Precipitation formation in a mountainous coast region

By PER B. STOREBÖ, *Norwegian Defence Research Establishment, Kjeller, Norway*

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ABSTRACT

Nuclear bomb debris particles appearing in world-wide fallout act as excellent condensation nuclei, and this effect has been utilized for tracer studies of extensive precipitation systems. Synoptic type and climatological type samples have been examined, and the results strongly indicate that raindrop scavenging of low-level clouds, which have undergone little lifting, is an important mechanism in precipitation formation. For sea-level rain in western Norway a mean cloud rise after saturation of the order of 300 metres is indicated.

Introduction

In the first year or two after a nuclear bomb-test series, that part of the bomb-debris particles which shows up as world-wide radioactive fallout apparently serves as excellent condensation nuclei. The concentration in the air is rather low, and the bulk of the particles will be activated as condensation nuclei in the early condensation phase of most clouds. Through a suitably designed measurement program for radioactivity in precipitation, it should thus be possible to draw conclusions about what happens to the first droplets formed in a precipitating cloud. This effect has been utilized in the present tracer study.

Short period measurements

The author (Storebö, 1966) has earlier inferred from statistical evidence that bomb debris particles normally become associated with water droplets because they serve as condensation nuclei. Similar conclusions are also drawn by Gatz & Dingle (1966). This may be a property acquired late in the atmospheric history of the particles, because at the time of formation they are probably not very hygroscopic.

It has been shown (Stewart, 1956) that the particles have a mean life of at least 1 month in the troposphere. Based on an idealised natural aerosol distribution in the atmosphere (Junge, 1962), it has been calculated (Storebö, 1965) that in ground level continental air a 0.5 μ diameter particle will pick up 21 other particles per day. The bomb debris particles may thus have acquired condensation nucleus properties by the time they normally take part in a condensation event.

Two measurements of rime deposits in Norway may indicate the condensation nucleus properties attained.

In Fig. 1 a map over western Norway is presented showing sites for all sampling mentioned in this paper. The coast is ragged with mountainous islands and deep fjords, where mountain tops and ridges reach heights in excess of 1000 m. The general level increases inland, and at the mountain divide, about 150 km from the extreme periphery of the coast, the passes usually are well above 1000 m. In the latter area rime deposits on obstacles are rather common during winter time, and may be utilized as cloud water samples.

In the autumn of 1956, when snow sampling was carried out at Finsenuten, at about 1400 m height close to Finse, deposits of rime were found on sampling rods which had been exposed overnight to the air current. Such deposits can be considered as samples of the cloud or fog present. Free particles in the air have little inertia and will not be able to strike the rods at all, while precipitation under those conditions will be in the form of snow, which does not stick to the rods.

The samples were taken in the mornings of 2 November and 7 December 1956, the deposits being formed during the preceding nights. The weather situations are illustrated in Fig. 2.

Two samples of 0.32 and 0.25 litres melted

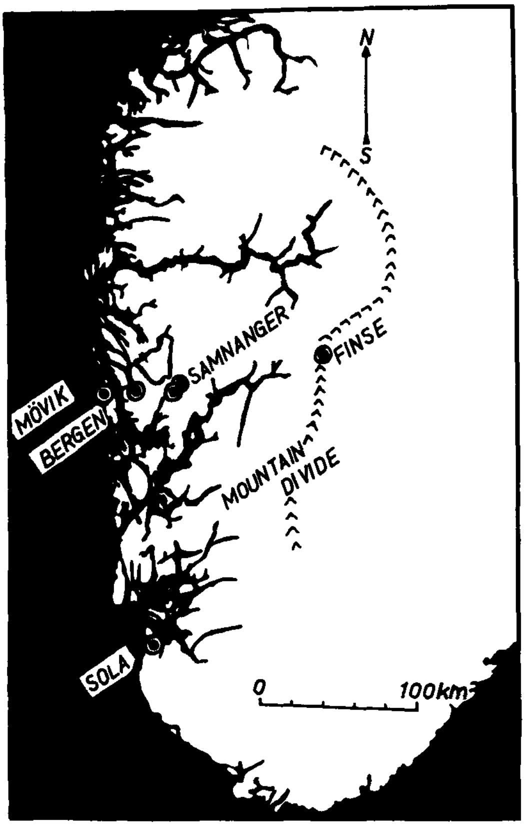

Fig. 1. Sampling area with all sampling locations indicated.

ice were taken on 2 November, and they showed a radioactivity of 169 and 160 dpm/litre. Top layers of snow taken the day before showed a radioactivity of 480 dpm/litre, and the same morning 250 and 490 dpm/litre. The rime deposit thus showed much lower concentration than the snow on the surface.

A precipitation area was lying over the region during the night. The samples should be regarded as representing a cloud having been elevated considerably since start of condensation under more or less steady precipitation. The deposit collected was in the form of rather compact ice, indicating that the droplets had been rather large and numerous.

