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Z–R RELATION FOR GRAUPELS AND AGGREGATES OBSERVED AT SYOWA STATION, ANTARCTICA

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Abstract: The radar reflectivity factor Z and the snowfall rate R were measured by a vertical pointing radar and a high sensitivity snow gauge, respectively. From these data we found a best fit Z–R relation for three snowfall events. The diameter and fall velocity of snow particles were also measured at the radar site by using a video camera and an image processor. The types of snow particles described in this paper are aggregates and graupel-like particles, which account for much of snowfall in Antarctica.

The range of snowfall rate is similar in all three cases, while the radar reflectivity factor is much different. For the same radar reflectivity factor, the snowfall rate of graupel-like particles was about seven times as large as that for aggregates.

1. Introduction

In measuring snowfall rate using radar, a Z–R relation is needed to calculate the snowfall rate from the radar reflectivity factor. Many Z–R relations have been obtained (for example, MARSHALL and GUNN, 1952; GUNN and MARSHALL, 1958; SEKHON and SRIVASTAVA, 1970; SATO *et al.*, 1981; FUJIYOSHI *et al.*, 1990). However, in the most of them the snowfall rate was not estimated from actual radar data, because Z and R for these relations were not obtained from the measurements of Z and R themselves. Most radar reflectivity factors were calculated from the size distribution of snow particles measured on the ground, and snowfall rates were calculated from the size distribution or estimated from the snow depth. There have been few Z–R relations obtained from the measurements of actual radar reflectivity and actual snowfall rate (FUJIYOSHI, 1990).

In this work we measured the radar reflectivity factor and the snowfall rate simultaneously to obtain the best-fit Z–R relations for each snowfall at Syowa Station (69°S, 40°E) on the coast of Antarctica. We also measured the size and fall velocity of snow particles to determine the type of particles for each snowfall event.

This paper describes three snowfall events which continued for several hours. The types of snow particles in the three cases were aggregates of bullets and crossed-plates, aggregates of dendrite crystals, and heavily rimed crystals. These types of snow particles are often observed at Syowa Station (KIKUCHI, 1969; IWAI, 1986). First we will show the size and fall velocity of snow particles in each case. Next we will show the Z–R relationships for each case.

2. Instruments

A vertical pointing radar was used to measure the amount of snowfall and ice water content in the atmosphere continuously at Syowa Station. The data of this radar were sampled from ground level to 6.4 km in altitude with height resolution of 50 m every 10 s during the period from 1988 to 1989 (WADA, 1989). A highly sensitive snow gauge was used to compare the radar reflectivity factor with the snowfall rate in 1989. The gauge was shielded by a wooden wall to protect it from strong wind. It measured the weight of snowfall in a bucket on an electric balance; the weight data were input to a computer by a cable and stored (KONISHI *et al.*, 1988). The minimum detectable snowfall rate of this gauge with a bucket 35 cm in diameter was 0.062 mm/hr, which corresponds to an increase of 0.1 g/min. The lowest level of radar data was 400 m in altitude. We compare the data at this level with the snow gauge data.

The size and fall velocity of snow particles were also measured by image analysis. A side view of falling snow particles into a vertical tunnel was taken by a video camera 1.2 m from the tunnel. The length of the tunnel was 2 m; its horizontal section was one by one meter. The images of falling snow particles were put into an image processor continuously every 1/30 s. These systems were constructed by MURAMOTO *et al.* (1989). We also used a microscope and a 35 mm camera to record the shape of snow particles.

3. Results

3.1. Size and fall velocity

Measurements of snowfall rate were difficult in most cases at Syowa Station, because precipitation was usually accompanied by strong wind. We took about one thousand pictures of snow particles by microscope when winds were weak. Most of the precipitating snow crystals were bullets, combination of bullets, columns, crossed-plates and dendrites. When the precipitation particles were single crystals or combinations of a few snow particles, the snowfall rate was usually small. On the other hand when the particles were combinations of numerous aggregates or rimed crystals, a high snowfall rate was observed. The three snowfall events which brought high snowfall rates to Syowa Station will be described later.

The meteorological conditions during the three snowfall events are summarized in Table 1. Case A was from 2200 LT on October 24 to 1000 LT on October 25, case B was from 1300 LT on July 1 to 2100 LT on July 1 and case C was from 2300 LT on May 21 to 0200 LT on May 22, respectively. Precipitation continued for several hours and wind didn't exceed 5 m/s during these periods. The types of snow particles observed in cases A, B and C were different from each other. The predominant snow particles were aggregates of bullets and crossed-plates, aggregates

Table 1. Meteorological conditions for three snowfalls.

Date	T(hr)	t (°C)	ws (m/s)	R (mm)	R_{max} (mm/hr)
Case A (October 24–25, 1989)	11	−3	2	1.85	0.35
Case B (July 1, 1989)	8	−9	2	1.40	0.40
Case C (May 21–22, 1989)	3	−14	3	0.38	0.27

T: Duration of the snowfall. t: Mean surface air temperature. ws: Mean wind speed. R: Total amount of snowfall. R_{max}: Maximum snowfall rate.

