NOTES AND CORRESPONDENCE

Relationships between Radar Reflectivity Factor and Liquid-Equivalent Snowfall Rate Derived by Direct Comparison of X-Band Radar and Disdrometer Observations in Niigata Prefecture, Japan

Sento NAKAI, Katsuya YAMASHITA, Hiroki MOTOYOSHI

*Snow and Ice Research Center,
National Research Institute for Earth Science and Disaster Resilience, Nagaoka, Japan*

Toshiro KUMAKURA

Department of Civil and Environmental Engineering, Nagaoka University of Technology, Nagaoka, Japan

Shigeki MURAKAMI and Takafumi KATSUSHIMA

Tohkamachi Experimental Station, Forestry and Forest Products Research Institute, Tokamachi, Japan

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Abstract

The relationships between the radar reflectivity factor for horizontal polarization (Z_h) at the X-band and the liquid-equivalent snowfall rate (R) are presented for six hydrometeor classes of solid precipitation. These relationships were derived by comparing the values of Z_h , R , and the hydrometeor class obtained by performing simultaneous observations in Niigata Prefecture, Japan. The relationships were assumed to be of the form $Z_h = B R^{1.67}$, where B denotes an experimentally determined coefficient. The values of R and the hydrometeor class were determined using a high-resolution precipitation gauge and an optical disdrometer, respectively, set up inside a wind-shield net. The average Z_h value was determined for an analysis area of approximately 100 km², located upwind of the ground-observation site. The prevailing hydrometeor class, its representative size, and the fall speed, along with the average Z_h , R , and B values, were determined for 48 cases considered over three winters. The average B value for the “heavily rimed snow aggregate” was smaller than that for the “rimed snow aggregate”. The largest B value was derived for a case of aggregates of unrimed dendritic particles (unrimed-D class). The case involving aggregates of unrimed low-temperature-type crystals (unrimed-C class) showed the smallest B value. For graupel cases, the average B value was roughly twice that of the rimed and heavily rimed snow aggregate classes and much smaller than that of the unrimed-D class. Snow aggregates demonstrated a stronger or weaker backscattering than graupel depending on the riming degree and types of constituent ice crystals in the X-band.

Corresponding author: Sento Nakai, Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Resilience, Suyoshi-Maeyama 187-16, Nagaoka, Niigata 940-0821, Japan

E-mail: saint@bosai.go.jp

1 Present affiliation: Kyushu Research Center, Forestry and Forest Products Research Institute, Kumamoto, Japan

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1. Introduction

The relationship between the equivalent radar reflectivity factor (Z_h , for horizontal polarization, in $\text{mm}^6 \text{m}^{-3}$) and the liquid-equivalent snowfall rate (R , in mm h^{-1}) changes significantly with the shape of solid precipitation particles (e.g., Sato et al. 1981), causing difficulty in quantitative precipitation estimation (QPE) using ground- and space-borne radars. Rasmussen et al. (2003) theoretically demonstrated that variations in the Z_h – R relationship for snow aggregates depend on the size distribution-function intercept, fall speed, and the dry/wet (including rimed snowflakes) condition of the precipitation particles. Further, the precipitation intensity varies by approximately four times for the same Z_h value. Additionally, they revealed that precipitation intensities determined using experimental formulas from existing literature fall within this range. However, Rasmussen et al. (2003) assumed the fall speed of particles to equal 0.9 m s^{-1} and they did not discuss the Z_h – R relationship for graupel.

Ohtake and Henmi (1970) derived the following Z_h – R relationship for graupel:

$$Z_h = 202 R^{1.6}. \quad (1)$$

Equation (1) is nearly identical to the well-known equation of Marshall and Palmer (1948), which was revised by Marshall and Gunn (1952), represented by

$$Z_h = 200 R^{1.6}. \quad (2)$$

Although the values of the exponents in Eqs. (1) and (2) differ from that reported by Rasmussen et al. (2003) (i.e., 1.67), they lie in the middle of the range for the Z_h – R relationships reported by Rasmussen et al. (2003). Applying Eq. (2) to snowfall as a rough approximation is not necessarily incorrect, as first indicated by Marshall and Gunn (1952). They assumed the fall speed of snow to be 1 m s^{-1} and described that “snowfall (rainfall) R can be determined within a factor of 3.5 (2.5)”. For radar QPE, the Global Precipitation Measurement (GPM) algorithm (Seto et al. 2021) and ground-based applications require Z_h – R relationships and other snow parameters such as DFR

(differential frequency ratio; Liao et al. 2020; Yu et al. 2021) to be derived considering the microphysical characteristics of precipitation particles, that is, the hydrometeor classes of solid precipitation and raindrop-size distribution.