Two samples of 0.5 and 0.48 litres were taken on 7 December, and they showed a radioactivity of 1310 and 1450 dpm/litre. Top layers of snow from the day before showed radioactivities ranging from 160 to 650 dpm/litre, from the same morning 240 to 1120 dpm/litre.

During the night no precipitation had occurred. The deposit must have been due to local clouds, which were formed over the higher mountain passes and tops when air was forced to pass over them. The deposit was white and light, typical for rime formed by small droplets, which is the type expected in air which has not been very much elevated since start of condensation.

This night the radioactivity concentration in the air was measured in the neighbourhood, and over 24 hours from morning to morning 6 to 7 December a mean radioactivity of less than 0.18 dpm/m^3 was found. (Measurement took place 9 December as compared to 20–22 December for the rime and snow samples.) If this can be considered to be representative for the night hours, 100 per cent capture of radioactive particles by the droplets would mean a liquid water content of the orographic cloud of less (due to radioactive decay probably considerably less) than 0.13 gram/m^3. At $-7°C$, as measured, this corresponds to an elevation of saturated air of about 50 m. With a capture efficiency less than 100 per cent, a lower liquid water content and therefore a smaller elevation would be a necessity. This strongly indicates that the cloud causing the deposit must be very local, and because of the wind present at the mountain top the droplets captured could not be older than a few minutes.

Such a simple calculation is vulnerable to inaccuracies in the material, but nevertheless a strong indication is apparent that the radioactive particles have associated themselves with the water droplets very rapidly and rather completely. All samples were taken shortly after a major bomb-test series, and the bulk of the radioactivity is estimated to have been associated with particles with radius in excess of 0.1 μ. Under such conditions no other process than capture as condensation nuclei could conceivably produce the measured result, and most of the bomb-debris particles must have been among the first condensation nuclei activated during the condensation process.

This conclusion clearly is valid only for the normal population of bomb-debris particles present in an air mass in which no recent condensation or precipitation process has taken place. When condensation and precipitation occur, the bulk composition of the bomb debris in the cloud will change.

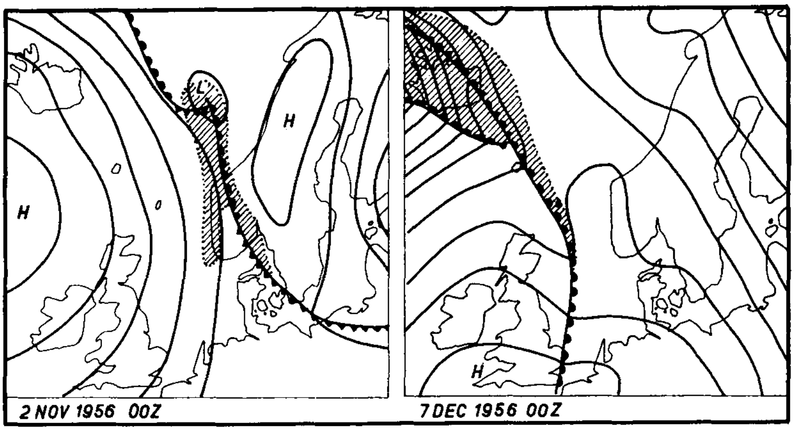

Fig. 2. The weather situations when rime deposits were sampled. Precipitation areas are indicated by hatching.

A freshly formed cloud will under such conditions be rich in radioactive particles. In an old cloud with precipitation history, the first droplets formed, and with them the particles, will have had time to rain out, and droplets formed later on will draw upon a condensation nuclei population depleted in radioactive particles. The old cloud should therefore have low radioactivity concentration. But this could also be true for a new cloud formed in air which recently was part of another cloud.

In an attempt to utilize the tracer potentialities of the nuclear bomb particles present in the atmosphere, two stations were established on the extreme western coast of Norway in order to collect hourly precipitation samples suitable for radioactivity analyses. The locations are shown in Fig. 1. One is found at Mövik, the other at Sola. These stations were operated from 15 May 1963 to 16 November 1964, the winter season of 1964 excluded.

The collection took place in a stainless steel funnel with an opening area of about 1600 cm^2, from which the water was led through a gutter-formed stainless steel distributor to one of 24 polythene bottles resting in a shielded cabinet beneath the funnel. An automatical arrangement moved the distributor one step each hour on the hour, making it possible to leave the instrument without attention for 24 hours.

The funnel and distributor were cleansed once a day with a moistened rag to remove dirt deposit, but no effort was made to remove strongly adsorbing radioactivity or to assure that no radioactivity from the rainwater was deposited before reaching the bottle. It was assumed that some sort of equilibrium between deposition and break away would be established.

The sample bottles were sent to Kjeller for measurement, and here a thorough cleansing took place, assuring a reasonably complete transfer of radioactive particles via evaporation vessels to the counting planchets.

