NORSK POLARINSTITUTT
SKRIFTER NR. 123

DEN NORSKE ANTARKTISEKSPEDISJONEN, 1956—60
SCIENTIFIC RESULTS NO. 1

TORBJØRN LUNDE

ON THE SNOW ACCUMULATION IN DRONNING MAUD LAND

NORSK POLARINSTITUTT
OSLO 1961

DET KONGELIGE DEPARTEMENT FOR INDUSTRI OG HÅNDVERK

NORSK POLARINSTITUTT
Observatoriegt. 1, Oslo, Norway

Short account of the publications of Norsk Polarinstitutt.

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Received for publication April 1961

PUBLISHED BY NORSK POLARINSTITUTT
DISTRIBUTED BY OSLO UNIVERSITY PRESS
OSLO 1961

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Abstract.

A brief description is given of the morphology of the ice shelf, Fimbulisen, and of the inland ice.

The annual accumulation is determined for the period 1940 to 1959; the mean is 495,2 mm of water. The accumulation for the years 1940 to 1956 was found studying the firn layers in a 16 m deep pit. From 1957 to 1959 the accumulation was measured directly at stakes, in an area of 37 km^2.

There is a seasonal variation in the rate of accumulation, with a marked minimum in November—December and a maximum in May—June. The accumulation is due, almost entirely, to precipitation of cyclonic origin; there is no gain or loss by drift snow, and the accumulation or ablation by sublimation is negligible. The found accumulation thus gives a good measure of the precipitation. The precipitation gauge is useless under the meteorological conditions prevailing at Norway Station.

On the inland ice the accumulation found decreases with increasing altitude, and with increasing distance from the ice shelf. It also decreases eastwards, both on the ice shelf and on the inland ice.

Introduction.

On the 10th of November 1956 two Norwegian sealing vessels, "Polarsirkel" and "Polarbjørn" left Oslo. On board were the fourteen members of the wintering parties of Den Norske Antarktisekspedisjonen, 1956–60, under their leader geodesist Sigurd Helle, with all their equipment.

The expedition, sent by Norsk Polarinstitutt, planned to stay in Dronning Maud Land (Fig. 1) as near the Greenwich meridian as possible and about 50 km inland, during the International Geophysical Year 1957–58. Later, the expedition's stay in Antarctica was prolonged by one year, and the return was made in February 1960. During the last year there were only nine wintering members.

The programme included meteorological, magnetical and glaciological work, measurements of ozone and photography of aurora australis. The mountain range from 2° 40′ E, eastwards to a small isolated nunatak at 30° 30′ E was mapped, and geological and biological material was collected.

The glaciological work consisted of measurements of snow accumulation, of ice flow, and of ice temperature on the ice shelf, especially in the neighbourhood of Norway Station. During the summers of 1957–58 and

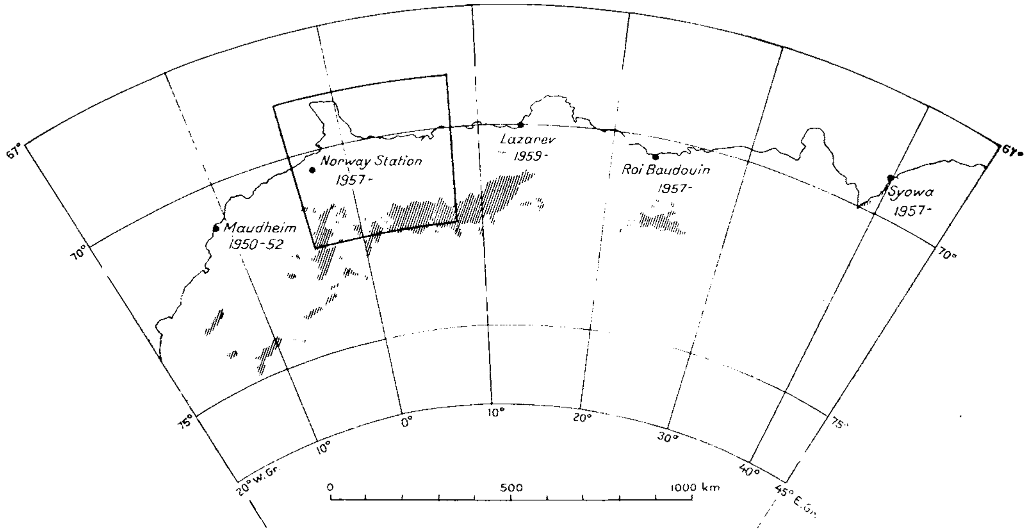

Fig. 1. Dronning Maud Land with the five wintering stations and the periods during which they have been used. Mountains are shown by hatching. Inset, the area covered by the map on Fig. 19.

1958–59 the accumulation on the inland ice was observed as far as possible, and the flow of three ice streams[1]) was measured.

While working in the field, the glaciologist also had to collect geological and biological material. He had the chance of an assistant only when in the field, rarely at the station. Therefore the glaciological work was rather more restricted than was desireable.

Earlier works.

The region of Dronning Maud Land investigated by Den Norske Antarktisekspedisjonen, 1956–60 (Fig. 1), was earlier a rather unknown country. No one had ever set foot on the ground except in one bay in the ice shelf, Fimbulisen, at the Greenwich meridian. This was visited by the American icebreaker "Atka" in February 1955.

The coast had been partly observed from vessels, and photographed from the air by the Norwegian–British–Swedish Antarctic Expedition, 1949–52. The mountain region was photographed from the air by the German Antarctic Expedition, 1938–39, and a map at the scale of 1 : 1,500,000 was published. This map, however, is quite unfit for use. The Germans also published maps of the easternmost part of the photographed region to larger scales (Wohlthatmassivet), and these were found

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[1] Swithinbank 1957. Terminology p. 10.
This designation is also used when the glacier is limited by mountains.

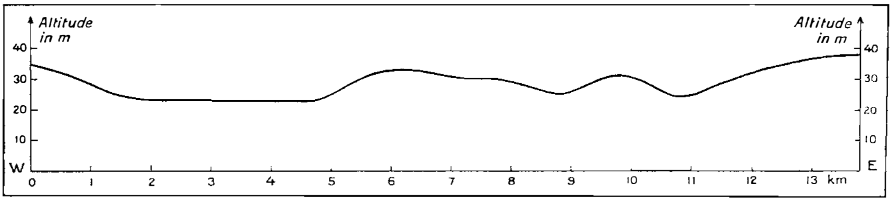

Fig. 2. Cross section of the western border of the ice stream north of Jutulstraumen The vertical scale is exaggerated 50 times.

to be far better. Unfortunately, the photographs were destroyed during the war.

The westernmost part of the mountain area (Jutulsessen and Risemedet) was also photographed from the air by the Norwegian–British–Swedish Antarctic Expedition, 1949–52. Preliminary maps at the scale of 1 : 200,000, constructed on the basis of this photography and terrestrial observations from mountains farther west, were used by the 1956–60 expedition.

Farther east, the Sør–Rondane mountains were photographed from the air by Lars Christensen's Expedition, 1936–37, and a map at the scale of 1 : 500,000 was produced by H. E. Hansen (Hansen 1946). He also produced a map at the scale of 1 : 250,000, published by Norsk Polarinstitutt in 1957, on the basis of air photographs taken by the United States Navy Antarctic Expedition, 1946–47.

The Belgians carried out terrestrial observations in these regions during the summers of 1957–58 and 1958–59.

Morphology.

Fimbulisen, the large ice shelf between 69° 20′ and 70° 30′ S, 3° W and 4° E, has been described by Swithinbank (1957). The borders are erroneous in some places, but otherwise his description seems to be quite accurate (Fig. 19). On three occasions, field parties of Den Norske Antarktisekspedisjonen crossed this ice shelf in the east–west direction at 70° 30′ to 70° 40′ S. Also, it was flown over on several occasions.

The ice stream from Jutulstraumen was found to extend out into the ice shelf. The borders of this large ice stream are very distinct, with broad belts of crevasses, making travel in these regions a most troublesome undertaking. The western border is found at approximately 1° 30′ W, the eastern border at 1° E. The ice stream where crossed was 90 km wide, much wider than farther inland. This is occasioned by the fact that the ice shelf is much more free to move laterally than is the inland ice.

The western border of the ice stream runs in the direction 340°. It is an immensely crevassed belt, 100 to 200 m wide, containing large "icebergs" lying haphazardly (Plate I a). In many places the ice between the "icebergs"

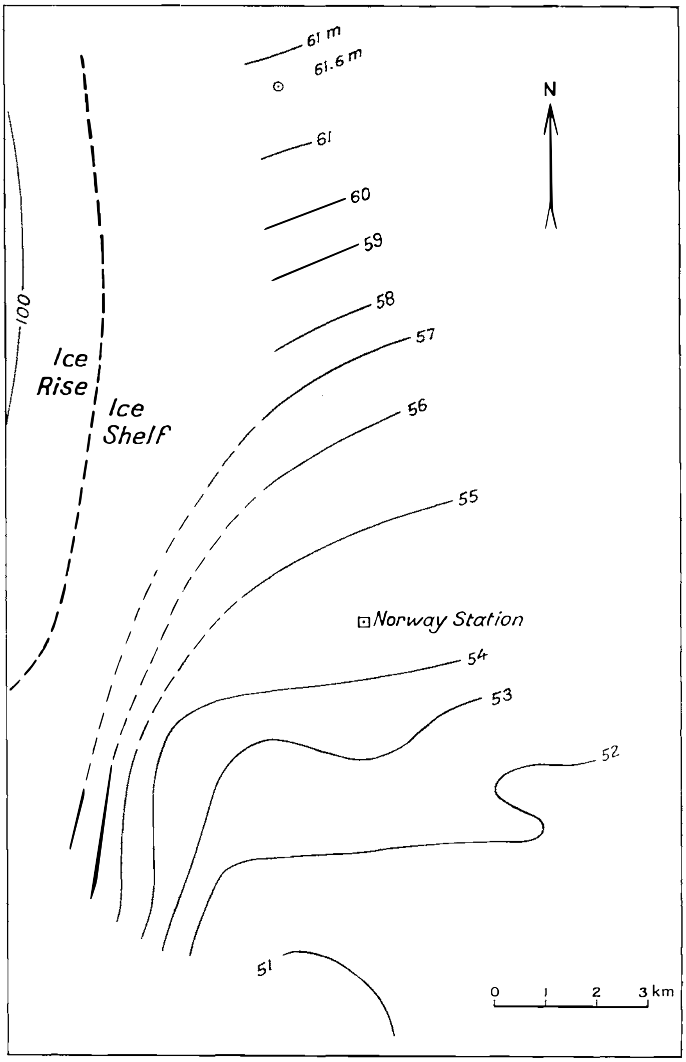

Fig. 3. The surface form of Fimbulisen at Norway Station.

is almost at sea level. Broad, shallow depressions, with crevasses along their sides, and orientated SE–NW, have their origin in shearing crevasses, showing that the area to the east moves faster than does the area to the west. Outside this belt there are a few small crevassed areas to the east, and the region has shallow undulations both on the eastern and on the western sides (Fig. 2).

The eastern border of the rapidly moving ice stream is a zone some 12 km wide and quite different from the one already described. Undulations and a few pressure ridges are to be seen only in the most intensely crevassed part. A most typical feature in this area is long, 0.5 to 1.5 m broad crevasses running SW–NE. As the whole crevassed region has a far more northerly trend, these are also shearing crevasses.

Outside these crevassed areas, the ice shelf seems quite flat, and only by accurate levelling is it possible to trace any departure from a horizontal plane (Fig. 3).

At the coast east of Blåskimen, the ice rise[1] at 3° W, there are three parallel bays facing westward (Plate I b). Shallow "valleys" continue eastward from the bottoms of these bays. To the south are several other undulations, parallel to the three mentioned. The amplitude of these undulations at maximum is some 20 m, and they grow shallower farther from the coast. The wave length varies from 1 to 4 km. At a distance of some 10 to 15 km from the coast the undulations have disappeared. These undulations and bays, as pointed out by Swithinbank (Swithinbank 1957, I A, p. 29), have "developed from the northward movement of the main mass relative to the part held fast by the adjacent grounded area".

The wind direction during driving snow (wind speed more than 10–12 knots) is mostly from the east (p. 32, 33). As usual this steady wind causes sastrugi. The size and frequency of these irregularities are very variable. The sastrugis are most numerous and also largest after a heavy snowfall at wind speeds from 20 to 30 knots. They were seldom observed taller than 50 cm.

Strand cracks[2] are observed at the border between the ice shelf and the ice rise NW of Norway Station, as well as at the border between the ice shelf and the inland ice, about 200 km east of Norway Station. At the border of the ice rise there is a shallow depression of ca. 0.5 m; at the border of the inland ice there is no such depression (Fig. 4). Here measurements were taken along a "smooth snow ridge" (Swithinbank 1957, p. 22).

From the ice shelf to the northernmost nunataks north of Risemedet, a distance of about 125 km, the inland ice ascends from about 50 to 1550 m. The gradient varies somewhat, in a rolling manner, but it is rarely negative or greater than 3 %, with a mean of 1.2 %. In the neighbourhood of the ice shelf the undulations run NE–SW, parallel to the border of the ice shelf and at right angles to the steepest slope. Farther inland they are directed E–W, and thus still at right angles to the steepest slope.

The western part of the mountain chain (Jutulsessen, Terningskarvet and Risemedet) consists of gneisses belonging to the "metamorphic complex" described by E. F. Roots from the neighbouring mountains to the west (Roots 1953). Farther east there are coarse-grained, highly metamorphic gneisses and granites.

Observations of striae on small outcrops north of Risemedet show that the inland ice in former times reached a level at least a few tens of metres

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[1] Swithinbank 1957. Terminology p. 10.

[2] Swithinbank 1957. Terminology p. 10.

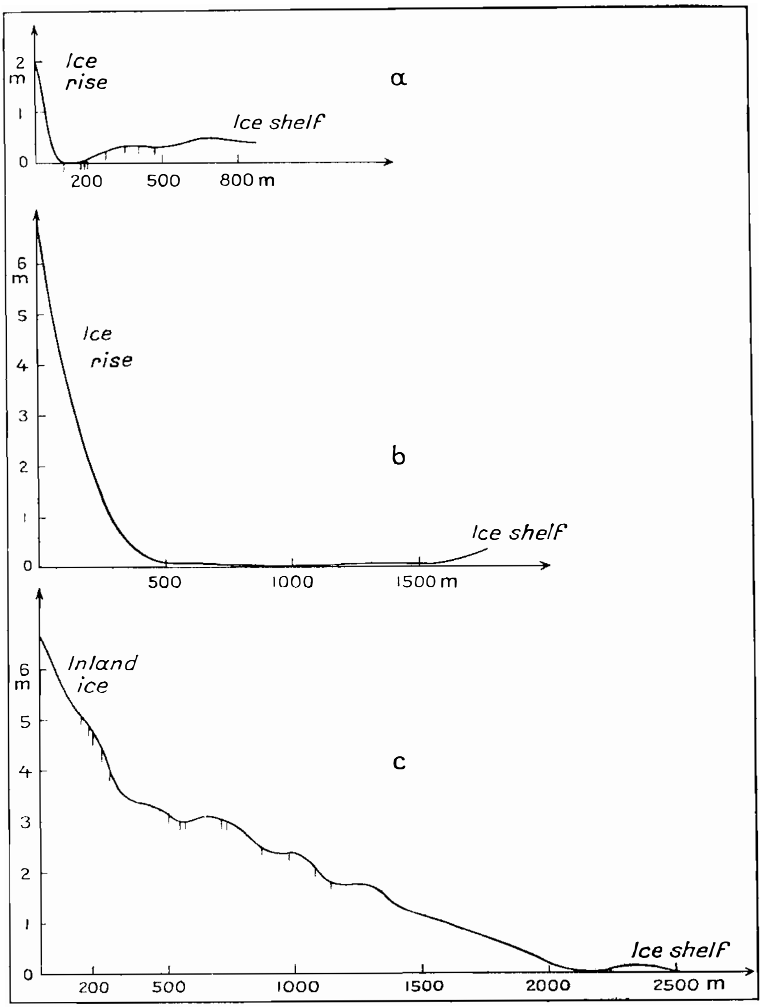

Fig. 4 a and b: Cross sections of the border between Fimbulisen and Blåskimen, northwest of Norway Station. 4 c: Cross section of the border between Fimbulisen and the inland ice 200 km east of Norway Station. Strand cracks are shown by vertical lines in a and c. The vertical scale is exaggerated 200 times.

higher than now. South of Risemedet there are several small nunataks at altitudes of 2000 to 2200 m, almost entirely covered by a thin ice cap. Striae, both here and up to altitudes of some 2500 m above sea level in Risemedet point downhill, independent of the surrounding inland ice, showing a heavier local glacierization in former times. Nothing implies that the inland ice has reached these altitudes, up to 1000 metres above its present level.

