Observations of Size Distributions of Hydrometeors Through the Melting Layer

Takeshi Ohtake

Geophysical Institute, University of Alaska, College

(Manuscript received 8 October 1968, in revised form 29 January 1969)

ABSTRACT

Size distributions of snowflakes and raindrops were obtained simultaneously at two altitudes along mountain slopes. The snow size distributions generally agreed with the Gunn and Marshall snowflake distribution, but were sometimes similar to the Marshall and Palmer raindrop distribution. Raindrops sampled just below the melting layer tended to have the same pattern of size distributions as snowflakes appearing at the upper station above the melting layer. The times at which the modes of distribution changed were the same at both stations. The implication is that most of the snowflakes do not break up into several small raindrops during melting.

1. Introduction

Many studies of the size distribution of raindrops have been published in the last 20 years. These observations and calculations were made in an attempt to understand the distribution on the ground of sizes of raindrops which originated from snow crystals, i.e., the history of the precipitation particles, and to obtain information to relate with weather radar reflectivities. However, most of these investigations involved only raindrops, without considering the process of the melting of snowflakes which should cause most of the raindrops observed on the ground.

Gunn and Marshall (1958) reported an average size distribution (GM distribution) of aggregated snowflakes based on 20 observations of snowfall and made an attempt to relate the GM distribution as an input at the top of melting layer to Marshall and Palmer's (1948) raindrop size distribution (MP distribution) at the bottom of the melting layer. They suggested that considerable breakup of the larger snow particles is required in the melting layer. Furthermore, to explain an observed increase of radar signal from the rain over that from the snow, they suggested a considerable increase in precipitation rate at or below the melting layer.

However, they compared only the average distribution of snowflake size, observed on days of snow and no rain, with earlier published average distributions for rain, for days when there was only rain at the surface. One could see that there would be an advantage in simultaneous observation of snowflakes and raindrops at different levels. To do this aircraft might be useful, but we would have considerable difficulties in the sampling of snowflakes. Hence, the present observations of snow and rain were carried out along mountain slopes. The present paper describes simultaneous observations of size distributions of snowflakes and raindrops at different stations along the ski slope of Mt. Zao, Japan, and Douglas Island, Alaska.

2. Methods of observation and data reduction

To sample snowflakes during the primary observations conducted in Japan, a horizontal sheet of Japanese silk wool was exposed on the ground, rather than the brushed "angora wool" used by Gunn and Marshall. The silk wool was dyed black for contrast with the snow sample and treated with silicone to make it hydrophobic; the fiber diameter was about 10 μ. After melting, small sheets of filter paper were used (as described below) to obtain the size distribution. Later, in Alaska, angora wool was used because the wool was available and allowed more flexibility in size, permitting the analysis of larger samples. After exposure to snowfall, the angora wool was carried into a warm room to allow the snow to melt to water drops. A sheet of filter paper (sized about 50 cm×40 cm), dusted with aniline blue powder, was then pressed onto the wool, resulting in various sizes of blue spots according to the masses of melted snowflakes. The size of these spots can easily be measured with the use of a previously prepared calibration curve. For raindrop measurement, the same kind of filter paper was directly exposed to rain on a vinyl or metal net suspended over a sampling board, thus eliminating splash error. These methods of sampling followed Gunn and Marshall's procedure, as it seemed to be the simplest, most accurate and most appropriate for observations in the field.

The data reduction used was also similar to that of Gunn and Marshall. However, in order to compare the size distributions of snowflakes and raindrops, the horizontal distributions N_H, which are the number of particles per unit size interval which fall on filter paper

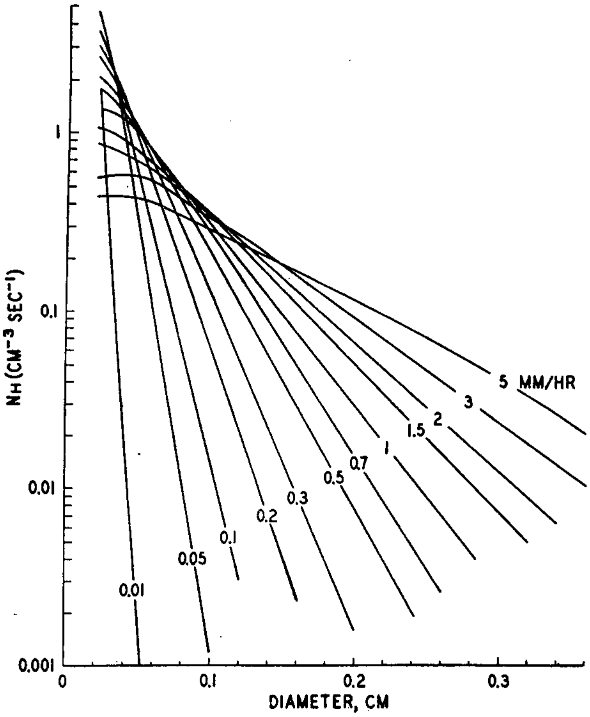

FIG. 1a. Gunn-Marshall horizontal size distribution of melted snowflake aggregates.

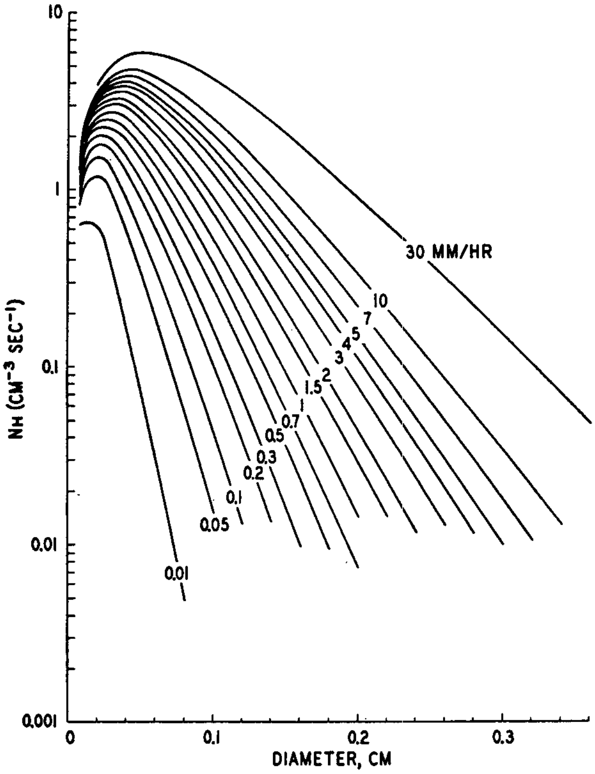

FIG. 1b. Marshall-Palmer horizontal size distribution of raindrops

of unit area during unit exposure time, were treated rather than spatial distributions N_D, as shown in Figs. 1a and 1b. The MP distribution of raindrop size and the GM distribution of snowflakes are based on spatial distributions N_D which are derived by dividing the horizontal distribution N_H by the corresponding fall velocity—V_r for raindrops or $V_s=200D^{0.31}$ for snowflakes. In a melting layer it is difficult to determine these velocities because they change with the conversion of snow to rain, so N_H was taken as a more conservative parameter. It is constant even if falling velocity or the shape of the particle should change, provided there is no mass exchange.

If the falling hydrometeors experience melting without coalescence, accretion or condensation, N_H remains constant. Thus, as long as the snowflakes are melting without liquid water exchange between them or without vapor exchange with the surrounding air, the same rain intensity R, given by

$$R=\int_0^\infty N_H D^3 \frac{\pi}{6} \rho dD,$$

where ρ is the density of water and D the diameter of the melted snowflake, will be observed on both sides of the melting layer within limits of observational errors. When the melting of snowflakes is accompanied by aggregation or breakup or other mass exchange, the value of N_H and the slope of distribution curve will change accordingly.

In this paper we do not intend to make any standard distribution of hydrometeors; our purpose is rather that of determining such changes as the shape of the size distribution or the precipitation rate as might be expected through the melting layer. Thus, the distributions of both snowflakes and raindrops were compared with both the GM and MP distributions, but in the horizontal distribution rather than the spatial one. Figs. 1a and 1b show the GM and MP horizontal distributions as the standards with which the present data were compared. These figures were converted from the equations of spatial distribution by multiplying by the fall velocity corresponding to each size.

The data at both stations were compared with GM and MP distributions of the size of snowflakes and raindrops, respectively, as standards.

