Retrieval of Raindrop and Cloud Particle Size Distributions with 14 GHz and 95 GHz Radars

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Abstract

We have developed a sequential algorithm to retrieve vertical profiles of cloud and rainfall microphysical information from radar reflectivities of a 14 GHz precipitation radar, and a 95 GHz cloud-profiling radar. This sequential algorithm retrieves the number density N_T , the mean volume diameter D_m and the liquid water content LWC from the nearest to the farthest ranges considering the significant attenuation and Mie scattering. To avoid the accumulation of numerical errors, the retrieval is computed in adjacent ranges assuming N_T to be constant in each pair. We demonstrate that our method retrieves N_T and D_m stably, even if the raindrop size distribution is different from our assumption, or even if some bias errors are appended to the radar constant. The method is applied to collocated ground-based observation by a 14 and a 95 GHz radar, and the retrieved results are evaluated by comparing them against disdrometer-derived size distributions, where the rainfall rate was from 0.1 to 4.6 mm/hr. The retrieved D_m , and the disdrometer-derived D_m , agree to within 30%. The retrieved $\log_{10} LWC$, and the disdrometer-derived $\log_{10} LWC$, also agree to within 30% when the rainfall rate is greater than 0.5 mm/hr.

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1. Introduction

The clouds with light rainfall or snowfall are important for the climate system and have been studied for several decades. The Global

Atmospheric Research Programme Atlantic Tropical Experiment (GATE) revealed that the stratiform radar echoes covered large area in the tropics (Houze 1977). Tokay and Short (1996) researched the details of the tropical rainfall and showed the occurrence of stratiform precipitation and its total rainfall were 74% and 32%, respectively, during the Tropical Ocean Global Atmosphere Couple Ocean-Atmosphere Experiment (TOGA COARE). Thus, stratiform precipitation is significant for the heat and water budgets. In addition, clouds with snowfall affect seeder-feeder precipitation mechanism (Jakob and Klein 1999). To measure clouds with precipitation, a 95 GHz radar and a 14 GHz radar observations are promising, since the 95 GHz radar has a great sensitivity for clouds, and the 14 GHz radar is appropriate for precipitation and cloud observations. Note: a radar of which wavelength is longer than that of precipitation radar, e.g., C-band radar, has little sensitivity for cloud particles.

The high attenuation at 95 GHz sometimes does not allow rainfall observations at altitudes higher than a few kilometers, and hence their retrievals need a sequential algorithm that retrieves from the nearest to the farthest ranges (hereafter called “forward sequential algorithm”). However, conventional forward sequential algorithms are difficult, since a positive feedback of the error is produced when the attenuation is not negligible (e.g., Hitschfield and Bordan 1954; Fernald et al. 1972). Hence, Iguchi and Meneghini (1994) proposed the hybrid method for the space- (air-) borne radar that refers the sea surface echo to avoid the divergence of the error for radar observations. L’Ecuyer and Stephens (2002) introduced an algorithm to retrieve light rainfall rate by a space-borne cloud radar, CloudSat (Stephens et al. 2002). The key to both methods is to determine the attenuation throughout range gates before retrieval of rainfall rate. Hence, their method is difficult to apply when attenuation throughout range gates is not determined. In addition, the methods that assume the formulas of the k - R relation and/or the Z - R relation (e.g., Fujita 1983) are not applicable when the Mie scattering is significant, where k , R , and Z denote attenuation, rainfall rate, and radar reflectivity, respectively. This is be-

cause the k - R and Z - R relations are not simply described in the Mie scattering. Hence, the abovementioned methods are not applicable to the analysis of rainfall observation when using the 95 GHz radar.

Okamoto et al. (2003), hereafter O2003, developed the forward sequential algorithm. They succeeded in stably retrieving the microphysics of ice cloud from synergy ground-based observations with a lidar and a 95 GHz cloud radar, though the lidar attenuation is not negligible. O2003 utilizes the difference of Rayleigh scattering and geometrical optics (Bohren and Huffman 1998), where the backscattering cross section C_{bk} is proportional to D^6 in the case of Rayleigh scattering, and proportional to D^2 in the case of geometrical optics, where D denotes the diameter of hydrometeor. Since C_{bk} by raindrops at 14 and 95 GHz are also different from each other (i.e., Rayleigh and Mie scattering), O2003 seems to be applicable to the 14 and 95 GHz observation. Note C_{bk} lies somewhere in between D^2 and D^6 for Mie scattering. However, the application of O2003 produces the instability of the numerical error, as discussed in Section 3.