Actual solid precipitation particles are a mixture of various particles (such as snowflakes and graupel) changing with time. Therefore, it is necessary to consider the prevailing hydrometeor class when deriving Z_h – R relationships for a mesoscale cloud system. Fujiyoshi et al. (1990) obtained Z_h – R relationships for snowflakes consisting of rimed dendrites by directly comparing 1273 pairs of data using 1-min-interval surface snowfall intensities and 3-min-interval Z_h values at a low elevation angle (1.5°). They also showed that the 30-min-average values yield a higher correlation coefficient of the Z_h – R relationship than the 1-min-interval data, indicating the difficulty in explicitly reflecting detailed changes inside a cloud in Z_h – R relationships.

This paper discusses variations in Z_h – R relationships with regard to the degree of riming. To this end, we have derived Z_h – R relationships for six hydrometeor classes of solid precipitation (“unrimed-C”, “unrimed-D”, “rimed snow aggregate”, “heavily rimed snow aggregate”, “graupel”, and “small particle”) by defining “cases” with time durations exceeding 30 min. A field experiment involving a weather radar and ground-observation site was conducted in Niigata Prefecture, Japan—a heavy-snowfall area (“gosetsu chitai”) facing the Sea of Japan (Steenburgh and Nakai 2020). Precipitation particles were observed on the ground within the range of the radar, and direct data comparison was possible. The specifications of the observations, data analysis methods, and results are described in Sections 2, 3, and 4, respectively. Section 5 presents the Z_h – R curves derived and summarizes the paper.

2. Observations

We conducted intensive observations in the field experiment in Niigata Prefecture during the winters of 2010/2011, 2011/2012, and 2015/2016. The field experiments included (1) X-band radar observations to

obtain Z_h , (2) high-frequency, high-resolution precipitation-intensity observations, and (3) optical-disdrometer observations of solid precipitation particles to determine their hydrometeor class, representative size, and fall speed. Observations 2 and 3 were conducted at the Tohkamachi Experimental Station of Forestry and Forest Products Research Institute (FFPRI), 34.4 km from the Snow and Ice Research Center (SIRC) of the National Research Institute for Earth Science and Disaster Resilience (NIED) and within the range of the X-band (9.4 GHz) weather radar at the SIRC, which was used for radar observations (Fig. 1).

The radar hardware was replaced in March 2014, whereas the scan strategy and relevant radar specifications remained largely unchanged with a 10-min measurement time resolution. The beam width was $< 1.25^\circ$. The data resolution was 1.0° (azimuth) and 100 m/150 m (range). The pulse repetition frequency (PRF) was 1800 Hz (the low frequency of the dual PRF was 1350 Hz)/1500 Hz, the number of samples in a ray was 64, and the antenna scan speed was 3.3 rpm/3 rpm. The detailed radar specifications are described in Nakai and Yamashita (2018), Yamashita et al. (2019), and Iwanami et al. (1996). The numbers before and after “/” indicate the specification before and after the hardware replacement.

A snowfall-particle-observation site (hereinafter referred to as the “snowfall site”) was set up in the observation field of the Tohkamachi Experimental Station. It is equipped with a PARSIVEL (also referred to as “PARSIVEL 1”) optical disdrometer (Löffler-Mang and Joss 2000; Löffler-Mang and Blahak 2001; Battaglia et al. 2010), an SR-2A high-resolution precipitation gauge [with specifications identical to those of the “precipitation detector” described in Tamura (1993)], and other supporting facilities housed inside a tower with a windshield net (Fig. 2a). PARSIVEL is a single-beam optical disdrometer, and fall-speed calculations are performed under certain assumptions (Battaglia et al. 2010) built into the embedded firmware. In this study, the fall-speed output obtained from PARSIVEL was used without modifications. The “size” of the PARSIVEL output corresponds to the diameter of an equivalent sphere. This output was subsequently converted to the maximum width using the axial ratio described in Eq. (1) reported by Battaglia et al. (2010). SR-2A has a precipitation-intensity resolution two orders higher than that of typical tipping-bucket precipitation gauges, making it suitable for comparison with PARSIVEL and radar data. The measurement time resolution of SR-2A and PARSIVEL equals 1 min. Table 1 summarizes the specifications of the

Fig. 1. Observation field. The open circle and cross mark indicate the SIRC and Tohkamachi Experimental Station (TES), respectively. The area Z_h averaging is indicated by an annular fan shape. A digital topographic map of the Geospatial Information Authority of Japan is used.

facilities. Monitoring images (Fig. 2b) were automatically recorded by a web camera at 10-min intervals and used for checking the snow accretion on the facilities. The height of the tower top and facilities was determined while considering the expected maximum snow depth (Fig. 2c). The whole site was powered by a single 100 V/15 A power supply and had battery backup.