Striae are not found in Jutulsessen or Terningskarvet, in spite of the fact that these consist of the same kind of rocks as Risemedet. East of Risemedet the rocks are too coarse-grained to preserve striae. However, erratics are found up to some tens of metres above the glacier ice. All this is proof of a greater glacierization in former times along the whole mountain chain. On the other hand, the wind erosion (Plate II a and b) and the lichens found all the way down to the snow surface, reveal that the ice for a long time has reached the same, or no higher level (Schytt 1958).

Most of the local glaciers have a very small accumulation area. The wind has swept the rest of the glacier quite bare of snow. Where the gradient of the bare local glaciers decreases, small undulations frequently occur, showing clearly the greater velocity in higher parts. The margins of these glaciers, where exposed to the sun, often take the form of a steep ice cliff; this is due partly to melting and partly to sublimation caused by warming of the adjacent rock, and long wave radiation from it. Leeward of many of the greatest nunataks (on the western or northwestern side) there were large areas of pure glacier-ice with some morainic material. This ice was also frequently at a lower level than the surroundings. As pointed out by Schytt (Schytt 1960), the easterly winds passing the mountain ridges become very dry, and sublimation from the ice surface on the leeward side takes place. The negative regime of these ice-fields is ascertained by the frequently occurring glacier tables formed by boulders which protect the underlying ice.

At one place northwest of Risemedet, on top of morainic material, in an almost horizontal area of some 100 by 200 metres, 20 to 30 cm of water was found under ice of 20 cm thickness. Although the altitude is as great as 1500 m above sea level, this must be one of the so-called "frozen lakes" which are observed in several places in Antarctica.

The great mountain range, Fimbulheimen, running east–west acts like a dam to the inland ice. From an elevation of about 2500 m, south of the mountains, the inland ice falls to about 1500 m on the northern side (Plate III a and b). Relatively steep ice streams divide the mountain chain into individual mountain areas. Frequently these ice streams are several kilometres wide. They seem to be steeper and more crevassed in the eastern than in the western part of the area. Measurements of flow show a greater velocity in the eastern part.

Along the whole mountain range there are remnants of palaeic surfaces (Plate III a and b and IV a) (Roots 1953). The elevation of these varies, but there is a mean of some 2000 m. These surfaces frequently bear thin glaciers which are almost stationary. Measurements from ice streams imply that the flow of these thin glaciers is less than one metre per year. The ice therefore protects the underlying ground from erosion (Swithinbank 1959, p. 107).

The nunataks are primarily eroded from their sides. The steep cliffs, especially on their northern side, are subject to the frequent changes in temperature which lead to intense erosion. As the eroded material soon is carried away as moraine, there are no rock-falls at the base of the mountains to protect them from erosion. As the lower parts of a north-facing cliff receive more of the radiation reflected from the ice than do the upper parts, the erosion caused by temperature oscillations is more intense here.

Another important agent in the destruction of the mountains is the wind (Plate II a and b). Strong winds carry sand and gravel which erode the underlying ground. At low temperatures the driving snow also is capable of eroding the rocks. (The hardness of ice at —40° C is 4 and at —70° C it is 6, the same as feldspar.) That the erosion by driving snow is of great importance can be seen at many nunataks where the weather side is formed by wind erosion, though the wind cannot carry sand in these locations. As the solid material, carried by the wind, is found essentially in the lower air layers, so the winds causing grinding on a rock cliff are most intense on its lowest parts.

All meteorological factors partaking in the breaking down of the landscape thus have their greatest effect on the lower parts of the nunataks. Steep cliffs are sustained as the falling of boulders from higher parts of the cliffs only keep space with the abrasion of the lower parts. This is the mature stage in the erosion cycle. The young stage – if it exists – is buried beneath the inland ice to the south. As the palaeic surfaces are on a higher level than the surrounding inland ice, the winds meeting them carry very small amounts of snow, hardly more than the true precipitation, and their net effect is erosion of the glacier caps until the wind is saturated with drift snow. The predominant wind direction here also is easterly, and the thin glacier caps thus are eroded on their eastern parts, whilst accumulation takes place on their western parts.

As the palaeic surfaces are eroded from the sides, the parts of their ice caps subjected to erosion by the wind, will grow relatively greater. At last the gain (especially by snowfall) can no longer keep pace with the loss (especially by drift snow), the protecting ice caps disappear, and the underlying rock is exposed to erosion (Plate III b).

How large a horizontal area in this location must be in order to maintain an ice cap is unknown, but the minimum extension in the direction east–west is probably a couple of kilometres. The size of the area also depends on its elevation above the surrounding inland ice.

The great, flat-topped nunataks are dissected, on their northern sides, into huge peaks (Plate IV a), and as the destructive forces now act at the tops as well, these forms soon break down to the final stage – small nunataks, frequently in the form of triangular pyramids or as very low rocks just in the snow surface (Plate III a). These are very common just north of the mountain range.

Thus from north to south along the mountain chain both the old and the mature (possibly also the young) stage in the erosion cycle occur within a distance of only a few kilometres.

Accumulation studies in a 16 m deep pit.

General remarks.

The climate at Norway Station (70° 30′ S, 2° 32′ W) is much the same as that at Maudheim at 71° 03′ S, 10° 56′ W (the base of the Norwegian-British–Swedish Antarctic Expedition, 1949–1952).

By means of stratigraphical studies like those carried out by Schytt at Maudheim, it was possible to find the accumulation during earlier years at Norway Station.

As Schytt has explained the causes of the different firn layers, details about this are not entered into here, but his conclusion is repeated (Schytt 1958, p. 26): "We have seen from this description, that a "normal" annual layer will be represented in a pit by a coarse-grained, highly metamorphic summer surface on top of a firn layer of varying grain size and ice content. This firn layer is coarse and has abundant ice pellets and ice layers in its upper part, showing that during a normal summer some melting takes place. This melting, however, is not normally sufficient to produce melt water enough to soak the whole annual deposit and raise its temperature to the melting point, so that some firn at the bottom remains unsoaked".

From August to September 1957 a 16 m deep pit was dug in order to study the accumulation which had occurred through a longer period. This work was done under cover at the base. Owing to the tramping round the station, however, the firn layers were disarranged in the upper two metres. Therefore another pit of 2.8 m depth was dug south of the station. The profile obtained here could be compared easily with the corresponding one in the deep pit. In Fig. 5 the profile from the pit south of the station has been used down to the firn from 1954, while the lower part of the profile is from the deep pit.

In order to find the firn layers of each year, it is best to use the "summer-surfaces" as the demarkation between the accumulation of different years. These summer-surfaces, however, are not necessarily formed at the change of the calendar-year; they are formed at the end of the season with intense solar radiation, and this may be considerably later (pp. 11, 12). As stated by Schytt (Schytt 1958, p. 38), one can hardly speak about accumulation per calendar-year, only per accumulation-year.

The thickness of the metamorphosed firn-layers and the grain-size of the firn gives an indication of the length and intensity of the summer. Ice layers and ice lenses indicate periods of fine weather and intense radiation in connection with temperatures near 0° C. When the stratigraphy is known, therefore, it ought to be possible to trace the summer climate to a certain degree of probability. The problem involves many great difficulties, however. Which of the climatic components are of most importance for the metamorphosis of the firn, for instance, is not evident. Furthermore there is also the question of to which of the evidences of the summer climate (thickness of the summer layer, grain-size or ice content) one is to attach the greatest importance. For instance, has a summer climate which has caused a thick layer of coarse-grained firn with no ice content been good or bad ? The tracing of the summer climate is also complicated as the difference between summer firn[1] and winter firn decreases with depth (p. 15). For these reasons, details will not be entered into with regard to the summer climate; it will be mentioned only that the following summers probably were rather bad: 1939–40, 1942–43, 1943–44, 1950–51, 1951–52 and 1953–54, whilst the summers of 1941–42, 1944–45, 1946–47, 1949–50, 1955–56 and 1956–57 in all likelihood had a relatively large amount of fine weather. This is in good agreement with Schytt's results from Maudheim (Schytt 1954, p. 81).

The greatest difficulties in the tracing of the summer surfaces were met with at the summer layer of 1948–49. This was first interpreted to be the lower part of the summer layer of 1949–50 as the firn was somewhat metamorphosed and contained some ice through the whole of this layer. On further study it appeared, however, that the summer climate (1949–50) had been so exceptionally good that all the winter-firn of 1949 had been somewhat metamorphosed. The melt water from the summer of 1949–50 had soaked all the winter-firn of 1949 and probably even the summer-firn of 1948–49[2].

The bottom of the winter layer of 1957 consisted of a 17 cm thick layer of somewhat metamorphosed firn. This was accumulated between 8th and 20th January 1957, while Norway Station was built. It was only slightly metamorphosed during the rest of the summer. As there was also much fine weather after 20th January, this shows that the essential part of the metamorphism takes place earlier in the summer when the radiation of the sun per square unit is far greater.

Measurements of specific weight.

As special equipment for specific weight measurement cylinders of steel with a saw-toothed end were used. The volumes were 0.50 or 0.25 litres. At depths greater than about two metres, the snow was too firm to be measured with these tools.

In the deep pit, therefore, the method of forming parallelepipeds with all angles as near 90° as possible was used. All edges were measured, giving

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[1] The somewhat misleading term "summer firn" does not mean that the snow has been accumulated during a summer, but that it is metamorphosed into a layer of coarse-grained firn during the relatively warm summer.

[2] After the return from Antarctica, it was found that Schytt (Schytt 1958, pp. 25, 27, 40) had found the same for these layers at Maudheim and had made the same interpretation. Unfortunately, Schytt's paper was not available at the time of departure for Antarctica in 1956.

four measurements of the distance between two opposite sides. The maximum error is ± 0.5 mm. For the weight measurements a featherweight with upper limit 500 gram and an accuracy of 2 gram was used.

The maximum error in the measured specific weight decreases with increasing firn volume and is ± 0.015 g cm^{-3} for volumes of about 400 cm^3. Of this value only one third is due to inaccuracy in the measured weight, and therefore it was found unnecessary to use a more exact but also more troublesome scale balance. Most of the given values (Fig. 5) for the specific weight are the means of 2, 3 or 4 measurements. The error is therefore less than the given ± 0.015 g cm^{-3}. The deviation in specific weights measured in one firn layer is usually less than 0.010 g cm^{-3}, except in layers containing ice, or firn of variable grain size. This implies that the given values of the maximum error ± 0.015 g cm^{-3} is too high.

Accumulation in the period 1940–1959.

On the basis of the thickness of the annual firn layers and the specific weight of the firn (Fig. 5), the annual accumulation was found for the seventeen accumulation-years 1940–1956. The accumulation in the calendar years 1957, 1958 and 1959 was found by direct measurements (more about these appears later, p. 19). The accumulation for the twenty year period 1940–59 is given in Fig. 6 and in Table 1 below.

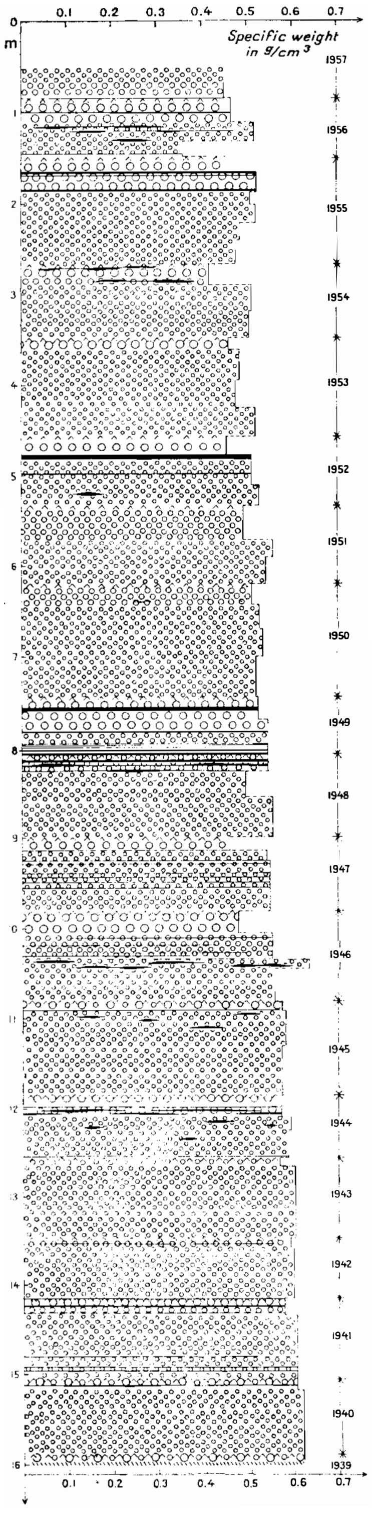

Fig. 5. The stratigraphic section and the density of the firn found in the deep pit at Norway Station. Summer-surfaces are shown as a row of angles. Ice-layers and ice-lenses are shown by black lines or areas. The firn is shown by circles whose diameters indicate the grain-size.

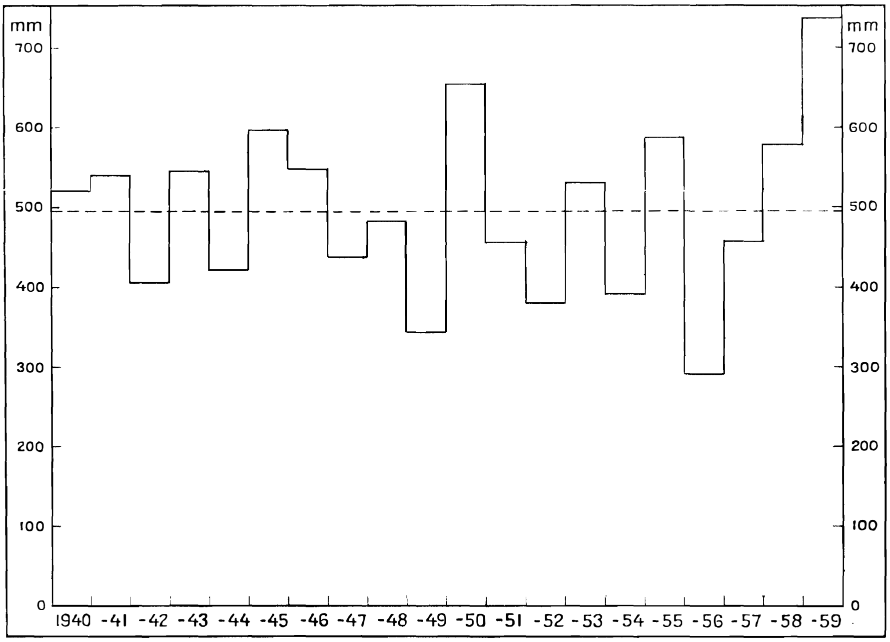

Fig. 6: Accumulation at Norway Station from 1940 to 1959. The 20-year mean is shown by a stippled line.

