 hours. The total ablation during the whole summer at 1580 m. above sea-level was calculated for normal climatological conditions at 2000 mm. of water. During July and August the ablation amounted to a mean value of 2·3 mm. per hour for days and to 1·8 mm. for nights. The investigations resulted in a first general idea of the connection between the process of ablation and the meteorological elements. Heat convection by the air was found to have approximately twice as much effect on ablation as radiation.

A drawback to these investigations was the fact that the records of the meteorological elements had to be made some little distance from the glacier, *i.e.* about 1 km. from the ablatograph. Another disadvantage was the lack of continuous values of the radiation, which was due to the lack of a suitable actinograph.

At the headquarters of the 1931 expedition, Sveanor (Plate 1), in lat. 80° and 4 m. above sea-level, the records of the ablation were taken from June 30 to August 6 on a snowfield in the immediate vicinity of the meteorological station which was equipped with a recording actinograph of the Robitzsch's type. The observations cover 49 time-intervals aggregating 661 hours. During this time the total ablation amounted to 878 mm. of water, *i.e.* an average of 1·3 mm. per hour. I have estimated the total ablation at this place during the whole summer at 1400 mm. of water. On account of these observations A. Ångström made a preliminary equation for the relation between ablation and some of the meteorological elements most important to it: *i.e.* radiation, air temperature, and wind velocity. The result was that 40 per cent. of the ablation was due to radiation and 60 per cent. to heat convection by the air.

Even these investigations I consider have not reached the standard of necessary accuracy and completeness. The collaboration between Professor Sverdrup and myself during the 1934 expedition has now brought this problem much nearer its solution.

Professor Sverdrup's object during this expedition was a detailed study of the heat balance between the atmosphere and the snow surface. For this purpose we mounted at our headquarters an instrumental equipment to enable Sverdrup and his Norwegian assistant to determine from June 26 to August 15, for every hour of the day and the night, the meteorological elements from the snow surface to 5 m. above it with the greatest accuracy. About 20,000 readings were taken, thus giving him more extensive and accurate material than has ever been previously obtained on a glacier. At the same time Mr. Olsson, my Swedish assistant, made all radiation intensity measurements. My object was to ascertain the ablation, *i.e.* the effective result of the action of the heat, transferred to the snow surface by air and radiation.

For this purpose I employed an ablatograph (Plate 3), designed by Doctor

[1] "Physico-Geographical Researches in the Horung Massiv, Jotunheim." I *Geografiska Annaler* 1923; II–IV *Geografiska Annaler* 1927; (IV The Ablation); V–VI *Geografiska Annaler* 1928.

O. Devik in Norway at my request.[1] A recording mechanism is fixed on a firm support above the surface of the snow, and this registers the subsidence of a float resting on the snow or ice; the float is connected to the recording mechanism by a string. The support had no independent movement, the string did not stretch or slacken, and the mechanism worked perfectly. The float however had independent movement, as when the radiation was considerable it absorbed more heat than the snow and consequently melted into it. When the sky was overcast, and still more in foggy weather, the snow surface sank on the other hand more quickly than the float, if the latter had previously sunk into the snow. The level of the float in relation to the snow surface was therefore ascertained at least a couple of times a day, especially when the weather changed. Additional control was obtained too by measuring the ablation two or three times a day on a slender bamboo or other stake stuck into the surface close to the instrument. After making these corrections for the independent movement of the float, continuous curves of the subsidence of the snow surface were obtained, which permitted the determination of the ablation every two hours with an accuracy of 0·5 mm. (Fig. 1).

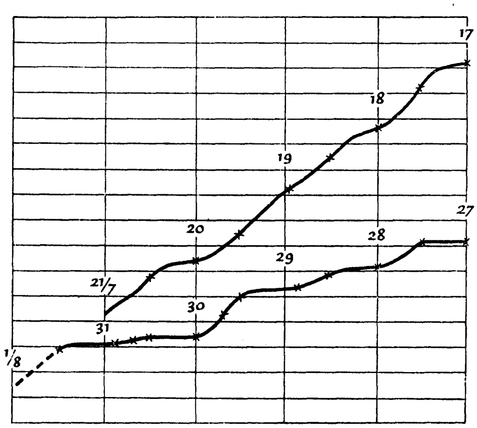


Fig. 1

The total ablation from June 26 to August 16 amounted to 415 mm. of water, or on an average 0·33 mm. per hour. The maximum for a two-hours' interval was 9 mm. of water. For the whole summer the ablation has been calculated at 480 mm. of water. Apart from this, 270 mm. of water remained of the snow accumulation from the preceding winter.

Professor Sverdrup's treatment of his meteorological observations is not yet completed,[2] but from what has hitherto been ascertained, it may be said that the results from the 1931 expedition have been confirmed concerning the much greater effect on ablation[1] of heat convection by air than of radiation. The air temperature was as a rule lowest at the surface of the snow and increased upwards. Consequently, a transference of heat generally took place from the air down to the snow, even when the temperature was negative. These observations also rendered it possible to determine in detail the importance of the humidity of the air for ablation. This is necessary for calculating the quantity of moisture condensed on the snow, when warm and humid air passes over it,

[1] The instrument, its technical use and the necessary corrections that must be made to its records are treated in: H. W:son Ahlmann, "Determination of the Ablation of Snow and Ice; Hyllningsskrift till Sven Hedin," 19 febr. 1935," *Geografiska Annaler* 1935.

[2] A preliminary report, "Varmeutvekslingen mellem en sneflate og atmosfaeren," is published in *Beretninger fra Chr. Michelsens Institutt*, Bd. V, Bergen 1935. The definitive treatise will be published in *Geofysiske Publikasjoner*, Bergen.

and the amount of evaporation when the air is dry. Professor Sverdrup has found that ablation is greatest in periods with warm and humid air, especially when wind velocity is great; in periods with warm and dry air ablation is much less. It will be remembered in this connection that the melting of 1 mm. of snow requires only one-eighth of the heat necessary for the evaporating of the same quantity. On the whole evaporation plays an unimportant rôle in ablation as compared with melting.

For studying the firnification of snow and the recrystallization of firn into ice we dug seven pits at our headquarters, five of which were 4–5 m. in depth. In the largest of them we bored another 10 m. with an auger specially constructed for this purpose.

In Figure 2 the sections of five pits are placed side by side and refer to the snow surface on June 25 at 8 p.m. We see that the firn is well stratified, which is due to the presence of a great number of horizontal ice layers in the sections marked in black. From this figure the following facts are obvious: firstly, even if an ice layer varies considerably in thickness, its base is horizontal; secondly, some ice layers are thicker and more continuous than others. The first circumstance is due to the fact that the ice layers are first established as relatively thin crusts, which have subsequently been increased by material from above. The second circumstance is due to the ice layers making the boundary between two accumulation periods, *i.e.* these layers have their origin in the ice crusts, which freeze on the snow surface during the autumn, after the summer melting, and are then covered by snow during the winter following. The correctness of this opinion is fully proved by facts, upon which I cannot however enter here. Thus the firn mass is very clearly laminated in annual layers, and I have marked the boundaries in question with the respective years during the autumns of which they were established as an ice crust on the snow surface. The profiles are therefore calendars, comprising the years 1924–34, in which every annual layer corresponds to the accumulation surplus of one year, *i.e.* the total accumulation of precipitation in solid form during the winter minus the ablation during the summer following. This surplus varies in the seven pits between 95 and 300 mm., the mean being 200 mm. of water. These numbers also represent the very important values of the yearly contribution of nourishment to the glaciers in this district of Spitsbergen.