On the other hand, Eccles and Mueller (1971) proposed an algorithm for the dual-wavelength radar observation by using the ratio of the two radar reflectivities at two range gates. Their algorithm also stably solves the liquid water content. Since they assume Rayleigh scattering for both wavelengths, their method is not simply applicable to the 14 and 95 GHz radar observations.

The objective of this paper is to improve O2003 and Eccles and Mueller (1971) to stably retrieve the size distribution of raindrops and cloud particles from 14 and 95 GHz radar reflectivities. The retrieval is performed by a forward sequential algorithm when the attenuation and Mie scattering effects are significant. We then analyze the synergy of vertical observations of a precipitation cloud system by the 14 GHz precipitation radar (CAMPR, Kumagai et al. 1996) and the 95 GHz cloud radar (SPIDER, Horie et al. 2000), where Table 1 indicates the specifications of the two radars. Note: although both radars were designed for air-borne observation, we have used them in ground-based systems. Additionally, the raindrop size distribution on the ground was mea-

Table 1. Specifications of the 14 and 95 GHz radar.

	14 GHz radar	95 GHz radar
Frequency	13.8 GHz	95.0 GHz
Wavelength	2.17 cm	3.15 mm
Pulse Repetition Frequency	2 kHz*	700 Hz*
Transmitted Power	3 kW	1 kW
Vertical Resolution	75 m*	82.5 m*
Pulse Width	2 μ s*	1.1 μ s*
Doppler capability	O	O
Polarization function	Dual	Dual

The values marked with an asterisk are the typical values that we used for the parameters.

sured by a disdrometer installed on the roof of the 14 GHz radar container.

Section 2 describes the preparation of the computations. The O2003 method is applied to analyze the model rainfall observed with a 14 and a 95 GHz radar in Section 3. Our modified forward sequential algorithm is explained and discussed in Section 4. Section 5 describes our synergy observations and shows the validation of retrieval results by a disdrometer.

2. Preparation of calculations

2.1 Size distribution

The gamma distribution (Eq. 1) is assumed as the size distribution $dn(r, D)/dD$ in number/ m^3/mm (Eq. 1a of Koza and Nakamura 1991),

$$\frac{dn(r, D)}{dD} = N_T(r) \frac{\Lambda(r)^{\mu+1} D^\mu}{\Gamma(\mu+1)} \exp[-\Lambda(r)D], \quad (1)$$

$$\Lambda(r) = (4 + \mu)/D_m(r)$$

where D , $N_T(r)$ and $D_m(r)$ denote the diameter in mm, the number density in number/ m^3 and the mean volume diameter in mm at a range r . μ is assumed as 3, that is the typical value measured by Koza and Nakamura (1991) at the same site as our observation site. Symbols and superscripts in the text are described in Tables 2 and 3. Every particle is assumed to be spherical throughout range gates.

2.2 Radar equation

The radar equation (Eq. 2) is widely used in radar observations (e.g., Stephens 1994).

Table 2. Definition of symbols in this paper.

$dBZ_e^0(r)$	$Z_e^0(r)$ in dB unit [dBZ]
$dBZ_e^{OBS}(r)$	$Z_e^{OBS}(r)$ in dB unit [dBZ]
C_{bk}	Backscattering cross section [m^2]
C_{ext}	Extinction cross section [m^2]
D	Diameter of a hydrometeor [mm]
$D_m(r)$	Mean volume diameter at a range r [mm]
dn/dD	Size distribution [number/ m^3/mm]
Δr	Vertical resolution [m]
μ	Shape parameter
$N_T(r)$	Number density at r [number/ m^3]
r	Range gate
$Z_e^0(r)$	Effective radar reflectivity factor at range r [mm^6/m^3]
$Z_e^{OBS}(r)$	Attenuated effective radar reflectivity factor at range r [mm^6/m^3]
$\sigma_{ext}(r)$	Extinction coefficient at range r [1/m]

Table 3. Definition of superscript symbols in this paper.