3. Observations and results

The operations were conducted at two different positions each along the slopes of the mountains, one in Japan and the other in Alaska. Since there are meteorological and topographical differences, the descriptions will be made separately.

a. Observations at Mt. Zao in Japan

The mountain is situated 40 km from the Pacific Ocean and 95 km from the Japan Sea. The altitudes of the stations are 1260 m (B station) and 890 m (C station), the horizontal distance between them being 1.9 km. Several records were taken at A station (1500 m) and B station, having a horizontal separation of 1.7 km, on 22 March 1959 (Figs. 2 and 3). In each case, the upper station was selected to be near the top of the melting layer and the elevation of the lower station near the bottom of the melting layer. Public telephones at both stations made it easy to check on existence of snow or rain at both stations. Observations were conducted on 22 March 1959, 16 March 1963 and 29 March 1963.

1) 22 March 1959. With the departure of a high to the Pacific Ocean a low moving from southeast Korea to the middle of the Japan Sea deepened rapidly. Observations were started at 1000 JST (135 E longitude; all times mentioned in Section 3a refer to this meridian) at the upper station and at 1005 at the lower. The crystal form of snow varied frequently, starting with needles, but sometimes varying to plane dendrites and graupel. The average hydrometeor size distribution could not definitely be classified into GM or MP at either station, because of the frequent changes in distribution as well as in crystal shapes, and because of changes in precipitation rates with gusty winds. Over short intervals, however, the distributions and precipitation rates tended to change systematically.

From 1000 to 1010, at the upper station and from 1005 (when the observation started) to 1007 at the lower station, GM type distributions with a peak at diameters of 1.0–1.2 mm were observed, with precipitation rates of 0.2–0.7 mm hr^{-1} at the upper station and 0.6–3.0 mm hr^{-1} at the lower station. The temperatures were -1.0 and 2.5C, respectively, and were increasing. The size distribution of aggregated snowflakes at the upper station agreed with GM as expected. However, the size distribution of raindrops at the lower station also agreed with GM rather than MP. At 1020 at the upper station the size distribution of snowflakes changed to the MP type, while at the lower station the MP type distribution of raindrops was also observed from 1009–1015. The size distribution changes were observed at the lower station several minutes prior to the corresponding observation at the upper station throughout the observations on this day. This is felt to be due to the fact the main wind direction around the stations was southwest to west (see Fig. 3) and the precipitation clouds must have moved over the lower station before reaching the upper station. After the appearance of a few indefinite distributions at both stations, the distributions changed into much less steep distributions than either those of MP or GM at both stations from 1030–1041 at the upper station and 1023–1027 at the lower station. At 1119 at the upper station, the size distribution changed to a steeper distribution in accord with MP with a precipitation rate of 2.75 mm hr^{-1}; the hydrometeors consisted of irregular needles. At 1114 at the lower stations a similar shape to MP was also observed with $R=3.45$ mm hr^{-1}. The examples are shown in Figs. 4a and 4b. Afterward the size distribution of hydrometeors at both stations changed into distributions much less steep than GM. The precipitation ceased at the lower station at 1135, and at 1150 at the upper station.

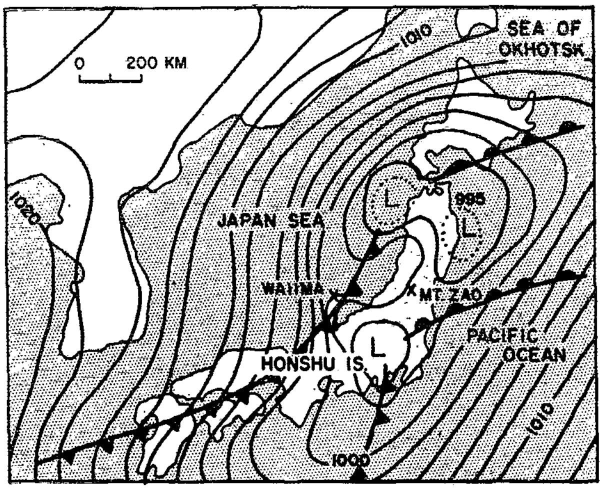

FIG. 2. Location of the observations conducted in Japan, and surface weather map for 0900 JST 29 March 1963.

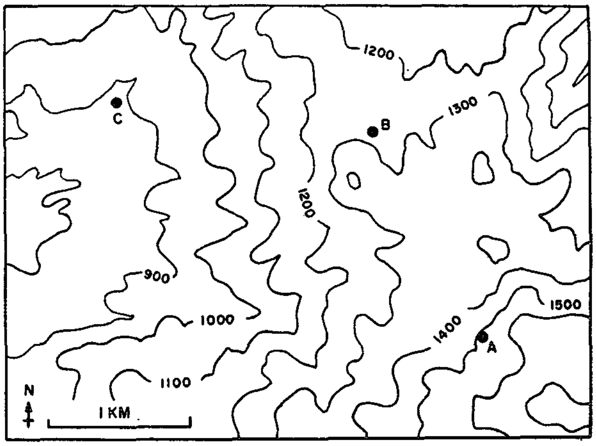

FIG. 3. Locations of the observation sites on Mt. Zao, Japan. Solid circles indicate the stations.

Starting at 1225, needles and irregularly shaped snow fell at the upper station until 1307, with precipitation rates of 1.1–5.2 mm hr^{-1}. At 1230 the temperatures were 1.5 and 3.2C at the upper and lower stations, respectively. The distribution of snowflakes observed during this time was similar to GM or less steep. At the lower station rain started at 1241 and continued to 1320 with precipitation rates of 0.34–2.99 mm hr^{-1}. The shape of the size distribution was less steep than but similar to GM, and identical to that of the upper station, especially the distributions at 1300 at the upper station and 1252 at the lower station, with precipitation rates of 1.59 and 2.00 mm hr^{-1}. After 1315, snow at the upper station B changed into rain and observations were

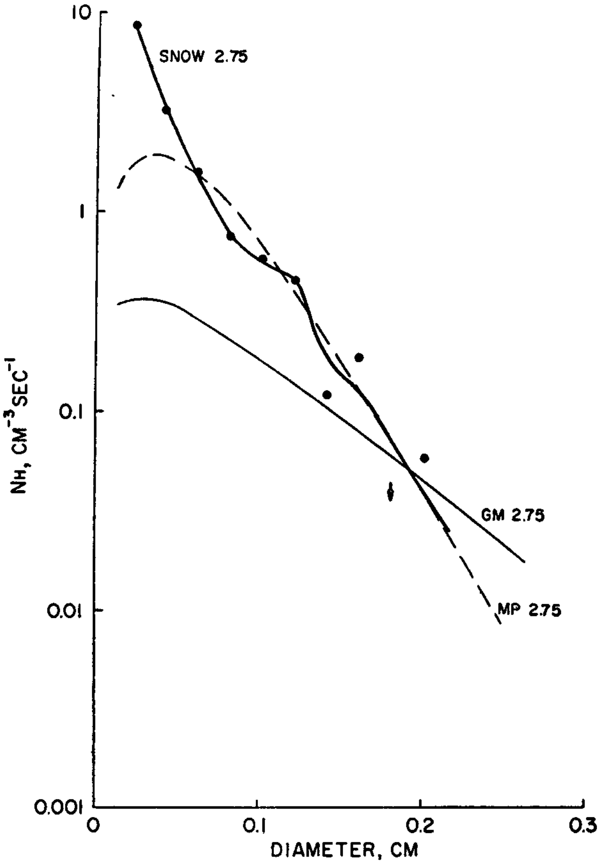

FIG. 4a. Size distribution of melted aggregate snowflakes (heavy solid line) at the upper station B, Japan, 1119 JST 22 March 1959 for $R=2.75$ mm hr^{-1}, $T=0.5$C. Thin solid line and broken line show GM and MP distributions, respectively, for same R.

transferred to stations A and B. Although only two sets of corresponding data were available at both stations all distributions were similar to GM, all curves showing a peak value. The temperatures at A and B were 0 and 2.5C, respectively. Precipitation rates were changing frequently, and crystal shapes were indefinite.