3. Data analyses

3.1 Classification of solid precipitation particles by the center-of-mass flux distribution method

A two-dimensional (2D) fall speed versus particle diameter histogram of falling snow particles can be obtained at 1-min intervals using PARSIVEL (Löffler-Mang and Joss 2000; Yuter et al. 2006); examples are shown in Fig. 3. The two 2D histograms in the figure have a clear difference in shape. The size and fall speed of the observed particles are distributed along the experimental line for conical graupel reported by Locatelli and Hobbs (1974), as shown by “G” in Fig. 3a. This indicates that almost all the particles observed in 1 min at the indicated time were graupel. Similarly, in Fig. 3b, almost all the particles observed in 1 min at the indicated time were snow aggregates.

Ishizaka et al. (2013) developed a new analysis method, the center-of-mass flux distribution (CMF)

Fig. 2. Snowfall site: (a) external appearance and facilities attached to the tower equipped with a windshield net, (b) sample web-camera images, and (c) site image captured during summer (left) and winter (right).

Table 1. Specifications of the snowfall-particle-observation site.

facilities (manufacturer)	variables	class/resolution	data interval	sampling area
PARSIVEL (OTT Hydromet GmbH) Firmware version: v1.17.0 (Löffler-Mang and Joss 2000; Battaglia et al. 2010)	particle size	32 classes (0.2 mm to 25 mm)	1 minute	W30 × D180 mm ²
	fall speed	32 classes (0.2 m s ⁻¹ to 20 m s ⁻¹)		
SR-2A (Tamura Seppyō Keisoku Laboratory) (Tamura 1993)	precipitation intensity	0.0052 mm	1 minute	14000 mm ²
Web camera (Panasonic BB-HCM581)			10 minute	
facilities	purpose			
LED lamp	monitoring at night			
wind shield net	to minimize wind-induced error			

method, to derive the representative size (D_c) and fall speed (V_c) of precipitation particles from a 2D histogram (Nakai et al. 2019; see also Supplement 1). The CMF method first converts the number density of precipitation particles in the size–fall-speed space to vertical mass flux density (F) using experimental functions of the mass and fall speed of various hydrometeor classes. Subsequently, D_c and V_c , both weight-

ed by F , are calculated. The CMF method has been used to estimate the characteristics of falling snow particles (Kouketsu et al. 2015; Minda et al. 2016; Masuda et al. 2018).

Ishizaka et al. (2016) proposed a hydrometeor classification diagram. The hydrometeor classes are determined by the location of the CMF (D_c , V_c) on a diagram like Fig. 4. In this study, the classification

Fig. 3. Sample 2D histograms of fall speed (m s^{-1}) versus size (mm) observed for 1 min at the snowfall site. The colors indicate the number of observed particles within each fall-speed-size bin. The solid lines indicate experimental relationships reported in the literature for water drops (R; Atlas et al. 1973), conical graupel (G; Locatelli and Hobbs 1974), aggregates of densely rimed radiating assemblages of dendrites or dendrites (D; Locatelli and Hobbs 1974), and aggregates of unrimed radiating assemblages of dendrites or dendrites (U; Locatelli and Hobbs 1974) extrapolated within the area of each panel. The data correspond to (a) 0437 JST on January 18, 2011 and (b) 0402 JST on February 18, 2012.

was modified by introducing the riming and melting index (RMI):

$$\text{RMI} = V_c/D_c^{0.5}. \quad (3)$$

Accordingly, the hydrometeor classification can be performed using a single parameter (RMI) instead of two (D_c and V_c). An exception to this is the use of D_c in the definition of “small particles”. The threshold of “rain” and “graupel” (graupel and aggregate) is $\text{RMI} = 2.5$ (1.0). “Small particles” are defined by $\text{RMI} < 1.0$ (RMI values correspond to snow aggregate) and $D_c < 3.0$ mm. The remaining values correspond to snow aggregates, which are divided into “heavily rimed snow aggregate” and normal “snow aggregate” by $\text{RMI} = 0.7$. These values were determined based on experimentally fitted relations (R, G, D, and U in Figs. 3, 4) and the observed size and fall-speed distributions.