14G	The value calculated by the Mie theory at 13.8 GHz
95G	The value calculated by the Mie theory at 95.0 GHz
DIS	The value measured by a disdrometer

e.g., dBZ^{14G} denotes the radar reflectivity factor of 14 GHz.

$$P(r_i) = C \frac{Z_e^0(r_i) A(r_i)}{r_i^2}, \quad (2)$$

where

$$\begin{aligned} Z_e^0(r_i) &\equiv \frac{\lambda^4}{\pi^5 |K(r_i)|^2} \int \frac{dn(r_i, D)}{dD} C_{bk}(D) dD \\ A(r_i) &\equiv \exp \left[-2 \int_0^{r_i - \Delta r/2} \sigma_{ext}[N_T(x), D_m(x)] dx \right] \\ K(r_i) &= \frac{m(r_i)^2 - 1}{m(r_i)^2 + 2} \\ \sigma_{ext}(r_i) &= \int \frac{dn(r_i, D)}{dD} C_{ext}(D) dD \end{aligned} \quad (3)$$

$Z_e^0(r_i)$ and $A(r_i)$ denote the radar reflectivity and the attenuation from the ground to range r_i , respectively. $m(r_i)$ denotes the complex

refractive index of hydrometeors at r_i , and it depends on the temperature, the wavelength, and the phases, e.g., liquid water or water ice. C denotes the radar constant that depends on several factors, e.g., the wavelength, the antenna gain, the transmitted power, and the loss of the antenna radome. Other symbols are denoted in Table 2. Hereafter, values of 14 or 95 GHz radars are denoted by the superscripts "14G" and "95G," respectively, e.g., $\text{dBZ}^{14\text{G}}$ denotes the radar reflectivity factor of 14 GHz (Table 3).

2.3 Look-up tables

Seventeen look-up tables for radar signals were prepared by applying the Mie theory before retrieval of $N_T(r_i)$, $D_m(r_i)$, and the liquid water content $LWC(r_i)$. Each table contains equivalent radar reflectivities and extinction coefficients of 14 and 95 GHz as a function of N_T and D_m , respectively. The value of N_T ranges from 10 to 1×10^5 number/m³, and that of D_m ranges from 0.01 to 5 mm. N_T and D_m are divided into 100 even intervals in the logarithm units.

Each table is used for the computations at each range gate. That is, one table is created for the computations above 525 m from the melting layer (for snow and ice particles), and another table is created for the computations below 525 m from the melting layer (for raindrops). The remaining 15 tables are created for computations at the ranges between -525 m and $+525$ m from the melting layer. These tables are prepared for every 75 m, where 75 m is the same as the vertical resolution of our observation. The distance of 525 m from the melting layer was also considered in Iguchi et al. (2000).

Optical constants of each table were calculated by Awaka et al. (1985). Table 1 in Awaka et al. (1985) shows the relationship of the volume content of water P_W , and the form factor U , at a distance from the melting layer. In addition, the dielectric constant is obtained from P_W and U by Eq. 2 of Awaka et al. (1985). We also assume the droplet temperature as 15°C, hence the optical constants of water and water ice in 14 GHz are $6.94 + i2.82$ and $1.79 + i2.34 \times 10^{-3}$, and those in 95 GHz are $3.06 + i1.64$ and $1.78 + i6.21 \times 10^{-3}$, respectively (Ray 1972; Warren 1984); $i^2 = -1$.

Therefore, optical constants of each range gate are determined and the tables are subsequently calculated.

2.4 Attenuation within the ground clutter

In general, there is a ground clutter from some objects such as trees due to the side lobe. In addition, our 14 GHz radar could not observe near the ground due to a hardware problem. Hence, estimation of the attenuation within several range gates from the ground is required.

The attenuation of 14 and 95 GHz within the ground clutter is calculated by assuming the uniform rainfall. That is, the raindrop size distribution within the clutter is assumed to be the same as that measured with a disdrometer where it measures the raindrop size distribution on the ground (see Appendix). Then attenuations through the clutter, $A^{14\text{G}}(r_1)$ and $A^{95\text{G}}(r_1)$, are solved by Eq. 3, where the range r_1 is the next higher range to the clutter.

3. Retrieval by the forward sequential algorithm O2003

3.1 Method

Most of the backscattering by raindrops is Rayleigh scattering for a 14 GHz radar, and Mie scattering for a 95 GHz radar. Hence, the equivalent radar reflectivities at 14 and 95 GHz, $Z_e^{0,14\text{G}}$ and $Z_e^{0,95\text{G}}$, are different.