Table 1.
The Accumulation in the twenty year period 1940—59 at Norway Station.

Year	Accumulation
1940	520.6 mm of water
1941	539.4 – – –
1942	406.4 – – –
1943	545.7 – – –
1944	421.8 – – –
1945	597.0 – – –
1946	547.6 – – –
1947	437.0 – – –
1948	482.0 – – –
1949	342.9 – – –
1950	654.2 – – –
1951	455.9 – – –
1952	379.4 – – –
1953	531.9 – – –
1954	391.0 – – –
1955	587.4 – – –
1956	290.5 – – –
1957	457.5 – – –
1958	578.0 – – –
1959	737.0 – – –
Annual mean accumulation from 1940 to 1959:	495.2 mm of water.

As stated on p. 9, only the accumulation per accumulation year has been found for the years 1940–56. There may therefore be some errors in the given annual accumulations. On p. 10, the very fine summer of 1949–50 was mentioned. The melt water that summer soaked all the winter snow of 1949 and even the summer snow of 1948–49. Some of the given accumulation for 1948 then in reality is from 1949. However, this is of no consequence for the calculated 20 years annual mean of 495.2 mm of water.

As the summer surface of 1956–57 was formed contemporarily with the change of the calendar year no error is committed by the transition from measuring the accumulation per accumulation year to the accumulation per calendar year.

The mean accumulation in the ten years 1940–49 is 484.0 mm, while it is 506.3 mm in the ten years 1950–59. This difference, however, is too small to be significant. Moreover, if the mean of the accumulation in the first eleven years is taken, it is found to be 499.5 mm, while the mean annual accumulation of the last nine years is 489.8 mm. This is due to the extraordinary great accumulation of 1950 (654.2 mm). Thus there is no tendency towards increasing or decreasing accumulation. In any case the period is too short to draw any conclusions about climatic variations.

The correlations between the values for the annual accumulation found by Schytt at Maudheim and those found at Norway Station for the same twelve years (1940–51) are rather bad.

The topographical and meteorological conditions at Norway Station are discussed in more detail later, p. 19. Here it is mentioned only that the wind usually was easterly. Catabatic winds from the inland ice did not occur. During longer periods no net accumulation or ablation by drift snow was established; *it seems to be a fact that all the accumulation is due to actual snowfall.* This is what is to be expected with this wind direction on a horizontal ice shelf several tens of kilometres in length, where the strength of the wind, and consequently its ability to carry drift snow will usually be constant.

No direct measurements of the ablation by sublimation were taken at Norway Station. Everything implies, however, that it has been negligible (an estimate (p. 35) gives a probably maximum of 10 mm of water for the whole period 1957–1959). Strong and dry winds did not occur and the average humidity was 87 % – a very high value for an Antarctic station. An estimate (p. 34) shows that the accumulation by hoar frost is negligible. *Thus it seems that the determined value of the annual mean-accumulation can be applied to the annual mean precipitation as well.* At least it gives the best obtainable value, as the precipitation gauge used was quite unsuitable (pp. 36–37).

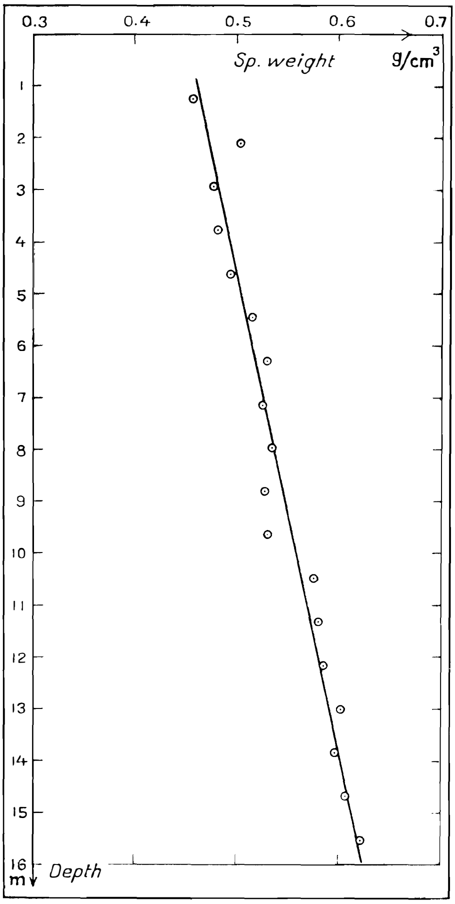

Fig. 7. Density-depth curve of the firn at Norway Station, and the mean density for each 0.84 m.

Variation in specific weight.

The metamorphosis of the summer snow makes it less dense than the winter snow. The influence of the ice layers is of course the exact reverse. Totally, however, the summer snow is usually lighter than the winter snow. Of the seventeen summer layers found in the deep pit, only the layers of 1945–46 and 1948–49 were heavier than the winter snow (Fig. 5). The summer snow of 1945–46 was only slightly heavier than the average at this depth (Fig. 7). The layer contained some ice which caused the high specific weight. As to the summer layer of 1948–49, the great density was due to a large ice content caused by the melt water from the extraordinarily fine summer of 1949–50 (p. 10).

Apart from the exceptionally light summer layers of 1946–47 and 1947–48, the difference in density between the summer firn and the winter firn grew less at greater depths. Near the bottom of the pit the density difference was very poor. In other words the density of the summer firn increased more rapidly with depth than did that of the winter firn. This is what is to be expected, as the lighter summer firn contains more air and thus has greater "possibility for settling" than has the winter firn. The ice content even makes it possible that at greater depths the summer layers will have the greater density.

The variation of the density with depth is shown in Fig. 7. The curve is calculated as a straight line by the method of least squares. The following equation is obtained.

The mean density-depth curve for the firn:

$$s = 0.452 + 0.0106\ h \qquad 0.84\ m \leqq h \leqq 15.96\ m$$

Calculated in the same way the following equations for the summer firn and the winter firn are found.

The density-depth curve for the summer firn:

$$s = 0.427 + 0.0113\ h \qquad 0.84\ m \leqq h \leqq 15.96\ m$$

The density-depth curve for the winter firn:

$$s = 0.459 + 0.0104\ h \qquad 0.84\ m \leqq h \leqq 15.96\ m$$

where s is the specific weight in g cm^{-3} and h the depth in metres from the snow surface.

Usually the mean density-depth curve will be convex upward, or, in other words, the increase in specific weight will be less in the lower than in the upper layers (Schytt 1958, p. 42). Here the density increase per metre is a constant, 0.106 g cm^{-3} m^{-1}. This does not mean, however, that the settling in percentage per year is constant. As the annual firnlayers are denser, and consequently thinner at greater depths, an annual firnlayer near the snow surface is shifted a greater step downward, relative to the surface, during one year, than is one at greater depth, and it is compressed proportionately more. The settling in percentage per year therefore also is greatest near the surface (it is supposed here that the annual accumulation is constant (p. 17)).

Fig. 8 gives smoothed density–depth curves for Maudheim (Schytt 1958, p. 45) and for Norway Station. The corresponding curve for the firn at the northern side of the mountain range is also given (p. 45). As can be seen, the density increases more rapidly with depth at Maudheim than at Norway Station. As the ice content in the firn and the annual temperature (–17.6° C at Maudheim, –18.2° C at Norway Station) were almost the same, and so also the specific weights in the upper firn layers, *this difference in the rate of settling must be due to the different annual accumulations at the two places* (365 mm of water at Maudheim, 495.2 mm of water at Norway Station). This difference results in different ages of firn at the same depth at the two places. The firn in the bottom of the deep pit at Maudheim (11.7 m depth) was 16 years of age and had a specific weight of 0.595 to 0.600 g cm^{-3}, while the firn at the same depth at Norway Station was only 12 years old

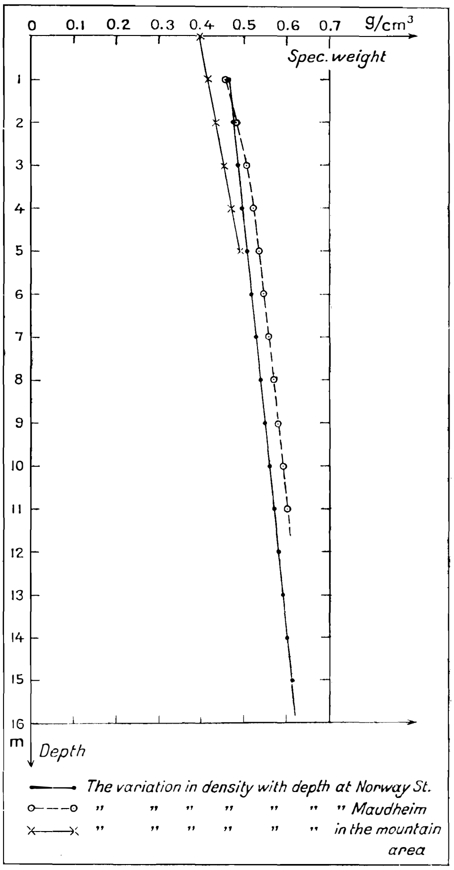

Fig. 8. Mean density-depth curves for the firn at Maudheim, Norway Station and the inland ice north of "Fimbulheimen".

and had a specific weight of 0.576 g cm^{-3}. At Norway Station firn 16 years of age was found at a depth of 15.05 m and its specific weight was 0.612 g cm^{-3}. The reason for the higher specific weight of firn of the same age at Norway Station is the greater pressure from the overlying firn.

As can be seen, firn at the same depth has a specific weight that is some 0.020 g cm^{-3} greater at Maudheim than at Norway Station, while firn of the same age is some 0.015 g cm^{-3} lighter at Maudheim than at Norway Station. This shows that *when the temperature, the original density of the firn and the ice content are the same, the specific weight is determined by the annual accumulation (the pressure from the overlying firn) and the age of the firn (the length of time it has been exposed to the pressure).* Comparing the values from Maudheim and Norway Station it seems as if age is of greatest importance.

Settling.

No direct measurements of settling were carried out at Norway Station. As mentioned on p. 15, however, the smoothed density–depth curve is almost a straight line (Fig. 8) and satisfies the equation:

$$s = 0.452 + 0.0106\,h \qquad 0.84\text{ m} \leqq h \leqq 15.96\text{ m}$$

From a value of 0.461 g cm^{-3} at the top of the annual layer of 1956 (0.84 m depth) the specific weight increases by 0.0106 g cm^{-3} m^{-1} to 0.620 g cm^{-3} at the bottom of the annual layer of 1940 (15.89 m depth). Apart from small variations in specific weight, caused by different meteorological factors (temperature, wind, radiation, rate of accumulation and so on), this increase of density is the result of settling, and can consequently be used to calculate the rate of this settling (Sorge 1935, 1938, Bader 1954).

Estimating the annual accumulation during the period 1940–1956 to be a constant 478.3 mm of water (the annual mean during these 17 years) (Sorge 1935, p. 157, Bader 1954, p. 319), the variation in specific weight with the age of the firn, or with the pressure of the overlying firn, can be calculated by the equation:

$$s_n = \frac{a}{h_n - h_{n-1}}$$

where s_n is the specific weight of the n'th annual firnlayer; a is the water equivalent of the accumulation, 0.4783 m year^{-1}; h_n is the total thickness of n annual firnlayers, measured from the top of the layer of 1956.
h is given implicitly by the following equation:

$$(s_t + \tfrac{1}{2}\,c\,h_n)\,h_n = n\,a$$

where s_t is the specific weight at the top of the layer of 1956, 0.461 g cm^{-3}; c is the increase of the specific weight with depth, 0.0106 g cm^{-3} m^{-1}. The results are given in Table 2.

Table 2.
The settling of the upper 16 m of firn at Norway Station.

Age of the firn (year)	Thickness of n annual layers (m)	Thickness of one annual layer (m)	Specific weight (g cm^3)	Settling (cm/year)	Settling (percent/year)
1	1.026	1.026	0.466	2.3	2.3
2	2.029	1.003	0.477	2.2	2.2
3	3.010	0.981	0.488	2.0	2.1
4	3.971	0.961	0.498	1.9	2.0
5	4.913	0.942	0.508	1.8	1.9
6	5.837	0.924	0.518	1.7	1.8
7	6.744	0.907	0.527	1.6	1.8
8	7.635	0.891	0.537	1.5	1.7
9	8.511	0.876	0.546	1.4	1.6
10	9.373	0.862	0.555	1.4	1.6
11	10.221	0.848	0.564	1.3	1.5
12	11.056	0.835	0.573	1.3	1.5
13	11.878	0.822	0.582	1.2	1.5
14	12.688	0.810	0.590	1.1	1.4
15	13.487	0.799	0.599	1.1	1.4
16	14.275	0.788	0.607	1.1	1.4
17	15.052	0.777	0.616		

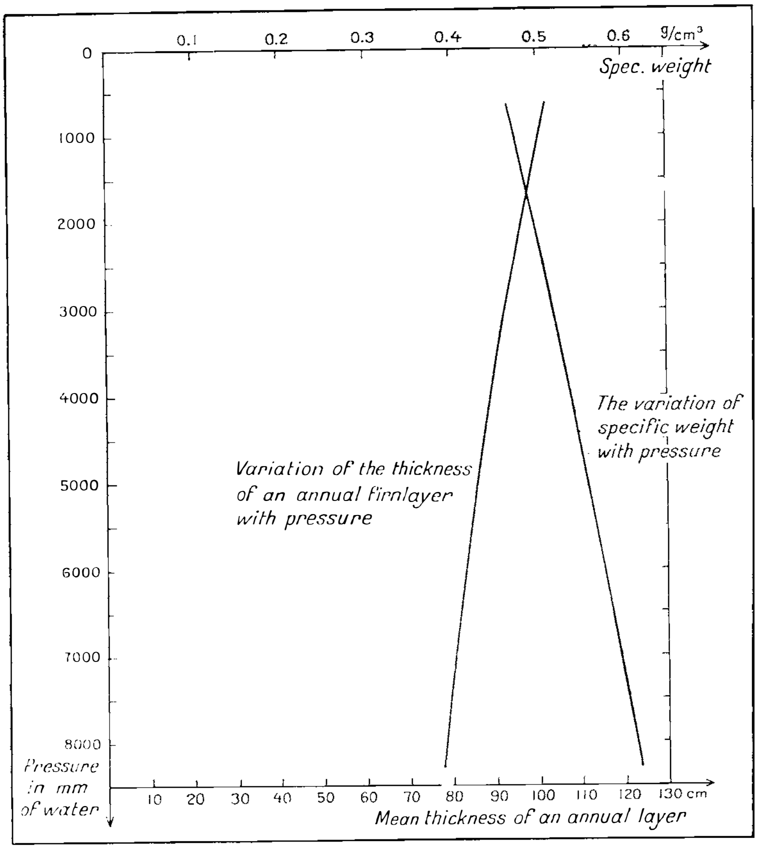

Fig. 9. The variation of the specific weight and the mean thickness of an annual firnlayer, with the pressure of the overlying firn.