The boring from 5 to 15 m. in depth showed that the same conditions prevail in that part of the firn mass as in the uppermost 5 m., *i.e.* during the period 1899–1934 the glaciers from Isachsen's Plateau have received an annual average of 200 mm. of water in the form of snow or firn.

I found exactly the same conditions in the accumulation area of the North-East Land glacier-caps. In these districts however the annual surplus of snow and firn was only 63 mm. of water on an average. This fact is closely allied to the circumstance that these glacier-caps are nearly dead or have at least only a very small activity.

Besides this I have systematically made microscopic investigations of the structure of the firn, determinations of its specific gravity, and its permeability of radiation. These investigations are not as yet completed.

Sverdrup determined the temperature and its variations every day in the firn masses in several places at our headquarters, by means of electrical resistance thermometers. In consequence of the facts established in North-East Land in 1931 we had expected to find on Isachsen's Plateau, where the mean annual temperature is about −12° C., frozen firn down to a considerable depth. As early as on June 25, when the largest pit was dug and the melting had just begun, I found however that at 3 m. the temperature was the lowest (−6° C.) and from there it rose to zero at 10 m. Sverdrup's systematic records have led him to the following conclusions about the thermal conditions in the snow and firn.[1] When the ablation water penetrates down into the firn, it freezes when it reaches the depth where the firn temperature is negative; it gives off its freezing heat and makes the temperature rise lower down. Exactly the same process occurs when a frozen fish for instance is put in water to thaw: an ice-shell forms round the fish. On August 1 every trace of the winter cold had disappeared and the whole firn masses were at zero.

Sverdrup has calculated that 145 mm. of water freezes in this manner in the first 10 m. when the annual surplus of snow is 400 mm. The rest of the ablation water passes down through the firn and runs off.

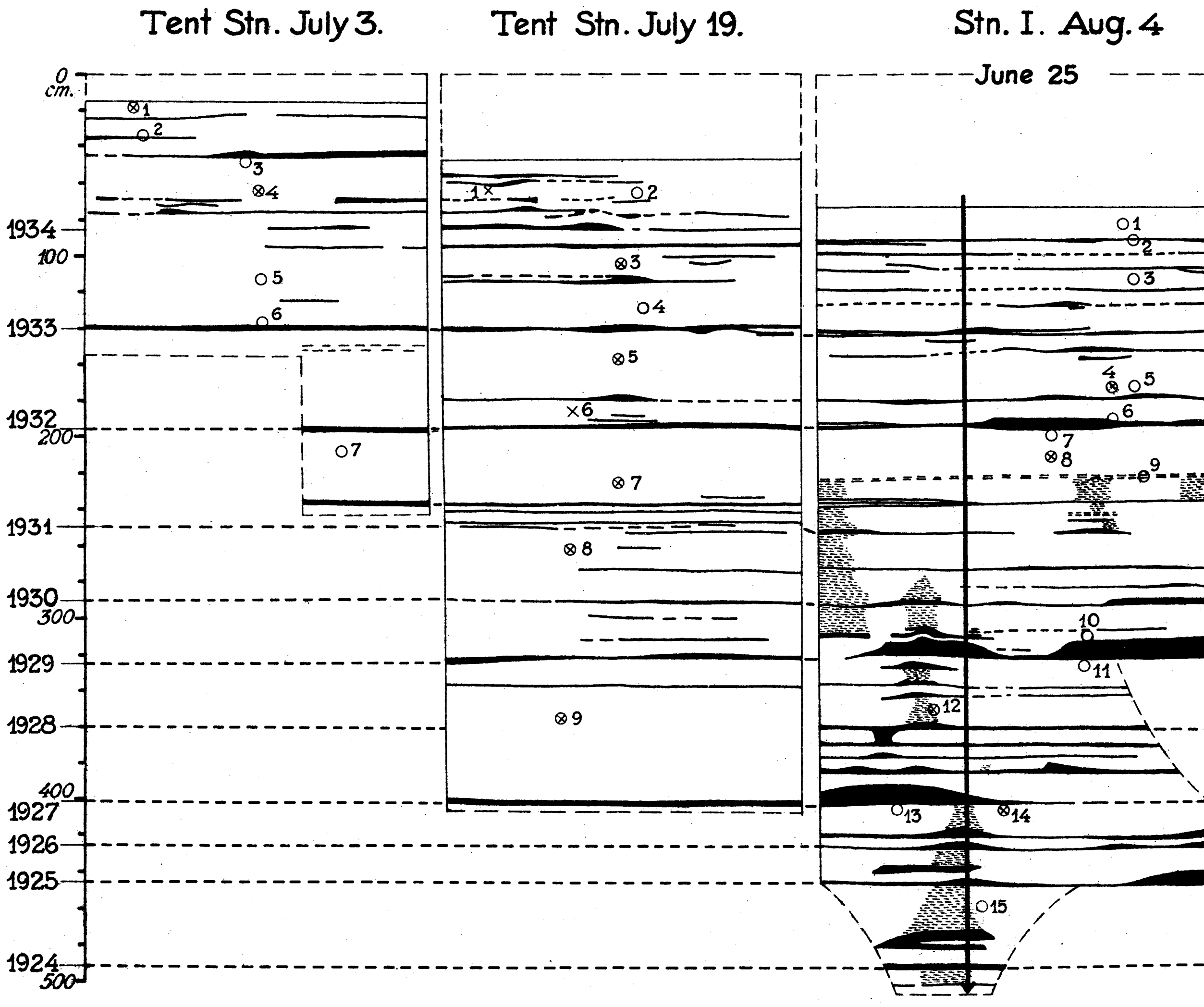
In consequence of these processes the ice crusts become thicker and the specific gravity of the annual layer of firn rises the lower we go. My measurements show that the density of the annual layers regularly increases from 0·54 in the layer 1933–34 to 0·64 in the layer 1924–25. This freezing process does not occur lower than 10 m., and Sverdrup believes that the transformation of the firn into glacier ice does not begin until the depth is so great that the pressure becomes the decisive factor. As a consequence of this freezing process a slow recrystallization of firn crystals will take place.

All these processes are of the greatest importance to our knowledge of glaciers. On the basis of the temperature observations made during my sledge journey over the glacier-caps of North-East Land in 1931 it has been calculated that under certain assumptions these glaciers are frozen to a depth of 270 m. at least. The glaciers with negative temperature, so important in the study of glaciology, were first discovered by Colonel J. P. Koch and A. Wegener in East Greenland during their expedition in 1912–13. The German Greenland Expedition Alfred Wegener continued these investigations at the station Eismitte in 1930–31. The results of these expeditions, our knowledge of Alpine glaciers, and various statements as regards the structure of glaciers in other parts of the Earth led me to classify glaciers geophysically as follows:

I. *Temperate glaciers* consist of crystalline ice formed by fairly rapid recrystallization of the annual surplus of solid precipitation. Throughout these glaciers the temperature corresponds to the melting-point of the ice, except in the winter time, when the top layer is frozen to a depth of not more than a couple of metres. The glaciers of Scandinavia and the Alps are included in this group.