3.2 Use of fixed β

The Z_h – R relationship depends on the hydrometeor class. Rasmussen et al. (2003) demonstrated that the Z_h – R relationships of snow aggregates could be expressed as

$$Z_h = B R^{1.67}, \quad (4)$$

where B denotes an experimentally determined coefficient. Additionally, based on a literature review and

theoretical considerations, they demonstrated that the value of B is affected by the size-distribution intercept, falling speed, and whether the snow is dry or wet (both mixed-phase and rimed particles). Further, they revealed that B varies by up to four times for a given Z_h . According to the Z_h – R relationship for graupel derived by Ohtake and Henmi (1970) (Eq. 1), the value of the exponent β differs from that reported by Rasmussen et al. (2003). However, the value of Z_h in Eq. (1) is located at the center of the variation range prescribed in the relationships reported by Rasmussen et al. (2003) (Fig. 6).

A slight change in β causes a large change in B , even when the actual shape of the function changes only slightly. A pair of appropriate B and $\beta = 1.67$ can be used, instead of the literature’s B – β pair, because most of these pairs of the existing experimental Z_h – R relationships were derived by fitting scattered data. Using Z_h – R relationships with various β values makes it difficult to understand the Z_h – R relationship systematically in relation to the microphysical characteristics of the precipitation particles. From a theoretical perspective, this exponent value of 1.67 is, presumably, the only one commonly applicable to Z_h – R relationships of multiple hydrometeor classes. Hence, we fix $\beta = 1.67$ and use Eq. (4) expressed also as

$$A = 10 \log_{10}(B) = \text{dB}(Z_h) - 16.7 \log_{10}(R). \quad (5)$$

Fig. 4. Hydrometeor classification based on the riming and melting index ($RMI = 0.7, 1.0$, and 2.5 , as indicated in the figure) and D_c . The CMFs (D_c, V_c) of the 48 cases analyzed in Section 4 are plotted. Thin, medium, and thick asterisks indicate the unrimed-D, rimed snow aggregate, and heavily rimed snow aggregate classes, respectively. The solid and open circles and solid diamond indicate, respectively, small-particle, graupel, and unrimed-C classes. The bold dotted (R), solid (G), dashed (D), and dot-dashed (U) lines correspond to the lines of the same annotations in Fig. 3, within the ranges reported in the existing literature. The gray bold lines indicate experimental relationships from Locatelli and Hobbs (1974) for unrimed side planes (solid); aggregates of unrimed radiating assemblages of planes, side planes, bullets, and columns (short dashed); and aggregates of unrimed side planes (long dashed).

3.3 Data processing

The analysis time resolution equaled 10 min, considering the radar observation cycle. Plan position indicator (PPI) data of $1.3^\circ/1.7^\circ$ elevation were used. These are the lowest elevation angles available without beam blocking. Z_h was averaged in an area of approximately 100 km^2 toward the prevailing wind direction of the ground site bounded by the radial lines and range circles of the radar (Fig. 1). No other manual masking was necessary for this area to eliminate ground clutter and beam-blocked areas. The average Z_h for a certain time was derived using all the PPI data of the indicated elevation in the abovementioned area within the preceding 10 min. First, the measured Z_h value in dB is converted to $Z_h^{1/1.67}$ (considered

approximately linear with respect to R , assuming $\beta = 1.67$); subsequently, the areal average of $Z_h^{1/1.67}$ was calculated and converted to the areal average of Z_h . Areas wherein no precipitation occurred were represented with $Z_h^{1/1.67} = 0$.

The observation interval for the snowfall site equaled 1 min. The CMF and RMI values were calculated using the data collected within the preceding 10 min through the method described in Section 3.1; subsequently, the hydrometeor class was determined using the criteria described in Fig. 4. The precipitation intensity (in mm h^{-1}) was calculated by accumulating the precipitation amount measured in the preceding 10 min at 1-min intervals (10 measurements) using SR-2A and multiplying by six. The data were filtered by considering a mean threshold temperature of less than 0.0°C over a 10-min duration at the Tohkamachi Experimental Station. Periods of snow capping on the observation facilities were eliminated using web-camera images.

Both radar and snowfall-site data at a certain time were derived from observation in the preceding 10 min without a time offset. Considering an antenna elevation angle of 1.3° (1.7°), a radar-antenna height of 114 m above sea level, and the snowfall-site altitude of 200 m above sea level, the beam-site height difference equaled approximately 700 m during winters 2010/2011 and 2011/2012 and 930 m during winter 2015/2016. Assuming that the fall speed of snow aggregates (graupel) is 1 (4) m s^{-1} , a particle observed at the center of the radar-analysis area (Fig. 1) reaches the ground approximately 11.7–15.5 (2.9–3.9) min later. The analysis time interval is 10 min. Following this assumption, a time offset of 10 min (0 min) between the radar and snowfall-site data for a 10-min analysis time resolution is desirable for snow aggregates (graupel). However, in this analysis, the time offset was set to 0 min for simplicity, which may cause errors, especially in the case of snow aggregates. Furthermore, the precise evaluation of time offset might require the three-dimensional wind and fall-speed distribution, which needs significant additional analysis and may not be possible using the data obtained in this study. We believe that this deficiency was covered by carefully checking the stability of the diameter and fall-speed distributions of the precipitation particles, as presented in Section 4. Moreover, the change of Z_h between the radar observation height and ground-observation site was assumed to be negligible.