As can be seen from the table, the settling decreases from 2.3 percent a year in one-year-old firn to 1.4 percent a year in seventeen-year-old firn. The settling mean in this interval is 1.74 percent a year. Schytt (1958) found by direct measurements that the settling between 2 and 11 metres depth – 3 to 16 years old firn - was constant, 1.6 percent a year. That the settling at Norway Station was somewhat greater than at Maudheim, probably was due to the greater accumulation (p. 15).

In Fig. 9 the increase of the specific weight and the decrease of the thickness of the annual layers are plotted as a function of the pressure of the overlying firn.

These calculations of the settling, as mentioned, are based only on the increase of density with depth. As this increase is due solely to settling, and only the mean values of the specific weights are used, the mean value of the settling, 1.74 percent a year, at least is fairly reliable. It is also in good agreement with Schytt's (1958) observations from Maudheim.

A "normal curve" for the increase in specific weight with depth is convex upward, instead of a straight line as was found for Norway Station for the period 1940–1956. Compared to this "normal curve" the found values for the settling are too low for the upper layers, and too high for the lower layers. This, however, does not agree with the constant settling of 1.6 percent a year between 2 and 11 metres depth that was measured directly by Schytt at Maudheim.

Altogether it seems as if the found values for the settling, given in Table 2, are relatively reliable.

Accumulation at Norway Station during the years 1957, 1958 and 1959.

Morphology of the area.

Norway Station is situated on ice shelf at an alevation of 56 m, 35 km from the coast (Plate IV b). The area is almost plane and nowhere broken by crevasses. The nearest noticeable unevenness is Blåskimen, an ice rise some 6 km to the northwest. The top is 21 km from Norway Station and ca. 390 m high. The border of the inland ice is 20–30 km to the southwest, and some 37 km east of Norway Station is the great belt of crevasses which forms the western border of the ice stream from Jutulstraumen (p. 3).

Strong winds do not meet with any obstacles. Therefore it is only exceptionally that they vary considerably in strength within the area, and their ability to carry drift snow is constant. This means that there is no net accumulation or ablation by drift snow (p. 13). In view of these considerations Norway Station must be regarded as an ideal place for accumulation studies (Fig. 3).

Stake measurements.

The accumulation from 26th February 1957 to 1st January 1960 was found by stake measurements in an area of 37 km^2 south of Norway Station (Fig. 10, 11).

The first stake was placed on 26th February 1957, nine others on 6th March, and four more on 25th March; the last twenty-five were placed on 23rd and 24th April 1957. By a mistake one stake was placed as late as 6th September 1957.

At four stakes (S 1, K 1, K 2 and K 3) the accumulation was measured every day from the date they were set out until 1st January 1960, except on 48 days when the winds were too strong, or there was no-one to make the measurements. Moreover, on 31st July 1958 ten other stakes (E 1 to E 10) were placed between these four. These also were measured every day, so

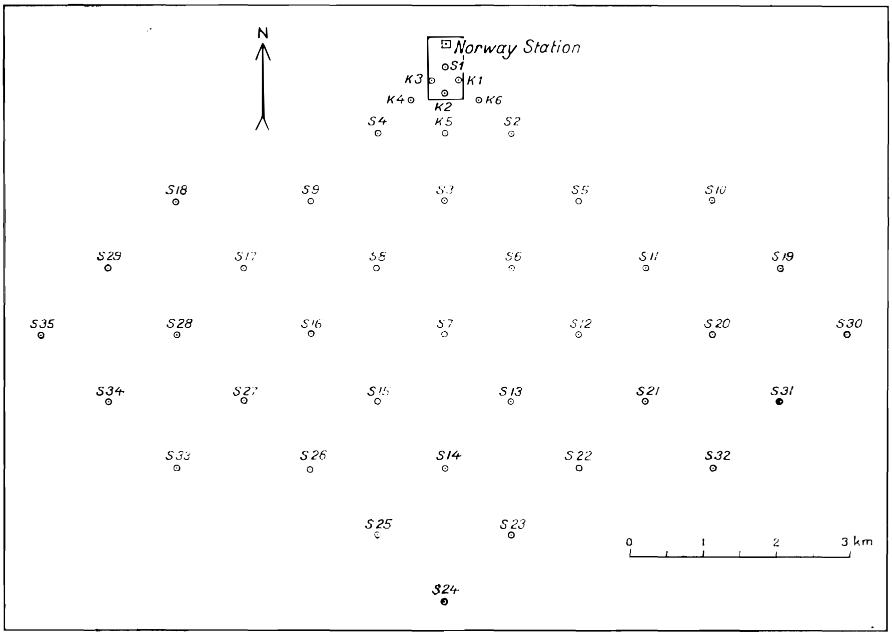

Fig. 10. The stake pattern at Norway Station. Inset, the area shown in Fig. 11.

making the daily measurements far better. In addition, these stakes made conditions less dangerous for the observer in bad weather.

Three other stakes (K 4, K 5 and K 6) were measured on the 1st, the 10th and the 20th of each month until 1st January 1959; later they were measured on the 1st of each month. Stakes S 2, S 3 and S 4 were measured on the 1st of each month.

At the other thirty stakes the accumulation was measured at various intervals (on 7th September 1957, 19th February, 20th July and 20th November 1958, and 15th January 1959). Three of these stakes – S 17, S 23 and S 30 – disappeared during the hurricane on 15th July 1958. The stakes were measured once more on 19th November 1959, but only seventeen were found on this occasion, ten more having disappeared during the winter, probably due to the great accumulation during 1959.

The stakes used were of bamboo, about 20 mm in diameter. They could be lengthened when necessary by extensions of about 1.5 m in length. The junction, made of brass, turned out to be too weak in strong winds. For instance, twenty-two of the stakes broke at the junction during the hurricane on 15th July 1958.

In order to measure the accumulation at all the stakes, it was necessary to travel a distance of nearly 50 km. Usually this was done on skis as the tractors were occupied in other duties. As the stakes had to be lengthened and all the equipment carried, the job took two or three days. Sometimes

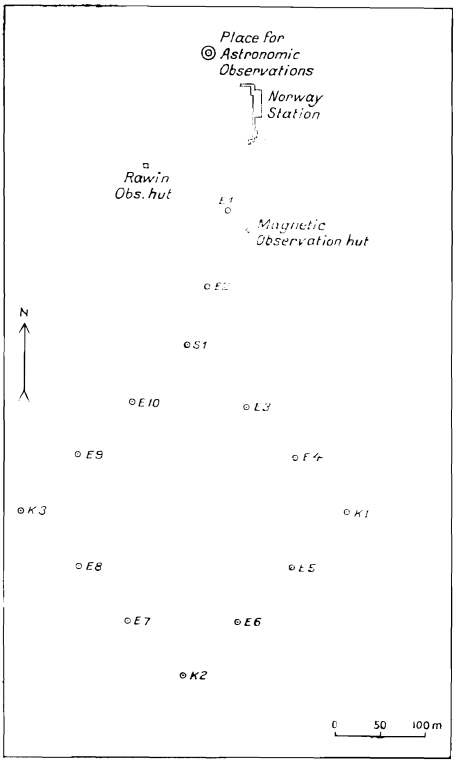

Fig. 11. Norway Station and the stakes measured every day.

the measurements were interrupted by bad weather, but on the occasions mentioned the accumulation was measured at all the stakes, and there was no accumulation or ablation during the days of measuring.

All the stake measurements have been used to find the accumulation. First, the monthly means are corrected, as explained below, according to the infrequent measurements of all the forty stakes. Then the 10-day means are corrected in the same way. Finally, the daily measurements are corrected according to the corrected 10-day and monthly means.

Example: The mean accumulation at all the forty stakes on 7th September 1957 was 68.7 cm of snow (this is the best obtainable value for the accumulation between 26th February and 7th September 1957), the mean of the ten monthly-measured stakes was 71.6 cm of snow. On 19th February 1958 the mean accumulation at the forty stakes was 95.4 cm of snow, while the mean for the ten stakes was only 94.2 cm of snow. The mean at the ten stakes on 30th November 1957 was 81.5 cm of snow.

The monthly measurements were thus 2.9 cm too high on 7th September 1957, while they were 1.2 cm too low on 19th February 1958. In other words, they have decreased relative to the mean of the forty stakes by 4.1 cm of snow during these 165 days. From 7th September to 30th November there are 84 days, and the mean accumulation found at the ten stakes on 7th September has to be reduced by $(2.9 - \frac{4.1 \times 84}{165}) = 0.8$ cm of snow. The corrected value for the accumulation from 26th February to 30th November 1957 is then: $81.5 - 0.8 = 80.7$ cm of snow.

Possible errors.

All the stakes were placed in boreholes about 1.2 m deep. From experience at other places with bamboo stakes this should have been sufficient, especially as the stakes were placed in the autumn. At the beginning of the summer about 2 metres of the stakes were buried by snow. The maximum temperature reached at this depth was –9° C. Moreover, due to sublimation, the stakes became fast to the snow only a few days after they were placed. Errors caused by sinking of the stakes thus are negligible.

Owing to the steady easterly winds some of the stakes became bent towards the west. This was especially the case with those which were measured only a few times, as it was of no use setting them vertically at each visit. This results in too high a value for the accumulation. The ten stakes placed on 31st July 1958 were guyed so that they always were vertical. The measured accumulation at these stakes, however, was rather greater than at the others. The error in the measured accumulation due to the bending of some stakes therefore probably is negligible.

Fair weather in the summers frequently formed small depressions in the snow surface close to the stakes. Drift snow caused lumps of snow or ice to form on the stakes. On these occasions it was often difficult to find the right level of the snow surface, and small errors in the measurements of accumulation, in positive or negative directions may have occurred (p. 35).

Local variations in the accumulation.

In order to find the variation, if any, in the accumulation within the investigated area, those stakes which were measured both on 23rd April 1957 and on 15th January 1959 (632 days apart) have been used. The mean accumulation at these thirty-six stakes is 206.2 cm of snow. The standard deviation is 10 cm. The position of, and the accumulation at, each stake is given in Fig. 12. From the map it is not possible to trace any tendency towards greater or less accumulation within the area. The accumulation in the two parts of the stake area formed by the full drawn line in the figure, drawn parallel to the border between Fimbulisen and Blåskimen, is 206.4 cm of snow in the northwestern part and 206.0 cm of snow in the southeastern part. This difference is quite negligible and implies that *the ice rise 6 km to the northwest of Norway Station does not influence the accumulation in this*

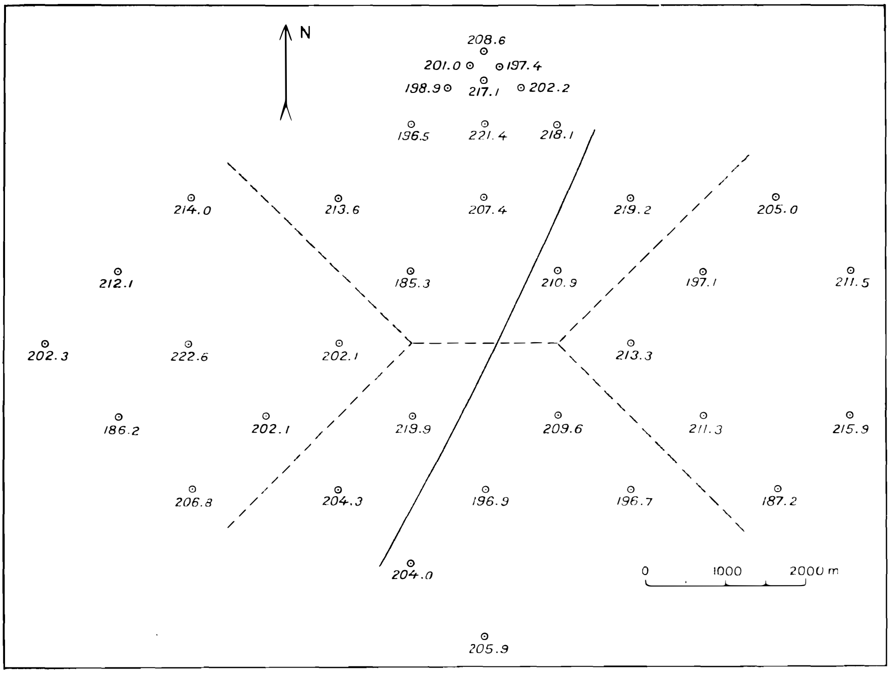

Fig. 12. Accumulation at Norway Station in cm of snow from the 23rd of April 1957 to the 15th of January 1959.

area. The accumulation in the four parts of the stake area, formed by the dotted lines in Fig. 12, was as follows:

Northern part.	Eastern part.	Southern part.	Western part.
207.0 cm	205.9 cm	205.3 cm	206.0 cm

The variation from one part of the stake pattern to another, maximum 1.7 cm of snow, is too small to be of any significance, especially as the standard deviation of the measurements is as great as 10 cm.

Specific weight.

The specific weight of the snow which had fallen from February 1957 to January 1959 was measured in January 1959. The measurements were carried out in three pits, one of which was between stakes S 1 and K 2, one at stake S 21 and one at stake S 27. The mean specific weights from the mentioned period in these three pits were 0.448, 0.445 and 0.443 g cm^{-3} respectively. The difference between these values is so small that no error of significance is involved in using the mean of the three density-depth curves (Fig. 13 a) to find the water equivalent of the accumulation. The water equivalents found by using the mean curve instead of the values measured directly are 5 mm too low for the accumulation at stake S 1, 1 mm

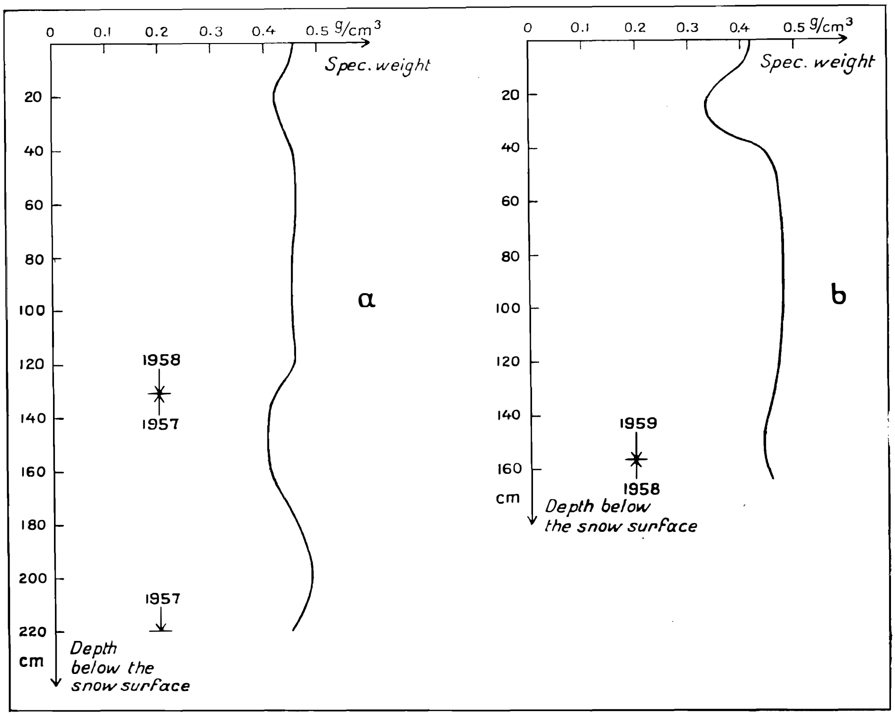

Fig. 13 a. Density-depth curve for the accumulation from February 1957 to January 1959.
13 b. Density-depth curve for the accumulation from January 1959 to January 1960.

too high at stake S 21, and 4 mm too high at stake S 27. These variations were so small that it was unnecessary to dig more than one pit to find the specific weight of the 1959 accumulation (Fig. 13 b).

