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Some observations on the vertical fallout profile on Grasubreen—A mountain glacier in Norway

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ABSTRACT. Snow and ice samples (116 Nos.), collected from six snow pits and three twin boreholes along the axis of Grasubreen, the highest mountain glacier in Norway, were analysed for their salt content, fission fallout concentration and fractionation of Oxygen-18.

The sodium fallout varied from 0·4 to 1·9 ppm and could be related to the origin of precipitation from the west (maritime) or from the southeast and northeast (continental). Another feature is of resistivity and sodium concentration having a periodic variation with about 18 years half cycle (*cf.* Bruckner period). The peaks of gross beta activity are well related to those observed in precipitation of 1958 and 1963. The tritium profiles for two boreholes in the accumulation zone shows distinctly that there is not much of mixing in ice of different years.

The fractionation of ^{18}O from snow samples shows no systematic altitude effect. However, the ^{18}O content of ice cores from one borehole shows some correlation with the average annual air temperatures for a neighbouring meteorological station.

Snow accumulation rates are determined from the fallouts and also Oxygen-18 and a favourable comparison is obtained with the standard stake data.

1. Introduction

Grasubreen (mean Long. 8° 36′ 10″ E, Lat. 61° 39′ 30″ N; length 3·5 km; area 3·95 km²; elevation 1700 to 2260 m) is possibly the highest glacier in Scandinavia. It is situated in the eastern part of southern Norway in Jotunheimen mountains, the highest mountain massif in north Europe. This glacier is known for its imposing end moraine ridges. The glacier lies in the mean precipitation area of about 1000 mm. The prevailing precipitation winds on the glacier are from NE and SE. Of all the glaciers in Norway, this glacier has the most continental climate and has the highest firn line, at about 2100 m (a.s.l.). A contour map (scale 1 : 10,000) of the glacier, printed by the Norwegian Water Resources and Electricity Board in 1968 is given as Fig. 1. It also shows the locations of the snow pits and the boreholes from where samples were collected.

The aim of the present investigation on the Grasubreen is to study the usefulness of fallout of salt and fission products. In addition to fallout studies, analysis of some samples was also done for the fractionation of Oxygen-18. These data are analysed with a view to estimate the average rate of snow accumulation on the glacier at different elevations.

2. Details of Investigation

(a) *Collection of samples*

Samples were collected from six snow pits taken at elevations of 1800, 1900, 2015, 2115, 2175 and 2183 m a.s.l. (Fig. 1) from the winter accumulation of the year 1969-70. A metal cylinderical sample (length 25 cm and cross-section 40 cm²), a steel plate and a rubber hammer were used during the sampling process. Continuous sampling was performed from the snow surface to the last year's summer surface at intervals of 25 cm and the samples were collected in double polythene bags. The density variations of snow samples is given in Table 1.

In three of the snow pits at 2183, 2175 and 2015 m, twin auger holes (separated by one metre) were drilled by a hand auger having an angular cutting edge and a provision to collect cores of firns of about 8 cm diameter. Cores of different lengths (minimum 5 cm and maximum 37 cm) were obtained from the six boreholes which varied in their depths from 295 to 380 cm. Their lithological sequence can be seen from the fallout profiles (Figs. 2 to 6). These ice cores were also packed in air-tight double polythene packing. Due to

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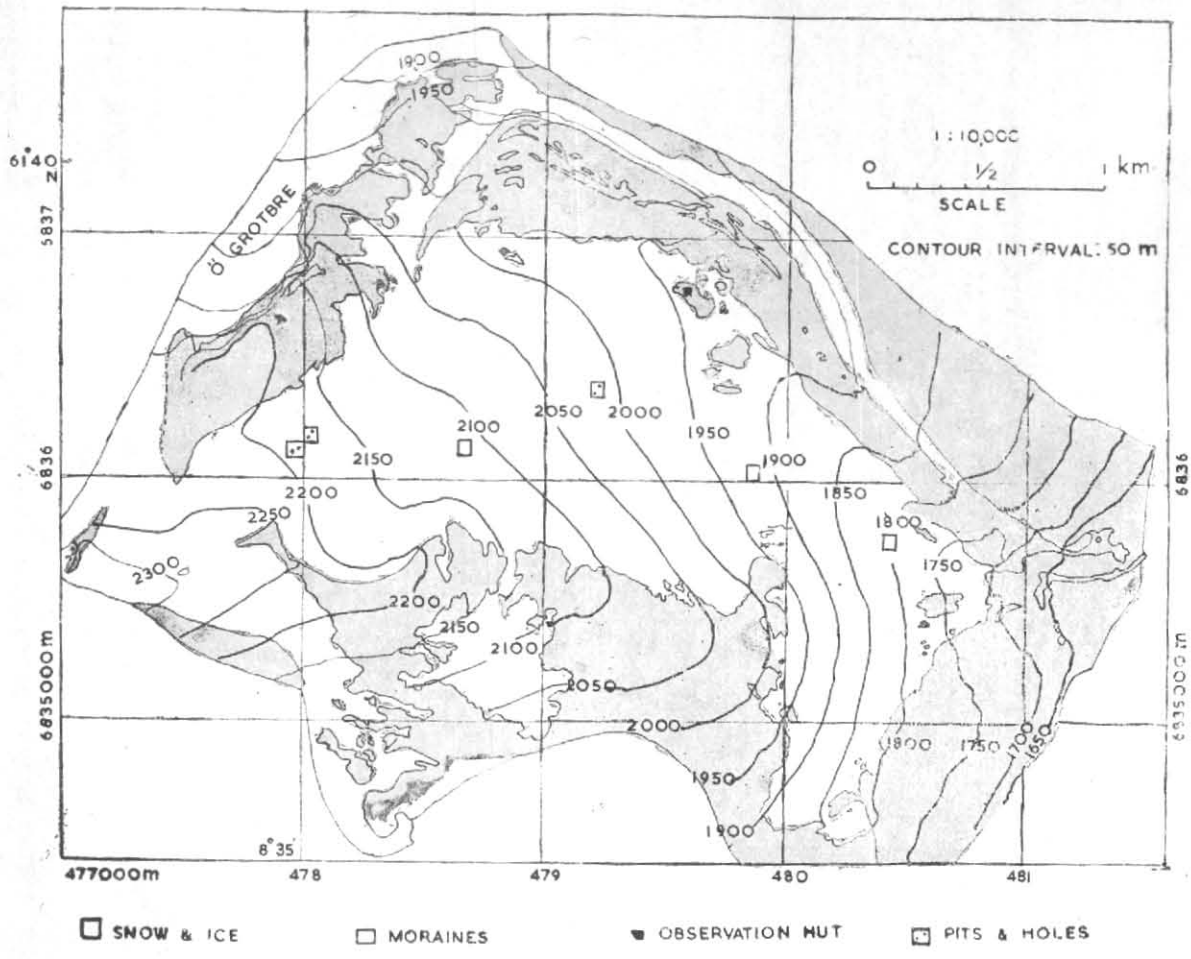