II. *Polar glaciers* consist, at least in their higher and upper parts, of hard crystalline firn formed by slow recrystallization of the annual surplus

[1] H. U. Sverdrup, "The Temperature of the Firn on Isachsen's Plateau"; will be published in *Geografiska Annaler* 1935.



Tent Stn. July 3.
Tent Stn. July 19.
Stn. I. Aug. 4
June 25
0 cm.
100
200
300
400
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1934
1933
1932
1931
1930
1929
1928
1927
1926
1925
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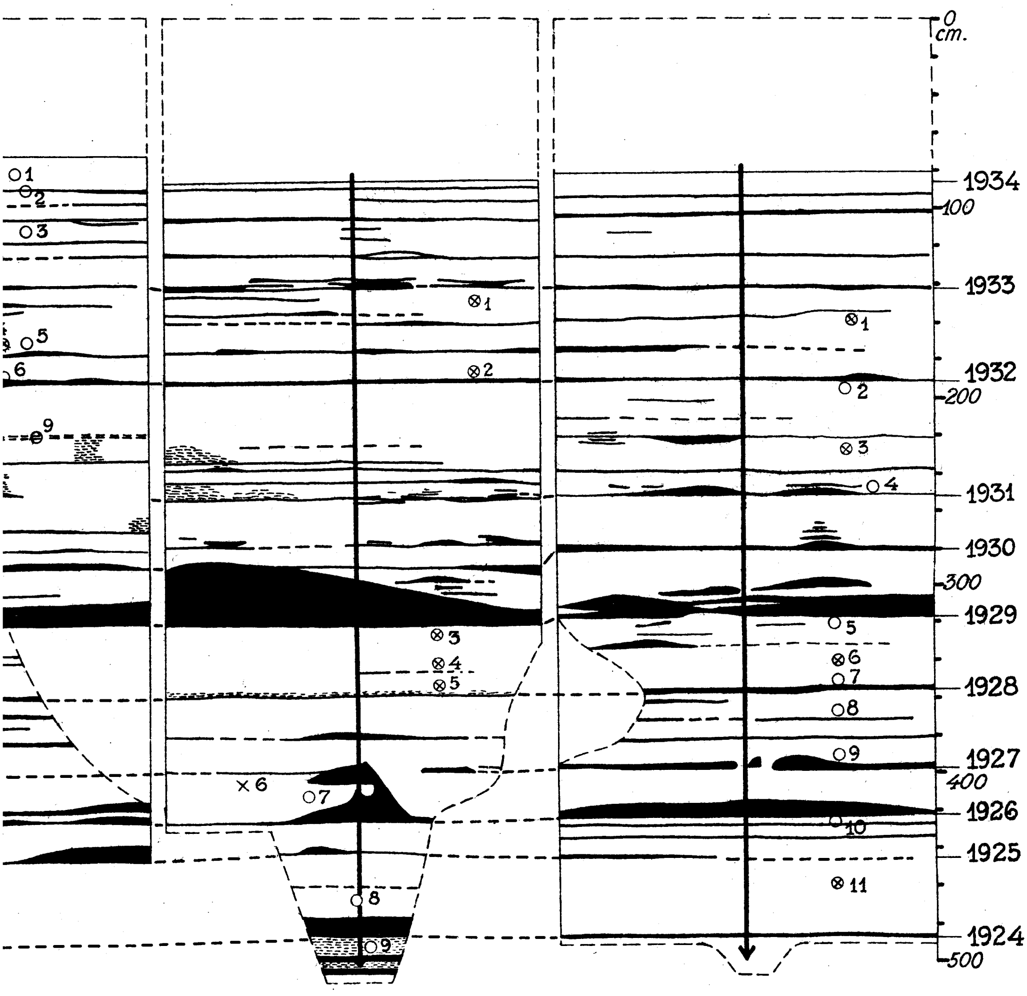
Fig. 2.

g. 4



Stn. V. Aug. 12
Stn. VIII. Aug. 9
0 cm.
1934
100
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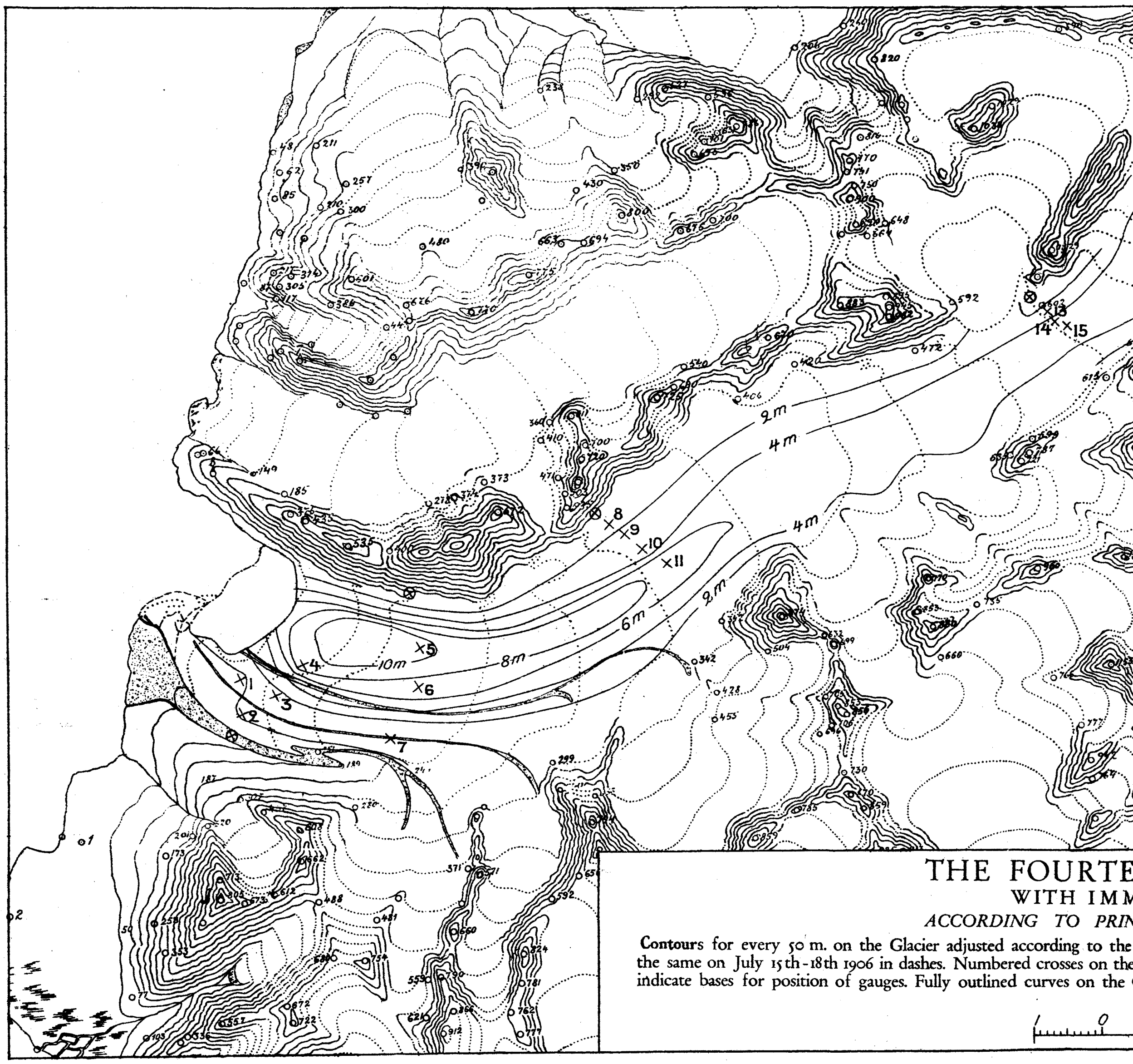