In summarizing the observation made on this day, the small recording papers used gave uncertain results. However, the size distribution of raindrops sampled at the lower station was similar to that of snowflakes taken at the upper station at the corresponding time, even though the distribution shapes frequently changed from a less steep distribution than GM to one similar to MP. This implies that the size distribution of snowflakes above the melting layer kept their characteristics during snow melt. The observations showed that most of the snowflake distributions at the upper station were similar to GM. This is in agreement with Gunn and Marshall's result. However, most of size distributions of raindrops just below the melting layer were not similar to MP, as was suggested by Gunn and Marshall, but were similar to GM as was observed in the distribu-

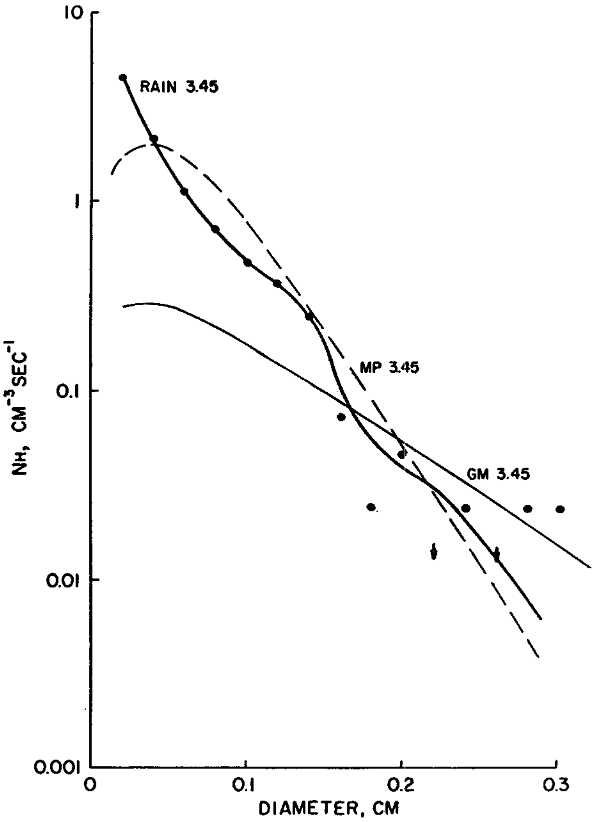

FIG. 4b. Size distribution of raindrops (heavy solid line) at the lower station C, 1114 JST 22 March 1959 for $R=3.45$ mm hr^{-1}, $T=3.1$C.

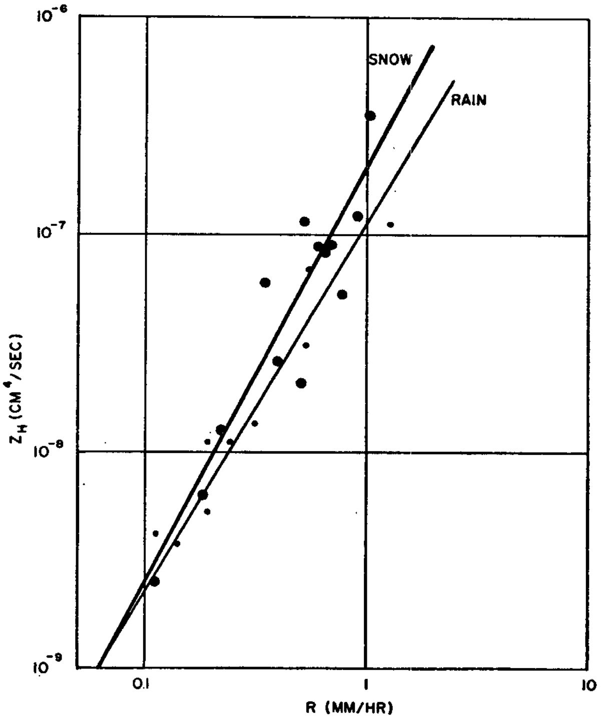

FIG. 5. Z_H-R relation for snowflakes (thick line) and raindrops (thin line) sampled on 16 March 1963.

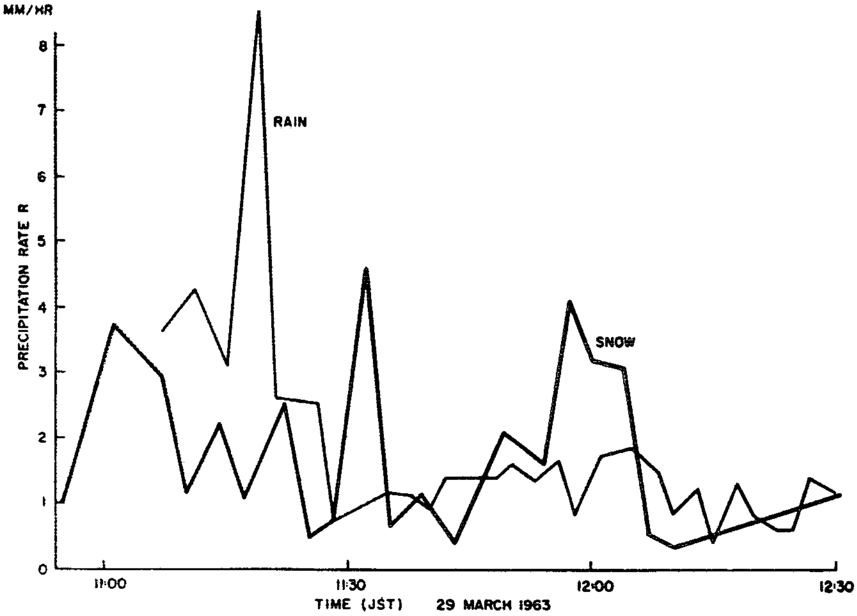

FIG. 6. Changes of precipitation rate throughout the observation at both stations on 29 March 1963. Thick line and thin line correspond to snow and rain, respectively.

tions of snowflake size at the upper station. However, the size distribution of snowflakes at the upper station sometimes agreed with MP rather than GM; under these circumstances the raindrop size distribution was also similar to MP.

2) 16 March 1963. A low of 1006 mb was passing the

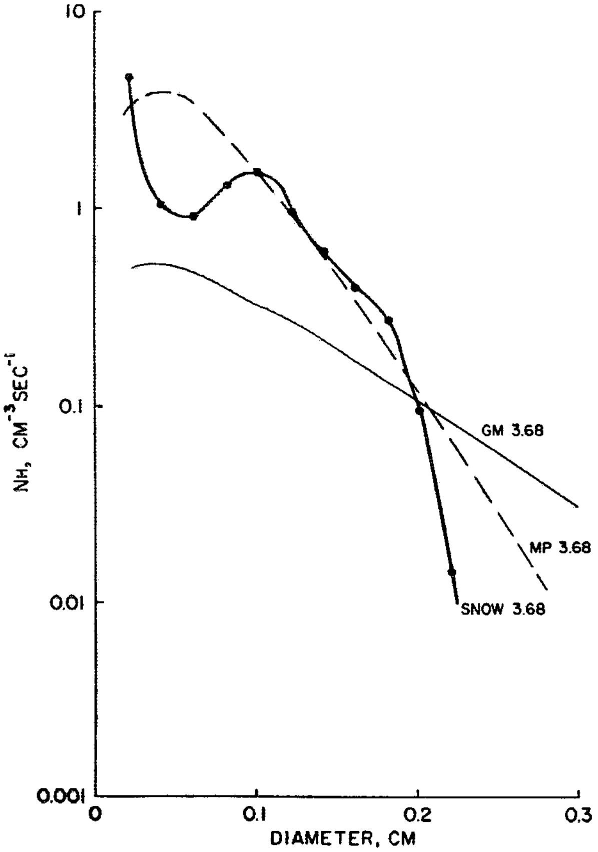

FIG. 7a. Same Fig. 4a except for 1101 JST 29 March 1959, for snow, $R=3.68$ mm hr^{-1}, $T=1$C.

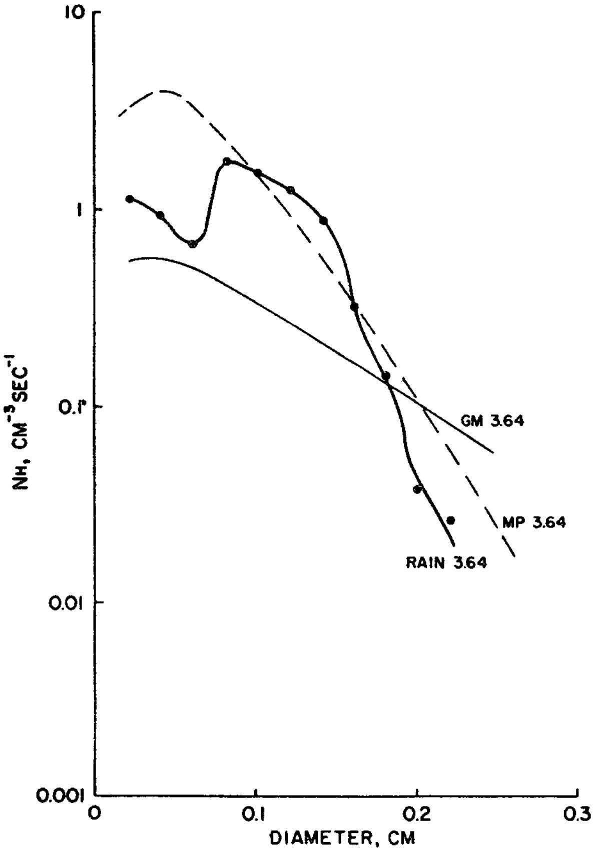

FIG. 7b. Same as Fig. 4b except for 1107 JST 29 March 1959, for rain, $R=3.64$ mm hr^{-1}.