Fig. 1

Location of snow pits and holes on the Grasubreen
(Map prepared by Hydrology Division of Norwegian Water Resources and Electricity Board, Oslo)

TABLE 1

Snow samples from the pits on the Grasubreen

(Collected during 29-31 March 1970)

Location of pit at elevation m (a.s.l.)	Depth of snow (cm)	Density variation (g/cc)
1809	250	·34 to ·51
1900	150	·30 to ·51
2015	100	·35 to ·47
2115	100	·35 to ·47
2175	98	·36 to ·44
2183	95	·38 to ·44

their irregular size and shortage of time, their density was not determined.

All the snow and ice samples were later melted at room temperature and stored in clean air-tight polythene bottles for laboratory analysis. The polythene bottles were earlier cleaned by dilute nitric acid and thoroughly rinsed by triple distilled water and dried in a dust-proof room to avoid chances of contamination of samples. The volume of melted samples varied from a few hundred millilitres to more than a litre.

(b) *Laboratory analyses*

The melted samples (total number 116) were subjected to tests for determination of electrical resistivity by a sensitive A.C. bridge, sodium content by a flame photometer, fractionation

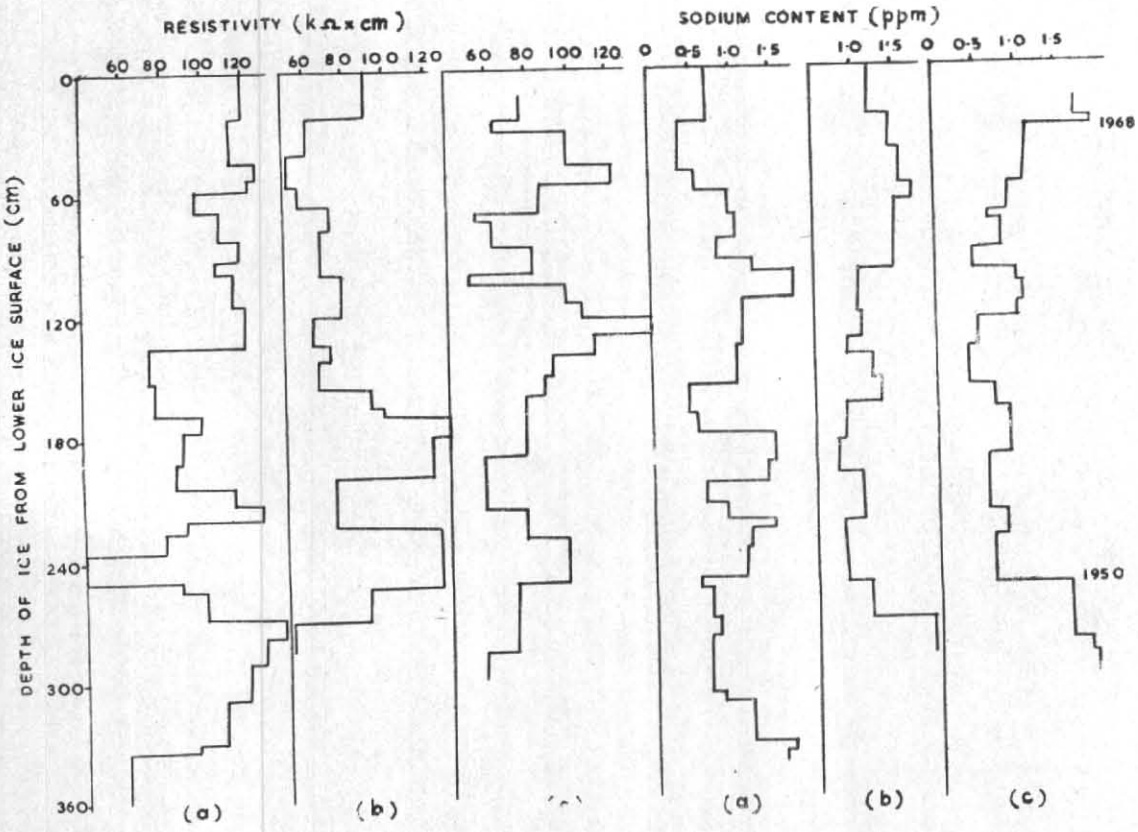

Fig. 2

Average resistivity and sodium content profiles for ice cores

(a), (b) and (c) belong to twin boreholes at elevations 2183, 2175 and 2015 m (a.s. l.) on Grasubreen