The radar-analysis area was located 2–12 km upwind of the snowfall site when the wind direction is west–northwest. Assuming a wind speed of 20 m s^{-1} ,

precipitation particles travel 12 km in 10 min. Thus, it is adequate to compare ground observations within the preceding 10 min with the average Z_h in this radar-analysis area. The Japan Meteorological Agency (JMA) operational composite radar precipitation intensity was additionally used to check the movement direction of the precipitating cloud systems manually. The cases selected in Section 4 were filtered by the condition that the cloud system reached the snowfall site from the direction between west and northwest (see also Supplement 2). An exception was the unrimed-C case described in Section 4.2. The precipitating cloud system in this case arrived from the direction between west-southwest and west-northwest. The radar-analysis area was located slightly northward of the upwind direction from the snowfall site. However, the precipitation in this case was highly uniform, and the precipitation in the radar-analysis area was considered equivalent to that at the snowfall site.

Thus, a dataset comprising Z_h (in dBZ), R (in mm h⁻¹), temperature (in °C), CMF (D_c in mm and V_c in m s⁻¹), RMI, and hydrometeor classes at 10-min intervals was prepared. Data obtained during winter 2010/2011 (from 1500 JST on December 7, 2010 to 1200 JST on March 28, 2011) and winter 2011/2012 (from 0000 JST on December 1, 2011 to 0940 JST on April 23, 2012) were used for the four types of solid precipitation particles indicated in Fig. 4. Additional analyses were conducted for two cases of unrimed particles in January and February 2015/2016.

4. Results

4.1 Analyses for winter 2010/2011 and 2011/2012

Case selection was performed to derive Z_h - R relationships for four hydrometeor classes of solid precipitation particles. The dataset described in Section 3 contains CMF and RMI at 10-min intervals. A case of a specific hydrometeor class was selected through the following steps. First, candidate cases satisfying the following conditions were selected as periods from the dataset at 10-min intervals: (1) a single hydrometeor class (e.g., graupel) continued to appear and (2) the temperature during the period was below 0°C. Next, size versus fall-speed scattergrams (Fig. 3) were plotted for the candidate case periods with the original observation time interval of 1 min. If similar distribution patterns continued stably through the period, then the candidate was confirmed as a “case”. If significant changes in distribution characteristics were found, then the candidate was rejected. In total, 46 cases of four hydrometeor classes, namely, snow aggregates, heavily rimed snow aggregates, graupel, and small

particles, were selected. The case-average CMFs of the 46 cases are shown in Fig. 4. The number of samples of each case ranged from 3 (30 min) to 35 (350 min).

Snow aggregates observed in Nagaoka (located in the central part of Niigata Prefecture) are usually rimed. The RMIs of most snow-aggregate cases in Fig. 4 were larger than the RMIs of “aggregates of densely rimed radiating assemblages of dendrites or dendrites” (“D” in Figs. 3, 4; Locatelli and Hobbs 1974) of the same D_c . This implies that the selected “snow aggregate” cases are actually dominated by rimed snow aggregates; we label these cases the “rimed snow aggregate” class.

The B values for four hydrometeor classes were derived using the data of the 46 selected cases. First, A in Eq. (5) was calculated using R and Z_h at 10-min intervals. Subsequently, the arithmetic mean of A during the case period was calculated (case-mean A). The statistics of the case-mean A for each hydrometeor class were calculated (Fig. 5). The average B of a hydrometeor class was derived using Eq. (5), and the arithmetic means of all the case-mean A values (A_m) were classified in the corresponding class. The average B value for graupel equaled 227.4, which was approximately twice that corresponding to rimed snow aggregates (107.4). This indicates that the backscattering of the X-band electromagnetic waves of graupel was stronger than that of rimed snow aggregates of the same R . The average B of heavily rimed snow aggregates was 69.1, and its backscattering intensity was weaker than that of rimed snow aggregates of the same R ; in other words, the heavily rimed snow aggregates showed stronger precipitation than rimed snow aggregates and graupel, even if Z_h was the same.