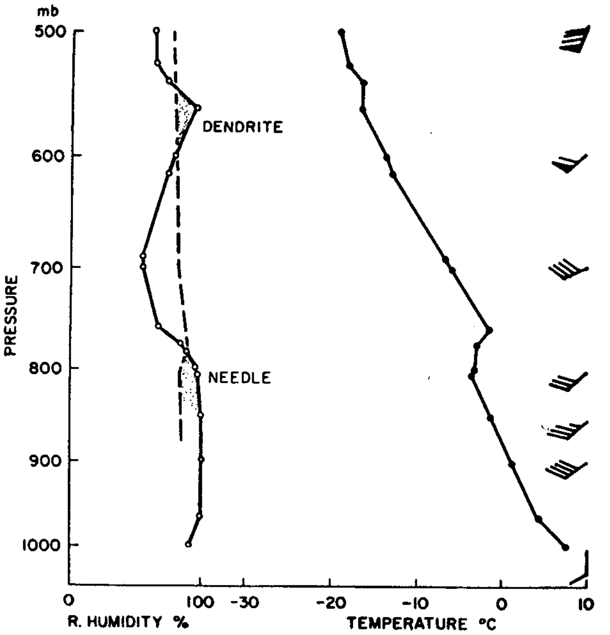

FIG. 8. Sounding made at Wajima, 0900 JST 29 March 1963. Shaded parts show the heights at which the indicated snow-crystal shapes would be expected. Broken line shows the relative humidity over water minus 20%, for saturation at subfreezing temperatures.

south coast of Honshu Island, Japan, with a cold front crossing the island from another low situated in the Sea of Okhotsk, both brought rain to most of Japan.

Observations were conducted from about 1700–1828 JST at both stations (B and C). At the upper station, throughout the observation, the precipitation was in form of snow with indistinct crystal shape, probably with needles or irregular needles. At the lower station (C), the precipitation was initially rain then changing to snow alternating with mixed rain and snow. At the time when snow fell at the lower station, fog was noticed in the melting layer, although it could not be seen before the precipitation changed into snow. From 1658–1709 both stations observed distributions which appeared closer to MP, although they were difficult to classify because standard distributions of GM and MP are similar at precipitation rates <1 mm hr^{-1}.

At 1712, the rain at the lower station suddenly changed into snow which lasted until 1732. The size distributions of snowflakes at both stations continued to be rather similar to MP. At 1741–1758 the lower station had snow mixed with rain with no fog around. Distribution patterns of both snow, and rain mixed with snow, were also indistinguishable, but seemed to be less steep than MP. The precipitation rates at both stations were about the same at 0.11–0.22 mm hr^{-1}. The curve derived from the GM equation becomes steeper than that of MP when the precipitation rates <0.3 mm hr^{-1}, which may be a result of extrapolation of the MP equation to rainfall rates less than those on which their distribution was based. Further collection of data is desired to improve the standard distribution. After 1800 mixed rain and snow at the lower station

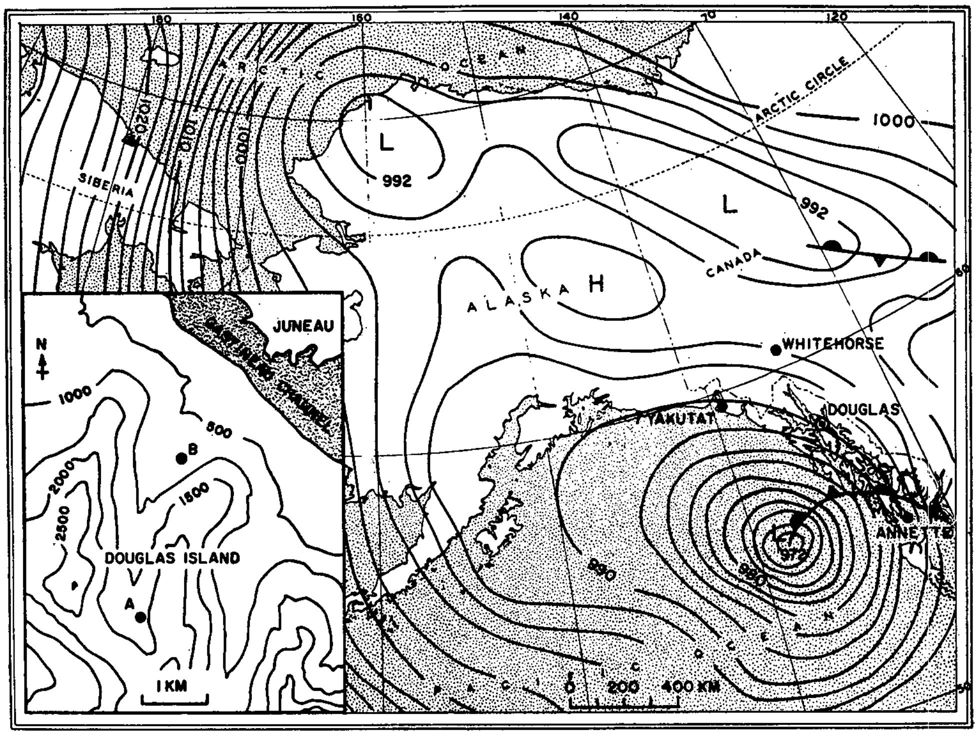

FIG. 9. Locations of the observations made in Alaska, and surface weather map at 1500 YST 30 November 1965.

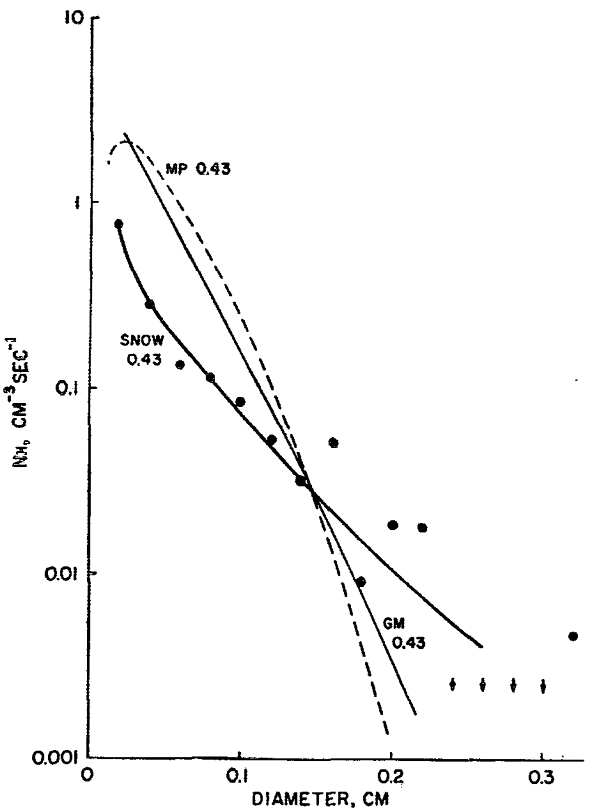

Fig. 10a. Same as Fig. 4a, except for Alaska, 1352 YST 30 November 1965, for snow, plane dendrites, $R=0.43$ mm hr^{-1}, $T=0.5$C.

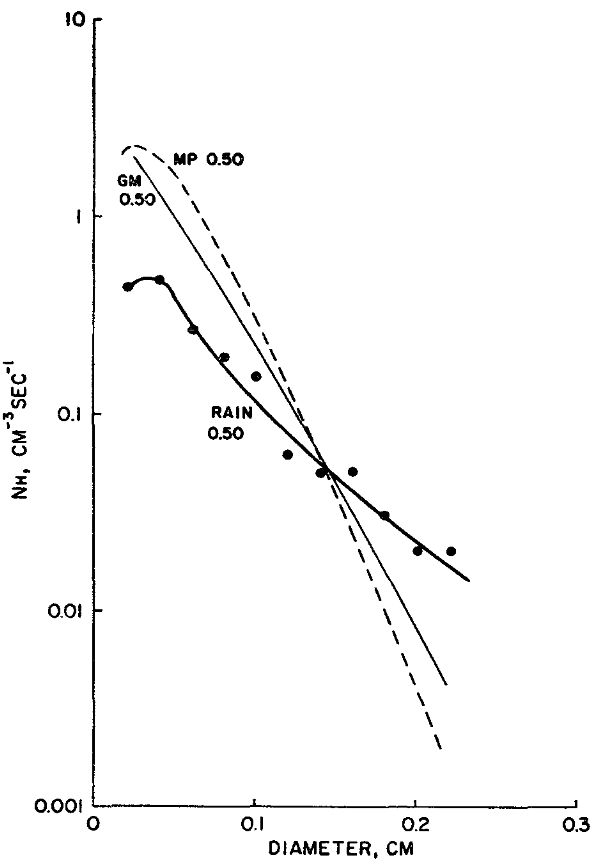

Fig. 10b. Same as Fig. 4b, except for Alaska, 1352 YST, 30 November 1965, for rain, $R=0.50$ mm hr^{-1}, $T=2.4$C.

again changed to snow with the appearance of fog around the station. The size distribution was less steep than either MP or GM.