Note a half cycle of about 18 yrs in sodium profiles

of Oxygen-18 (^{18}O) by a mass spectrometer and for determination of fission fallout products, in the form of gross beta activity, tritium (^{3}H) and Caesium-137 (^{137}Cs).

The tests for determination of electrical resistivity, sodium content, gross beta and ^{137}Cs activity were carried out by the author at the low level laboratory at the Institute of Radiochemistry, Oslo University. The tritium measurements were made in a gas counting set-up at the Radiological Dating Laboratory, Trondheim and in a liquid scintillation system at the Institute of Meteorolgoy, Stockholm. Measurements for the fractionation of Oxygen-18 were made at the Physical Laboratory of the University of Copenhegen.

Standard methods of analysis were used with necessary precautions required in each case.

3. Experimental Data

(a) *Wash out of salts*

In general, there is a geographical distribution of the chemical elements in precipitation. This prompted the author to look for salt content in melted samples from Grasubreen. As the quantity of sample was limited, only tests for determination of electrical resistivity by a sensitive A.C. bridge and sodium content by flame photometry were carried out.

The resistivity varied from 40 to 138, 52 to 130. and 52 to 122 K ohm × cm while the sodium ion concentration varied from 0·35 to 1·7, 0·75 to 1·95, and 0·4 to 1·95 ppm for boreholes at 2183, 2175 and 2015 m respectively (Fig. 2). The fallout peaks of beta activity are also roughly related to the lows in resistivity and highs in the sodium content.

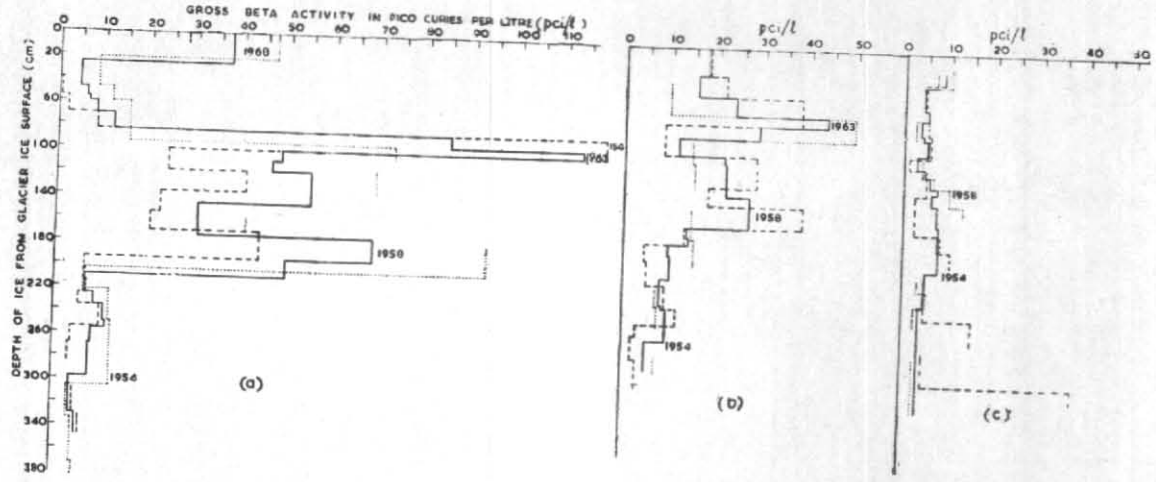

Fig. 3

Total beta-activity profiles in melt water samples of firn cores from three twin boreholes on Grasubreen (Norway). (a), (b) and (c) are the profiles for boreholes at 2183, 2175 and 2015 m (a. s. l.). The dashed (a) and dotted (b) plots show the data for twin boreholes at each location while the solid line is the mean activity profile. The boreholes A's are located 1 m upstream of B's aligned roughly along the axis of the glacier. Gaps are due to lost samples

TABLE 2

Tritium and Oxygen-18 data for snow samples at different elevations on the glacier for the accumulation year 1969-70

Location of pit at elevation m(a.s.l.)	Depth of snow pit (cm)	Water equivalent factor	Tritium in TU		$\delta^{18}O$ in ‰ SMOW	
			Unweighted	Weighted	Unweighted	Weighted
2183	95	1·64	124·7			
2175	98	1·65	124·7	75·6	—17·75	—10·75
2115	100	1·64	39·2	23·9	—17·50	—10·67
2015	100	1·67	79·4	47·6	—17·50	—10·48
1900	150	2·52	45·6	18·1	—19·04	— 7·55
1800	250	4·76	52·3	11·0	—18·80	— 3·94

(b) *Radioactivity fallout*

The cumulative snow samples representing the precipitation of 1969-70 on the glacier at elevations 2175, 2015 and 1800 m gave the gross beta activity content of 14·0, 5·6 and 7·0 pCi/litre respectively. The gross beta activity is shown in Fig. 3 (a, b, c) for the three twin boreholes. The experimental data is plotted simultaneously for the twin holes at each location. The maximum and minimum values for the observed beta activities are (342, 8), (109, 5) and (84, 3) pico-curies per litre (data not corrected for decay) of melted samples from the boreholes at elevations 2183, 2175 and 2015 m respectively. Several oscillations are observed in these activity profiles which are discussed later. Two samples at 229-250 and 286-299 cm depth for borehole 2015 m appear to be contaminated.