$Z_e^{0,14\text{G}}(r_1)$ and $Z_e^{0,95\text{G}}(r_1)$ are obtained by Eq. 4, since the observed radar reflectivities, $Z_e^{\text{OBS},14\text{G}}(r_1)$ and $Z_e^{\text{OBS},95\text{G}}(r_1)$, are given by observations, and $A^{14\text{G}}(r_1)$ and $A^{95\text{G}}(r_1)$ are given by the disdrometer.

$$\begin{aligned} Z_e^{0,14\text{G}}(r_1) &= Z_e^{\text{OBS},14\text{G}}(r_1)/A^{14\text{G}}(r_1) \\ Z_e^{0,95\text{G}}(r_1) &= Z_e^{\text{OBS},95\text{G}}(r_1)/A^{95\text{G}}(r_1) \end{aligned} \quad (4)$$

Therefore, $N_T(r_1)$ and $D_m(r_1)$ are retrieved by independent parameters $Z_e^{0,14\text{G}}(r_1)$ and $Z_e^{0,95\text{G}}(r_1)$.

Next $A^{14\text{G}}(r_2)$ and $A^{95\text{G}}(r_2)$ are retrieved from $A^{14\text{G}}(r_1)$ and $A^{95\text{G}}(r_1)$ where the 14 and the 95 GHz attenuations at r_1 are derived from $N_T(r_1)$ and $D_m(r_1)$. $Z_e^{0,14\text{G}}(r_2)$ and $Z_e^{0,95\text{G}}(r_2)$ are calculated by $A^{14\text{G}}(r_2)$ and $A^{95\text{G}}(r_2)$. Then $N_T(r_2)$ and $D_m(r_2)$ are retrieved by $Z_e^{0,14\text{G}}(r_2)$ and $Z_e^{0,95\text{G}}(r_2)$. $N_T(r_i)$ and $D_m(r_i)$ are iteratively retrieved by these calculations up to the end of radar echo.

Table 4. Parameters we use in the error analysis, where $R = 5$ mm/hr.

	$\text{dBZ}_e^{0,14\text{G}}$	$\text{dBZ}_e^{0,95\text{G}}$	$a^{14\text{G}}$ [dB/km]	$a^{95\text{G}}$ [dB/km]	$\log_{10} N_T$	D_m
$\mu = 0$	34	22	-0.30	-9.7	3.6	1.2
$\mu = 3$	34	21	-0.29	-8.7	2.8	1.4
$\mu = 6$	33	21	-0.30	-8.1	2.5	1.4

$a^{14\text{G}}$ and $a^{95\text{G}}$ are attenuation of a round trip at 14 and 95 GHz.

3.2 Computation for the model rainfall

O2003 explained in subsection 3.1 is implemented for a model rainfall that falls from a height of 5 km. The raindrop vertical profile for the model is assumed to be uniform throughout range gates; $\mu = 3$ and $R = 5$ mm/hr (Table 2 of Kozu and Nakamura 1991; see Table 4 in $\mu = 3$). That is, radar reflectivities of 14 and 95 GHz are 34 and 21 dBZ, respectively. The specific attenuations of a round trip at 14 and 95 GHz are -0.29 and -8.7 dB/km, respectively. Hence, attenuated radar reflectivities are calculated as

$$\begin{aligned} \text{dBZ}_e^{14\text{G}}(x) &= 34 - 0.29x \\ \text{dBZ}_e^{95\text{G}}(x) &= 21 - 8.7x \end{aligned} \quad (5)$$

where x denotes the distance from radars in km unit.

Figure 1 displays retrieved radar reflectivities at 14 and 95 GHz in dB unit ($\text{dBZ}_e^{0,14\text{G}}$ and $\text{dBZ}_e^{0,95\text{G}}$) by attenuated radar reflectivities. It clearly shows that $\text{dBZ}_e^{0,95\text{G}}$ gradually begins to diverge above the height of 1 km, and goes beyond the range of the look-up table at a height of 4 km or more. Since $\text{dBZ}_e^{0,95\text{G}}$ diverges, the retrieved $N_T(r_i)$ and $D_m(r_i)$ also diverges (figure not shown). Therefore, the analysis by O2003 for 14 and 95 GHz radar observation is not practical.

The mechanism of the error divergence is the same as Hitschfield and Bordan (1954), that is, the progressive accumulation of the numerical errors. Since the difference of the backscattering by Rayleigh scattering and Mie scattering is smaller than that of Rayleigh scattering and geometrical optics, O2003 is not applicable.