Throughout this observation, the size distributions of snow and rain at both stations were not classifiable into GM or MP because of the low intensity of precipitation.

In applying size distribution data to radar meteorology, the usual relationship of importance is between rainfall intensity R and

$$Z=\int_0^\infty \frac{N_H}{v} D^6 dD,$$

where v is the fall velocity and D the diameter of the hydrometeor. Due to the abovementioned difficulties in obtaining fall velocities for melting snowflakes, we considered instead the relationship between R and Z_H, where

$$Z_H=\int_0^\infty N_H D^6 dD.$$

While Z_H no longer has any direct physical meaning for radar reflectivity, it is a convenient expression for hydrometeors which change fall speed in a melting layer. On a Z_H-R diagram, snowflakes and raindrops will give separate lines if breakup occurs during melting. This is useful for comparing the present data on snow and rain without considering the GM or MP distributions, especially for the lower rates of precipitation where GM and MP come together. Fig. 5 is an example of this application. Although the size distributions of neither snowflakes nor raindrops could be classified into GM or MP, there was no significant difference between the straight lines fitted to snow and rain. This means the snowflakes melted into raindrops without noticeable breakup on this day.

3) 29 March 1963. A big depression consisting of three lows passed Honshu Island from the Japan Sea to the Pacific Ocean, the precipitation probably coming from the cold front as can be seen in Fig. 2. Observations from about 1100–1230 at stations B and C are shown in Fig. 6. After 1128 the precipitation rate for snow was greater than that for rain. Throughout the observation, rain was observed at the lower station; at the upper station the precipitation consisted of snow with irregular needles sometimes mixed with dendritic crystals, with fog restricting visibility to ~60 m. The elevation of the cloud base was about 1100 m.

The size distributions at both stations deviated markedly from straight lines on a semi-logarithmic

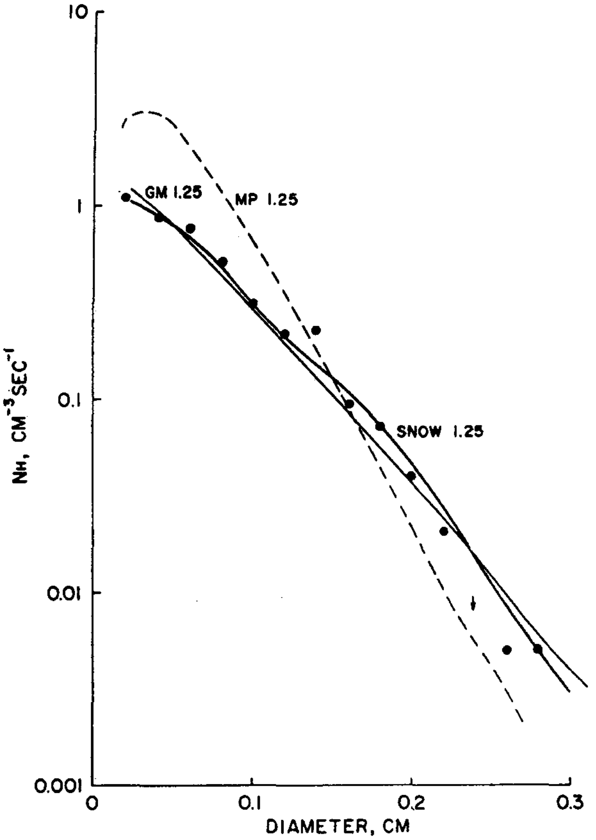

FIG. 11a. Same as Fig. 4a, except for Alaska, 1557 YST 30 Novermber 1965, for snow, plane dendrites, $R=1.25$ mm hr^{-1}, $T=$OC.

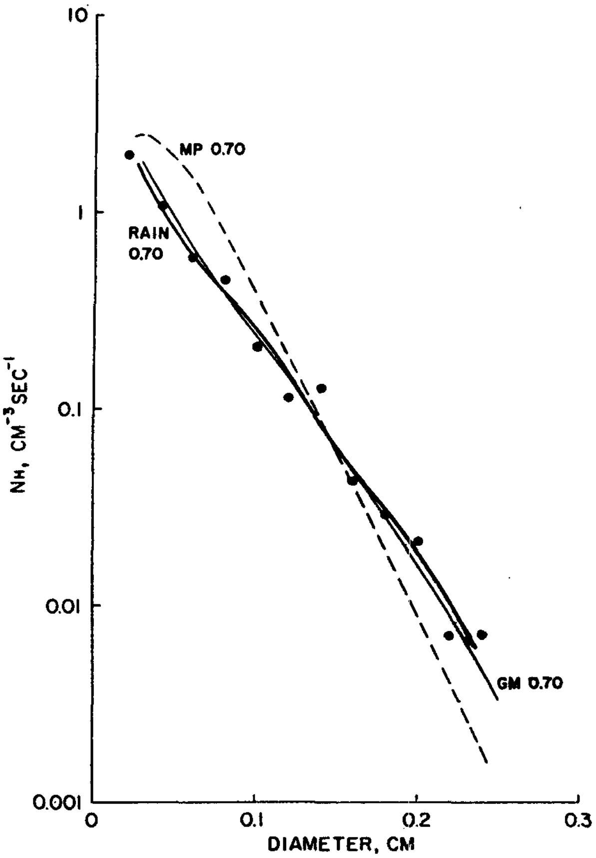

FIG. 11b. Same as Fig. 4a, except for Alaska, 1604 YST 30 November 1965, for rain, $R=0.70$ mm hr^{-1}, $T=1.4$C.

graph, most of the distributions having a hump (see, as examples, Figs. 7a and 7b). Sometimes bimodal humps were noticed; these may have resulted from precipitation elements formed in different humid layers of atmosphere. Fig. 8 shows the upper air sounding made at 0900 JST of the same day at Wajima 320 km west-southwest of the stations. The sounding shows that the formation of needle-shaped crystals at an elevation of 2000 m and dendritic crystals at about 4800 m would be expected, according to Nakaya's classification (1951). The broken line indicates the expected humidity region for snow crystal formation according to Ohtake (1963). This agrees fairly well with the observed crystal shapes at the upper station, assuming slight modification due to orographic convection.

The size distributions of aggregated snowflakes taken at the upper station from 1100 through 1200, at which time observations were terminated, were similar to MP or steeper. The distributions of raindrop size at the lower station were similar to the snow distribution above, except for the last few data which agreed with GM. Sometimes distributions with a peak or hump were noticed, the peaks tending to occur at larger sizes with the passage of time. Distributions with peaks showed quite similar shapes (with appropriate lag time) at both stations. The characteristics appearing in these observations both indicate that the aggregated snowflakes were melted into raindrops without appreciable change of distribution of hydrometeor size, and thus without breakup during their fall through the melting layer. Although we could not observe a well-defined relationship with precipitation rate between the upper and the lower stations, an increase in precipitation rate from 0–20% seems to be reasonable from the present observation if enough clouds exist through a melting layer. This amount of increase of the precipitation rate may be due to the liquid water content in the upper melting layer rather than in the lower melting layer because we could normally see fog in the upper melting layer. While the collection efficiency of completely melted snowflakes should be higher than that of melting snowflakes, because of higher fall speed, the larger cross section of the melting snowflakes and the higher liquid water content higher in the cloud could have the reverse effect. Nevertheless, it could hardly explain the 1–3 mm hr^{-1} increase of precipitation rate which was suggested by Gunn and Marshall, although such a sizable increase of R might sometimes be observed in orographic rain quite aside from the existence of the melting layer. Possibly we should consider the absolute