Radioactivity analysis was confined to total beta measurement. For each sample an estimate of a 68% confidence interval was sought; this was based on the accuracy of the precipitation measurements, the counting accuracy and the sampling accuracy as described by Storebö (1966).

This estimate did not take into account any possible cross-sample contamination, which would be most serious for small samples. Those samples usually spring from small precipitation amounts, where additional errors may come into existence. Small samples should therefore be considered more doubtful than the computed confidence estimates indicate.

Confidence intervals for precipitation comprise only accuracy of measurements performed at Kjeller, where samples were weighed under the assumption that all dry bottles had the same weight. Additional uncertainty might arise due to possible water accumulation or evaporation in the funnel and distribution system, and because the sample taken may not represent the rainfall correctly.

The type of measurements given by the experiment is illustrated in Fig. 3. In this case, 11 October 1963, a precipitation system moved

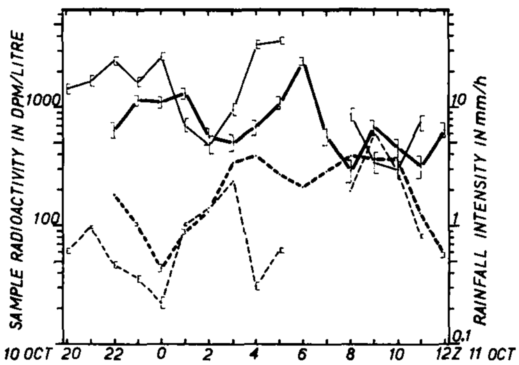

Fig. 3. Measurements while a precipitation system passed the sampling area from the west. Solid lines indicate radioactivity, broken lines precipitation. Thick lines show measurements at Mövik, thin lines at Sola. 68 per cent confidence intervals are indicated by square brackets.

in from the west and precipitation was measured over a time-span of 17 hours. During this period the rain was not continuous, but with the system described a break can only be recorded if at least one bottle is dry. During unfavourable circumstances the sampling procedure might have let breaks close to 2 hours go unnoticed. Therefore, when the sampled amount of water is interpreted as rainfall rate, one should bear in mind that rain may have occurred only part of that particular hour. Especially for samples at the start or at the end of the rainfall, or adjacent to an observed break, there is a high probability that the apparent rainfall rate is too low.

Fig. 3 seems to reflect some inverse relationship between rainfall rate and bomb debris concentration. In order to utilize relationships like that, it is necessary to know the normal behaviour. An approximation to this may be found by examining all the data collected.

In the upper two lines of Table 1 an account is given of the tendencies in the measurements for all samples adjacent in time, separately for the two stations. A direct relationship means that successive samples show a change in the same direction for both rainfall rate and concentration of radioactivity in the rain, while an inverse relationship means rise in one number and fall in the other. Whenever the change in one of the numbers was less than 10 per cent, the case was considered uncertain. It is seen that more than half the transitions show an inverse and about a quarter a direct relationship between rainfall rate and bomb debris concentration, and that there is not much difference between the stations.

Another way to establish a background against which the results may be evaluated, is to examine how possible processes in a precipitation system may affect the measurements.

Table 1. *Account of changes in same and opposite way for the nuclear-bomb debris concentration in rainwater and corresponding rainfall rate for samples in close sequence*

The class "uncertain" contains all cases where one or both numbers showed a change less than 10 per cent.

		Number of transitions with tendency			Percentage of transitions with tendency		
		Inverse	Uncertain	Direct	Inverse	Uncertain	Direct
Total survey	Mövik	82	35	43	51	22	27
	Sola	138	39	50	61	17	22
Extensive precipitation systems classified after gradient wind during rainfall							
W–WSW	Mövik	17	7	4	61	25	14
	Sola	16	4	6	62	15	23
SW	Mövik	10	3	14	37	11	52
	Sola	31	4	8	72	9	19
SSW	Mövik	25	8	16	51	16	33
	Sola	50	9	11	71	13	16
S–SSE	Mövik	30	17	12	51	29	20
	Sola	31	7	12	62	14	24
SE–E	Mövik	5	2	—	71	29	—
	Sola	7	1	2	70	10	20

Bleichrodt, Blok & Dekker (1959) and Kruger & Hosler (1963) have sought explanations for measured inverse relationships in terms of rainfall dependence on height of cloud base or height of cloud top or intensity of condensation. The possibilities for working mechanisms in a precipitation system are by no means exhausted by this. But while it seems relatively easy to find simple hypotheses for inverse relationships, a direct relationship proves more difficult. The time dispersion in the present experiment is one hour, so that micro-cloud processes will be balanced and one is left with processes having a more long-term character.

It was felt that the direct relationships observed might be influenced by the orography. Such an influence should vary somewhat with the wind direction, because the effect of the orographical features must vary with the relative orientation of land obstacles and wind direction during the precipitation period. The results were therefore classified according to wind direction. The classes had to be fairly wide because the wind turns somewhat during passage of a precipitation system, and it is not easy to make a univocal decision if the classes are too fine. The main part of Table 1 presents classified results for passages of 35 extensive precipitation systems.