The tritium values of snow samples are given in Table 2. The tritium profiles could be determined for three boreholes at 2183, 2175 and 2015 m. The maximum activity values observed are 1689, 1520 and 34 tritium units (Fig. 4) while the minimum were below the detection limit of the equipment used.

(c) *Fractionation of Oxygen-18*

Out of six samples of snow, one was lost and

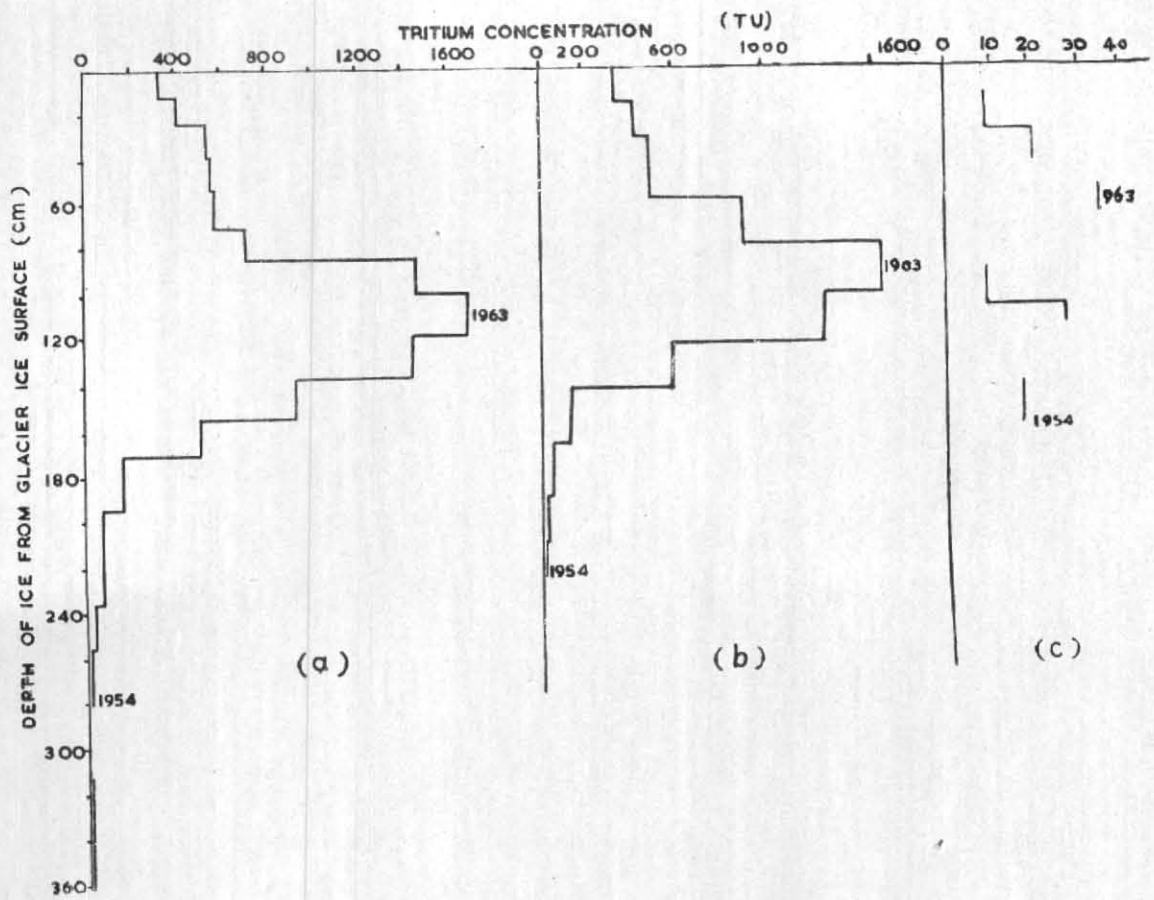

Fig. 4

Tritium content in firn cores from three boreholes located at (a) 2183, (b) 2175 and (c) 2015 m (a.s.l.) on Grasubreen

so only five samples could be analysed with a view to study the effect of altitude variation on $\delta^{18}O$ (Table 2).

The $\delta^{18}O$ variation with depth of samples for borehole at 2175 m is shown (Fig. 5). Here the extreme values observed are —13·37 and —18·03 $^{0}/_{00}$ SMOW.