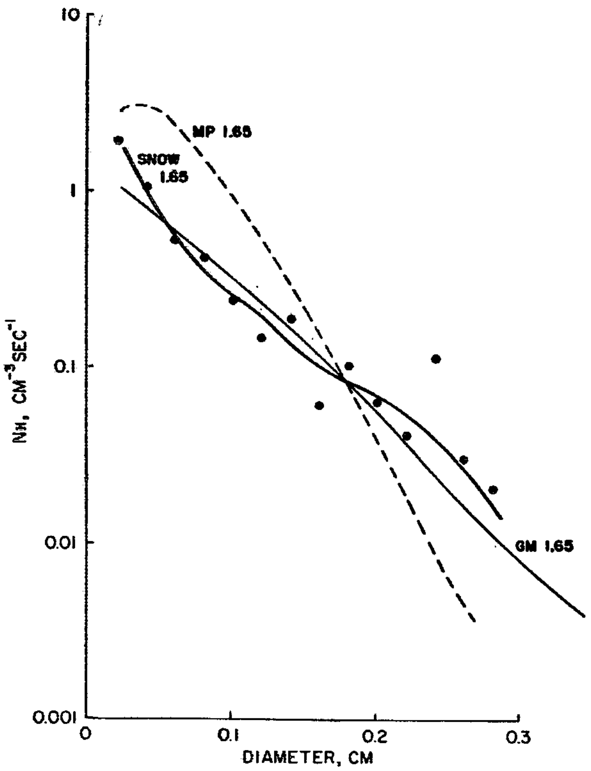

Fig. 12a. Same as Fig. 4a, except for Alaska, 1830 YST 30 November, for plane dendrites, $R = 1.65$ mm hr^{-1}, $T = 0.5$C.

increase of the rate through a melting layer rather than a relative increase. It is less easy to envisage 3 mm hr^{-1} snow rate changing into a 10 mm hr^{-1} rain rate, for instance, than 0.3 mm hr^{-1} of snow changing to 1 mm hr^{-1} of rain.

b. Observations at Douglas Island in Alaska

As can be seen in Fig. 9, the difference of altitude between the upper and lower stations was 311 m with horizontal distance of 2.5 km. The observations were made from 28 November through 1 December 1965. The general weather situation was as follows: Around 1500 YST (135 W longitude; all times mentioned in this section refer to this meridian) 28 November 1965, a low pressure system gradually approached the station from the west of the Gulf of Alaska and stagnated just west of the station until it weakened and disappeared the afternoon of 1 December. During this time an occluded front was intermittently active. For the estimation of upper air structure, the following three stations are available: Yakutat (340 km NW Douglas), Annette (400 km SSE) and Whitehorse (280 km N). Considering the wind direction at this time, the sounding at Annette may be the most appropriate.

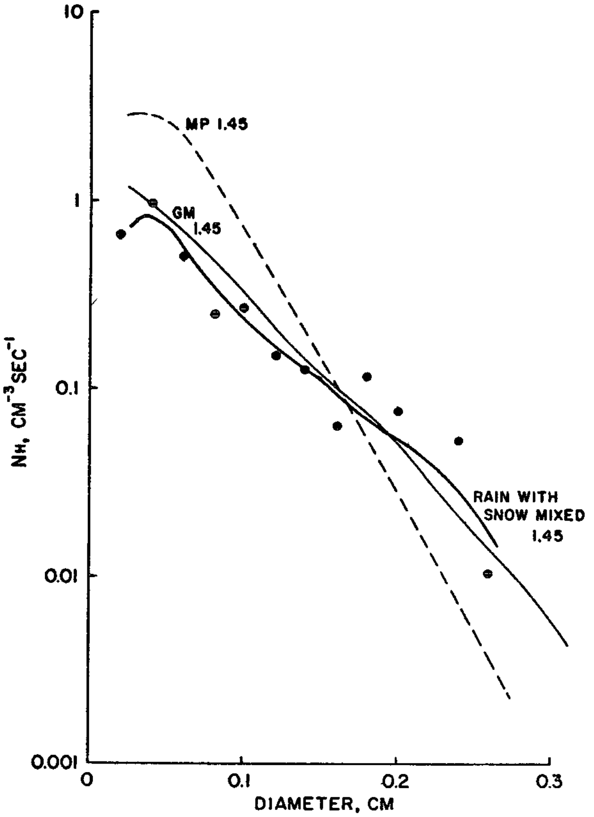

Fig. 12b. Same as Fig. 4b, except for Alaska, 1828 YST 30 November, for rain with snow mixed, $R = 1.45$ mm hr^{-1}, $T = 2.2$C.

1) 28 November 1965, 1614–1800. Observations at both upper and lower stations began at 1125 with temperatures of -2 and 1.3C, respectively. Precipitation at both stations was snow from 1125–1140, the

Table 1. Precipitation rates (expressed as rain intensity) above and below melting layer for selected Alaska observations on 30 November 1965.

Upper station Time (YST)	Rain intensity (mm hr^{-1})	Distribution	Lower station Time (YST)	Rain intensity (mm hr^{-1})	Distribution
1352	0.43	less steep than GM	1352	0.50	less steep than GM
1356	0.80	less steep than GM	1358	1.15	GM
1414	1.39	less steep than GM	1413	1.02	GM
1438	1.51	GM	1440	1.09	GM
1503	2.27	MP	1515	2.55	MP
1510	1.42	MP or GM	1519	1.31	MP
1618–1807	no observation				
1807	0.76	less steep than GM	1809	0.38	less steep than GM
1830	1.65	GM	1828	1.45	GM

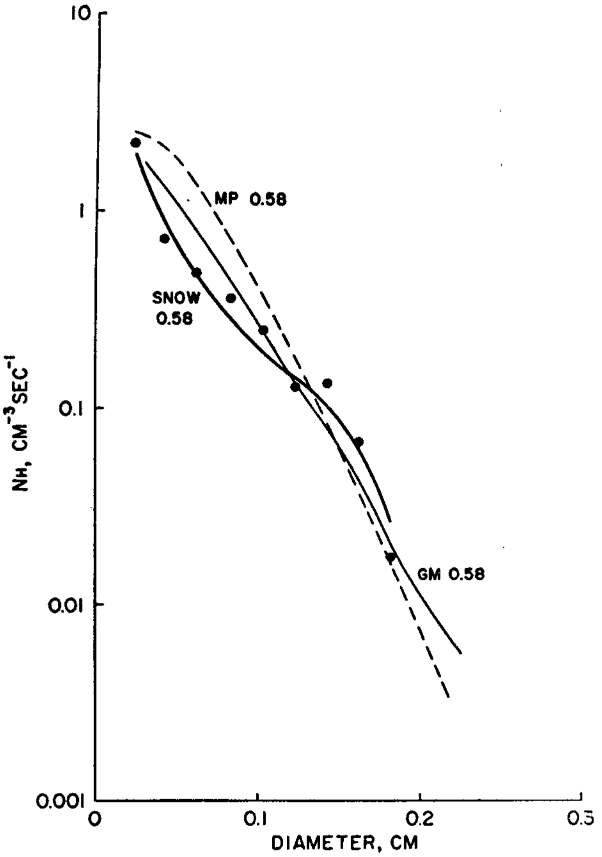

Fig. 13a. Same as Fig. 4a, except for Alaska, 1133 YST 1 December 1965, for capped columns, $R=0.58$ mm hr^{-1}, $T=0.8$C.

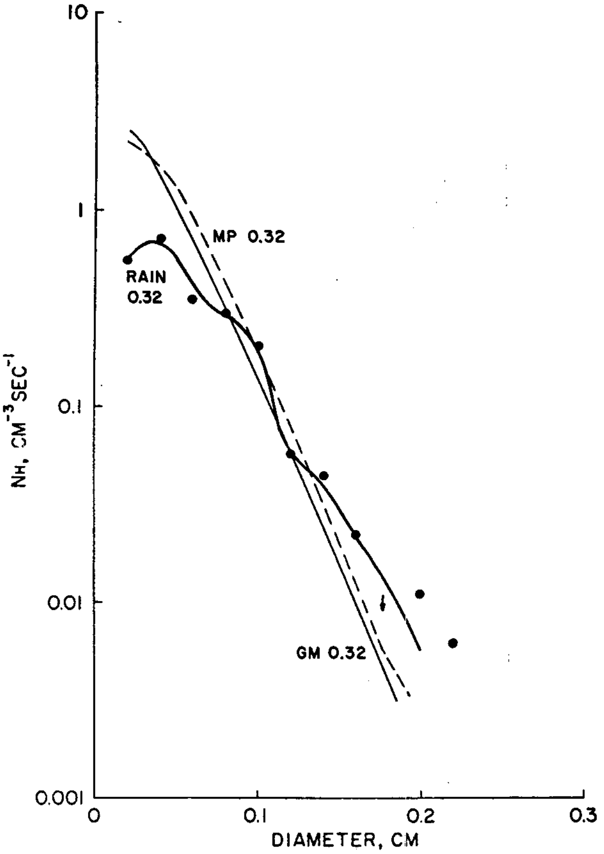

Fig. 13b. Same as Fig. 4b, except for Alaska, 1137 YST 1 December 1965, for rain, $R=0.32$ mm hr^{-1}, $T=3.0$C.

rates were between 0.2 and 0.7 mm hr^{-1}, the crystal shape was plane dendritic, and the size distributions were less steep than GM at both stations.