No trend appears for Sola, but for Mövik an increase in direct relationships occurs when wind direction is between SW and SSW. The measurements from one such situation are shown in Fig. 4.

It is possible that the difference between the stations is due to their different locations. Sola is situated at the southern end of the west coast, on the flat mainland with no island in the neighbourhood, and further inland only the southern lower spurs of the mountain ridge are found. Mövik has a better defined position. It is situated in the middle of the western coast, on an island in a district rather rich in ragged islands, just off the middle part of the mountain ridge, which at this place is rather high. It is to be expected, therefore, that orographic influences would be more felt and more clear-cut at Mövik.

Looking at Table 1 one might accept as a working hypothesis that the increase in tendency towards a direct relationship between rainfall rate and rain water nuclear bomb debris concentration in SW-ly winds is due to orographical influences. For such an orientation relative to a coast Bergeron (1949) has shown that it is normal, even in a flat country, to have a coastal maximum in precipitation. His hypothesis for explaining the increase in rainfall is much higher friction over land than over sea, which puts a brake on the low-level air flow, causing it to deviate more towards low pressure, i.e. towards the sea. In this way a low-level convergence takes place at the coast, causing uplift of the air with consequent condensation of water vapour.

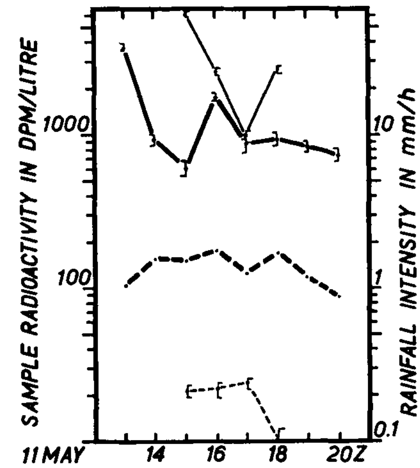

Fig. 4. Measurements while a precipitation system produced rain with a S–SW-ly wind direction. Solid lines indicate radioactivity, broken lines precipitation. Thick lines show measurements at Mövik, thin lines at Sola. 68 per cent confidence intervals are indicated by square brackets.

In order to explain the local character of the precipitation increase under these and a number of other conditions (Bergeron, 1960*a* and *b*, 1965) he postulates that low level cloud droplets are scavenged by precipitation from an overlying cloud, and this may increase the intensity several times. He leaves the impression that he regards the better part of the local, orographically influenced precipitation increases as caused by low clouds being scavenged from above.

During the passage of a precipitation system, it is obvious that the conditions causing low-level convergence vary considerably, and one would consequently expect precipitation intensity to vary. Naturally systematical variations in precipitation intensity are found within the precipitation systems. But if low-level convergence is able to increase the original rain intensity several times, one might expect, periodically at least, the variations in the convergence to dominate the rain intensity.

Because the occurrence of direct relationships between rainfall rate and the concentration of nuclear bomb debris in the rain water is peaked under those circumstances for which Bergeron predicts the low-level coastal convergence, it seems rational to examine if his hypothesis is able to produce such results. The rain should according to Bergeron come from two sources:

(*a*) The upper releaser or seeder cloud formed by the general convergence in the precipitation system, and where the precipitation release might be influenced in a general way only by the large-scale orographical features of the land mass.

(*b*) The low-level feeder or spender clouds formed by local topographical features either because of low-level convergence or due to forced lifting of air over obstacles. Scavenging by precipitation elements from the releaser cloud is necessary if significant amounts of water are to be released from the feeder cloud.

Under these circumstances a direct relationship between rainfall rate and debris concentration is possible provided that the releaser cloud is poor in bomb debris and the feeder cloud is rich in debris. This may be illustrated by an example: Assume that the releaser cloud invariably supplies one rain unit per hour with a radioactivity of r. Let it be further assumed that the radioactivity of the feeder cloud is $s \cdot r$ per rain unit. If α units of rain are produced by the feeder cloud, the resulting intensity will be $(1+\alpha)$ and the specific radioactivity will be $r(1+s\cdot\alpha)/(1+\alpha)$. Therefore, if s is greater than 1, a tendency towards a direct relationship is produced.

The crucial point in this line of arguments is that the releaser cloud must be poor and the feeder cloud must be rich in radioactive debris.

The releaser cloud has under these circumstances been followed on the weather maps as a precipitation area. It is an old cloud with a long precipitation experience before reaching the Norwegian coast. A large part of the first generation droplets, and with them the radioactivity, is expected to have rained out, leaving the cloud rather poor in this respect.