The case-mean A distributions of heavily rimed snow aggregates and graupel are different. Graupel and small particles showed similar A_m values. Despite the overlap in their case-mean A distributions, the average B values for rimed snow aggregates and graupel differed. The case-mean A distribution of heavily rimed snow aggregates was positively skewed with its median value less than A_m . Other distributions were symmetric with median values close to A_m . Statistics of the cases analyzed in Sections 4.1 and 4.2 are shown in Supplement 3.

4.2 Analyses of unrimed cases in winter 2015/2016

Unrimed-snow-aggregate cases were not detected in the analyses in Section 4.1. Therefore, additional analyses were performed using the data from winter 2015/2016. The dataset was constructed using the

Fig. 5. Arithmetic mean (A_m), standard deviation (σ), minimum, median, and maximum of case-mean $A (= 10 \log_{10} B)$ in dB for rimed snow aggregate, heavily rimed snow aggregate, graupel, and small-particle cases, respectively. The B values shown in the panel correspond to the A_m of each hydrometeor class. The numbers of cases are shown in parentheses.

method described in Section 3.

Case selection for unrimed snow aggregates was performed differently from the analysis in Section 4.1. First, a time series of CMF at 10-min intervals was drawn, following which periods satisfying the following conditions were manually selected: (1) the CMF fall speed V_c continued to be near 1.0 m s^{-1} , (2) R was observed continuously at 10-min intervals by SR-2A, and (3) the variations in Z_h and R were similar. Such precipitation had a small R , and often, the average Z_h could not be derived. In this study, only one good case that satisfied the above conditions for as long as 4 h (24 samples) was obtained. The period was from 1339 JST to 1729 JST on February 15, 2016. The JMA operational radar observations mainly indicated snowfall in a weakened winter monsoon condition over land in this case. The values of A at 10-min intervals varied significantly. To derive B for this case, averages of R and $Z_h^{1/1.67}$ were calculated for the whole period, and $B = 343.4$ was derived for the relationship between these two values. The mean V_c (D_c) of this case was 1.03 m s^{-1} (6.46 mm). The CMF expressed by the mean D_c and V_c (a large thin asterisk) was located slightly below the line of “aggregates of unrimed radiating assemblages of dendrites or dendrites” of Locatelli and Hobbs (1974) (U) (Fig. 4). Thus, the prevailing solid precipitation particles of this case were deduced to be unrimed aggregates composed of dendritic particles (referred to as the unrimed-D class).

We also investigated the precipitation associated with a south-coast cyclone (SCC; Araki 2016a, b).

SCCs recently attracted attention as a phenomenon that causes snowfall composed of unrimed crystals forming weak layers of snowpack, causing avalanches (Araki and Nakai 2019a, b, c). Yamaguchi et al. (2019) conducted detailed observations of the specific surface area (SSA), a parameter that expresses the particle shape and surface condition, for various types of snowfall at the SIRC. They measured the time variation of the SSA of snowfall caused by an SCC from January 29 to 30, 2016. They confirmed that the snowfall was characterized by a very small SSA with precipitation particles composed of unrimed crystals that include cold-type habits, such as bullets and their aggregates, which did not change throughout this period (see Fig. 5d in Yamaguchi et al. 2019). The snowfall was mostly continuous for 12 h at the SIRC. Furthermore, the JMA operational radar precipitation intensity showed that the precipitation was widely and uniformly spread in the northern edge of the SCC. Colle et al. (2014) reported that cold-type habits (side planes and bullets) commonly occur “within the outer comma head to the north and northeast of the cyclone center”.

The precipitation particles in the SCC case were small. The case-average D_c value equaled 3.18 mm. In contrast, the case-average V_c was as large as 1.91 m s^{-1} . In Fig. 4, the CMF was located near the triple point of the hydrometeor classes of graupel, small particles, and heavily rimed snow aggregates, although the particles were dry and unrimed. This indicates that the classification using Fig. 4 cannot be applied to this case. Some classes of unrimed solid precipi-

tation particles in Locatelli and Hobbs (1974) were not used to construct the CMF method of Ishizaka et al. (2013). One of them is “aggregates of unrimed radiating assemblages of planes, side planes, bullets, and columns”. Precipitation particles of this class show large fall speeds relative to their size, despite being unrimed. The fall speed is greater than that of heavily rimed snow aggregates at about more than 3 mm (short-dashed gray bold line in Fig. 4; Fig. 24 in Locatelli and Hobbs 1974). Moreover, a fall speed close to 1 m s^{-1} was measured for unrimed side planes with the diameter measuring 1 mm (solid gray bold line in Fig. 4; Fig. 16 in Locatelli and Hobbs 1974), although another type of unrimed particles did not show such an increase in fall speed (long-dashed gray bold line in Fig. 4; Locatelli and Hobbs 1974). It is noteworthy that side planes and bullets are cold-type habits.