THE FOURTE
WITH IMM
ACCORDING TO PRIN
Contours for every 50 m. on the Glacier adjusted according to the
the same on July 15th-18th 1906 in dashes. Numbered crosses on the
indicate bases for position of gauges. Fully outlined curves on the
2m
4m
6m
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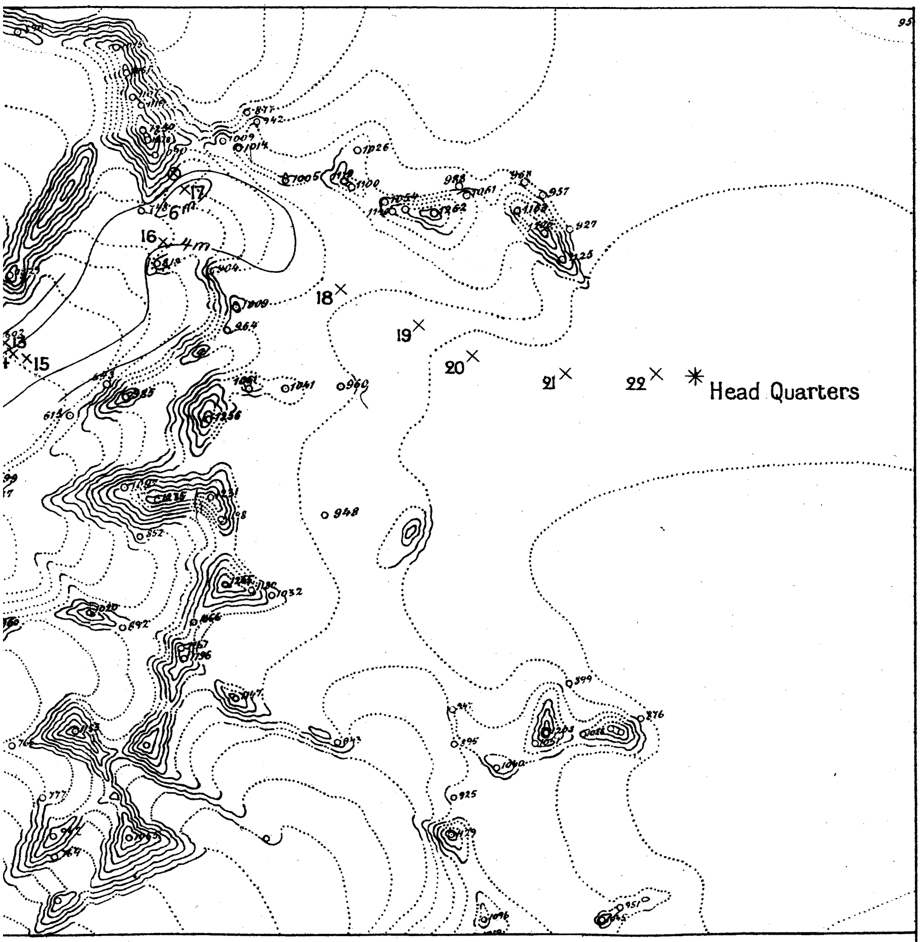
Fig. 3.



)URTEENTH OF JULY GLACIER
TH IMMEDIATE SURROUNDINGS
TO PRINCE ALBERT I (MISSION ISACHSEN) 1906-1907

rding to the present conditions. The margin of the Glacier in the fiord on Aug. 19th 1934 in full outline, rosses on the Glacier and on Isachsen's Plateau mark the gauges. Encircled crosses on side of the Glacier ·ves on the Glacier mark its movement in m. for 60 days from middle of June to middle of Aug. 1934.

0 1 2 3 4 5 km

of accumulated solid precipitation. The temperature of the glacier, at least in the accumulation area, is negative even in summer down to a depth of at least 100 m. or more. These Polar glaciers can be subdivided into:

A. *High-Polar glaciers*, which consist, at least in their accumulation areas, of crystalline firn to a depth of a couple of hundred metres or more. Even in summer the temperature in the accumulation area is so low that as a rule there is no melting accompanied by formation of water.

B. *Sub-Polar glaciers*, which in their accumulation areas consist of crystalline firn down to a depth of some 10 or 20 metres. In the summer the temperature allows melting accompanied by the formation of some water. This group includes the North-East Land glacier-caps.

This geophysical classification of glaciers is of course only a preliminary one, and it is only a first attempt to gain a broader and more rational survey than the morphological one, which principally refers to their external qualities and says very little about their most important characteristics, that is the physical ones.

It is undoubtedly correct that a close relation exists between the two essential physical qualities of the glaciers and the proportion of firn to ice, *i.e.* their temperature and their composition of firn and glacier ice. The temperature of the air, especially during the summer, is of great importance, not directly however, as this depends upon the quantity of ablation water, which it determines. In districts where the ablation water is sufficient to raise the negative winter temperature in firn and ice to zero, the glaciers are temperate and consist mostly of ice. In districts where the ablation water is not sufficient to make the winter cold disappear, glaciers are polar and consist mostly of firn. In these latter regions we must first mention the Antarctic, in which pure blue ice is very rare; in the second place we have Greenland, the inner and larger parts of which consist mostly of firn with very low temperature. Those portions of the Greenland inland-ice which consist of ice can also have a negative temperature, which is due to the ice being formed in the deeper parts of the central districts where the temperature is low; carried forward to the peripheral districts with ablation, it is difficult for the melt-water to penetrate the ice in the same manner as it can the porous firn, thus increasing its temperature to zero.

The investigations carried out at headquarters on Isachsen's Plateau formed the basis for the quantitative determinations of the material that pass through the Fourteenth of July Glacier, these being necessary in order to form an opinion of its character and life; the same holds good for every glacier.

Figure 3 is a copy of part of the excellent maps of N.W. Spitsbergen of the Isachsen Mission, 1906–07. Only the contours on the glacier have been changed in order to suit present conditions; the margin of the glacier in the fjord on 19 August 1934 and in August 1906 has been drawn as well as the curves showing the rapidity of the movement of the glacier during sixty days from the latter part of June to the middle of August 1934 and from a maximum of 10 m. to zero.

The ablation determinations on the 22 gauges placed at different altitudes on the glacier and on Isachsen's Plateau, showed that ablation decreases with rising altitude and falling temperature, but that this decrease does not occur continuously. At the firn-line it drops, thus giving the curves the courses seen on Fig. 4. Ablation is much greater on snow-bare ice below the firn-line than on snow above this line, this being due to the fact that ice utilizes much more radiation heat than snow. This difference almost corresponds to the unequal albedo of ice and snow. The consequence is that ablation on a glacier, which has been long in recession or is dying and therefore comprises large areas of snow-bare ice, is more dependent on radiation than a glacier which advances or is in a stage of equilibrium and is thus covered by snow over at least two-thirds of its area.