4. Results and Discussion

(a) *Distribution of salts*

The study of absolute and relative concentration of various elements in precipitation and their geographical distribution has been the subject of research by several investigators. Eriksson (1960) has shown that the chloride concentration in precipitation over Scandinavia decreases from the coast to the interior of the continent. The value of chloride ion concentration is less than 2 kg $ha^{-1}\,a^{-1}$, *i.e.*, 0·5 ppm for an annual precipitation of 330 mm corresponding to average snow accumulation of 1000 mm around Grasubreen. The experimental values for sodium content range from 0·4 to 1·9 ppm for ice cores. The snow sample at 2175 m has 1·1 ppm Na^{+} ion. These give Cl/Na ratio as 1·3 to 0·26 and 0·58 respectively which are less than the value of 1·8 for sea water. Brocas and Delwiche (1963) have also reported the same result for Antarctic snow and ice. According to these investigators the sodium concentration varied between 0·5 to 2·5 ppm and did not show any seasonal variation on a time scale. An annual recurrence seems to be indicated by maximum of concentrations, resulting perhaps from the evaporation due to long exposure to sun of the upper snow layers during summer. It may be pointed out here that Rossby and Egner (1955) having investigated the Cl/Na ratio for Swedish precipitation showed that their distribution was a function of the prevailing circulation. With

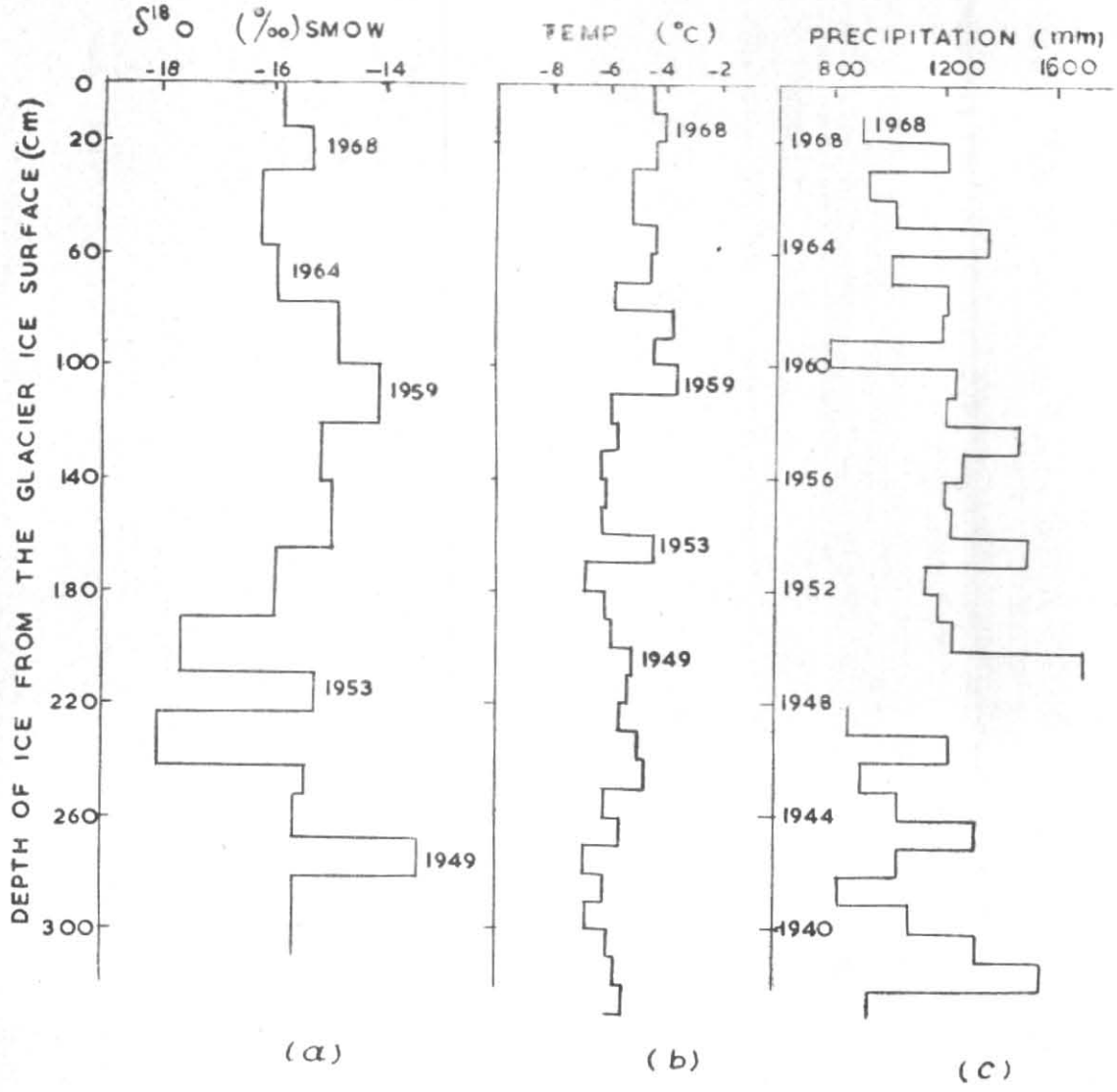

Fig. 5

$\delta^{18}O$-profile (a) for the firn cores from borehole 2175 m. (b) and (c) give the annual averages of air temp and precipitation at Fanaraki (61·52° N, 7·90° E) at 2069 m located about 30 km west of the glacier for correlation

TABLE 3

Correlation of resistivity with sodium content of ice cores

(Units : R in 100K Ohm and S in 100^{-6})