Between 1405 and 1538, both stations observed snowfalls consisting mainly of needle crystals and a few dendrites with rates of 1.3–3.2 mm hr^{-1}. The distributions of both stations agreed fairly well with MP and with each other.

Starting at 1614, snow at the lower station changed to rain and snow mixed, and then, as the temperature increased to 2.5–3.0C, to rain. The upper station had snow with needle and dendritic crystal shapes and with precipitation rates varying from 0.4 to 1.4 mm hr^{-1}, and a temperature of -1C. At this time the rates at the lower station were 0.3–1.3 mm hr^{-1}, almost the same range of rates as at the upper station. The size distributions of snowflakes at the upper station were similar to GM. The distributions of raindrop size at the station just below the melting layer were also similar to GM through 1644.

During 10 min starting at 1646, the precipitation rates increased suddenly to 3.2–4.5 mm hr^{-1} at both stations. At the upper station, with needle crystals, the distribution pattern resembled MP as in the second observation. At the lower station the distribution of raindrop size lay between MP and GM, being closer to GM at smaller drop sizes and MP at larger sizes.

Further observations, which continued till 1800, indicated that the rates of precipitation were less than 1 mm hr^{-1} at both stations and the shapes of the snow crystals were needle, plane dendritic, graupel and irregular needle mixed. No distinction between the MP and GM distributions could be made, because the horizontal standard distributions N_H of MP and GM approach each other for precipitation rates <1 mm hr^{-1}. However, the data taken at both stations did not depart from the standard distribution for less than 1 mm hr^{-1} of precipitation rate, and it is significant that distributions at both stations were the same.

2) 29 November 1965, 1229–1330. The observations showed snow partially melted at the upper station with a temperature of about 3C. The shape of the crystals was unknown. The distributions were similar to GM for the first half hour. At the lower station the temperature was $\sim$3.7C. The size distribution of raindrops were between GM amd MP, but closer to GM until 1300. Between 1310 and 1330 both distributions were roughly in accord with the MP distribution with a scarcity of drops <0.6 mm at both stations.

3) 30 November 1965, 1229–1848. The period was

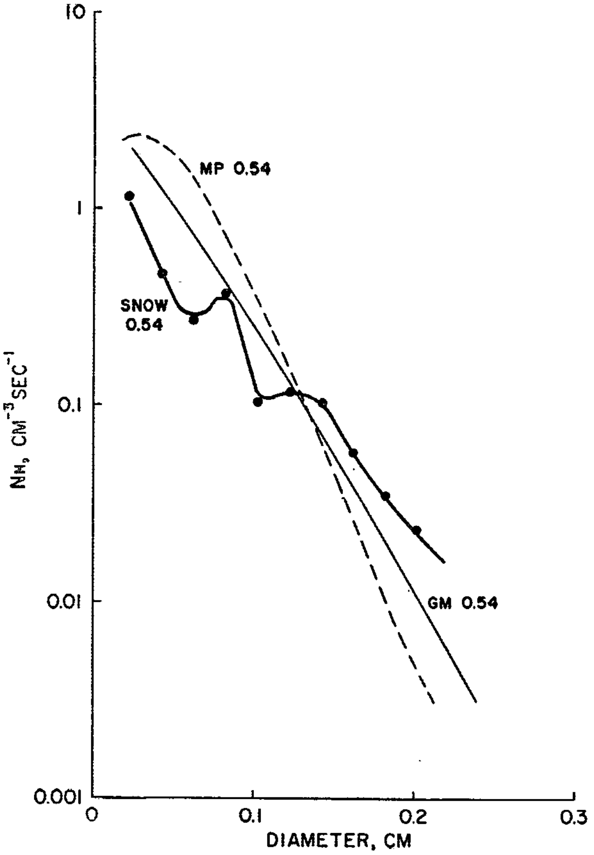

FIG. 14a. Same as Fig. 4a, except for Alaska, 1140 YST 1 December 1965, for capped columns, $R=0.54$ mm hr^{-1}, $T=0.8$C.

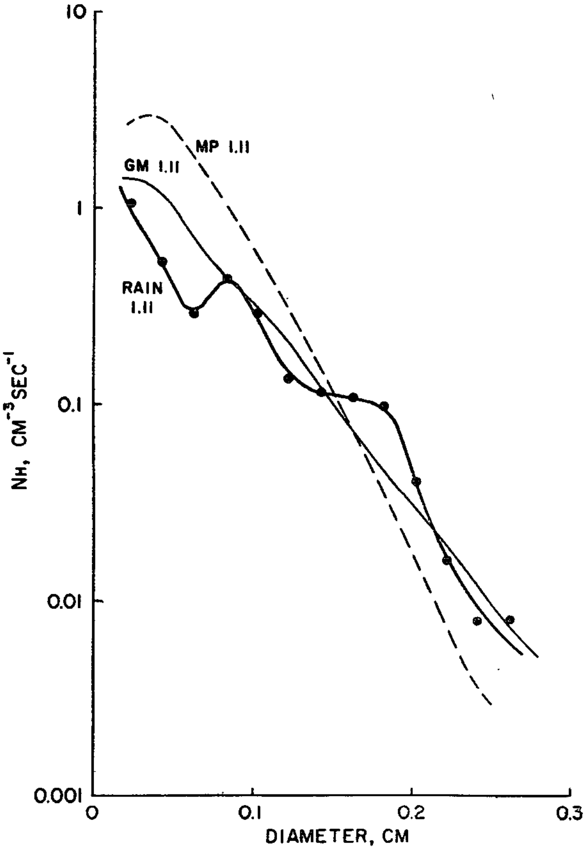

FIG. 14b. Same as Fig. 4b, except for Alaska, 1147 YST 1 December 1965, for rain, $R=1.11$ mm hr^{-1}, $T=3.0$C.

preceded by snowfalls with plane dendritic crystals, which agreed with the GM distribution at both stations. After a change in temperature from 1.2 to 2.4C, rain fell from 1230 at the lower station. During the observations the temperature at the upper station was 0–0.5C. The size distributions at both stations were similar to GM or a little less steep than GM (see examples in Figs. 10a to 12b). The crystal shape continued to be plane dendritic until the time the precipitation at the lower station changed from snow to rain. Rain at the lower station was sometimes mixed with melting snow.

For the majority of the observations the distributions of both stations agreed with each other and with GM, in the range of 0.03–2.5 mm hr^{-1}, although a few distributions were closer to MP than to GM when the crystal shape changed into irregular needles and a few single dendrites.

Throughout the observations of this day, the shapes of the size distribution of both snowflakes and raindrops above and just below melting layer agreed especially well with each other as shown in Table 1. It can also be seen that the precipitation rates corresponded well.

4) 1 December 1965, 1025–1152. The temperature at the upper station was 0.8C. Snow crystal shape seemed to be plane and spatial dendrites. At the lower station temperature was 3.0C. Precipitation rates lay between 0.2 and 2 mm hr^{-1} at both stations. Both distributions started out as MP type, then changed to between GM and MP. However, after 1133, the size distributions of both snowflakes (with crystals in the form of a capped column) and raindrops were in agreement in having distributions steeper than GM (see Figs. 13a to 14c as examples).

Throughout the observation period, despite the time changes of size distributions and precipitation rates at the respective stations due to changing weather condition, the distribution changes at both stations appeared almost simultaneously. In other words, the size distributions of raindrops below the melting layer were followed by those of snowflakes above the melting layer. The conservation of the distribution curve could be seen not only in the slope when the curves were monotonic but also in the positions of the peaks of distribution when these appeared. The slope of the distribution curve also changed due to changes in the shape of snow crystals composing the snowflake aggregates.