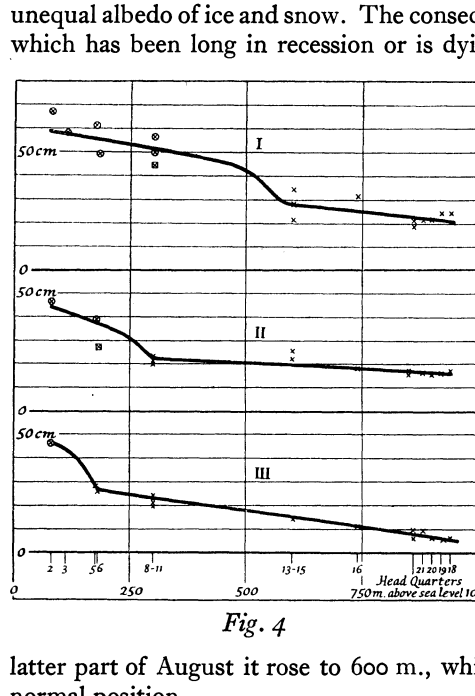


Fig. 4

After the last measures were taken on August 18 the ablation continued on the lower parts of the glacier right to the end of September, which was due to the exceptional heat of this month. For this period the ablation has been calculated with sufficient accuracy from the observations at the Norwegian Meteorological Station on Cape Linné. On August 18 the firn-line was at 550 m. above sea-level, but during the latter part of August it rose to 600 m., which is 150–200 m. higher than its normal position.

As a consequence of the determinations of the depth of the snow during the journey up to Isachsen's Plateau on June 20–23, and as a result of additional calculations, the accumulation of snow has also been determined on the whole glacier from the autumn of 1933 to the autumn of 1934. The curve representing this accumulation from sea-level to 1000 m. above it differs considerably from that of the precipitation. The reason of this is that during the winter the wind sweeps away large quantities of snow from the higher parts of the glacier and this accumulates on the lower and more sheltered portions. The quantity of material thus shifted is estimated at about 9,000,000 cubic m. of water.

In the same way, *i.e.* with the aid of the figures of the areas between the different contours, I have calculated the excess of accumulation above the firn-line and the excess of ablation below it. The result of this is that during the last season, 1933–34, the ablation surplus was about 4½ times as much as the accumulation excess. The preliminary value of the former is about

53,000,000 cubic m., and of the latter 12,000,000 cubic m. of water. This incongruity between the accumulation and the ablation is so considerable that it cannot but prove disastrous to the maintenance of the glacier at its present size. These facts are not at all impossible, as last summer was characterized by such meteorological conditions that the firn-line, as has already been said, rose 150–200 m. above its normal position, and therefore an additional 13·5 sq. km. were exposed to the great ablation which always occurs on snow-bare ice. This also shows the very great importance of every change in the position of the firn-line, the decisive rôle of the ablation factors in these changes, as well as their effect on the whole life of a glacier. Most of the Spitsbergen glaciers have been receding for many decades and the conditions of last summer even brought this to a culmination.

The following data also confirm that the Fourteenth of July Glacier is at present in a very bad condition. Its margin has receded about 1000 m. since 1911 (Plate 4), the thickness of the ice had diminished 25–40 m. in the lower part, the movement of the whole glacier is slow, and some of its peripheral parts are dead or dying (Fig. 3).

As I have said before, warm humid air with a strong wind greatly contributes to ablation. Spitsbergen receives its supply of such air from the winds which blow from the northernmost part of the Atlantic Ocean, called the Norwegian Sea, the heat capacity of which is regulated by the Gulf Stream. The investigations of this stream, which Fr. Nansen and B. Helland-Hansen began and the latter continued, have shown[1] that its variations of heat quantity are so great, that these correspond to the unequal climatological conditions regulating the ablation on the Spitsbergen glaciers. When the capacity of heat increases in the Norwegian Sea, the frequency and force of the warm humid south-west winds on Spitsbergen also increase. The activity of the atmosphere connected with the heat conditions in the northern Atlantic may possibly explain the recession of glaciers, not only on Spitsbergen but also on Franz Josef Land and in Scandinavia; the very remarkable gradual death of inland ice on the northern island of Novaya Zemlya may also be attributed to this fact. If the continued analysis of last summer's observations can prove this, it may be possible to form a basis for a general discussion of the present glaciation on the Earth and its fluctuations.

It must be remembered however that the observations hitherto published by U. Monterin[2] on the ablation on the Lys Glacier on the southern side of Monte Rosa, lat. 45° N. and 2300–2500 m. above sea-level, most likely show that in this place radiation is more important than heat convection by the air.

It may be assumed that the variations of the heat capacity in the Gulf Stream are connected with the general circulation of the atmosphere of the Earth. In this case we come to a question similar to that which G. C. Simpson[3] has

[1] Björn Helland-Hansen: The Sognefjord Section. "Oceanographic Observations in the Northernmost Part of the North Sea and the Southern Part of the Norwegian Sea," James Johnstone Memorial Volume. Liverpool 1934.

[2] U. Monterin: "Recerche sull' ablazione e sul deflusso glaciale nel versante meridionale del Monte Rosa," *Bollettino del Comitato Glaciologico Italiano*, N. 11, 1931. Torino 1931–IX.

[3] G. C. Simpson: "World Climate during the Quaternary Period." *Quarterly Journal of the Royal Meteorological Society*, vol. lx, October 1934.

recently discussed theoretically. If the radiation from the sun increases, then the general circulation of the atmosphere as well as the activity and heat of the Gulf Stream will also increase; the south-west winds from the northern Atlantic will increase in strength, and ablation on glaciers will be greater in districts where melting is principally due to this heat supply by air, as well as in districts where it is mainly due to radiation.

This series of theoretical possibilities must however be regarded as only an hypothesis. We must first secure detailed glaciological material of the same character as this I have now mentioned from Spitsbergen and the North-East Land, in different climatological regions and on different heights round the Earth. In conclusion I should like to express the hope that the Royal Geographical Society has been sufficiently interested in my lecture to wish to support my suggestion.

Additional Notes

(1) After I had delivered this lecture my attention was called to an article by G. Slater ("Studies on the Rhone Glacier, 1927. The Relationship between the Average Air Temperature and the Rate of Melting of the Surface of the Glacier," *Quart. Journal of the Royal Meteorological Society*, vol. lv, October 1929). Concerning this article I only wish to say that analyses hitherto made (such as G. Slater, "Observations on the Nordenskiöld and neighbouring Glaciers of Spitsbergen, 1921," *Journal of Geol.*, vol. xxxiii, Spitsbergen Papers 1–32) between ablation and average *temperatures* cannot give any answer to the question of the dependance of ablation on the *meteorological* elements. First and foremost wind velocity, turbulence, and air humidity play such an important rôle that one must make the same consideration to these factors as to the air temperature. Further, it is not the mean air temperature but the high temperature during some hours or days that is most decisive for the amount of ablation. I am glad to see that Mr. Slater (on p. 392) has come to the same conclusion as I have concerning the necessity of locating the meteorological station, the records of which might be correlated with the ablation, right on the glacier. This was one of the objects of my expedition in 1934 and it was also fully realized.