Note that the iterative computation does not cause significant errors for 14 GHz while it does for 95 GHz, because the attenuation of 14 GHz is much weaker than that of 95 GHz. Hence, if the iterative computation is not

needed for the 95 GHz attenuation correction, $N_T(r_i)$ and $D_m(r_i)$ would be retrieved stably. Therefore, we propose a new method to retrieve microphysics of precipitation and cloud particles with no iterative computation in the 95 GHz in the next Section.

4. Modified method

The retrieval methods by O2003 and Eccles and Mueller (1971) are modified in order to ap-

Fig. 1. Vertical profiles of $\text{dBZ}_e^{0,14\text{G}}$ and $\text{dBZ}_e^{0,95\text{G}}$ retrieved by the conventional forward sequential algorithm, assuming $\mu = 3$ and $R = 5$ mm/hr. $\text{dBZ}_e^{0,95\text{G}}$ are solved unstably.

Fig. 2. Flow chart of our algorithm. Subsection numbers in the figure correspond to those in the text. The attenuation from the ground to range r_i of 95 GHz is not used for retrieval of N_T and D_m .

ply to the 14 and 95 GHz radar observations. Figure 2 shows the schematic diagram of our method. Subsection numbers in the figure are the same as those in the text.

4.1 Pairing two range gates

Adjacent ranges are paired, e.g., the first pair consists of layers at range gates r_1 and r_2 , and the second pair consists of layers at r_2 and r_3 . Each pair consists of layers at r_i and r_{i+1} , where i denotes an integer. There are four unknowns in the pair: $N_T(r_i)$, $D_m(r_i)$, $N_T(r_{i+1})$, and $D_m(r_{i+1})$. $N_T(r_i)$ is assumed to be constant in each pair due to reducing the independent parameters, that is, $N_T(r_{i+1})$ is the same as $N_T(r_i)$ during the computation in pair i . This assumption is justified when the vertical resolution is fine enough. Note N_T is never assumed to be constant throughout the range gates. That is, $N_T(r_1)$ is assumed to be the same as

$N_T(r_2)$ during the computation in pair 1, and $N_T(r_2)$ is assumed to be the same as $N_T(r_3)$ during the computation in pair 2. Hence, $N_T(r_2)$ in pair 1 is not always the same as $N_T(r_2)$ in pair 2. The merit of this assumption is explained in subsection 4.2.

4.2 Retrieval by the modified forward sequential algorithm

To retrieve $N_T(r_i)$ and $D_m(r_i)$, simultaneous equations are used. First, we retrieve $N_T(r_1)$ and $D_m(r_1)$ at the first observable range gate r_1 . Dividing $Z_e^{\text{OBS},95\text{G}}(r_1)$ by $Z_e^{\text{OBS},95\text{G}}(r_2)$, and the Eq. 4 at 14 GHz yields

$$Z_e^{0,14\text{G}}(r_1) = \frac{Z_e^{\text{OBS},14\text{G}}(r_1)}{A^{14\text{G}}(r_1)}$$

$$Z_e^{0,14\text{G}}(r_2) = \frac{Z_e^{\text{OBS},14\text{G}}(r_2)}{A^{14\text{G}}(r_2)}$$

$$\begin{aligned}
&= \frac{Z_e^{\text{OBS}, 14\text{G}}(r_2)}{A^{14\text{G}}(r_1)} \exp[2\sigma_{\text{ext}}^{14\text{G}}(r_1)\Delta r] \\
\frac{Z_e^{0, 95\text{G}}(r_1)}{Z_e^{0, 95\text{G}}(r_2)} &= \frac{Z_e^{\text{OBS}, 95\text{G}}(r_1)}{Z_e^{\text{OBS}, 95\text{G}}(r_2)} \exp[-2\sigma_{\text{ext}}^{95\text{G}}(r_1)\Delta r]
\end{aligned} \quad (6)$$