It can be seen from the figures that the summer layers have very low specific weights (p. 14). The uppermost 5 to 10 cm of snow, however, is a little denser. This is caused by settling due to the high temperature (p. 25). This layer may lighten in the autumn and winter by upward vapour transport from the summer layer to the colder snow fallen on top of it (Schytt 1958, p. 25).

For the specific weight measurements a cylinder of volume 0.5 l, and a feather-weight with an accuracy of 2 gram (p. 10) were used. Where the snow was fairly homogeneous, two measurements at the same depth gave almost the same result. This shows that the accuracy of the measurements was sufficient.

Calculation of the water equivalent.

For the calculation of the water equivalent of the accumulation during the three years 1957, 1958 and 1959, the values for the specific weight already given (Fig. 13 a and b) were used. The measurements at 5 cm depth were used for the upper 10 cm, each of the other values was used from 10 cm above to 10 cm below where the measurements were taken. As to the density of the 1959 accumulation, the measurement at 25 cm depth was estimated to apply from 10 to 35 cm depth and that at 125 cm from 115 to 140 cm depth.

On pp. 17–19, an estimation is made of the value of the settling in the interval 0.84 to 15.89 m depth. This is firn of an age of from one to seventeen years, and the settling was found to decrease from 2.3 percent per year in the one-year-old firn to 1.4 percent per year in the seventeen-year-old firn. By interpolation, the settling of new snow is found to be 2.4 percent a year.

Some corrections, however, are to be made to this value. In calm weather the snow surface sometimes sank by one or two millimetres during a day. This sinking appears to have been about four times as frequent in the summer of 1957–58 as in the winter of 1957, three times as frequent in the summer of 1958–59 as in the winter of 1958 and two and a half times as frequent in the summer of 1959–60 as in the winter of 1959. The reason for the faster settling during the summer is the high snow temperature. As the high temperature, and thus the settling, is especially marked in the upper layers, the settling is relatively less in the last summers than in the first one because the total snowlayer, measured from the bottom of the stake, is growing gradually thicker[1].

It is now estimated that the greater settling in the summers only takes place in the upper 0.5 m and that it is twice as great in the top 0.25 m as in the next 0.25 m. The following values for the settling per month are then obtained:

Settling in snow at an age of 3 years:	0.17 % per month
Settling in snow at an age of 2 years:	0.18 % per month
Settling in snow at an age of 1 year:	0.19 % per month
Settling in new snow:	0.20 % per month
Settling between 0.25 and 0.50 m depth, from November to February:	2.0 % per month
Settling between 0.00 and 0.25 m depth, from November to February:	4.0 % per month

The measured accumulation is first corrected for the settling in the lower snow layer of 1.20 m thickness, the depth to which the stakes were set down. In this way the accumulation of snow is found from 26th February 1957 to any date until 14th January 1960.

In order to find the water equivalent of the accumulated snow, the settling in the period between accumulation occurring and the specific

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[1] Because the stakes were driven down to a depth of 1.20 m, and the bottoms of the stakes were held fast at this depth (p. 22), one has to take into consideration that the settling is occurring in the whole snow layer from the bottom of the stake to the snow surface. This may involve a small error, as sublimation may cause the stakes to be fast to the snow not at the bottom, but somewhere else. (Swithinbank 1954, p. 130).

weight being measured also has to be taken into account. As the specific weight for the snow accumulated during 1957 and 1958 was measured in January 1959, and the specific weight for the snow accumulated during 1959 was measured in January 1960, the settling for each of these two periods must be computed separately.

The accumulation during a certain period, for instance one month, is found by considering also the settling in the earlier accumulated snow layers during the period for which the accumulation is to be found.

Occasionally there was accumulation of snow during calm weather. The specific weight of this snow was very small, less than 0.1 g cm^{-3}. During the next blizzard the snow would be windpacked, and consequently the surface would sink, though there had been no true ablation. The best illustration of this was from the end of September to the beginning of October 1957. On 28th and 29th September there was an accumulation of 12 cm of snow. On 2nd and 3rd October the snow surface sank by 7 to 8 cm (Fig. 14). This sinking was entirely due to windpacking of the loose snow which had fallen when winds were not stronger than about 10 knots. (There is no drift snow at these wind speeds.) The snow had a specific weight of 0.079 g cm^{-3}. During 2nd and 3rd October, contemporary with the sinking of the snow surface, the specific weight increased to about 0.3 g cm^{-3}. It thus transpires that in reality there was some accumulation instead of ablation on these days (there was light snowfall on 3rd October). Such things probably happened several times. When it has been ascertained, it is taken into account on calculating the water equivalent. Curves showing the accumulation during the three years 1957, 1958 and 1959 are drawn (Fig. 14, see backflap) from the observations corrected for settling and windpacking.

There remain some sinkings of the snow surface which have not been explained. Most of them likewise probably are due to settling during strong winds. Especially previous to 1st August 1958, when only four stakes were measured per day, one cannot set aside the possibility that these sinkings of the snow surface may have been due to the fact that the snow had been transported away from the stakes and accumulated in drifts elsewhere between the stakes. The likelihood of such errors is very much reduced from 1st August 1958 when fourteen stakes were measured each day (p. 34).

It is also possible that exceptionally there may have been some transport of snow by the wind away from the area where the measurements were carried out, though there is little evidence for this (pp. 19, 34).

The wind speed and direction are plotted in Fig. 14. It can be seen that the greater part of the accumulation came with easterly winds (see pp. 32, 33) (Swithinbank 1957, pp. 63–65 and Fig. 9).

The accumulation during the three years was very variable. From the time measurements were commenced, on 26th February 1957, until the end of the year, there was an accumulation of 381 mm of water. When the accumulation from 1st January to 26th February 1957 is added, the total accumul-

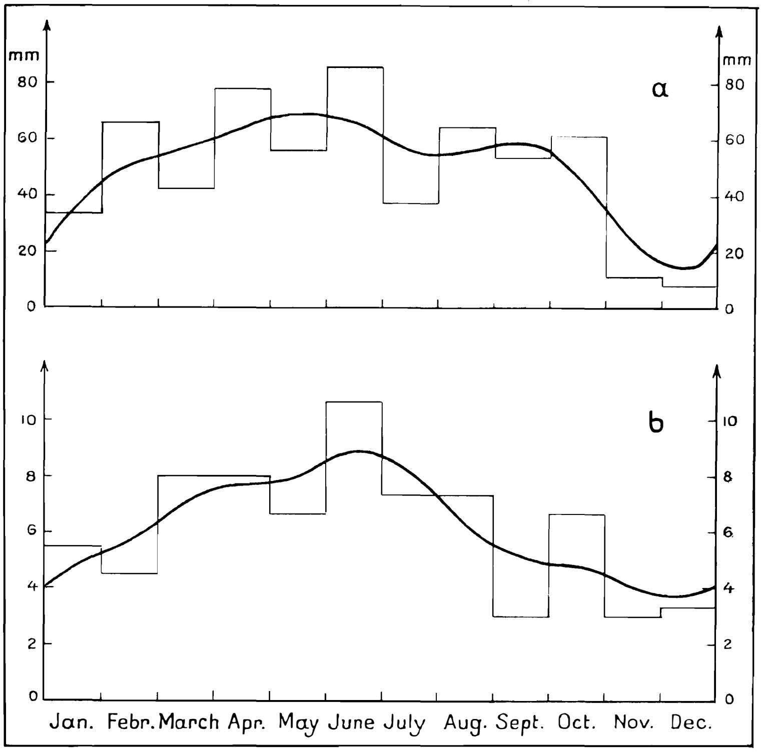

Fig. 15 a. Monthly means of the accumulation in mm of water. 15 b. The mean frequency of days with greater wind speed than 22 knots (strong breeze).

ation during 1957 is 457.5 mm of water. The annual accumulation in 1958 was 578 mm of water; and in 1959 as much as 737 mm of water. The annual mean for these three years is 590.8 mm and thus considerably higher than the mean of the 20 years period 1940–59 (459.2 mm of water) (p. 12).

The accumulation per month is given in Table 3. It can be seen that the variation in the accumulation is very great. The monthly means, given in the lower column show the seasonal variation in the accumulation. (These

Table 3.

Monthly accumulation in millimetres of water at Norway Station.

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1957			6	65	1	137	16	67	23	27	5	30
1958	39	34	99	58	26	87	15	66	92	69	5	-12
1959	28	98	21	111	141	33	81	61	46	88	23	6
Mean	33.5	66.0	42.0	78.0	56.0	85.7	37.3	64.7	53.7	61.3	11.0	8.0

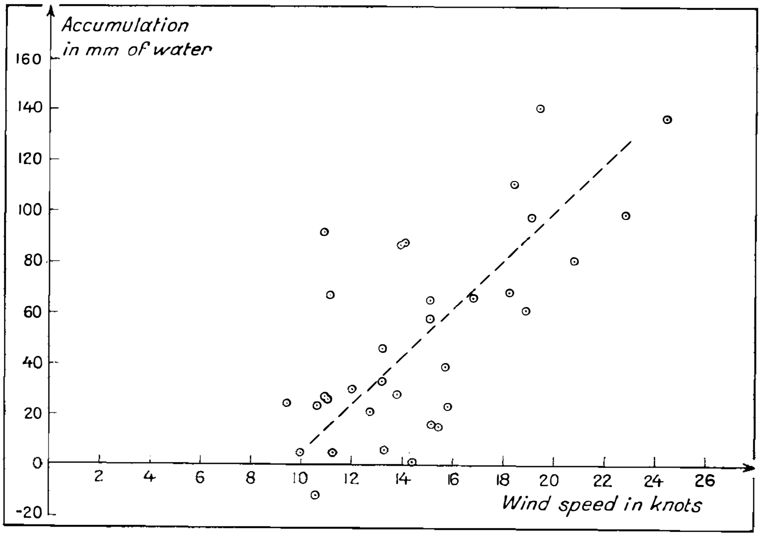

Fig. 16. The monthly accumulation plotted against the mean wind speed. The stippled line indicates the increasing accumulation with wind speed.

are the means of only two years for January and February; for the other ten months they are the means of three years.)

Fig. 15 a shows the monthly means of the accumulation, and Fig. 15 b the frequency of days with a wind speed of at least 22 knots (strong breeze). There is a marked minimum in the accumulation for the months of November, December and January. The relatively poor accumulation in March, May and July, however, probably is due to random variations during the too short observation period (3 years).

The smoothed curve probably gives a far more reliable result (the equation $a_i = \frac{1}{4}(a_{i-1} + 2a_i + a_{i+1})$ is used, where a_i is the mean accumulation of a certain month, the indexes $_{i-1}$ and $_{i+1}$ referring to the preceding and following months).

The histogram and the smoothed curve in Fig. 15 b show in their broad features the same variations. The winter months frequently have strong winds and great accumulation, while the summer months are calm and have poor accumulation (Swithinbank 1957, p. 70, 71).

The mean accumulation in the winter (April to September) is 375.4 mm of water. The mean accumulation in the summer (October to March) is 221.8 mm of water (Kotljakov 1959, Table 2).

In Fig. 16 the monthly accumulation is plotted as a function of the mean wind speed, which is also given in Table 4. Of course, there is a great scattering of the values, too great to use the method of least squares for drawing the curve. However, there is a marked tendency towards greater accumulation at higher wind speeds. If it is assumed that the variation of accumulation with wind speed is a linear function, the equation: $a = 9.5\,f - 90$ is obtained where a is the monthly accumulation in millimetres of water and f is the mean wind speed in knots.

Table 4.

Mean wind speed and accumulation per month at Norway Station.

Year		Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1957	Wind speed				15.1	14.4	24.4	15.1	11.1	10.6	10.9	11.3	12.0
	accumulation			[1]	65	1	137	16	67	23	27	5	30
1958	Wind speed	15.7	9.4	22.8	15.1	11.0	13.9	15.4	16.8	10.9	18.3	9.9	10.6
	accumulation	39	34	99	58	26	87	15	66	92	69	5	-12
1959	Wind speed	13.8	19.1	12.7	18.4	19.4	13.2	20.8	18.9	13.2	14.1	15.8	13.3
	accumulation	28	98	21	111	141	32	81	61	46	88	23	6

Accumulation at different meteorological conditions.

Precipitation.

In order to find the causes of the accumulation, and under what meteorological conditions it takes place, the meteorological observations have been examined. These include surface observations every third hour, at 0000, 0300, 0600 hours and so on, from 1st April 1957 until 1st January 1960. The wind was measured 10 m above the ground, the temperature and humidity 2 m above the ground.

Of these 1006 days there were observed 510 days[2] with snowfall (Table 5). Out of these 510 days there were 276 days with an accumulation of at least 1 mm of water (in total 2035 mm of water), 141 days when the snow surface was constant, and 93 days with an ablation[3] of at least 1 mm of water (in total 343 mm of water).

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[1] The accumulation in March 1957 was 6 mm (Table 3, p. 27), the wind speed, however, was not measured regularly, and consequently the month is omitted here.

[2] All the days of snowfall are counted here, even those with only a slight snowfall between the observations.

[3] With "ablation", as this word is used in the text, I mean every sinking of the snow surface not already explained as settling. It may be due to wind transport away from the area, sublimation, or circumstances that do not directly refer to true ablation, such as wind transport within the area under investigation, packing of the upper layers of snow during strong winds, or settling.

Table 5.
Observations of snowfall and accumulation at Norway Station.

	Snowfall	Dense drift snow	No snowfall	Total
Accumulation	276 days	4 days	66 days	346 days
Constant snowlevel	141 »	3 »	293 »	437 »
Ablation	93 »	2 »	128 »	223 »
Total	510 days	9 days	487days	1006 days

The great number of days with ablation (223) is due partly to the small sinkings of the snow surface corresponding to an ablation of one or two millimetres of water. These frequently were not over within one day, but continued slowly for several days. (This is discussed in further detail on pp. 34–36.)

In Table 6 the total values of accumulation and ablation during days with snowfall and days with no snowfall are given.

Table 6.
Accumulation and ablation under different precipitation conditions.

	Snowfall	Dense drift snow	No snowfall	Total
Accumulation	+2035 mm	+89 mm	+179 mm	+2303 mm
Ablation	— 361 »	— 9 »	—241 »	— 611 »
Net accumulation	+1674 mm	+80 mm	— 62 mm	+1692 mm

It can be seen that almost all the accumulation (88.3 %) came on days when snowfall was observed, while only 7.8 % came on days with no snowfall. 39 % of the ablation took place on days with no snowfall, while the corresponding value on days with snowfall was 59 %. That the ablation on days with snowfall was so great, was due to the fact that usually there was snowfall when the wind was strong enough to pack the snow. A considerable part of the measured ablation was due to small reductions in the level of the snow surface corresponding to 1 or 2 millimetres of water (p. 34).