(2) In 'Scientific Results of the Swedish-Norwegian Arctic Expedition in the Summer of 1931,' Part VIII: C (1933) I proposed that the glaciers from a geophysical point of view should be divided into *temperate glaciers*, *high-arctic*, and *sub-arctic glaciers*. These names have been changed in my lecture to *temperate glaciers*, *high-polar*, and *sub-polar glaciers*. When I wrote my treatise in 1932 I did not know the article of M. Lagally ("Zur Thermodynamik der Gletscher," *Zeitschrift für Gletscherkunde* 1932, 4–5). In this article he writes: "Man hat also für weitergehende Untersuchungen verschiedene Typen von Gletschern zu unterscheiden. 1. einen *kalten Typ*, der nirgends Schmelztemperatur hat; 2. einen *Warmen Typ*, der überall, von einer Oberflächenschicht mit schwankender Temperatur abgesehen, Schmelztemperatur hat; 3. einen *Übergangstyp* mit einer mehr oder minder dicken Schmelzschicht." It is with great pleasure that I have established that the principles of Lagally's classification fully agree with mine, and I think that they are of such a significant character that they will be of lasting value. Another question is the suit-

ability of the terms proposed, which subject can be decided by international discussion. My account of the relation between the fundamental thermal conditions and the different proportion between firn and ice in the formation of glaciers is also of only a preliminary character. I am convinced of the great importance of these circumstances for our knowledge of the nature of glaciers, but considerable additional investigations must certainly be achieved before the problem is solved.

(3) Professor Sverdrup emphasizes that, when discussing the relative importance of melting and evaporation, it must be borne in mind that the temperature of the snow (or ice) surface cannot rise above 0° C., and that the air which is in contact with the snow (or ice) has a temperature of 0° and contains an amount of water vapour which corresponds to saturation at the given air pressure. Furthermore, it must be remembered that the processes of evaporation and condensation do not depend upon the relative humidity of the air, but upon the specific humidity, the content of water vapour in unit volume. If the air is warm and wet, the content of water vapour increases rapidly with increasing distance from the surface, and, since the air motion is turbulent, water vapour is conveyed towards the surface where it condenses and the liberated heat is used for melting the snow. A snow surface will nevertheless appear almost dry since the melting water rapidly trickles down through the snow, but an ice surface will appear wet. If the air is warm and dry similar processes take place, unless the air is very exceptionally dry. At an air temperature of 10° the relative humidity must be less than 50 per cent., and at an air temperature of 15° the relative humidity must be less than 36 per cent., if the content of water vapour is to decrease with increasing distance from the surface. Even when evaporation takes place the effect on the ablation is small, since 680 gram calories are needed in order to evaporate 1 gram of snow or ice, but the effect of condensation on ablation is considerable, since condensation of 1 gram of water liberates 600 gram calories which are sufficient for melting 7·5 grams of snow or ice.

DISCUSSION

Before the paper the PRESIDENT (Major-General Sir PERCY COX) said: The paper this afternoon is a "Contribution to the Physics of Glaciers," and is to be read by Professor Ahlmann, Professor of Geography in the University of Stockholm. This study of glaciers he has made specially his own, and I am glad to see that there are present several who are specially interested in glaciology, so that we hope to have an interesting discussion after the paper.

Professor Ahlmann then read the paper printed above, and a discussion followed.

The PRESIDENT: I will call first upon Dr. Sandford, who was a member of the Oxford Arctic Expedition to North-East Land, 1924.

Dr. K. S. SANDFORD: Professor Ahlmann is one of those who are engaged in making glaciology an exact and precise science, and he is doing it at the right moment, because our ordinary observations are beginning to lead us into some difficulty. There have been many classifications of ice forms, and I think one of the last, that of Wright and Priestley, was highly satisfactory and stood us in good stead for many years, but now we see this very precise work coming along and supplementing the early classifications, which in part at least have served ability of the terms proposed, which subject can be decided by international discussion. My account of the relation between the fundamental thermal conditions and the different proportion between firn and ice in the formation of glaciers is also of only a preliminary character. I am convinced of the great importance of these circumstances for our knowledge of the nature of glaciers, but considerable additional investigations must certainly be achieved before the problem is solved.

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As to the question of wind, which is mentioned once or twice in the paper, the blizzards are very severe perhaps in winter, but certainly in summer, and clearly there must be an appreciable loss to the surface by blizzard removal throughout the whole year, but probably in certain months especially so. I am not quite sure how that would be represented in such sections as he was showing us. Some of the snow of course is entirely lost to the whole system. A second point which particularly interested me, especially in relation to North-East Land, was the reference to ice crusts. When we were at the highest part of North-East Land we noticed blue ice, and all three of us who were there formed the impression that it was blue ice to a considerable depth. That is of great importance to the expedition going up to North-East Land this year. If they are superficial blue ice layers they are merely incidental and probably of no great thickness underneath; otherwise it may be impossible to dig it into blocks to obtain shelter.

I should like to ask Professor Ahlmann how he overcomes the direct rays of the sun shining on his ablatograph. We saw a photograph of that instrument which he has himself invented and constructed, and it seems to me that there will be some reciprocal effect from the instrument from such rays. I have no doubt he has some method of allowing for that in making his calculations. It would certainly cause, I should think, an addition of ablation in the immediate vicinity. I congratulate Professor Ahlmann and thank him for the lucid and extremely interesting account to which I have just listened.

The PRESIDENT: I will ask Mr. Gerald Seligman to speak. Mr. Seligman is the author of a paper on "Properties of Ice and Snow" in a Ski Club Year-book.

Mr. GERALD SELIGMAN: I have listened to Professor Ahlmann with the greatest interest. It is no small achievement to deal with so complex a subject in a foreign language. It is like heaping Pelion upon Ossa and climbing them both. We have just heard from Dr. Sandford that it took him three months to digest Professor Ahlmann's earlier work, so that for you, Sir, to call upon me to give an opinion on a lecture of this character at short notice is to expect a great deal of me. I, personally, was immensely interested in it as being of the greatest help in the work that some of us are trying to do in the Alps to elucidate certain of the snow problems we are meeting there.

I have one question to ask. In his paper Professor Ahlmann states that the greatest ablation takes place with a humid wind of high speed. I can very easily understand that wind of high speed containing a great deal of moisture would deposit much of that moisture on the snow, and in doing so would generate heat. That, no doubt, is one of the reasons why it helps the ablation. What I do not quite understand is why the moisture should assist, as it were, the wind in respect to the ablation, because evaporation must be taken into account, and evaporation, although it has been said that it is of not so great importance, is cut out altogether by raising the humidity of the wind. If we take the extreme case of wind containing 100 per cent. moisture we should get no evaporation taking place under those conditions. I am sure there is some explanation, and I should like to know what it is. A point entirely new to me is that in Antarctic regions we get very little blue ice. If that is the case it is most interesting, and would, no doubt, be accounted for by the great altitudes from which the ice is derived in Antarctic regions, where melting cannot take place.

The PRESIDENT: Dr. Fritz Loewe, one of the party at the Central Ice Station of Wegener's expedition to Greenland, will make a few remarks.

Dr. FRITZ LOEWE: I must, in the first place, apologize for my poor English. Nevertheless I wish to congratulate Professor Ahlmann on his very important new "Contribution to the Physics of Glaciers."

It is astonishing that our knowledge of glacier conditions in the accumulation area is much greater in polar regions than in the Alps, which afford easier facilities for an intensive study of glaciers. For instance, no systematic measurements of the temperature of alpine névés exist, a fundamental necessity if we are to understand the likewise unknown way in which in the highest alpine regions snow is transformed into firn and firn into ice. It is to be hoped that the knowledge gained by Profesor Ahlmann and his companions with regard to polar and Scandinavian glaciers will stimulate the study of the corresponding alpine conditions.