First, pair 1 is calculated. Since Z_e and σ_{ext} in Eq. 6 are functions of $N_T(r_1)$, $D_m(r_1)$, and $D_m(r_2)$, and since $A^{14\text{G}}(r_1)$ is given by a disdrometer, $N_T(r_1)$, $D_m(r_1)$, $N_T(r_2)$ [= $N_T(r_1)$], and $D_m(r_2)$ are solved by substituting $Z_e^{0, 14\text{G}}(r_1)$, $Z_e^{0, 14\text{G}}(r_2)$, and $Z_e^{0, 95\text{G}}(r_1)/Z_e^{0, 95\text{G}}(r_2)$ in Eq. 6 for those in the look-up tables at r_1 and r_2 . In order to retrieve N_T in fine vertical resolutions, we neglect values at the upper range gate in pairs. That is, after $N_T(r_1)$, $D_m(r_1)$, $N_T(r_2)$, and $D_m(r_2)$ are retrieved, $N_T(r_2)$ and $D_m(r_2)$ in pair 1 are neglected before the computation of the next pair (explained later). Next, pair 2 is calculated, and $N_T(r_2)$, $D_m(r_2)$, $N_T(r_3)$ [= $N_T(r_2)$], and $D_m(r_3)$ are retrieved, since $A^{14\text{G}}(r_2)$ is obtained by $A^{14\text{G}}(r_1)$ and $\sigma_{\text{ext}}^{14\text{G}}(r_1)$. Then, $N_T(r_3)$ and $D_m(r_3)$ in pair 2 are also neglected before the retrieval of the pair 3. We solve N_T and D_m in a pair i , then neglect $N_T(r_{i+1})$ and $D_m(r_{i+1})$ at the upper range gate in this pair. Hence, $N_T(r_i)$ at the adjacent range gates does not always have the same value, i.e., the values of $N_T(r_2)$, $N_T(r_3)$, and $N_T(r_4)$ are not always the same as those of $N_T(r_1)$, $N_T(r_2)$, and $N_T(r_3)$, respectively.

If the pairing is changed, and range gates in a pair do not overlap with ranges in other pairs, i.e., if pair 1 comprises layers at r_1 and r_2 , and pair 2 comprises layers at r_3 and r_4 , then the vertical resolution becomes sparse. That is, $N_T(r_1)$ and $N_T(r_2)$ [= $N_T(r_1)$] are obtained by the retrieval in pair 1, and $N_T(r_3)$ and $N_T(r_4)$ [= $N_T(r_3)$] are obtained by that in pair 2. Hence, the vertical resolution of N_T becomes sparse.

Note that even if there is a bias error in $Z_e^{\text{OBS}, 95\text{G}}$, it is canceled in Eq. 6. Thus, calibration is not needed for the 95 GHz radar while it is needed for the 14 GHz radar. In addition, since Eq. 6 does not include the 95 GHz attenuation below the pair of interest, there is no iterative computation of the 95 GHz attenuation correction. Therefore, the numerical error is reduced as shown in the next subsection.

4.3 Computation for the model rainfall: 1

Our improved forward sequential algorithm is implemented for the same model rainfall that was described previously in subsection 3.2. Figure 3 is the same as Fig. 1, but using our method for the retrieval. Legend “+x dB” denotes the result retrieved by attenuated radar reflectivity that has +x dB bias error in 14 GHz. The bias error is not added to $Z_e^{\text{OBS}, 95\text{G}}$, because it is canceled in Eq. 6. Figure 3 displays ± 1 dB errors occur though there is no bias (see “+0 dB” in 95 GHz). This is because the bin numbers in the look-up tables are not fine enough to save computation time, where the computation time of one vertical profile is approximately 3 s when using a Pentium III 800 MHz. Notice that Fig. 3 shows our forward sequential algorithm stably corrects the attenuation though some biases are appended. Therefore, the retrieved $N_T(r_i)$ and

Fig. 3. The same as Fig. 1 but solved by our method. Legends “+x dB” denote that result retrieved by attenuated radar reflectivity that has +x dB bias error in 14 GHz.

$D_m(r_i)$ are also stable (not shown), while the retrieved $N_T(r_i)$ has a large error (as is discussed in subsection 5.2).

4.4 Computation for the model rainfall: 2

Three different raindrop vertical profiles are utilized to test our method; $\mu = 0, 3$, or 6 , and $R = 5$ mm/hr. Each raindrop profile is assumed to be uniform throughout range gates, and those raindrop size distributions are the same as Table 2 of Kozu and Nakamura (1991). Table 4 summarizes typical values of the rainfalls. Table 4 shows that the 14 GHz attenuation is negligible, but not for the 95 GHz.

Figure 4 is the same as Fig. 1, again using our retrieval method. Figure 4 also shows that our algorithm corrects for the attenuation stably though the shape parameters of raindrop size distribution are different from that of the look-up table ($\mu = 3$). Hence, even if the raindrop size distribution is different from our assumption, N_T and D_m are retrieved stably (not shown).