Of the net accumulation 98.9 % came on days with snowfall. There was also some net accumulation (4.7 %) on days with such strong winds and consequently such dense drift snow, that it was impossible to observe whether or not it was snowing. On days with no snowfall there was a net ablation corresponding to 3.6 % of the total accumulation of 1692 mm of water. Naturally these values are not very exact. There may have been unobserved snowfall between weather observations, especially during bad weather when it was preferable to remain indoors. On the other hand, relatively great accumulation sometimes was measured on days when only "slight snow" was observed for a couple of hours. In these cases, there was always some wind and drift snow. The essential part of the accumulation of this type came in the period from 1st April 1957 to 31st July 1958, when only four stakes were measured each day. After 1st August 1958, when fourteen stakes were measured every day, such extraordinary accumulations were very rare. This indicates that these variations in the snow-surface were not true accumulations, but moving of snow from one part of the stake area to another. Some of the recorded ablations could be explained similarly. To illustrate this better, the days of accumulation and the days of ablation in the two periods, 1st April 1957 to 31st July 1958 (487 days) and 1st August 1958 to 1st January 1960 (519 days), are specified in Table 7.

Table 7.
Observations of snowfall and accumulation in two periods at Norway Station.

	1st April 1957—31st July 1958				1st August 1958—1st January 1960			
	Snowfall	Dense drift snow	No snowfall	Total	Snowfall	Dense drift snow	No snowfall	Total
	Days	Days	Days	Days	Days	Days	Days	Days
Accumulation	116	4	37	157	160	–	29	189
Constant snow level	82	–	133	215	59	3	160	222
Ablation	45	2	68	115	48	–	60	108
Total	243	6	238	487	267	3	249	519

The frequency of days with snowfall was almost the same in the two periods (49.9 % against 51.4 % of the days), but whilst there was accumulation on 47.7 % of the days with snowfall in the first period, it occurred on 59.9 % of the days in the second period. Days without snowfall also are almost as frequent in the first as in the second period (48.9 % against 48.0 % of the days). Of these, the proportion with accumulation decreased from 15.5 % in the first period to 11.6 % in the second period, proportion with constant snow level increased from 55.9 % to 64.3 %, and the proportion with ablation decreased from 28.6 % to 24.1 %.

From this it can be seen that an accumulation of snow usually occurred only when it was snowing, and that snowfall usually led to accumulation. In measuring only a few stakes every day the measured accumulation or ablation frequently may be due to a local transfer of the snow by the wind (p. 9). (Picciotto and Gonfiantini 1959.)

Wind.

Table 8 shows the accumulation and ablation at different wind speeds and wind directions.

Table 8.

Accumulation and ablation in mm of water at different wind speeds and wind directions at Norway Station.

	N		NE		E		SE		S		SW		W		NW		Total	
	Acc.	Abl.	Acc.	Abl.	Acc.	Abl.	Acc.	Abl.	Acc.	Abl.	Acc.	Abl.	Acc.	Abl.	Acc.	Abl.	Acc.	Abl.
00–09 kts.	3	–	37	2	20	12	23	7	10	3	18	12	22	2	–	–	133	38
10–19 »	–	–	75	24	432	96	97	38	21	9	11	16	44	23	21	–	701	206
20–29 »	28	–	74	4	717	102	37	–	–	–	2	–	4	5	–	–	862	111
30–39 »	–	–	20	5	300	99	–	–	–	–	–	–	–	–	–	–	320	104
40–49 »	–	–	–	–	178	4	–	–	–	–	–	–	–	–	–	–	178	4
50–59 »	–	–	–	–	14	11	–	–	–	–	–	–	–	–	–	–	14	11
60–69 »	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	2	–
Total	31	0	206	35	1663	324	157	45	31	12	31	28	70	30	21	0	2210	474

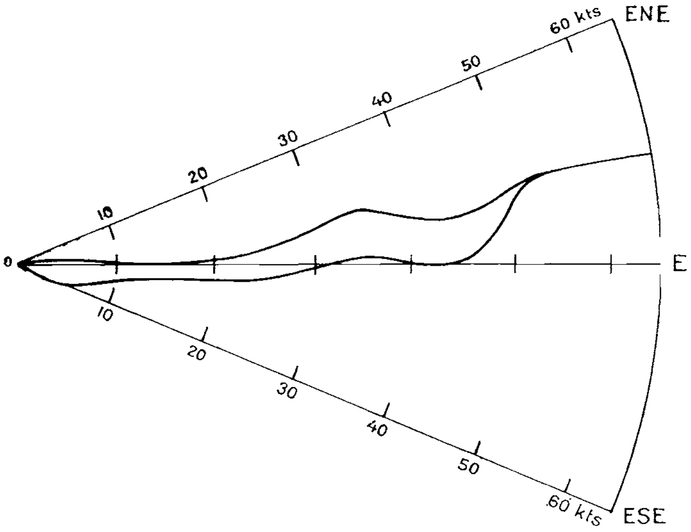

Fig. 17. Mean wind direction by accumulation (upper curve) and by ablation (lower curve) at different wind speeds.

The essential part of the net accumulation (84 %) came at wind speeds of from 10 to 39 knots (the last column). At low wind speeds (0–9 kts.), winds from all directions except NW and N gave approximately the same amount of accumulation. Even at wind speeds as low as 10 to 19 kts. 68 % of the net accumulation came with winds from the east; the percentage increased to 82 % at wind speeds of 20 to 29 kts., and to 93 % at wind speeds of 30 to 39 kts.; with stronger winds all the accumulation came with winds from this direction. Of the total net accumulation 77.5 % came with winds from the east. (When the wind directions northeast and southeast are included, the value is 93.4 %.) Of the accumulation from other wind directions the greatest part (2.3 % of the total) occurred with westerly winds.

In Fig. 17 the mean direction of the wind is plotted for different wind speeds when there was accumulation or ablation. (Only wind directions from the northeast, east and southeast are considered). The percentages of the total accumulation and ablation at these wind directions are respectively: 60 % and 55 % at wind speeds 0 to 9 kts., 86 % and 77 % at wind speeds 10 to 19 kts., 96 % and 95 % at wind speeds 20 to 29 kts. and 100 % for both the accumulation and the ablation at higher wind speeds.

On the average, the winds causing accumulation have a more northerly component than those causing ablation. In order to explain this it is necessary to look at the course of the blizzards at Norway Station. As shown earlier, almost all the accumulation occurred at the time of snowfall (p. 30); furthermore, practically all the precipitation in this part of Antarctica is of cyclonic origin[1] (Kotljakov 1959). The ordinary route of the cyclones is eastwards, north of Norway Station. As the wind is almost parallel to the isobars, its direction, when a cyclone is approaching, is from between north and east. As the cyclone passes to the north of Norway Station, the wind becomes easterly, and it continues to change to southeast or south as the cyclone proceeds towards the east.

The areas of precipitation usually arrive a little ahead of the cyclones. The mean wind direction during precipitation, and consequently during accumulation, therefore is somewhat more northerly than the mean wind direction during the course of a cyclone. The measured ablation is not a true ablation, but mainly the result of packing of the snow or local moving of it (pp. 30, 35). That this takes place at mean wind directions a few degrees further from the southeast than the mean wind direction causing accumulation, results only from the fact that the more infrequent snowfalls at these wind directions cannot compensate for the sinking of the snow surface.

The tendency towards a more northerly component of the wind direction at higher wind speeds than at lower ones, both when accumulation and when ablation are taking place, possibly can be explained by the frequently occurring steeper pressure gradient, and thus greater wind speed, at the front than at the back of a cyclone.[2]

Sublimation.

As no measurements of the sublimation at Norway Station were made, its influence on the accumulation and ablation can be determined only by studying the variations of the snow level on days without snowfall or drift snow. Of 208 days with such meteorological conditions there were 59 days with particularly great amounts of fog and hoar frost, conditions favourable for accumulation by sublimation. In these 59 days, however, there was

Table 9.
Accumulation and ablation at different relative humidity intervals.

Relative humidity	Number of days	Accumulation	Ablation	Net accumulation
60– 69 %	6	0 mm	3 mm	– 3 mm
70– 79 %	50	3 »	9 »	– 6 »
80– 89 %	110	7 »	25 »	–18 »
90–100 %	42	5 »	5 »	0 »
60–100 %	208	15 mm	42 mm	–27 mm

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[1] A few snow showers during the summers were due to convection.

[2] Personal communication from meteorologist Torgny Vinje.

as a whole an accumulation of only 7 mm of water, whilst the total ablation was 15 mm of water, a net ablation of 8 mm of water. Table 9 shows the total accumulation, ablation and net accumulation during the 208 days at different mean values of relative humidity.

By comparing the periods with the highest and lowest relative humidities, it can be seen that the accumulation was greater, and the ablation smaller at the highest relative humidity interval, 90–100 %. This implies that the sublimation could be of some consequence, but the matter is very uncertain especially as there were only six days with relative humidity within the interval 60–69 %. It is noticeable that, even in the humidity interval 90–100 %, the ablation equalled the accumulation.

The percentage of days with accumulation was almost the same on days with a relative humidity of from 70 to 79 % as on days with a relative humidity of from 80 to 89 %. The percentage of days with ablation, however, was less in the relative humidity interval 70–79 % than in the interval 80–89 %. As these two humidity intervals contained a large proportion of the total number of days, this analysis suggests that the accumulation and the ablation by sublimation was insignificant – probably less than 10 mm of water for the whole period of 33 months. The measured accumulation of 15 mm and ablation of 42 mm of water therefore must be the result of other factors. Small errors in the measurements may be partly the reason. Unobserved snowfall or drift snow also may have occurred. The small depressions formed by melting due to the long wave radiation from the stakes during fine weather in the summer may bring in small errors (p. 24). All this, however, probably is of relatively little significance, and would give about the same values for the accumulation and the ablation. Consequently, the essential cause of the net ablation of 27 mm of water is the settling (p. 25).

From Table 6 (p. 30) it can be seen that the total accumulation in days with no snowfall is 179 mm of water, whilst the ablation is 241 mm of water. There is no reason for believing that the drift snow will cause any net accumulation or ablation during a longer period (pp. 13, 19, 26, and 31). Furthermore the sublimation and errors in the measurements, as shown above, are of small significance. The accumulation during days with no snowfall, 179 mm of water, then should equal the ablation, which thus also should be 179 mm of water. The essential cause of these variations in the snow surface is drift snow. As the ablation is found to be 241 mm of water, the net ablation of 62 mm of water in days with no snowfall must have other causes. The only probable explanation for this deficit is that *the values used for the settling are too low.* As other investigations support the results for the firn below 84 cm depth (p. 18), it must be the settling rate above this level that is greater than assumed.

Ablation takes place most frequently during the months of November, December and January, and therefore it is especially the settling during these months which was greater than the values used (p. 25). The consequence of this is that the given monthly means of the accumulation (p. 27. Table 3 and Fig. 15) are too low for November, December and January, and consequently too high for the preceding months of October, September and possibly also August.

As there may have been unobserved snowfalls (p. 30, 35), and the measured accumulation sometimes is not in proper relation to the observed snowfall (p. 30) the absolute values are uncertain, and the determined net ablation of 62 mm of water cannot be used to correct the values for the settling rate, but only to indicate that they are too low.

Correlation between measured precipitation and accumulation.

The precipitation at Norway Station was measured four times a day during the twenty-one months from April 1957 to December 1958. The precipitation gauge was of the ordinary Norwegian type. The total precipitation of 950.9 mm of water agrees strikingly well with the total accumulation during the same period, 949 mm of water. However, on comparing the "precipitation" and the accumulation for each month (Table 10), it appears that the correlation is far less striking.

Table 10.
Measured monthly precipitation and accumulation at Norway Station.

		Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1957	Prec.				16.5	38.2	161.0	67.9	41.5	30.5	26.8	3.8	8.8
	Acc.				65.0	1.0	137.0	16.0	67.0	23.0	27.0	5.0	30.0
1958	Prec.	11.7	4.8	89.9	50.8	3.9	35.9	59.8	84.8	32.6	158.6	22.7	0.4
	Acc.	39.0	31.0	102.0	58.0	26.0	87.0	15.0	66.0	92.0	69.0	5.0	-12.0

Table 11.
Precipitation and accumulation at Norway Station.

Wind speed	Precipitation	Accumulation
00–09 kts.	3.5 %	8.8 %
10–19 »	13.6 »	33.3 »
20–29 »	27.9 »	48.6 »
30–39 »	31.0 »	5.7 »
40–49 »	19.7 »	3.3 »
50–59 »	4.3 »	0.3 »
00–59 kts.	100.0 %	100.0 %

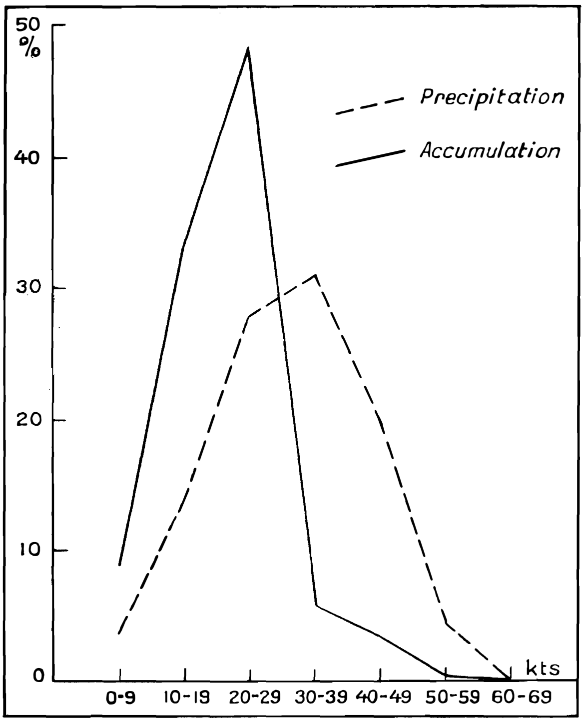

Fig. 18. The percentage of the total measured accumulation and precipitation at Norway Station from April 1957 to December 1958 at different wind speeds.

The correlation coefficient is only + 0.63. As can be seen, it is only June, September, October and November 1957 and March and April 1958 which have values that agree fairly well; the other values in fact are of a quite different quantity.

In Table 11 the percentage of the precipitation and accumulation at different wind speeds is given. This is also shown in Fig. 18.

The measured precipitation fell at much greater wind speed (mean 31 kts.) than did the measured accumulation (mean 21 kts.). As there is reason to believe that the accumulation gives a good measure for the real precipitation in this area (pp. 19, 30, 31), this shows that the precipitation gauge is quite useless in these parts of Antarctica (Swithinbank 1957, p. 68).

Obviously drift snow is the reason for the great accumulation of snow in the precipitation gauge. At high wind speeds, large precipitations frequently were measured, though there was no observed snowfall. On the other hand, the precipitation gauge sometimes remained empty during relatively heavy snowfall. The cause of this was that the precipitation gauge, mounted 2 m above the ground, was above the limit reached by the drift snow at these wind speeds, and the wind kept it empty of falling snow.

Accumulation away from Norway Station.

Accumulation between Norway Station and the Secondary Station.

Between Norway Station and the Secondary Station at the coast, a distance of 34 km, the accumulation was measured at different time intervals from 18th October 1957. About half the stakes had disappeared before the end of one year. The remaining stakes were measured for about one year, apart from one that was measured for more than a year and a half, and two that were measured for a little more than two years. The results are given in Table 12. They are correlated with the accumulation at Norway Station during the same period. For the settling and the specific weight the same values as those found for Norway Station are used (pp. 23, 24, 25).