The feeder cloud is a young cloud, which has been elevated very little, and consequently only a small fraction of the water vapour has been liquified. The cloud will therefore be rich in nuclear bomb debris, provided that it is formed in air which has not recently been purified for particles. The recent history of this air must therefore be examined: When a precipitation system is coming in towards the coast in a SW-ly pressure field, the low-level convergence line must appear where the SSW- or S-ly air current over the ocean meets a low-level SSE- or SE-ly current among the islands or over the land. The latter current has not earlier been associated with the precipitation system. However, under the circumstances described rain is falling all over the area, and the question arises whether or not this rain may purify the low-level air.

A closely related subject has earlier been examined by Greenfield (1957), and he found that for particles in the size range of interest, 1 μ radius and lower, the collection efficiency of the raindrops was extremely low. With regard to nuclear bomb debris particles, the composition of the low-level air current should be virtually unhampered by the rain. Rain will, of course, have some consequences for the model as a whole, because evaporation from the drops would tend to moisten the air, which could originally be very dry, and thereby facilitate formation of a feeder cloud.

It therefore looks as if a proper foundation has been laid for the suggestion that the peak in direct relationships between rainfall rate and concentration of nuclear bomb debris in the rain water, occurring in a SW-ly pressure field, has been caused by interference between a high-level releaser cloud poor in debris and a low-level feeder cloud rich in debris.

Climatological measurements

It is obvious that the mechanism for precipitation formation must have effects also on a climatological time-scale. In Norway the large precipitation systems are responsible for most precipitation and also for most deposition of nuclear bomb debris. Some debris is of course deposited directly from the air, as "dry fallout", but Small's (1960) figures indicate that the error made in neglecting dry deposition should not be very large for climatological calculations.

One type of climatological data of interest in this connection is found in soil samples. Numerous investigations have shown that most of the radioactive particles stay in the very upper part of the soil cover once they have been deposited there. This seems especially to be true when the investigation is based on certain isotopes, among them ^{137}Cs.

Because of its rather long half-life of 33 years, measurements of the content of ^{137}Cs in soil will yield an estimate of the accumulated deposition of this isotope from all the bombs exploded. The data have of course to be applied with some caution: Since the first bomb explosion was performed in 1945 about 20 years have elapsed, leaving room for some radioactive decay, and the rate of deposition has been highly variable during these years. Further, even if leakage of ^{137}Cs from the sampled soil has been small, the magnitude is not known.

A set of soil samples taken at Samnanger just east of Bergen at the end of August 1965 is presented in Fig. 5 together with a rough topographical map and existing precipitation measurements. During sampling special care was taken to find a site where the soil had not been turned the last 15 years and where the terrain did not indicate any local accumulation or run-off of rain water. The precipitation date are mean yearly precipitation from 1 January 1953 to 1 September 1965, i.e. to the date of sampling, and should thus give a reliable estimate of normal precipitation conditions in the area.

The Samnanger fjord opens up towards SW, is not much narrower in the inner than in the outer part, and has only a few small and low islands situated between the ocean and the fjord opening. Studies of single precipitation systems clearly show that the highest precipitation amounts are found with SW-ly winds. Apparently the fjord channels the air current, and having reached the bottom, there is no other way for the air to go than upwards over the surrounding hills and mountains. The forced updraught produces heavy precipitation in the inner part of the fjord and in the valley in extension of it. A number of other fjords in western Norway with a similar orientation show similar rainfall distribution, but details are seldom known, because usually no more than one station is found in one particular fjord.

An interesting feature in the present fjord is the threshold-like formation at its inner end.

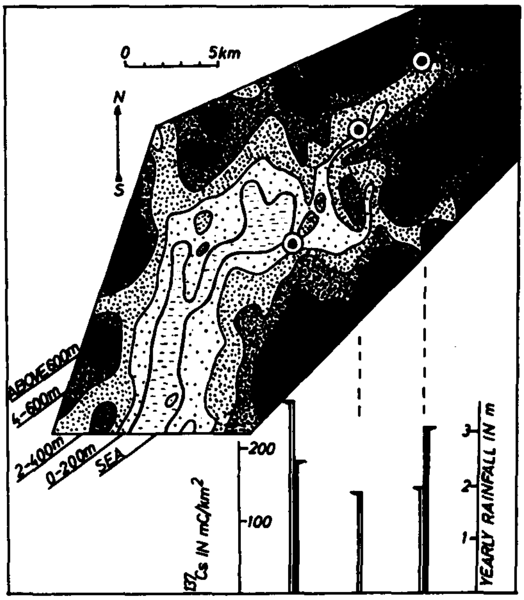

Fig. 5. Topographical and radioactivity conditions in the Samnanger fjord area. The topographical map at the top shows the soil sample sites at the inner end of the fjord and in the valley. Radioactivity measurements and mean precipitation amounts 1953–1965 are shown at the bottom.

The valley stretching up towards NE has its outlet between S and SSE to the side valley, but this outlet is rather narrow and takes an intricate course, and cannot have much capacity for air transport when the wind is from SW. As a result most of the air from the fjord must pass over a threshold hill in order to reach the valley. The lowest pass is at 150 m height, and most of the air is probably lifted some 200–300 m during this passage.