Professor Ahlmann mentioned Alfred Wegener as one of his predecessors. Unfortunately, on Wegener's last expedition two of the three glaciologists were unable to do scientific work. One died, and the other got seriously frostbitten. We made a thorough study of the mass balance and heat balance at the Ice-Cap Station under high polar conditions, the results of which will, I hope, be published soon. There, melting as a factor in transport of mass and energy is entirely absent and conditions are therefore relatively simple. We gained however little knowledge in regard to the condition in the transitional zone where melting takes place in summer, but nevertheless accumulation preponderates over ablation, as it does on the Isachsen Plateau. This gap Professor Ahlmann has filled. I was interested to hear that ablation is higher in periods of warm and humid air than in those when the air is warm and dry. If other conditions are the same, that can hardly be understood. Is it because humid air is connected with greater cloudiness and consequently the outgoing radiation is diminished? Thus the layer of cold air covering the snow surface is easily disturbed, and the heat convection at the surface is consequently greater. That the ice crusts separating the layers of different years are formed in the autumn confirms the somewhat uncertain hypotheses of De Quervain and Wegener and the estimates of annual accumulation on the Greenland Ice-Cap based thereon.

One component of the accumulation of polar ice-caps is hoar-frost with clear sky due to direct sublimation by cooling through outward radiation. It has been suggested that this kind of deposit is the most important component in the accretion of the central inland ice regions. I do not agree with that suggestion, but it would be highly interesting to know whether the measurements in Spitsbergen gave any hint as to the relative importance of this component. It is most interesting to know that on the Spitsbergen Ice-Cap there is a large surplus of ablation over accumulation which corresponds so well to the external appearance and behaviour of the front of many Spitsbergen glaciers. We have not yet a very clear idea of what happens in Greenland; but it seems that there the conditions are inverse to those found in Spitsbergen: that the accumulation, in the mean, exceeds the ablation.

As far as I understand, Professor Ahlmann makes temperature conditions the touchstone in his classification of glaciers, calling "temperate" such glaciers which are at melting-point throughout, and "polar" those which, at least in the accumulation area, are frozen to a certain depth. In that I agree completely with him. As Professor Ahlmann found, the Isachsen Plateau shows temperate conditions. But the additional qualities given by Ahlmann's definition to the temperate glaciers do not seem to exist there. Their snow and firn should form a rather thin layer, whilst in Sverdrup's opinion the firn reaches down to a considerable depth, which in Professor Ahlmann's classification is a quality of a polar or even high-polar glacier. Also the "slow" recrystallization of firn crystals mentioned by the lecturer means rather " polar glacier" conditions. Thus his last studies seem to show that slight alterations in his "Geophysical Glacier Types" of 1933 would make his classification more valuable still.

In conclusion, I wish once more to emphasize what a lot of valuable new information Professor Ahlmann has laid before us this afternoon.

The PRESIDENT: We should like to hear Mr. Glen, the leader of the forthcoming Oxford Expedition to North-East Land. I may say that the lecturer is the only man who has visited the district where Mr. Glen proposes to make his base camp.

Mr. ALEXANDER GLEN: I may point out that it was largely due to my good fortune in meeting Professor Ahlmann in King's Bay during the summer of 1934 that the first idea of this North-East Land Expedition came into my mind, and I should like to record how very grateful I am to Professor Ahlmann for the help he has given us on every possible occasion. It is our intention to establish two winter stations on either the East or West Ice of North-East Land. The reason for two stations is that part of our programme covers the investigations of wind conditions as well as of general meteorological conditions, an interesting study of which ought to be possible from one inland station on the ice summit (about 2400 feet), another at perhaps 1200 feet or lower, and from observations at the base station in Rijps Bay, at sea-level. In addition we hope to carry on investigations on the precipitation and to continue Professor Ahlmann's work on ablation. This last will be done by one of the above two stations over the whole year, and the change over from winter to summer conditions should prove especially interesting. Professor Ahlmann is coming to Oxford in a day or two to give us his advice on our plans, and we are very grateful to him for the assistance he has given us.

The PRESIDENT: Mr. John Wright, of the Hagavtn Expedition, Iceland, 1934, and a member of Glen's expedition, may like to add something to what has been said.

Mr. JOHN WRIGHT: I do not feel at all qualified to express any opinion of Professor Ahlmann's lecture since I have had practically no experience of glaciological work, but I have two points which I should like to raise in comparing his observations with those that we made in Iceland. We were not making a detailed investigation of glaciology, but chiefly doing survey work, and endeavouring to discover the general physical régime of this lake. In the light of this lecture however I cannot say whether our observations support Professor Ahlmann's theories or not. In one or two cases they certainly do. First of all, he said that radiation was very much greater on snow-free areas of ice, and our observations certainly confirm that, because where the snow had been melted off the ice-cap on the edge of which we were working, the importance of radiation was clearly shown by the usual phenomena of ice-dirt cones, in which the dirt blown on to the glacier protected the glacier from radiation, and so raised a cone which might be anything up to 4 or 5 feet high; also by ice wells in which dust sinks into the ice because of the increased heat due to radiation. We were fortunate enough to be shown photographs of the ice-cap on which we were working taken nine years previously, and these showed that there had been a retreat of something like a kilometre of the ice. It has been mentioned that in the 1934 Expedition the air temperature was measured and the ordinary meteorological phenomena taken at the snow surface and also at heights up to 5 metres. I believe that some difficulty in measurement was encountered, and I should like to know how they obtained accurate readings.

The PRESIDENT: A Fellow who could not be present this afternoon has sent a request that the lecturer would offer some suggestion as to the cause of that very disturbing and even terrifying noise which he heard occasionally upon the ice-pack in the middle of Greenland.

Professor AHLMANN then made the following reply: As regards Dr. Sandford's question about the effect of strong winds on the glaciers, there is beyond doubt a great drifting of snow especially in winter from one place to another on the North-East Land glacier-caps as well as on the other ice- and firn-plateaus in Spitsbergen. Concerning the Fourteenth of July Glacier, as I have just said, the amount of this transport of loose snow can be calculated at about 9 millions of cubic m. The quantity that the accumulation area thus loses will be represented in the sections of the ablation area. This drifting can be so great that the whole quantity of precipitation in solid form will be swept away from large parts of the accumulation areas. According to M.M. Ermolajeff such conditions prevail on the northern island of Novaya Zemlya. During my sledge journey across the central parts of the North-East Land glacier-caps I did not find any snow-bare ice and the pits showed more than 2 m. stratified firn.

It is quite correct that the radiation from the sun has some effect on the float of the ablatograph. In my description of this instrument, mentioned in my lecture, I have given an account of the corrections necessary for these "independent movements of the float." The examples here given represent exceptionally great values of the independent movements. In general they are much less and on ice they are of very little importance.

I am very glad to have had the opportunity of giving Mr. Glen some advice about his expedition to North-East Land this summer and I am looking forward with great interest to a more detailed discussion with him about the glaciological programme; at the same time I should like to wish the expedition every success.