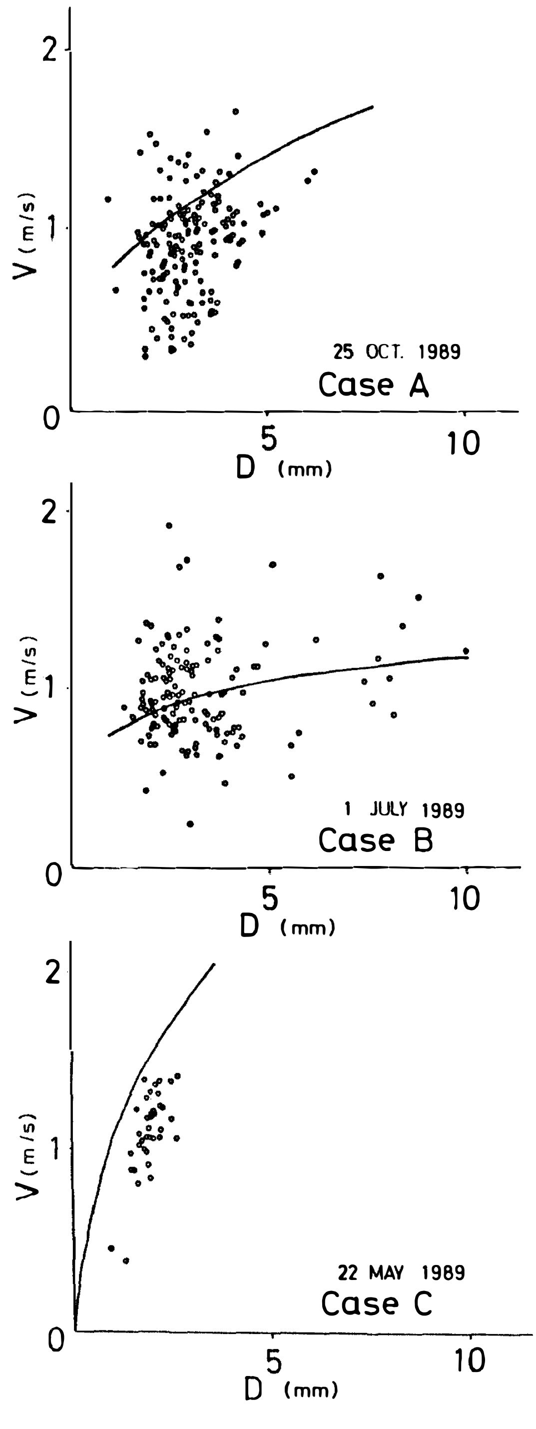

Fig. 1. Fall velocity versus diameter of snow particles at Syowa Station. The lines show the best fit curve for particles by LOCATELLI *and* HOBBS *(1974). A: Aggregates of unrimed side planes assemblages of plates bullets and columns, B: Aggregates of unrimed dendrites and radiating assemblages of dendrites, C: Hexagonal graupels.*