Fig. 5 shows that much more radioactive debris has been brought down just in front of the threshold than in the valley behind in spite of smaller precipitation amounts at the inner part of the fjord than in the valley. It seems to be very difficult to find an explanation for this distribution other than that offered by the feeder cloud hypothesis in combination with the hypothesis that the bomb debris particles are excellent condensation nuclei.

Beneath the releaser cloud in a precipitation system the air will ordinarily be moist enough for condensation to start if the air is lifted 200–300 m. Accordingly a feeder cloud must form when the air is forced over the threshold

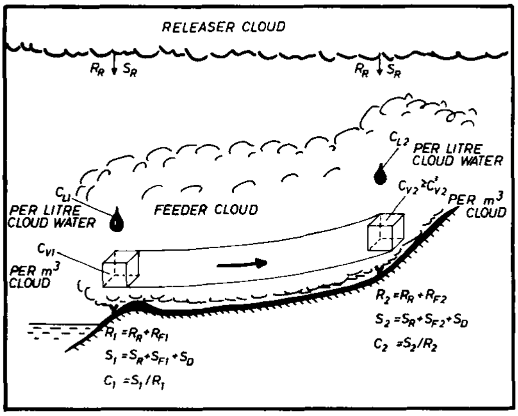

Fig. 6. Ground-level profile between the precipitation stations. The fjord is on the left side, the mountain on the right. Releaser cloud, feeder cloud and quantities used for scavenging considerations are indicated.

hill. If the bomb debris particles are among the best condensation nuclei in the air, most of them will form droplets in the threshold feeder cloud and thus be exposed to rain-drop scavenging and deposition on the hill or in front of the hill.

In the valley a new and much stronger elevation of the air occurs, causing a revitalization of the feeder cloud. This results in a very high local precipitation rate, probably among the very highest in western Norway. However, the bomb debris particles are already much washed out in the first cloud, and even if most of those left may be deposited in this second wash-out event, it does not amount to much more than half the deposition in front of the hill.

It is possible to apply the data from the two precipitation stations for an estimation of a lower limit for the scavenging efficiency of the raindrops between the two precipitation stations with regard to the droplets in the feeder cloud. The quantities used for this estimate are shown in principle in Fig. 6 together with a ground-level profile between the precipitation stations.

The basic assumptions in the model are that the releaser cloud parameters do not vary from the fjord to the valley station, the rainfall is R_R with a radioactivity deposition S_R. Every difference in measured amounts of rainfall and deposition on the two stations must therefore be due to the feeder clouds.

Let C_{V_1} be the concentration of the radioactivity associated with droplets per volume unit of the feeder cloud above the fjord station, and C_{V_2} that at the valley station. Because the valley station is situated at a higher level, more of the available moisture may be condensed in the cloud, and this may have activated more radioactive particles as condensation nuclei. Let therefore C'_{V_2} be the concentration left of the originally activated radioactive nuclei. The scavenging efficiency sought will then be

$$E = 1 - \frac{C'_{V_2}}{C_{V_1}} \qquad (1)$$

and the following relationship will hold:

$$\frac{C'_{V_2}}{C_{V_1}} \leqslant \frac{C_{V_2}}{C_{V_1}}. \qquad (2)$$

The measured rainfall amount R_1 at the fjord station is smaller than the rainfall amount R_2 at the valley station. It is postulated that the releaser cloud rainfall is R_R. Let the feeder cloud rainfalls be called R_{F_1} and R_{F_2}, with radioactivity carried down S_R, S_{F_1} and S_{F_2} respectively. Direct deposition (without rain) on the ground S_D is assumed to be the same at the two stations.

The soil samples give the total deposition S_1 and S_2 at the two stations, where $S_1 > S_2$ and therefore

$$\frac{S_2}{S_1} > \frac{S_2 - S_R - S_D}{S_1 - S_R - S_D} = \frac{S_{F_2}}{S_{F_1}} \qquad (3)$$

For the rainfalls, where $R_1 < R_2$

$$\frac{R_2}{R_1} < \frac{R_2 - R_R}{R_1 - R_R} = \frac{R_{F_2}}{R_{F_1}}. \qquad (4)$$

If C_1 and C_2 are the radioactivity per rainfall unit measured at the stations, and C_{L_1} and C_{L_2} are the concentrations per liquid water unit in the feeder clouds, the following relation appears by division of (3) by (4)

$$\frac{C_2}{C_1} = \frac{S_2/R_2}{S_1/R_1} > \frac{S_{F_2}/R_{F_2}}{S_{F_1}/R_{F_1}} = \frac{C_{L_2}}{C_{L_1}}. \qquad (5)$$

It is here assumed that the rainout from the cloud has the same composition as the cloud itself.