Distributions equal to or less steep than GM distribution could be seen in snowflakes composed of plane dendrites, while snowflakes of needle crystals gave MP distributions. In addition, upper air soundings tended

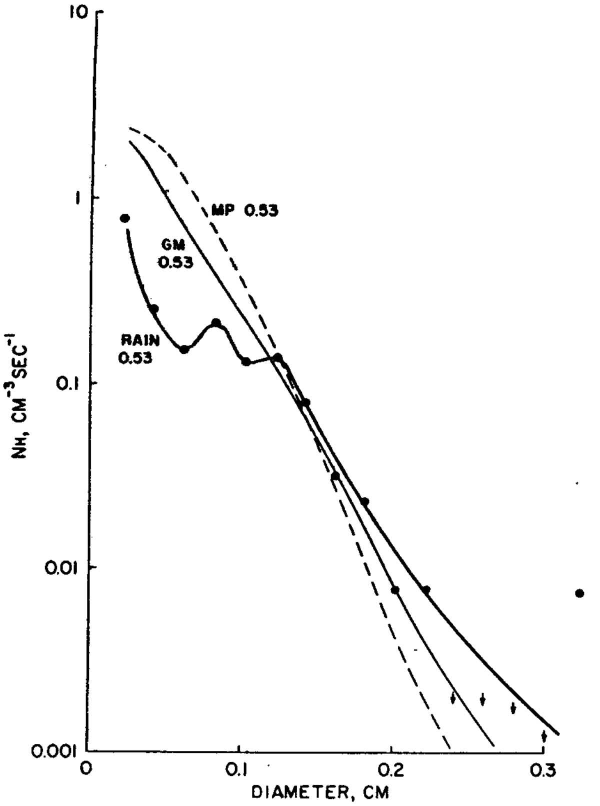

FIG. 14c. Same as Fig. 4b, except for Alaska, 1152 YST 1 December 1965, for rain, $R=0.53$ mm hr^{-1}. Note similarity of irregularities in Figs. a and b. $T=3.0$C.

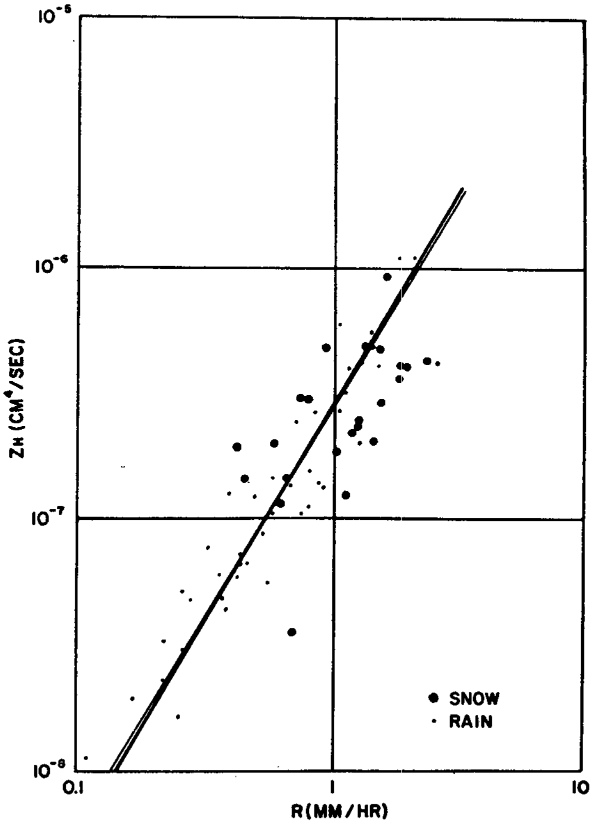

FIG. 15. Z_H-R relation for snowflakes and raindrops sampled on 30 November 1965, Alaska.

to verify that the crystal shapes were determined by the conditions of temperature and humidity according to Nakaya's classification. This means that the size distribution of raindrops at the bottom of the melting layer is controlled by upper air conditions such as temperature and humidity, that the sizes of melted snowflakes are conserved through the melting layer, and that a snowflake melts into a single raindrop without breakup. Precipitation rates were almost the same at both stations. Fogs in the melting layer due to cooling by the latent heat of fusion of snowflakes did not appear during the observations.

A plot of Z_H vs R was made for each of the four days of observations, the lines being fitted by eye. Slopes of the lines, $d(\log Z_H)/d(\log R)$, were sometimes greater for rain and sometimes greater for snow. This may be due to the uncertainty of R or Z_H in the observations, since a single large drop can change R and Z_H very easily in these cases. In order to make Z_H-R relationships from such observations huge numbers of snowflakes or raindrops should be measured, or R should be measured in some other way independent of its computation from the filter paper recordings. However, the combined plots of both snowflakes and raindrops for the present data give good average results as shown in Figs. 15 and 16. In these figures, the fitted lines for raindrops agree remarkably well with those for snowflakes, indicating that each snowflake is melted into a single raindrop.

4. Conclusions

We have found no evidence for the breakup of snowflake aggregates during melting, or of a considerable increase in the rate of precipitation from the top of the bright-band melting layer to the bottom. Both of these findings are contrary to the earlier suggestions of Gunn and Marshall (1958), based on drop-size observations that were not directly related, and on such radar observations as were available at that time.

We do not believe that evaporation, accretion and coalescence can transform the GM distribution into the MP type below the melting layer during heavy precipitation. Dyer (1968) reported that the Doppler fall speed of raindrops below the melting layer generally remains virtually constant with height. This suggests that only minor modification of the drop-size distribution or precipitation rate would be expected between the melting level and the surface, and that the size distribution of raindrops is thus dependent on that of the precursor snowflakes. The widely used MP drop-size distribution tion would in this view represent an average derived from individual storms with GM, MP, and warm rain

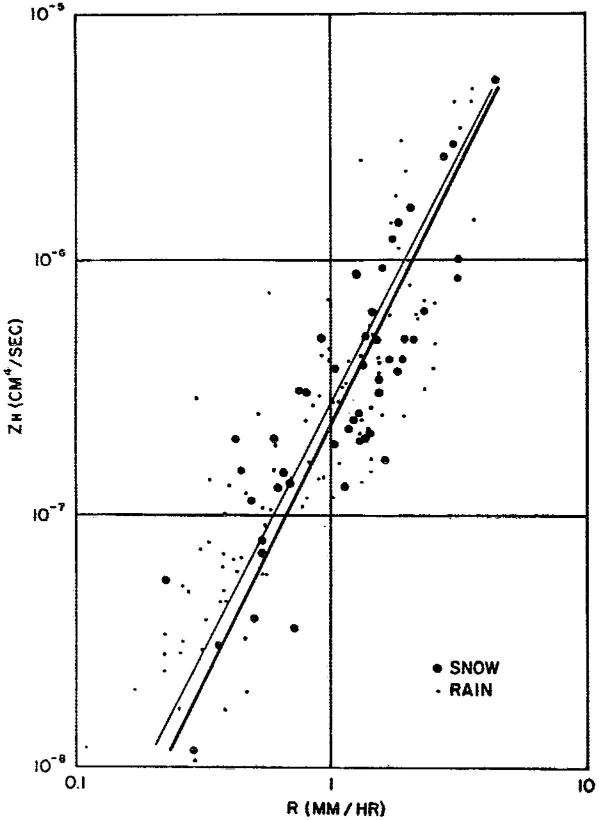

FIG. 16. Z_H-R relation for snowflakes and raindrops sampled on 28 November through 1 December 1965, Alaska.

drop-size distributions, warm rain giving steeper distributions than MP and GM (Blanchard, 1953). There is some evidence that the type of distribution observed in a given snowfall depends on the shape of the crystals. Further research is indicated on both the relationship of crystal shape with size distribution and the radar reflectivity of snowfall of varying crystal shapes.

But as far as the melting band itself is concerned, our observations indicate explicitly the absence of either breakup of drops or considerable changes in precipitation rate.

Acknowledgments. The author wishes to thank Mr. T. Shimura and Mr. H. Isaka, who were students of Tohoku University, and Mr. G. Lindholm, University of Alaska, for their assistance in collecting the data. The author is also indebted to Prof. G. Yamamoto, Tohoku University, for his encouragement throughout the course of this work and to Prof. J. S. Marshall, McGill University, for his discussion and critical review of this report. The research is supported by the Atmospheric Sciences Section, National Science Foundation, under Grant NSF GP-4839.

REFERENCES

Blanchard, D. C., 1953: Raindrop size-distribution in Hawaiian rain. *J. Meteor.*, **10**, 457–473.

Dyer, R., 1968: Doppler measurements in stratiform rain. *Proc. 13th Radar Meteor. Conf.*, Amer. Meteor. Soc., 144–147.

Gunn, K. L. S., and J. S. Marshall, 1958: The distribution with size of aggregate snowflakes. *J. Meteor.*, **15**, 452–461.

Marshall, J. S., and W. M. Palmer, 1948: The distribution of raindrops with size. *J. Meteor.*, **5**, 165–166.

Nakaya, J., 1951: The formation of ice crystals. *Compendium of Meteorology*, Boston, Amer. Meteor. Soc., 207–220.

Ohtake, T., 1963: Hemispheric investigation of warm rain by radiosonde data. *J. Appl. Meteor.*, **2**, 594–607.