The stakes numbered 1 to 12 were placed on the ice shelf, which, as far as could be seen was quite level. The mean accumulation at these twelve stakes were 99.4 % of that at Norway Station during the same period of 289 days (Fig. 19). The stakes numbered 13 and 16 were placed on top of two undulations and stakes 14 and 15 in the depression between them (p. 5). The mean accumulation for stakes 13 and 16 in 403 days was 96.9 %, and for stakes 14 and 15 in 370 days 94.5 % of that at Norway Station. Further north, the amplitude of the undulations was greater (p. 5). The accumulation in 85 days at stakes 17 and 19, which were placed in the depression between two undulations east of the two bays in Fig. 5, was as much as 171 % of that at Norway Station. The accumulation on the higher point between these "valleys" and on the higher point at the secondary station in 818 days was only 46.8 % of that at Norway Station.

Thus the accumulation at Norway Station and that on the horizontal ice shelf to the north were approximately equal. Near the coast, where there were marked E–W undulations, other values were found for the accumulation; it was high in the "valleys" and low on the heights between them. It is difficult to say whether the mean accumulation in this area was greater or less than that at Norway Station. The measurements at stakes 17 and 19 were carried out during only 85 days; the figure of 171 % therefore is not to be trusted. Furthermore, the number of stakes measured was too small to give a reliable result.

Accumulation at Blåskimen.

On 22nd October 1957 three stakes were placed at the border between Fimbulisen and Blåskimen (p. 5). Another three were placed on the top of the ice rise, at an altitude of some 390 m, 21 km northwest of Norway Station. These stakes were re-measured in January 1958, after three months, but later they could not be found.

On 1st October 1958 six other stakes therefore were placed at the border between Fimbulisen and Blåskimen, and five in the slope up, to a distance of 4.1 km from the border of the ice rise. These stakes were re-measured in

Table 12.

Accumulation between Norway Station and the Secondary Station.

Stake number	Distance from Norway Station	Accumulation in mm of water from 18th October 1957.											Accumulation as a percentage of that at Norway Station
		1st Dec. 1957	11th Jan. 1958	15th May 1958	28th June 1958	25st July 1958	21th Sept. 1958	25th Nov. 1958	29th May 1959	7th June 1959	31st July 1959	14th Jan. 1960	
Norw. St.	0.0 km	8	49	294	382	400	504	630	994	1038	1047	1351	100.0 %
1	2.7 »	23	64	306	392	409	509	563	1056	1119			107.8 »
2	4.7 »	56	77	322	364	393	584						115.6 »
3	6.7 »	31	77	306	347	374	553	485					77.0 »
4	8.7 »	-2	93	319	390	409	530	531					84.3 »
5	10.0 »						0	113					89.7 »
6	10.7 »	21	107	353	442								115.7 »
7	12.7 »	14	65	314	442	466							116.5 »
8	14.7 »	-5	85	214	335	391	523	526					83.5 »
9	16.7 »	22	38										77.6 »
10	18.7 »	66	104	345	412	463							115.8 »
11	20.7 »	8	33										67.3 »
12	22.7 »	17	78	311	326	408							102.0 »
13	24.7 »	32	65	271	340	353	486	614					97.5 »
14	25.1 »	47	43	234	323	339	447						88.7 »
15	26.0 »	5	36	210	342	367	515	625					99.2 »
16	28.0 »	21	28	320	316	315	470	607					96.3 »
17	29.8 »	17	40										81.6 »
18	30.2 »	-1	14	113	149	156	198	251				463	34.3 »
19	31.9 »	32	128										261.2 »
20	33.6 »	-1	11	158	211	221	315	373			607	801	59.3 »

November 1958 and in January 1959. One of the stakes also was found on 1st April 1959. The results are given in Table 13.

The accumulation at Norway Station during the same time is given too. The values for the settling and for the specific weight are assumed to be the same as at Norway Station (pp. 23, 24, 25). As all these measurements were carried out during the summer, they cannot be taken as representative for the whole year.

Stakes 1, 2, 3, 7, 8, 9, 10 and 11 were placed in the neighbourhood of the border between the ice shelf and the ice rise, most of them on the ice shelf, stakes 3 and 11 on the ice rise. Aside from stake 7, which was placed at the greatest distance from the ice rise, the accumulation at all of them was greater than at Norway Station during the same period. (The mean was 143.7 % in 114 days). Stakes 12, 13, 14 and 15, which were placed on the ice rise, 900 to 2500 m from the ice shelf in 113 days, had a mean accumulation of only 22.1 % of that at Norway Station, whilst the accumulation at stakes 16 and 17, which were placed at a still greater distance from the ice shelf, in 113 days was as much as 134.5 %.

The remarkable great accumulation at the top of the ice rise (467 % of that at Norway Station) probably was due to orographic precipitation.

The great accumulation at the border between the ice shelf and the ice rise contrasts with Swithinbank's findings for the regions further west (Swithinbank 1957, p. 17) and with the author's for an area 200 km further east (pp. 42, 43), where the accumulation was very small at the border between the ice shelf and the inland ice. The reason for this probably is the direction of these borders, and thus the direction of the steepest slope. The slope of the ice rise northwest of Norway Station forces the easterly winds upwards. The great accumulation at the border can therefore probably be explained by the forming of local whirls. That the sublimation is of some importance in this location is implied by the small ablation measured at almost all those stakes visited twice during the summer.

Accumulation between Norway Station and Risemedet.

From November 1957 to January 1958, fifty-five stakes for accumulation measurements were placed at intervals of about 5 km along the 320 km route used by field parties between Norway Station and the northernmost nunataks in Risemedet. The stakes were re-measured in April and in November 1958. The accumulation thus was measured throughout almost one year, and the summer and winter accumulations were found separately. The results (in percentages of the accumulation at Norway Station during the same period) are given in Table 14.

The specific weights used for calculating the water equivalents on the ice shelf were found in one pit. On the sloping inland ice the specific weights were found in two places, and the mean was used.

Table 13.
Accumulation at the ice rise northwest of Norway Station.

Stake number	Location	Accumulation in millimetres of water.							Accumulation as a percentage of that at Norway Station	
		22nd Oct. 1957	21st Jan. 1958	23rd Jan. 1958	1st Oct. 1958	24th Nov. 1958	22nd Jan. 1959	1st Apr. 1959		
Norway Station	Ice shelf	0	54	54						100.0 %
1	Ice shelf, 700 m from ice rise	0	77	74					137.0 %	
2	Ice shelf, 350 m from ice rise	0	64	58					107.4 »	
3	Ice rise, 150 m from ice shelf	0	68						125.9 »	123.5 %
4	Top of ice rise	0	310						574 %	
5	Top of ice rise	0	192						356 »	
6	Top of ice rise	0	255						472 »	467 %
Norway Station	Ice shelf				0	74	87	209		100.0 %
7	Ice shelf, 1200 m from ice rise				0	106	62		71.3 %	
8	Ice shelf, 500 m from ice rise				0	105	98	234	112.0 »	
9	Ice shelf, 200 m from ice rise				0	238	202		232.2 »	
10	Border between ice shelf and ice rises				0	132	142		163.3 »	
11	Ice rise, 300 m from ice shelf				0	213	193		221.8 »	149.6 %
12	Ice rise, 900 m from ice shelf				0	20	5		5.7 %	
13	Ice rise, 1400 m from ice shelf				0	42	39		44.8 »	
14	Ice rise, 1900 m from ice shelf				0	55	49		56.3 »	
15	Ice rise, 2500 m from ice shelf				0		–16		–18.4 »	22.1 %
16	Ice rise, 3300 m from ice shelf				0		158		181.6 %	
17	Ice rise, 4100 m from ice shelf				0		76		87.4 »	134.5 %

Table 14.
Accumulation between Norway Station and Risemedet.

Distance from Norway Station		Topography	Summer		Winter		Total acc.
			St. No.	Acc.	St. No.	Acc.	
		Ice shelf					
0 km		Norway Station		100.0%		100.0%	100.0%
35—55 »		Undulating ground, crevsased belt	6	52.0 »	4	112.1 »	89.0 »
59—101 »		Flat	9	56.5 »	7	85.2 »	74.1 »
107—131 »		Almost flat, crevassed belt	4	56.5 »	3	104.4 »	86.3 »
136—151 »		Flat	4	38.8 »	3	93.7 »	74.2 »
156—188 »		Flat, distant ice rises towards N and E, inland ice toward S	6	38.3 »	4	86.3 »	68.7 »
194—197 »		Border: Ice shelf — inland ice	3	2.8 »	2	50.0 »	37.0 »
Distance from ice shelf	Altitude.	Inland ice					
6—16 km	100—300 m	Relatively uneven ground	3	3.3%	3	108.3%	75.4%
21—59 »	350—650 »	Undulating ground	9	19.9 »	9	86.5 »	67.2 »
64—95 »	700—1300 »	Relatively steep, undulating ground	6	44.5 »	3	62.4 »	57.2 »
100—122 »	1300—1500»	Slightly rolling ground	5	40.8 »	4	46.6 »	44.9 »

The mean accumulation for the shelf ice during the summer was 49.6 % (29 stakes), and that during the winter was 94.3 % (21 stakes) of that at Norway Station. The mean for the whole period was 77.5 %. The decrease from west to east of the total accumulation was primarily a decrease in the summer accumulation; the winter accumulation was almost constant in the whole area. To obtain an explanation of this, the available material from the stations east of Norway Station has been studied.

Monthly means of some climatic elements at the Russian station Lazarev (latitude 69° 58′, 2 S, longitude 12° 54′, 4 E) are given in "Information Bulletin of the Soviet Antarctic Expedition". The mean wind speed is about 22 knots (strong breeze), which is somewhat more than at Norway Station; the mean wind direction is ESE. It thus seems as if the catabatic winds are of relatively great importance in this location.

At the Belgian "Base Roi Baudoin" (latitude 70° 25′ S, longitude 24° 18′ E) the catabatic winds seem to be of still greater significance (de Maere 1959). The mean wind direction was S to SE during 1958–59, and easterly winds only predominated during the presence of a cyclone north of the station. The mean wind speed was some 15 knots, apart from the months March, April and May when the mean wind speed exceeded 20 knots.

The accumulation is not given for Lazarev. At Base Roi Baudoin it was some 50 cm of snow from March 1958 to January 1959, probably corresponding to some 200–220 mm of water. At Norway Station it was 533 mm of water during the same 11 months.

This is a rather mixed material. The tendency, however, is that the importance of the catabatic winds increases, and the accumulation decreases, eastwards from Norway Station. The decrease in the accumulation from west to east, found by the field parties from Norway Station (Table 14, p. 42), thus is in accordance with the general information. The decrease is caused by the increasing southerly component of the wind, which may give ablation by drift snow, and, as these winds are very dry, possibly also marked sublimation. The available information, however, is quite insufficient to explain why the accumulation east of Norway Station is especially low during the summer.

It is not likely that the variation in the accumulation on the ice shelf is of topographic origin. The ice rise northwest of Norway Station, and the ice rises and the inland ice surrounding the eastern part of the investigated area are all at a great distance from the areas under observation. Moreover there is no clear difference from one part to another within the measured area at Norway Station (pp. 22, 23).

The small summer accumulation may be due partly to greater continentality at the eastern part of the ice shelf caused by the heavier pack ice to the east of Trolltunga, the ice tongue at the Greenwich meridian (Swithinbank 1957, p. 72). This, however, should also cause a similar difference in the winter accumulation, as the ocean north of Norway Station was almost free from ice during the winter of 1958. The explanation therefore is not satisfactory.

At the border between the ice shelf and the inland ice, the summer accumulation is extremely small (p. 40). This is due to catabatic winds from the inland ice. On crossing this border on 16th December 1957 the following meteorological data was observed:

Hour	Temperature	Humidity	Wind speed	Wind direction
1030 GMT.	+ 3.2° C	68 %	5 kts.	SSE
1500 »	+ 0.9 »	78 »	22 »	E

Such weather conditions probably will cause marked sublimation from the snow surface. This was also implied by a hard snow surface; the wind speed of 22 knots, for instance, did not cause any drift snow. As the wind probably achieves its greatest speed in this area, falling snow is usually transported away and only small accumulation takes place. Which of the agents is the predominant cause of the small accumulation, the sublimation or the wind transport, it is impossible to say.

On the sloping inland ice the summer accumulation is especially poor in the neighbourhood of the ice shelf. Here again the reason is that owing to increasing wind speed only small amounts of snow will be accumulated, and that there is some erosion of the snow cover by strong winds, and sublimation caused by dry catabatic winds. With increasing altitudes, or with increasing distance from the ice shelf, the mean accumulation decreases from about 75 % to 45 % of that at Norway Station. This is due to the increasing continentality as the cyclones less frequently are able to force their way so far inland (Kotljakov 1959, Mellor 1958).

The variation in the accumulation from one stake to another frequently is very great, both at the crevassed areas on the ice shelf and on the inland ice. "Valleys" and declivities towards the west receive the greatest accumulation, whilst the accumulation is less on ridges and declivities towards the east.

Accumulation on the northern side of Fimbulheimen.

At the foot of a relatively steep slope (10°–20°) north of the northernmost nunataks in Risemedet, the accumulation was measured at four stakes from 16th January to 3rd December 1958. The mean accumulation was 32.7 % of that at Norway Station, or somewhat less than the mean in this region as a whole (Table 15). This value, however, cannot be taken as representative for the area, as the accumulation is totally determined by the morphology causing strong catabatic winds, which at times erode the already accumulated snow.

At the beginning of February 1958 thirteen stakes were placed along a 61 km route eastwards from Risemedet, on the northern side of Fimbulheimen, at an altitude of some 1500 m. These were re-measured at the end of March and in December 1958. The results, in percentages of that at Norway Station, are given in Table 15 (Fig. 19, see backflap). The specific weights used are the means from three pits.

Table 15.
Accumulation on the northern side of Fimbulheimen.

Distanse east of Risemedet	February — March		April — November		Total accumulation
	Number of stakes	Accumulation	Number of stakes	Accumulation	
Norway Station		100.0%		100.0%	100.0%
2—23 km	7	20.0 »	6	50.8 »	43.5 »
33—61 »	6	26.4 »	6	35.3 »	33.3 »

None of these stakes were placed in the area where the accumulation is influenced by the mountains. The ground is rolling, and there is thus great variation in the accumulation from stake to stake. Here, as on the ice shelf, there is a marked decrease in the accumulation from west to east (p. 42). The reason is probably the same: an increasing importance of the catabatic winds towards the east (p. 43).

Accumulation studies in a 5 m deep pit.

In order to find the accumulation during a longer period, a pit was dug at the easternmost stake (Table 15), 61 km east of Risemedet, at an altitude of some 1450 m. The work, done on 17th-18th February 1958, was interrupted by bad weather.

As at Norway Station (p. 9), that snow which had been at the surface during the summer could be distinguished from the rest by the greater grain size. Also, the specific weight of the summer firn was less than the mean for the surrounding firn. However, there was no ice-content in the firn layers; the reason for this, of course is, the low temperatures. The highest temperature measured in the pit was –16.0° C (at the surface), and the lowest temperature –24.8° C (at a depth of 6 m). The annual mean temperature probably is below –25° C. The highest air temperature measured at this altitude in fine weather was –7.7° C (on 18th January 1958), and although the radiation is very intense, these low temperatures make melting impossible.

The firn from the year 1949 was found at the bottom of the pit. The accumulation thus was traced for a period of eight years, 1950–57, and the results are given in Table 16. The accumulation also is calculated as a percentage of that at Norway Station. The mean accumulation found in the pit was 57.5 % of that at Norway Station, somewhat more than the 48.3 % found by direct measurements at the stake near the pit. The correlation coefficient between values for the annual accumulation found in the mountain region and that found at Norway Station is + 0.65.

Table 16.
Accumulation on the northern side of Fimbulheimen for the period 1950–58.