In order to advance further it is necessary to examine the possibilities within the framework of the theory for a precipitation increase from the fjord to the valley station. This increase must be mainly due to the feeder clouds and may be achieved in different ways:

(*a*) The feeder cloud at the valley station is at least as deep as over the fjord station and has a higher liquid water concentration. Additional condensed water may result in new droplets and in increased size of the original ones. Scavenging efficiency per volume unit of the original droplets could therefore be higher in the valley, because the droplets are bigger and the rainfall rate higher, i.e.

if $S_{F1} = k \cdot C_{V1}$,

then $S_{F2} \geqslant k \cdot C'_{V2}$,

$$\frac{C'_{V2}}{C_{V1}} \leqslant \frac{S_{F2}}{S_{F1}}. \tag{6}$$

Combining (1) with (3) and (6), and using measured values

$$E = 1 - \frac{C'_{V2}}{C_{V1}} \geqslant 1 - \frac{S_{F2}}{S_{F1}} > 1 - \frac{S_2}{S_1} = 0.45.$$

(*b*) The feeder cloud above the valley station is deeper than above the fjord station, but has the same liquid water concentration. Such a situation might come into existence if low-level horizontal convergence forced the air to pile up over the area.

Under these conditions the ratio between cloud water radioactivities per liquid water unit would be the same as that per cloud volume unit, i.e.

$$\frac{C_{L2}}{C_{L1}} = \frac{C_{V2}}{C_{V1}}. \tag{7}$$

Combining (1) with (2), (5) and (7) and using measured values

$$E = 1 - \frac{C'_{V2}}{C_{V1}} \geqslant 1 - \frac{C_{V2}}{C_{V1}} = 1 - \frac{C_{L2}}{C_{L1}} > 1 - \frac{C_2}{C_1} = 0.57.$$

(*c*) The feeder cloud above the second station is deeper than above the first station, because air bypassing the first feeder cloud may contribute to the second. If it is assumed that no decrease in liquid water concentration has occurred, the result is a cloud where scavenging of radioactive particles occurs more easily, and one may proceed as under (*a*).

(*d*) Within the framework of the model a conceivable working mechanism is that the first generation droplets in the feeder cloud over the valley station are smaller than in the feeder cloud over the fjord station. This would mean a decreased scavenging efficiency for the droplets, and the increased rainfall must be due to a deeper feeder cloud than for the earlier described cases. Another possibility is a more shallow cloud over the valley station than over the fjord station, but with a much higher water content so that the precipitated amount could come out higher.

For these last mechanisms it is not possible in a stringent way to find a lower limit for the scavenging efficiency. For the present conditions these mechanisms may, however, be discarded as unreasonable. Due to the chanelling effect of the valley on the air current and the higher elevation of the valley station, the air must be elevated, and increased condensation must occur between the stations. Under such circumstances it is incredible that the feeder cloud should be more shallow or that remaining original droplets, presumably formed on the best condensation nuclei present, could decrease in size for the benefit of new droplets formed on less good nuclei.

In nature probably most conceivable working mechanisms are present. A combination of mechanisms would give results in between those quoted. An absolute lower limit for the scavenging efficiency between the stations will thus be the lowest value calculated. By choosing that value the uncertainty in the working mechanism is taken into account. One may thus state that the releaser cloud drops have scavenged at least 45 per cent of the feeder cloud droplets during their transport from the fjord to the valley station.

Data from the normal monitoring network for radioactive fallout in western Norway may give further quantitative information about the importance of the feeder clouds for precipitation formation.

For a coastal station in a mountainous region most precipitation occurs when the systems come from the ocean side. Systems coming from the land side are apt to undergo some subsidence causing part or full evaporation of the precipitation forming clouds.

For a coastal station, therefore, the low feeder

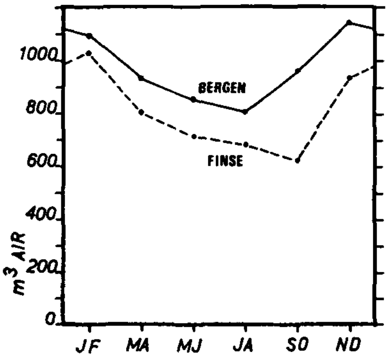

Fig. 7. Collection efficiency of rain with regard to radioactivity. The figure shows that volume of air which contains the same ^{137}Cs amount as 1 litre rain for Bergen and for Finse. The figure is based on bi-monthly values for the years 1958–1964.

clouds will usually be formed in air which has not been purified in advance, and these feeder clouds should be rich in nuclear bomb debris. Consequently a climatological meaure for the bomb debris collection efficiency of the rain at that station ought to show a high value.

For a mountain station the precipitation systems may come from any direction. But before reaching the station most ground level air will have had some condensation experience, because some influence of the orography will be found in the air trajectory. Within a precipitation system this will generally be combined with raindrop scavenging, leading to some purification of the air for radioactive particles. When a feeder cloud is formed over the mountain station, this cloud should normally be less rich in radioactivity than a corresponding sea-level cloud. Mean air concentration would not be influenced in the same degree, because weather situations with no precipitation would dominate in the records. A climatological measure for the bomb debris collection efficiency of the rain should therefore be lower than at the coast station.