Fig. 4. The same as Fig. 3, but for $\mu = 0, 3$ and 6 , and no bias is appended.

5. Results

5.1 Observations

Rainfall observations by vertical pointing 14 and 95 GHz radars were carried out at Kashima, Japan, from 1900 to 2200 JST on 15 November 2000. Figure 5 illustrates the equivalent radar reflectivity measured with (a) 14 GHz radar, and (b) 95 GHz radar. Figure 5c shows the rainfall rate observed with a disdrometer, and the rate was from 0.1 to 4.6 mm/hr. All of them are averaged for one minute. Since vertical resolutions of $\text{dBZ}_e^{\text{OBS},14\text{G}}$ and $\text{dBZ}_e^{\text{OBS},95\text{G}}$ are 75 m and 82.5 m, respectively, $\text{dBZ}_e^{\text{OBS},95\text{G}}$ are linearly interpolated to match the vertical resolutions of $\text{dBZ}_e^{\text{OBS},14\text{G}}$. Note that the color bar scales in Figs. 5a and 5b differ, the radar reflectivities are not corrected for attenuation, and the optical constant of water is applied to all range gates. The ground temperature was 15.3°C during the observations.

Unfortunately, the 95 GHz radar could not measure rainfall at heights below 100 m due to the ground clutter. The 14 GHz radar could not observe most of rainfall at a height of 400 m or lower because of hardware problems. Hence, r_1 is assumed as a height of 525 m. The calibration was implemented using disdrometer comparisons, as described in the Appendix. The sensitivity of the 14 GHz radar at a distance of 5 km is 0 dBZ for water particles. When it is not rainy, the sensitivity of the 95 GHz radar at a distance of 5 km is -30 dBZ for water particles. Under rainy conditions, the value of the 95 GHz radar is -19 dBZ, because the loss of the wetted radar radome increases by 11 dB.

Figures 5a and 5b indicate that $\text{dBZ}_e^{\text{OBS},14\text{G}}$ and $\text{dBZ}_e^{\text{OBS},95\text{G}}$ differed markedly, especially at the melting layer and at heavier rainfall. It suggests some particles may have been large enough to produce Mie scattering in the 95 GHz, while undergoing Rayleigh scattering at 14 GHz.

5.2 Retrieval results

Figure 6 displays the retrieved values of (a) $\log_{10} N_T$ and (b) D_m . It shows results which do not suffer from the positive feedback of numerical errors. Apart from this, the retrieved values of raindrop parameters are valid, because the values in the look-up tables include the raindrop's ranges that were measured by Kozu and Nakamura (1991). The retrieved

Fig. 5. Equivalent radar reflectivity factor of the cloud with precipitation observed with (a) 14 and (b) 95 GHz radars at Kashima, Japan, on 15 November 2000. The water optical constant is applied to all range gates, and the attenuation is not corrected. The scales of the color bars in (a) and (b) differ. (c) Rainfall rate observed with the disdrometer.

diameters in Fig. 6 show that snowflakes fall as a streamer from a height of about 6 km, and reach the melting layer, and then raindrops fall from the melting layer to the ground assuming the horizontal uniformity. Note: when

Fig. 6. Retrieved values of (a) $\log_{10} N_T$ and (b) D_m for one-minute averages.

one of radars can not measure, retrieval is not possible.

The white areas in Fig. 6(a), e.g., the echo top at around 1940 JST, denote retrieval is not possible since $Z_e^{0,14G}$ and $Z_e^{0,95G}$ are close enough and 95 GHz attenuation is weak. Hence, our method is not applicable when the backscattering is Rayleigh scattering in 95 GHz. In addition, results at around melting layer are sometimes discontinuous because the model of the melting layer may be invalid, $N_T(r_i)$ is not constant at those pairs, and/or optical constants are not correct. However, the retrieved error of the melting layer does not cause the significant error without the melting layer, because our method does not need 95 GHz attenuation from the ground to the pair of interest. To minimize the error derived from constant N_T , the vertical resolution should be set as fine as possible. When the model of the melting layer is completely established for accuracy, our method will retrieve with less error.