Boreholes	No. of samples	Equation $R=a+bS$*	Percentage explained	Correlation	
				Coefficient	Error
2015	23	$R=1{\cdot}4464-0{\cdot}4309S$	48	·69	·29
2175	26	$R=1{\cdot}4617-0{\cdot}5136S$	56	·75	·28
2183	26	$R=1{\cdot}4787-0{\cdot}3808S$	60	·78	·20

*where R is resistivity & S is sodium content and a and b are constants

prevailing westerly winds the Cl/Na ratios were always lower than 1·80 and around 1·2 to 1·5 at the Swedish west coast, decreasing regularly inland and to the north. Extremely low Cl/Na ratios were found during the winds from the north whereas very high ratios were obtained with southerly wind. Hence, it can be said that the lower values of Na^+ are connected with the precipitation from the continental air, *i.e.*, from the northeast and southeast, while the higher values are due to oceanic winds from westerly or northerly direction.

The sodium content and resistivity values were correlated with the results as given in Table 3. The correlation coefficients are significant.

Another feature of resistivity and sodium distribution which may be seen from Fig. 2 is the indication of a periodic variation with about 18 years half-cycle which, to a first approximation, could be related to the Bruckner period of about 35 years with alternate cold and warm climates. This half-cycle is the period of recession on most of the Norwegian glaciers. This could not, however, be confirmed due to small duration of the data collected. It may however be noted that the Icelandic glaciers recede on the ascending branch of solar activity in all high cycles and advance in all low cycles (Kupetskity 1969).

(b) *Radioactive fallout profiles*

The past several nuclear weapon tests in atmosphere have labelled the precipitation with sufficient radioactive debris. This has been extensively investigated on a world-wide scale. The radioactive fallout found application in meteorology and hydrology practically immediately after the first nuclear blast but its application to glaciological investigations is of relatively recent origin (Pieciotto and Wilgain 1963). Ambach *et al.* (1969) have recently dealt with the studies on vertical total beta activity profiles of fission products in the accumulation area of a glacier in Austria. These investigators have observed that the melting of the uppermost snow layers causes an enrichment of dust and aerosol particles on the glacier surface as their vertical displacement by melt or rainwater transport into deeper snow layers is very poor. The fission produced debris is bound to these particles mainly by adsorption and coagulation processes. The higher the dust content of the surface layer, the better becomes its capacity to retain fission produced compounds.

An interesting review on radioactive fallout in Norway is given by Storeb ϕ (1965) in his thesis on 'Particulate Nuclear Bomb Debris as a Meteorological Tracer.' The gross beta fallout data supplied by Norwegian Defence Research Establishment was plotted for all the thirteen stations (Fig. 6). Two maritime stations, *viz.*, Bergen (60° 23′N, 5° 37′E) and Alesund (62° 06′N, 6° 01′ E), and two continental stations, *viz.*, Roros (62° 34′N, 11° 22′E) and Gardemoen (60° 12′N, 11° 05′E), very close to the mean location of the glacier, *i.e.*, 61° 39′N, 8° 36′E, and it can be assumed that the average fallout in precipitation at the mean location follows the fallout pattern in the accumulation region of the glacier under investigation. The plot of annual averages of gross beta activities of all the stations in Norway show more or less a similar character as of the four stations around the glacier (Fig. 6). They show distinct peaks in the years 1958-59, 1962-63 and 1968. The order of activity indicated by this curve and the profiles for the boreholes at 2183 and 2175 m in the accumulation zone of the glacier would be the same if the activities of the melt water in the profiles are divided by the cross-section of the core (50 cm^2). This gives the actual fallout in precipitation. It may be recalled that the beta activity due to natural radioactive nuclides (1 dpm to ^{210}Pb and 0·7 to ^{40}K) comes to about 6 pCi per litre of melted samples. Therefore the profiles give the marker levels at (297, 306), (240, 254) and (—, 175) cm for the set of twin boreholes (A and B) at 2183, 2175 and 2015 m for the bomb produced beta activity which resulted in a marked change of the background radiation (6 pCi/litre) in 1954. It is also observed that the activity peaks can be easily marked for 1958 and 1963. The increase of radioactivity level in 1968 is due to atomic blasts by China. These data give the average rates of snow accumulation as 17·67, 13·33 and 11·48 cm firn/year.

The tritium content of snow samples shows an altitude effect except at 2115 m. The lower values at low altitudes may be due to predominance of precipitation from oceanic winds. The tritium profiles (Fig. 4) show a remarkable picture of the activity (data not corrected for decay). This is an evidence that there has not been much of mixing taking place at 2183 and 2175 m, which is pertinent as there are no crevasses on the glacier. The markers of 1954 and 1963 have given the accumulation rates of 18·62, 14·62 and 11·26 cm firn/year (Table 5) at 2183, 2175 and 2015 m. During the investigations of ice-cored morraines around Grasubreen, Ostrem (1963) could distinguish between permanent snow bank and glacier ice by X-ray crystallographic method. The tritium dating of one of these snow banks (Ostrem 1965) located NE of the glacier at around 1900 m