In Fig. 7 is shown on a bi-monthly basis the volume of air which contains the same bomb debris amount as 1 litre rain water. The figure is based on measurements of ^{137}Cs, and the values shown are means of individual bi-monthly figures for the years 1958–1964. The Finse sampling has not always been as systematically performed as in Bergen, but it is unlikely that this has influenced the diagram in any systematic way.

The air volume which contains the same radioactivity as one unit precipitation may be read as a climatological measure of the efficiency of the precipitation in collecting the debris. It is seen from the diagram that Bergen, the coast station, shows a higher value throughout the year than Finse, the mountain station, as anticipated. It may be of interest that the average air concentration of ^{137}Cs during these 7 years was the same at the two stations. Finse, being at a height of 1250 m, would show even lower efficiency relative to Bergen if reference had been made to mass of air instead of volume.

If all particles in the air are associated with droplets, it is seen that for precipitation in Bergen a mean release of about 1 gram liquid water per m³ air is indicated. For saturated air at about 15°C this corresponds to cooling by expansion during an elevation of 250 m, for 10°C 350 m. For air which is not saturated, the elevation would be higher, but the humidity during the passage of precipitation systems is seldom far from the saturation point. For an association with droplets less than complete, less water and lower elevation would be a necessity.

The calculated rise is substantially less than what is expected in a large precipitation system. One might, of course, try to explain the results by postulating a higher radioactivity concentration in the upper cloud level, but in that case Finse ought to show a higher concentration in liquid water than Bergen, not a lower one as is measured. It is difficult to avoid drawing the conclusion that the main part of the radioactivity deposited by rain has been collected in feeder clouds having been lifted but very little, and then scavenged by droplets from higher lying clouds. This would further indicate that a substantial part of the rain water must originate from the feeder clouds, as emphasized by Bergeron.

Fig. 7 shows a seasonal variation. Precipitation apparently collects radioactive particles more easily during the winter than during the summer. Due to the very high collection efficiency indicated for droplets, it is unlikely that this can be due to an even higher efficiency for snow. However, it is possible that the effect is caused by the temperature difference. The lower temperature during the winter would lead to less condensed water for the same rise or the same temperature decrease, resulting in a feeder cloud with a higher radioactivity/liquid water ratio.

The time delay of the Finse measurements compared to those in Bergen is certainly not statistically significant. But seasonal temperature extremes are delayed with height, so the effect observed is in the expected direction.

Concluding remarks

The possibility of using nuclear bomb debris measurements as a probe for investigating precipitation mechanisms has been apparent for some time. Problems arise, however, mostly because the properties of the debris are insufficiently known, so that its behaviour within the precipitation systems cannot be predicted accurately.

The present method of investigation was made possible because earlier work had shown the debris, when it appears in world-wide fallout, to work as excellent condensation nuclei. During the investigation it was possible to put this finding up to independent tests, and it is reassuring that all types of measurement indicated the debris to work as suggested.

The conclusions from the tracer application on precipitation are in support of Bergeron's theory for precipitation formation: A high level releaser cloud producing comparatively large precipitation elements but not always large precipitation amounts, and a low-level feeder cloud producing smaller droplets, which are scavenged by the drops from the releaser cloud, so that large precipitation amounts may be the result. For western Norway the indications are that the scavenging mechanism must be a very important feature of the precipitation mechanism, and that a substantial part of the lower cloud system has undergone but marginal lifting.

It must be emphasized that western Norway is a rather mountainous area; orographical effects are very pronounced, and the results are not necessarily applicable to other regions. However, it is unlikely that completely new effects have developed, and in principle one might look for similar effects in other places. It may be of interest to notice that Bergeron found evidence for the releaser/feeder cloud hypothesis in such a flat country as the Netherlands, and especially in the surroundings of Uppsala.

The present investigation was concerned with large-scale precipitation systems only. Most published precipitation tracer work with bomb debris has had to do with smaller scale, shower-like systems. The ordinary meteorological network will in principle give little information under such circumstances, but very often special observational networks are set up, giving good description of the systems. It is then possible to examine the structure rather thoroughly, and it would be interesting to see if indications of scavenging of small droplets appear also in showers.

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ФОРМИРОВАНИЕ ОСАДКОВ В ПРИ- БРЕЖНОЙ ГОРИСТОЙ ОБЛАСТИ

Частицы загрязнений от ядерных бомб, выпадающие на всем земном шаре, действуют как прекрасные ядра конденсации. Этот эффект был использован для трассерных исследований обширных систем осадков. Были изучены синоптические и климатологические типы проб и результаты с большой очевидностью указывают, что капли дождя, выпадающие из облаков низкого уровня, подверженных небольшому поднятию, являются важным механизмом в образовании осадков. Для дождя на уровне моря в Западной Норвегии отмечено среднее поднятие облака после насыщения на 300 метров.