In answer to Dr. Loewe's question about the hoar-frost, I should like to say that its formation plays an important rôle in the alimentation of glaciers in districts with maritime climates. In Norway I have proved this in the highest part of Jotunheim, and my assistant in 1934, Mr. Olsson, measured very great quantities of hoar-frost on Mount Nordenskiöld in Spitsbergen during the Polar Year 1932–33. Most of the "snow" accumulated on this mountain is not snow fallen but hoar-frost. In districts with continental climates, as for instance Central Greenland, I cannot believe that hoar-frost plays any really great rôle.

Concerning the application of my geophysical classification of glaciers to the Isachsen's Plateau and the Fourteenth of July Glacier, it is obvious that they must be regarded as "temperate." I also refer to my note about this classification, added to my lecture.

Mr. Wright's question about the temperature measurements on Isachsen's Plateau can only be answered by Professor Sverdrup's treatise on his investigations, the methods and instruments employed being of such new and exact types that they require a detailed description.

Concerning the important and complicated problem of the relative importance of melting and evaporation, I shall take the liberty of asking Professor Sverdrup for a short account (see above, p. 107, Additional Notes no. 3).

The PRESIDENT: I am sure you will have appreciated, as I have, the lucid and practised way in which Professor Ahlmann has delivered his paper. Some of the uninitiated among us, including myself, have no doubt found that in the more technical parts of his address he has been to some extent speaking over our heads, but we can all appreciate the interest and importance of his subject and admire the skill which enabled him to deal with it effectively in a language not his own. As you are all aware, we have constant reason to be grateful to our Scandinavian friends for cooperation in connection with exploration in the north polar regions; and, as you have just heard, Professor Ahlmann has already been giving Mr. Glen the benefit of his cooperation and will continue to give it in connection with the latter's coming expedition to North-East Land.

It has been a great pleasure to us to welcome Professor Ahlmann and his wife, and we hope that during their stay in England it will not be all work and no play for him, but that they will have time to see something of our countryside.

Mr. N. E. Odell *sends the following contribution to the discussion:* Professor Ahlmann has made a long series of observations upon the glaciers of Scandinavia and of Spitsbergen, and it was a pleasure both to hear the lecture upon his important conclusions and to have the opportunity later to discuss some of those conclusions, as well as the deductions that may be made from them.

His studies with those of Professor Sverdrup, upon ablation processes, and the determination of heat-convection as opposed to radiation, and the evaluation of these relative to melting, are of the greatest importance, not only for their explanation of the way in which glaciers of the regions studied are at present so fast wasting away, but for the emphasis they lay on the value of such observations in countries and districts which derive their water supply in large part from mountain snows and glaciers. Some studies with this end in view have recently been begun on the western slopes of the Cascade Range and the Sierra Nevada of western U.S.A., and from my friend Mr. François Matthes, Chairman of the Committee on Glaciers of the American Geophysical Union, I have lately received a small paper[1] treating of ablation on snowfields. Under the conditions prevailing in those parts, Matthes has shown that so great is the ablation by evaporation from the upper snowfields that the latter must be excluded from any estimates of run-off based upon "snow surveys." On the glaciers of Mount Rainier, for instance, surficial melting in sufficient quantities to produce rills and rivulets on the ice does not extend above an altitude of about 7000 feet. "On warm days," Matthes states, "these streamlets form miniature river-systems, with miniature waterfalls, lakes, and canyons in the ice. They are truly impressive for the volume of water they carry off, but far more impressive, if one stops to consider it, is the fact that from this low level upward to the summit of the peak (14,408 feet), through an altitude range of some 7000 feet, the snow and névé extend with dimpled, sun-cupped, sun-pitted surfaces (due to evaporation) that are perpetually dry." Matthes considers that any quantities of water that may be released by the warmth of the mountain or by pressure melting from the basal layers of these névé-fields are probably so small for all practical purposes as to be negligible. It is therefore from the lower portions of the glaciers, and those alone, that the great floods of melt-water in summer are derived, the function of the névé-fields being the indirect one of supplying water only in the solid state to the glaciers. Observers taking part in the "snow-surveys" in the Sierra Nevada are now engaged in trying to find the level of the zone of maximum snow-precipitation and of melt-water yield.

As to the important rôle played by melting as opposed to evaporation which

[1] François Matthes, "Ablation of Snow-Fields at High Altitudes by Radiant Solar Heat," *Transactions of the American Geophysical Union*, Fifteenth Annual Meeting, 1934.

Professor Ahlmann has shown takes place on the low altitude, "Sub-Polar," glaciers of Spitsbergen and North-East Land, I am able to bear him out if only from qualitative observations made during two sledging journeys (1921 and 1923) in Spitsbergen. Nothing is more striking than the vast amount of melting and the resulting rivers and lakes of melt-water which form during the summer, even under prolonged conditions of saturated atmosphere and thick fogs. With regard to the general recession and shrinkage of glaciers and snow-fields, to which Professor Ahlmann makes reference, I can fully support him with quantitative field evidence from southern New Friesland and Garwoodland. In the latter region of eastern Spitsbergen certain higher peaks now project above the highland ice-covering some 1000 to 1500 feet. On many of them, owing either to similar adjacent formation, intensive frost-splitting, or other causes, there is no definite evidence from erratic perched blocks of an earlier and higher level occupied by the ice. But in one instance at least, on the great mountain-nunatak, at the head of the Nordenskiöld Glacier, Mount Ferrier, there was unequivocal evidence—and a minimum measure of the amount—of the former much higher stand of ice in these parts. On the eastern ridge of that limestone mountain were found granite blocks at 1000 feet above the general level of the highland ice-sheet lying eastward of it, their composition arguing their derivation from the Chydenius Mountains to the north-east, and their elevated position proves that the ice in this region was formerly far more inundated. Only future exploration and observation can determine what the maximum "glacierization" of Spitsbergen amounted to and whether it ever entirely enveloped all the highest peaks or not, apart from the question as to when it last occurred, and if its incidence has been cyclical and entirely due to the variable heat capacity of the North Atlantic Drift, as Professor Ahlmann supposes.

Although Professor Ahlmann puts forward his geophysical classification of glaciers purely as a preliminary one, I think it is definitely to be welcomed, since its basis emphasizes a side of glaciological study that has been singularly neglected. Morphological studies of glaciers, which have been pursued for so many years, have really done little to advance our knowledge of the real constitution of glaciers, their mode of motion, and the question of their potency as erosive or merely abrading agents. The intensive physical examination of the kind that Professor Ahlmann and his collaborators are carrying out seems therefore to afford new hope for the immediate future of glaciology as a whole. What is clearly wanted now is a series of similar observations upon the glaciers of other regions, and particularly at the highest altitudes, where a peculiar combination of arctic and tropical external conditions are to be found. If systematic and detailed observations of the kind that Professor Ahlmann has made with such admirable enterprise in high latitudes, could be extended by some of the projected expeditions in the near future to the high altitudes of the Himalaya, and especially perhaps the coming Mount Everest Expedition, we should be going some way in our support of the suggestion of cooperation made by him to the Society.

Professor AHLMANN: After reading Mr. Odell's contribution to the discussion I am very glad to acknowledge the importance of his observations in Spitsbergen. I should also like to call special attention to the advisability of physico-glaciological investigations on glaciers at the highest altitudes. In my opinion these observations are now the most important contributions to glaciology. Special methods can be worked out and instruments constructed for climbing parties on the highest parts of the Himalayas or Karakoram. I should feel more than pleased if my lecture could bring this about.