TABLE 4

Some results from gross beta activity profiles

Elevation (m)	Profile	Marker year	Depth to the marker horizon from profile (cm)	Rate of accumulation (cm firn/yr)	Mean value (cm firn/yr)
2183	A	1954	297	19·80	
	B	,,	306	20·40	
	Mean	,,	298	19·81	
	A	1958	182	16·55	
	B	,,	191	17·28	
	Mean	,,	189	17·18	
	A	1963	91·5	15·25	17·67
	B	,,	99·5	16·59	
	Mean	,,	97	16·17	
	A	1968	6	*	
	B	,,	11		
	Mean	,,	12·5		
2175	A	1954	240	16·00	
	B	,,	254	16·93	
	Mean	,,	254	16·93	
	A	1958	145·5	13·23	
	B	,,	—	—	
	Mean	,,	142	12·9	13·33
	A	1963	54	9·00	
	B	,,	58	11·33	
	Mean	,,	62	10·33	
	A	1968	12·0	*	
	B	,,	11·5		
	Mean	,,	11·5		
2015	A	1954		11·66	
	B	,,	175	12·73	
	Mean	,,	188		11·48
	A	1958	111	10·09	
	B	,,	135	12·27	
	Mean	,,	117	10·63	

*No horizon could be marked sensibly for 1968 at 2183 m and 2175 m due to large size of core sample. For the borehole at 2015 m, the peaks are marked due to snow melting as it is located below the firn line.

showed that the precipitation of the last 10 years had formed the upper 1·5 m of ice in the snow bank. From this an average value of 15 cm firn/year is obtained for the rate of accumulation during the years 1954-63 which is very close to the values obtained during the present investigation.

(c) *Fractionation of Oxygen-18*

Recently, Dansgaard *et al.* (1969) have used Oxygen-18 as a tool for studying the paleoclimatology of one thousand centuries from the ice cores of Greenland ice-sheet. Earlier it has been used for identification of summer layers on glacier ice and also for studying the altitude and latitude effects by several investigators. In general, the $\delta^{18}O$ values are influenced by micrometeorological conditions at each location.

The fractionation of ^{18}O of melt water of snow samples collected at different altitudes, *viz.*, 1800, 1900, 2015, 2115, 2175 m shows no regular altitude effect (Fig. 7) and this approach appears illusory. This is mainly due to different *in situ* field conditions of snow and its drifting. Their weighted values against mass of snow cover, however, show that the $\delta^{18}O$ values decrease linearly with increase in altitude upto 1975 m, the variation being 3·6 $^0/_{00}$ for each 100 metres. From 2015 m upwards it shows a variation of 0·16 $^0/_{00}$ for 100 metres. This is in accordance with the effect observed in the deuterium measurements on snow samples from Alps (Moser and Stichler 1970) where enrichment of the isotope is reported to occur under snow cover by ageing (caused by thawing) and longer exposure to solar radiation at higher level compared to that at lower level on the glacier. Further it is also known that the ocean vapour is richer in ^{18}O than fresh water.

The average of observed values in the melted samples from snow accumulation for the year 1969-70 is —18·20 $^0/_{00}$ which is lower than the mean value of —15·56 $^0/_{00}$ observed in the firn core samples from the borehole at 2175 m. This could be attributed to the enrichment obviously due to thawing and longer exposure to sun at the high altitude.

There is, at present, no permanent meteorological station on Grasubreen or very near to it. In absence of this, it was considered desirable to look for the climatological data of a mountain meteorological station at Fanaraki (elevation 2069 m), about 30 km west of the glacier. Some correlation is observed between the average annual air temperatures and the ^{18}O peaks. This is not a very satisfactory approach but in presence of other controls, it was thought desirable to evaluate