Year	Acc. in the moutain region	Acc. at Norway Station	Acc. in the mountain region
1950	397.7 mm	654.2 mm	60.8%
1951	265.5 »	455.9 »	58.2 »
1952	177.9 »	379.4 »	46.9 »
1953	260.6 »	531.9 »	49.0 »
1954	285.4 »	391.0 »	73.0 »
1955	231.7 »	587.4 »	39.4 »
1956	160.7 »	290.5 »	55.3 »
1957—Febr. 1958	404.4 »	506.5 »	79.8 »
Febr.—Dec. 1958	259.0 »	536.0 »	48.3 »

The variation in specific weight with depth is shown in Fig. 20. As at Norway Station (p. 15), a straight line seems to fit the observed values best. Using the method of least squares, the equation:

$$s = 0.396 + 0.0188\ h \qquad h \overset{=}{<} 5\ m$$

is obtained for the variation of specific weight (s) with depth (h) (Fig. 20). The increase in specific weight with depth is somewhat greater inland (0.0188 g cm^{-3} m^{-1}) than at Norway Station (0.0106 g cm^{-3} m^{-1}) (p. 15). This is due partly to the low density of the surface snow, 0.396 g cm^{-3} against 0.452 g cm^{-3} at Norway Station, and partly to the total absence of

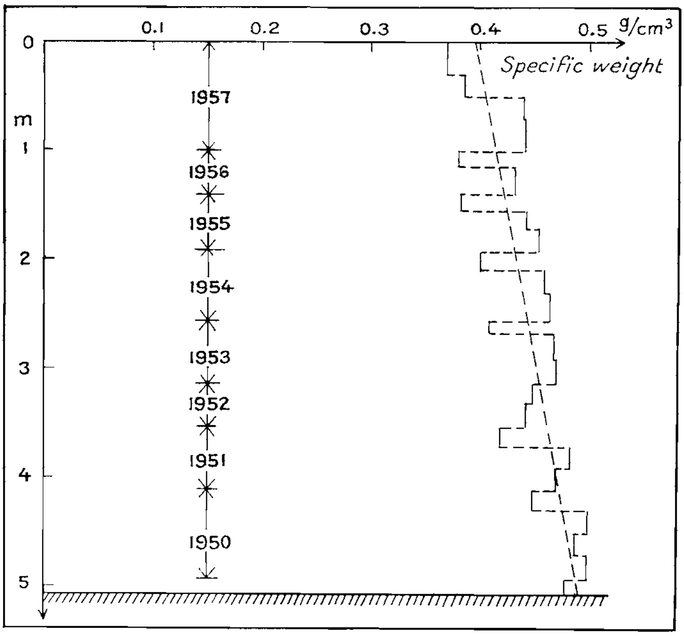

Fig. 20. Density-depth curve of the firn on the inland ice at an altitude of about 1450 m. The curve is calculated by the method of least squares.

ice in the firn layers. Moreover the accumulation is less, and the firn at a given depth is thus of a greater age than that at the same depth at Norway Station (p. 16). The low temperature inland, however, will lead to a slower rate of settling.

Accumulation on three ice streams.

On Slithallet, the ice stream between Jutulsessen and Risemedet, at an altitude of some 1800 m, the accumulation was measured at ten stakes from 27th January to 24th November 1958. The mean value obtained was 35.7 % of that at Norway Station. The ice stream sloped towards the north. The accumulation was very small at the eastern side of the ice stream, and also where the slope became steeper at the northern end of the measured area.

Some 10 km further southeast, on Bakhallet, the ice stream between Terningskarvet and Jutulsessen, at an altitude of some 1700 m, the mean accumulation at nine stakes was found to be 47.8 % of that at Norway Station from 1st February to 28th November 1958. This ice stream is directed to the northwest, and there is a marked gain by drift snow.

On an ice stream, Lundebreen, about 100 km east of Risemedet, southwest of Gessnertoppen, the mean accumulation at eleven stakes was found to be only 6.2 % of that at Norway Station from 26th February to 11th

December 1958. The ice stream goes to the north, is relatively steep and is surrounded by very high, steep mountains.

These mean values of the accumulation are plotted in Fig. 19.

Between the mountains, the topography, and consequently the wind, obviously determines the accumulation. For example, on Lundebreen there was an ablation of from 10 to 86 mm of pure ice at seven of eleven stakes measured. Here the catabatic winds sweep the valley free from snow. These winds are strongest in the steepest and narrowest part of the valley. Owing to the adiabatic warming the winds are very dry. Sublimation therefore is of great importance (pp. 7, 42, 43).

In the western part of the mountain range the catabatic winds were seldom strong. In the eastern part, however, nearly constantly, but especially at night, they blew out of the valleys with a speed of 5 to 6 Beaufort, though the weather might be calm and fine elsewhere. In association with cyclones, the wind here also blew from the east. This accords well with the information about wind conditions at Lazarev Station and Base Roi Baudoin (p. 42).

Conclusion.

All observations of accumulation by the field parties from Norway Station are in accordance with the results obtained by other expeditions in this part of Antarctica. There is a general decrease in the accumulation eastwards from Norway Station. West of Norway Station, the only accumulation measurements are those from Maudheim. These, however, show that the accumulation decreases markedly westwards also. Accumulation was found to decrease southwards from the coastal region as well.

The annual accumulation on the ice shelf at Norway Station, 495.2 mm of water, as far as it has been possible to ascertain, is the greatest measured in Antarctica.

Acknowledgements.

The author is indebted to all the members of the Norwegian Antarctic Expedition 1956–60, particularly to geodesist S. Helle, leader of the expedition; to H. M. Henriksen; to P. Madsen, who took care of the glaciological observations at Norway Station during the summers of 1957–58 and 1958–59, and the winter of 1959; and to B. Grytøyr and L. A. Hochlin, who were indefatigable assistants in the field. In addition to these, H. Bjerke, N. S. Nergaard and J. Snuggerud frequently gave assistance at Norway Station.

The meteorologists of the expedition, J. Tønnesen and T. Vinje, have given me valuable meteorological information, both during the period spent in Antarctica and after the return to Norway.

I also take the opportunity of thanking glaciologist O. Liestøl for the help he has given me for several years. My wife, Fredrikke, and glaciologist W. H. Teakstone have given invaluable help in reading and correcting the manuscript.

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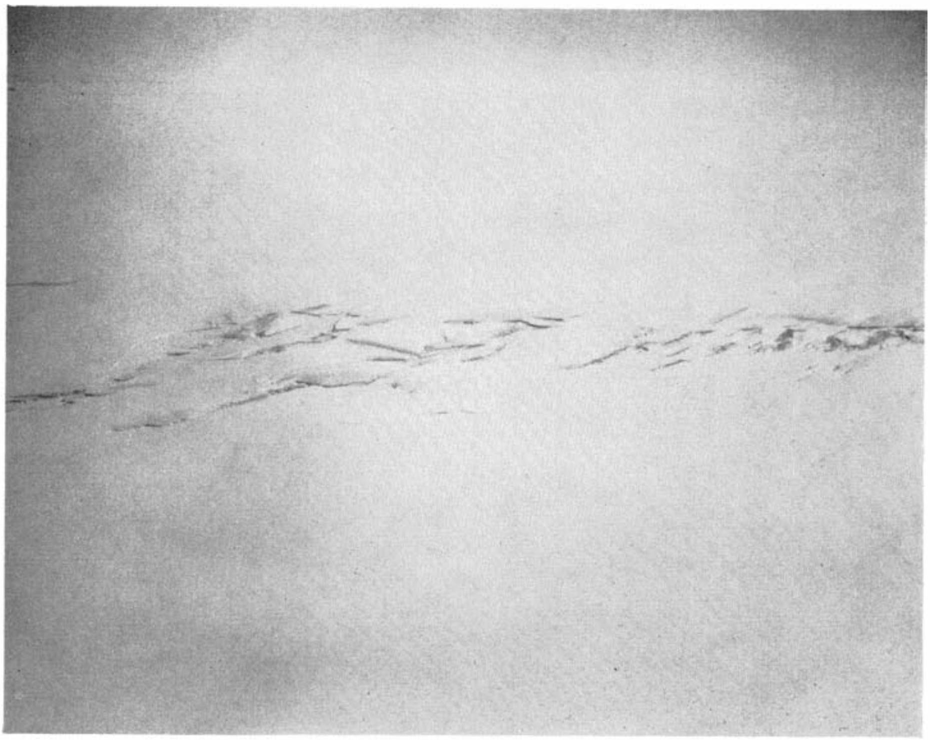

Plate I a. Air photograph of the ice stream north of Jutulstraumen. Looking west

Plate I b. Air photograph of bays in the ice shelf. Blåskimen, the ice rise northwest of Norway Station, to the right. Looking south.

Plate II a. Wind erosion in medium-grained granite.

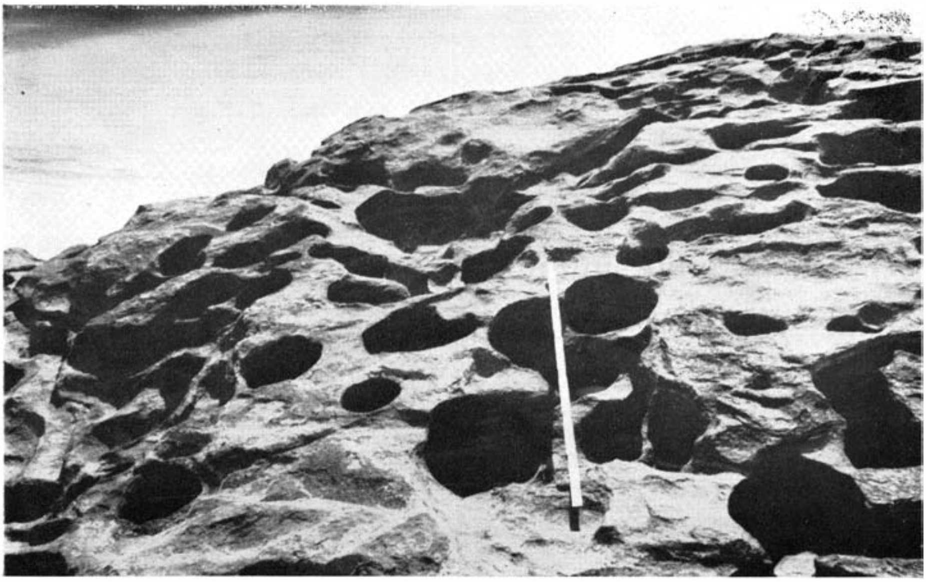

Plate II b. "Pot holes" in gneiss, caused by drifting snow.

Plate III a. Air photograph eastwards along the mountain chain, Fimbulheimen. Gessnertoppen in the left background. The altitude of the inland ice decreases from about 2500 m south of the mountains (right) to about 1500 m on the northern side (left). The photograph also shows the reduction of the surface forms from great, flat-topped mountains in the southern part of the mountain range to small mountains of pyramid form just north of the real mountain range.

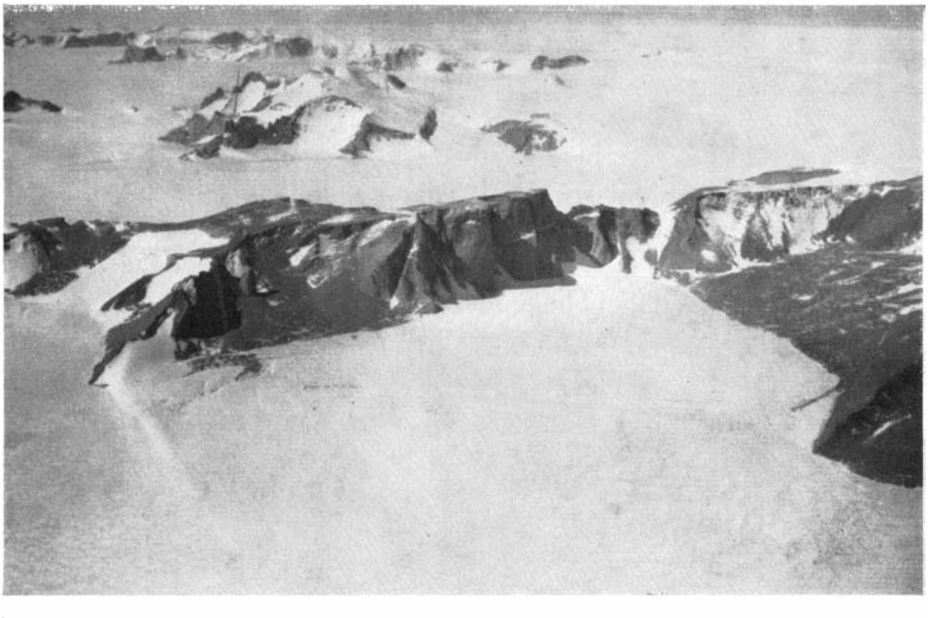

Plate III b. Air photograph towards eastsoutheast of the northern part of Jutulsessen. Remnant of a palaeic surface so small that an ice cap cannot be maintained. Palaeic surfaces with protecting ice caps and the rapidly decreasing altitude of the inland ice from the southern to the northern part of the mountain range can be seen in the background.

Plate IV a. Erosion of the mountains from their sides results in such enormous peaks. The vertical distance from the top of the flattopped mountains to the snow surface in the foreground is some 500 m.

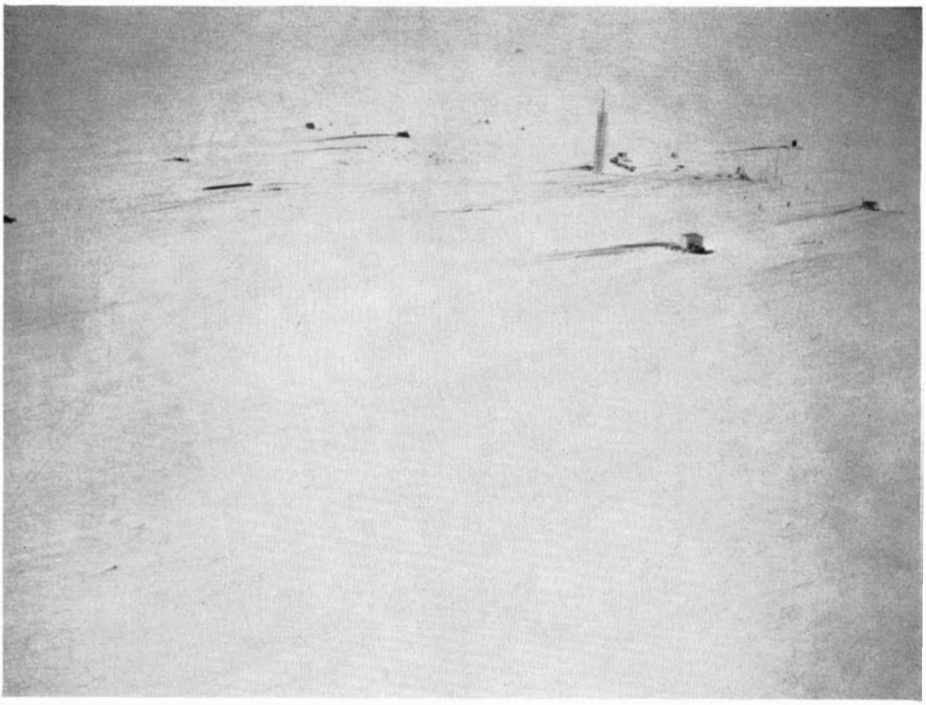

Plate IV b. Air photograph of Norway Station, looking N.N.E.

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