In this study, surface observations were performed at the snowfall site, rather than at the SIRC. However, the precipitation distribution demonstrated a high spatial uniformity in the present case. Therefore, the precipitation particles at the SIRC and the snowfall site were considered similar. In accordance with the characteristics of the two former categories of unrimed particles reported by Locatelli and Hobbs (1974) which were discussed above, the microphysical characteristics investigated at the SIRC by Yamaguchi et al. (2019), and the CMF determined in this study at the snowfall site with small D_c and relatively large V_c , the precipitation particles observed at the snowfall site were considered unrimed crystals of cold-type habits and their aggregates (hereinafter referred to as the unrimed-C class).

According to the analyses so far, the B of an unrimed class was expected to be large; however, the B value for this SCC case was very small (44.0) and consistent with the CMF for this case with small D_c and large V_c . A class with a smaller D_c (larger V_c) leads to a smaller Z_h (larger R), albeit the hydrometeor mass per unit volume remains unchanged. Both the small D_c and large V_c make the B value for this case small; that is, the precipitation intensity appears weak in radar observations. The average R value for this case derived from SR-2A observations equaled 1.4 mm h^{-1} . Although the magnitude of R is comparable to the precipitation intensity typically observed for L-mode sea-effect snowfall dominated by graupel in Niigata Prefecture (Nakai et al. 2005), the radar-detected snowfall in this case has less than half the intensity of the L-mode snowfall.

Fig. 6. Z_h – R relationships. The shaded area indicates the range of relationships described in Rasmussen et al. (2003) bounded by the relationships for wet/rimed particles with a large N_0 and dry non-rimed particles with a small N_0 , where N_0 is the intercept of the size distributions of particles. The thick gray line indicates the relationship for graupel (Ohtake and Henmi 1970; OH). The other lines indicate the relationships derived in this study for rimed snow aggregate (long-dashed), heavily rimed snow aggregate (medium-dashed), graupel (white solid), small-particle (short-dashed), unrimed-D (solid), and unrimed-C (dot-dashed) classes.

5. Discussion and summary

The coefficient B values of the Z_h – R relationships of six hydrometeor classes of solid precipitation were derived from simultaneous observations of an X-band weather radar and a ground-observation site equipped with an optical disdrometer, a high-resolution precipitation gauge, and a windshield net. A fixed value, 1.67, was used for the exponent of the relationship, β . The Z_h – R relationships derived in this study were compared with those in the literature (Fig. 6). The range of relationships reported by Rasmussen et al. (2003) for snow aggregates is indicated (shaded) in Fig. 6, with the upper (lower) edge indicating the relationship of heavily rimed (unrimed) aggregates for dry snow. The value of B increases from the upper to lower edges. The relationship for graupel reported by Ohtake and Henmi (1970) lies at the center of the range indicated in Fig. 6. The relationships derived in this study, except for the unrimed-C class, are spread across the

range of relationship from the upper to lower edges in the order of the heavily rimed snow aggregate, rimed snow aggregate, and unrimed-D classes. This order, confirmed by direct comparison of radar and ground observations, is consistent with that reported by Rasmussen et al. (2003). The curves for graupel and small-particle classes are near the center of the range of relationship, similar to the graupel relationship reported by Ohtake and Henmi (1970). The CMFs of the small-particle cases were concentrated around the upper corner of the “small particle” area in Fig. 4, suggesting that the small particles were graupel-like rimed ice crystals and small aggregates.

Here, we consider the relationship between the “degree of riming” and B . Figure 6 indicates that a snow-aggregate class with a larger degree of riming (from the smallest unrimed-D class through rimed snow aggregates to large heavily rimed snow aggregates) has a smaller B and stronger precipitation for a certain Z_h . These classes are observed during snowfall from cloud systems that develop over the Sea of Japan by the sea effect (Steenburgh and Nakai 2020) during the winter monsoon. These cloud systems typically propagate from between the west and northwest directions in Niigata Prefecture, and the snow aggregates are typically composed of crystals including dendrites. The variation of B associated with the increasing “degree of riming” indicates that the increase of vertical mass flux (mass multiplied by fall speed) is larger than the increase of backscattering intensity as long as the particles belong to the snow aggregate classes, when riming occurs in snow aggregates composed of dendritic ice crystals. In contrast, the riming process to generate graupel may be dominated by the increase of backscattering intensity rather than the increase of vertical mass flux, resulting in the increase of B . This difference leads to errors in radar precipitation intensity when the hydrometeor class is unknown.