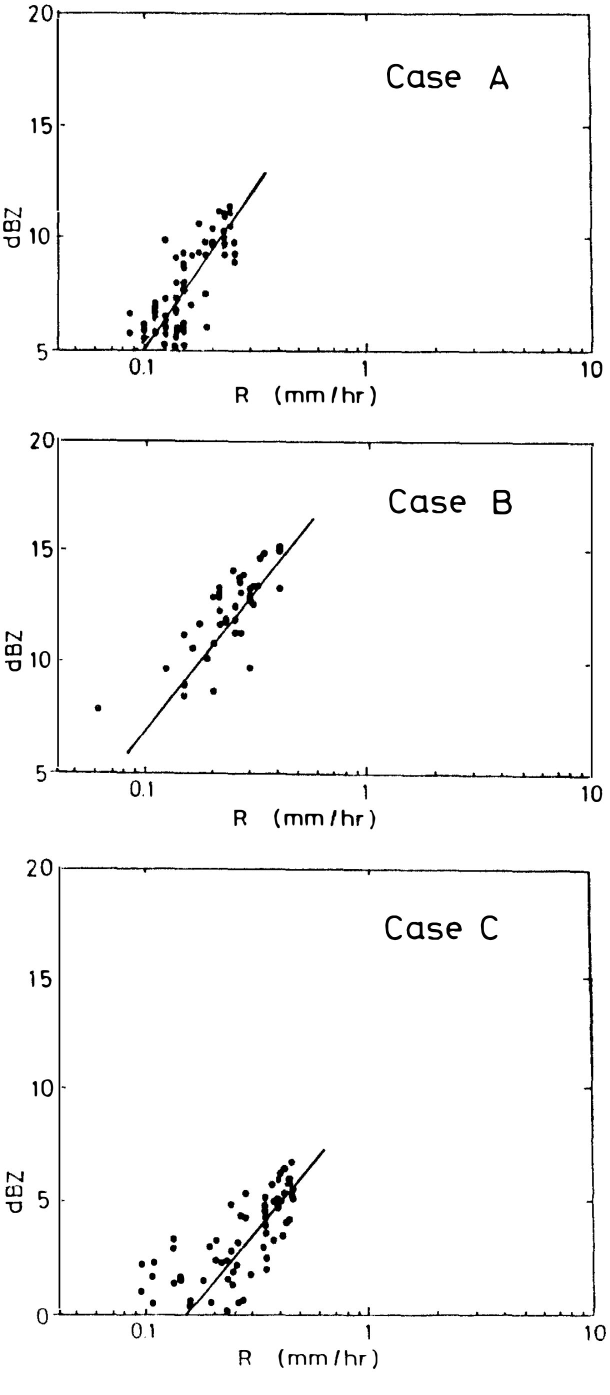

Fig. 2. The relationship between snowfall rate and radar reflectivity factor observed at Syowa Station (Case A: October 25, 1989, Case B: July 1, 1989, Case C: May 22, 1989).

of dendrite crystals, and heavily rimed crystals, respectively. The diameters and fall velocities of these particles are shown in Fig. 1. Each open circle in this figure indicates the relation between diameter and fall velocity for each particle detected by video camera.

The type of snow particles can be seen in the diameter and fall velocity distributions of the snow particles. In case A, the circles were up to 6 mm in diameter and 1.7 m/s in velocity. In case B, they were distributed more widely, up to 10 mm in diameter and 2 m/s in velocity. On the other hand in case C, they were concentrated in a narrow region, up to 3 mm and 1.4 m/s. The maximum sizes of aggregates in cases A and B were larger than those of the rimed crystals in case C, though the averaged velocities are similar in each case. The aggregates of dendrite crystals in case B had a wide range, up to 10 mm, which was larger than aggregates of bullets and crossed-plate crystals in case A.

The size and fall velocity of snow particles have been measured by earlier workers in various places. The solid lines in this figure show the relation of size and fall velocity for the same type of snow particles obtained in the Cascade Mountains in winter by LOCATELLI and HOBBS (1974). Our results are widely distributed around the lines.

3.2. *Z–R relation*

Since the clouds were stratus in all three cases, the snowfall rate and the echo intensity didn't change so fast as they would with convective clouds. Therefore we can correlate Z and R.

Figure 2 shows the relationship between snowfall rate and radar reflectivity factor. Each solid circle represents a 5 min averaged value. The snowfall rates were weak in all cases in comparison with that at middle latitude. The snowfall rates in the three cases were not much different from one another. The maximum snowfall rates were 0.3, 0.4, 0.5 mm/hr, respectively. On the other hand, the radar reflectivity factors were different from one another. The maximum radar reflectivity factors were 12, 16 and 7 dBZ, respectively. Between cases A and B for aggregates and case C for heavily rimed crystals, the ranges of radar reflectivity factor were much different. Therefore, the regression lines for the Z–R relations were much different between the aggregates and the heavily rimed particles.

The coefficients of B and β in the equation $Z=B\cdot R^{\beta}$ were obtained from Fig. 2. Table 2 summarizes the coefficients Z–R in these three cases. The coefficient β which represents the slope of the regression line was similar in the three cases, while the coefficient B was much different.

Table 2. The coefficients (B and β) in the Z–R relation ($Z=B\cdot R^{\beta}$).

	B	β
Case A	74	1.4
Case B	104	1.3
Case C	10	1.2

4. Discussion

The coefficient B in the Z–R relation is the radar reflectivity factor on the regression line when the snowfall intensity is 1 mm/hr. The radar reflectivity will become large when the particle size increases by coalescence because the radar reflectivity factor is proportional to the sixth power of the snow particle radius. On the other hand, the snowfall rate does not change so much because the fall velocity of snow particles does not change much with size. Therefore the radar reflectivity factor for large particles like aggregates will be large compared to that for densely rimed small particles at the same snowfall rate. The difference of radar reflectivity factor at the same snowfall rate show the difference of apparent density of particles defined the mass in unit volume contains the open spaces in the particles. When the apparent density is small, such as in the case of aggregates, the coefficient B will be large, as shown in cases A and B of Fig. 2. On the other hand, when the apparent density of snow particles is large, such as in the case of graupels or heavily rimed crystals, coefficient B will be small, as shown in case C of Fig. 2. The apparent density of snow particles can be estimated from the coefficient B.

The regression lines show that the snowfall rate in case C is about 7 times as large as that in case B if the radar reflectivity factor is the same. If we use the same coefficients B and β for all precipitation, the snowfall rate may contain large errors. We can estimate the snowfall rate accurately using radar by using the best Z–R relation for each type of snow particle.

5. Summary

Z–R relations for three cases observed at Syowa Station were investigated. The types of snow particles described in this paper were aggregates and graupel-like particles, which account for much of the snowfall in Antarctica. The shapes of snow particles were recorded by microphotograph and video camera, and classified according to size and fall velocity.

The range of snowfall rate was similar in all three cases, while the radar reflectivity factor was much different. For the same radar reflectivity factor, the snowfall rate for graupel-like particles was about 7 times as large as that for aggregates.

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