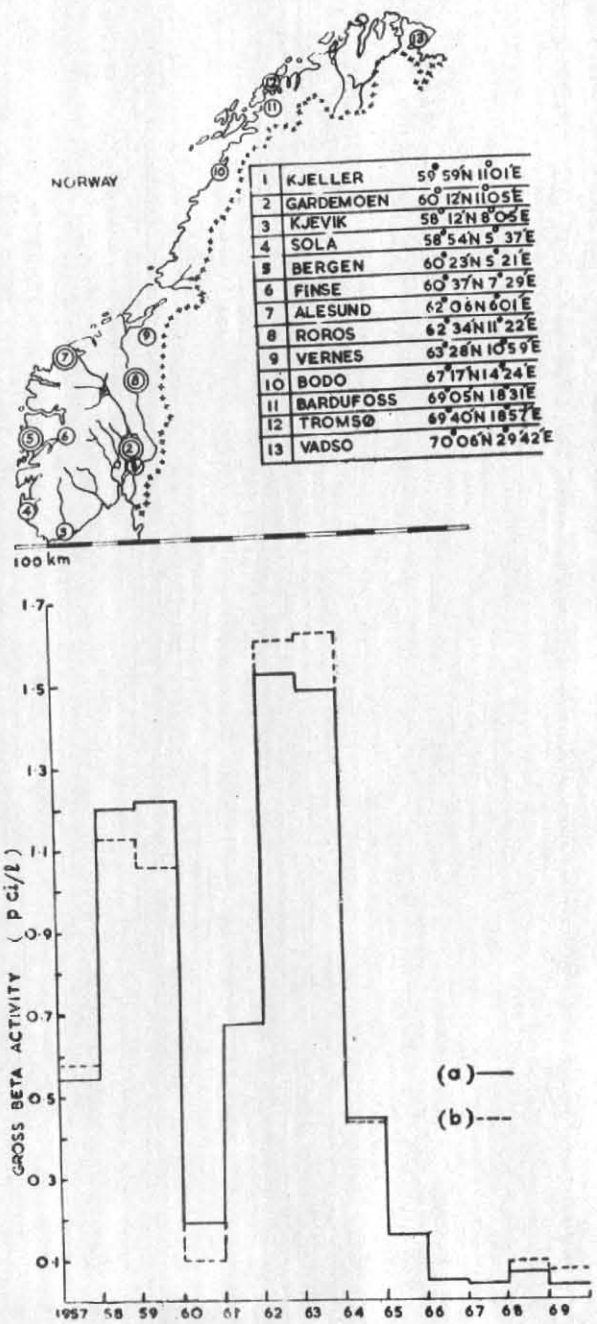

Fig. 6

Annual averages of gross beta fallout in precipitation in Norway. (a) shows the average of all the stations while (b) gives the average of four stations marked by double circles. The arrow indicates the location of Grasubreen

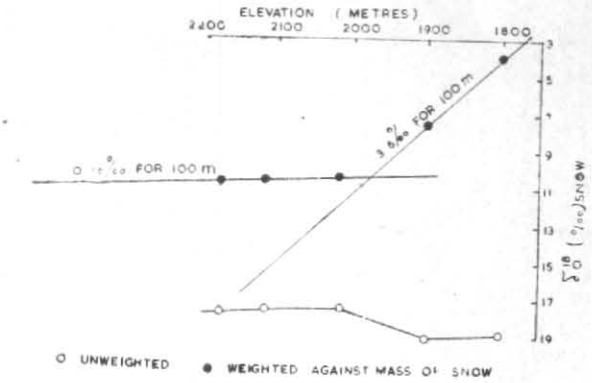

Fig. 7

Altitude effect on $\delta^{18}O$—variation on snow sample from Grasubreen

TABLE 5

Results from Tritium profiles

Elevation (m)	Marker year	Depth to the marker horizon from profile (cm)	Rate of accumulation (cm firn/yr)	Average rate of accumulations at the different elevations (cm firny/r)
2183	1954	286	19·07	18·62
	1963	109	18·17	
2175	1954	224	14·73	14·62
	1963	86	14·50	
2015	1954	174	11·60	11·26
	1963	65·5	10·91	

TABLE 6

Results from $\delta^{18}O$ of firn cores from 2175 m (Borehole B)

Marker year	Depth to the marker horizon (cm)	Rate of accumulation (cm firn/year)	Average value of accumulation rate (cm firn/year)
1968	23·5	23·50*	
1964	68·0	13·60	
1960	110·5	12·28	13·30
1953	217·0	13·56	
1949	275·0	13·75	

*The value is high and so is not considered for average values as could also be seen from gross beta activity data

TABLE 7

Mass balance data as observed from stakes and profiles

Elevation interval (m)	Net mass balance in equivalent metres							Mean (cm/yr)
	1963	1964	1965	1966	1967	1968	1969	
2150—2200	—0·66	+0·16	+0·81	+0·05	+0·87	+0·20	—0·74	+10·71

TABLE 8

Accumulation rates at three locations by different methods

Elevation (m)	Accumulation rates (cm firn/yr)				Conventional method [cm (water equivalent)/yr]
	Gross beta activity	Tritium activity	^{18}O content	Mean	
2183	17·67	18·62		18·15	
2175	13·33	14·62	13·30	13·75	10·71
2015	11·48	11·26		11·37	

the average rate of accumulation from the peaks observed in the years 1968, 1964, 1959-61, 1953 and 1949 (Table 6). A least square fit of average ground air temperatures for five years (1949, 53, 60, 64 and '68) and the corresponding $\delta^{18}O$ values give the equation $\delta = 1{\cdot}66\,t - 8{\cdot}35$ (standard error of $\pm$ 1·01 based on 95 per cent confidence level) compared to the relation $\delta = 0{\cdot}69\,t - 13{\cdot}6$ between annual means of ^{18}O content in precipitation and the surface air temperature (Dansgaard 1970) over a very wide temperature range including North Atlantic coast stations and Greenland ice cap stations.

To compare these data with that observed by stakes and snow profiles in the accumulation zone, the conventional data* is given in Table 7. The average rate of accumulation at elevation 2175 m comes to 10·71 cm/yr (water equivalent). The mean accumulation rate at the same elevation by isotopic method has a value of 13·75 cm firn/yr. The ratio of these two values gives the average density of firn layers as 0·78 g/cc (general variation of firn density is from ·55 to ·84 g/cc). Table 8 gives the data obtained by different methods for a ready comparison. As is natural, there is larger net accumulation at higher elevations on the glacier.

*Norwegian Water Resources Board Publn.—*See Ref.*

5. Conclusion

1. The fallout of salts from the atmosphere has been helpful to trace the origin of precipitation.

2. The isotopic methods give the average snow accumulation rates in the positive balance region of the glacier in a short time for a precipitation of longer period.

3. The average rates of accumulation determined by gross beta activity are 17·67, 13·33 and 11·48 cm firn/yr at elevations of 2183, 2175 and 2015 m. The respective values obtained by the measurement of tritium activity are 18·62, 14·62 and 11·26 cm firn/yr. Oxygen-18 analyses of ice cores at 2175 m gave an average rate of accumulation of 13·30 cm firn/yr. These values compare favourably with the value of 10·71 cm/yr (water equivalent) obtained from mass balance data as observed from stakes and profiles on the glacier ice surface for the years 1963-69.

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