The small B value of the unrimed-C class cannot be explained using the consideration above. Rather, the large V_c of the unrimed-C class reflects the characteristics of ice-crystal habits with a relatively large fall speed or “aggregates of unrimed side planes, assemblages of planes, bullets and columns” (Locatelli and Hobbs 1974). The small B indicates weak backscattering, which leads to a significant underestimation of radar precipitation intensity. Currently, the unrimed-C class can only be distinguished from, for example, the characteristics of a mesoscale precipitation system (radar-echo pattern) without precipitation-particle observations. If the small B is attributed to the size distribution, shape, fall speed, and attitude of the fall-

ing precipitation particles, it may be possible to detect unrimed-C-class particles from the distribution of radar polarimetric parameters and to clarify the variation of B when unrimed-C-class particles undergo the riming process.

A polarimetric Doppler radar was used in this study. In future endeavors, we intend to examine the polarimetric parameters for each hydrometeor class in relation to the B values derived in this study. The analyses performed in this study involved certain simplifications. The measurement errors in PARSIVEL were not considered in this study. The authors qualitatively compared the size and the fall speed that were measured using PARSIVEL to that measured using the collocated CCD camera system of Ishizaka et al. (2013). The size (fall speed) observed by the PARSIVEL was similar to (slightly larger than) that of the CCD camera system. This error in the fall speed affects the hydrometeor classification threshold lines (Fig. 4). However, the hydrometeor classification was confirmed by checking all the size–fall-speed scattergrams at 1-min intervals, and the contamination of particles of different classes was eliminated. Thus, the PARSIVEL measurement error in the fall speed does not affect the Z_h – R relationships that were derived in this study. However, the modification of the threshold lines in Fig. 4 might be necessary for the future. The matching between radar data for a fixed area and ground-observation data for selecting appropriate cases was performed by checking the direction of radar-echo motion and stability of the particle size versus fall-speed distributions. Only one case each of the unrimed-C and unrimed-D classes was analyzed. Thus, the B values reported in this paper might be modified in a future study owing to the consideration of additional cases and polarimetric parameters. However, it is expected that the qualitative difference in B values among hydrometeor classes will remain unchanged, because all cases were carefully checked and analyzed using the same method, with the exception as described in Section 4.2. Moreover, the results obtained in this study are consistent with those reported in existing literature. It is noteworthy that the B values described in Fig. 6 are statistically determined. The B value changes for each case as depicted in Fig. 5 (see also Supplement 4). If B is related to microphysical parameters using continuous functions, the resulting relationship can be described more definitely. However, this might be difficult to realize considering the significant temporal changes in the nature of hydrometeors as inferred by Fujiyoshi et al. (1990) (Section 1).

This study has shown a systematic description of

Z_h – R relationships with the “degree of riming”. However, the results of this study still need to be validated through further analyses of the measurement errors and the application of the Z_h – R relationships to other cases. Furthermore, the changes in the B value when the precipitation particles of the unrimed-C class experienced riming is not apparent. The Z_h – R relationship for each class of the precipitation particles is typically required for the practical applications of the radar QPE. Hence, it is important to clarify the influence of these errors for the application of Z_h – R relationships and GPM ground validation.

Supplement 1: Center-of-mass flux distribution (CMF) and its application to hydrometeor classification

The center-of-mass flux distribution (CMF; Ishizaka et al. 2013) comprises the parameter pair of the representative size (D_c) and fall speed (V_c) of precipitation particles derived from the corresponding two-dimensional (2D) histogram. A brief description of the CMF is given in Supplement 1.

Supplement 2: Radar-echo motion vector near the ground-observation site

Case filtering by the moving direction of the precipitating cloud system was conducted by visual inspection using the grid data of the Japan Meteorological Agency (JMA) operational composite radar precipitation intensity. The radar-echo motion vector was calculated using the same data for verification. The verification result is shown in Supplement 2.

Supplement 3: Table listing the cases analyzed in Sections 4.1 and 4.2

Statistics of the cases analyzed in Sections 4.1 and 4.2 are shown in Supplement 3.

Supplement 4: Verification of the result

The Z_h – R class-based liquid water equivalent (precipitation intensity) estimate ($R_{\text{estimated}}$) was derived for the four hydrometeor classes described in Section 4.1. This was carried out by applying the Z_h – R relationship shown in Fig. 6 to the observed Z_h on the polar coordinate of the radar. The same method as described in Section 3.3 was used for the selection and averaging of the data. The comparison of the case-average precipitation intensity with the SR-2A gauge measurement (R_{measured}) is shown in Supplement 4.

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