Figure 7 shows comparisons of (a) $\log_{10} N_T$, (b) D_m , and (c) LWC between the disdrometer measurements (dashed curve, "DIS") and retrieved results at a height of 1.5 km (solid curve, "ret."), respectively. The observation time of the disdrometer is shifted by -5 minutes by assuming a fall velocity as 5 m/s

Fig. 7. (a) Comparison between $\log_{10} N_T$ retrieved by our method at a height of 1.5 km (solid curve, "ret.") and that measured by the disdrometer (dashed curve, "DIS"). (b) The same as (a) but D_m . (c) The same as (a) but LWC .

Fig. 8. The ratio of the retrieved values to the disdrometer-derived ones, i.e., D_m^{ret}/D_m^{DIS} and $\log_{10} LWC^{ret}/LWC^{DIS}$. The ranges of D_m^{ret}/D_m^{DIS} and $\log_{10} LWC^{ret}/LWC^{DIS}$ are described on the left-hand y-axis, and the range of rainfall rate is described on the right-hand y-axis, where the rainfall rate is the same as Fig. 5c.

throughout range gates. Figure 7 indicates that the retrieved results of D_m and LWC agree with the disdrometer data. This is because dBZ is sensitive to the changes of D_m , and LWC is the integrated value of the size distribution. Note this consistency is independent from the calibration method that uses a disdrometer (Appendix). On the other hand, $\log_{10} N_T$ has a large error, hence a bias or an error in N_T is a characteristic of the algorithm. Moreover, the retrievals of D_m and LWC agree with the disdrometer data, though N_T has a large error.

Figure 8 shows the differences between the retrieved and the disdrometer-derived values of D_m^{ret}/D_m^{DIS} and $\log_{10} LWC^{ret}/LWC^{DIS}$. Most of the time, D_m agrees to within 30% for rainfall rates between 0.1 to 4.6 mm/hr. On the other hand, $\log_{10} LWC$ agrees to within 30% when the rainfall rate is heavier than 0.5 mm/hr. The main reason of this error is the neglect of the collision-coalescence process, and the evaporation of raindrops from the ground to the height of the comparison.

6. Conclusion

The forward sequential algorithm has been modified to retrieve vertical profiles of raindrop size distribution and cloud microphysical information using radar reflectivity from a 14 and a

95 GHz radar. The problem of the conventional forward sequential algorithm is the accumulation of the numerical error. To avoid the instability, the retrieval methods by O2003 and Eccles and Mueller (1971) are modified, that is, our method does not include the 95 GHz attenuation below the range of interest. For the faster calculations, look-up tables for the radar signals are prepared before the retrieval.

The modified method was applied to the model rainfalls. Our method retrieved stably, even if the raindrop size distribution was different from our assumption, or even if some bias errors were appended to the radar constant. In addition, it was applied to the analysis of the synergy precipitation and cloud observation with the 14 and the 95 GHz radar. Notice that the accumulation of the numerical error did not occur. The comparisons between disdrometer data and our retrieved results were also carried out to validate our method. D_m and LWC measured by the disdrometer and those retrieved by our method showed good agreement. Though $\log_{10} N_T$ has a large error, the retrieved D_m and the disdrometer-derived D_m were in agreement to within 30%, and the retrieved $\log_{10} LWC$ and the disdrometer-derived $\log_{10} LWC$ were in agreement to within 30% when the rainfall rate was heavier than 0.5 mm/hr. These facts conclude that our forward sequential algorithm is valid, and stably solves microphysics of the cloud with rainfall.

The 95 GHz cloud radar is therefore not only effective for observing clouds, but also holds promise for observing clouds with rainfall.

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Appendix

Calibration of radars

The radar constants C in each wavelength are determined to fit Z_e^0 (Eq. 2) into the

disdrometer-derived radar reflectivity Z_e^{DIS} as described in Eq. (A1), where the disdrometer observes the number of raindrops with diameters ranging from 0.35 mm to 5.25 mm by measuring the sound of the raindrops' impact.

$$C = \sum_{\text{Time}} Z_e^0 / \sum_{\text{Time}} [Z_e^{\text{DIS}} A(r)], \quad (\text{A1})$$

where

$$Z_e^{\text{DIS}} = \frac{\lambda^4}{\pi^5 |K|^2} \sum_{\text{Size}} C_{\text{bk}}(D_i) n(D_i) \quad (\text{A2})$$

$$A(r) = \exp \left[-2r \sum_{\text{Size}} C_{\text{ext}}(D_i) n(D_i) \right]$$

$n(D_i)$ denotes the number of raindrops in number/m³ with the diameter D_i on the ground. r denotes the fitting height. Because of the ground clutter, we fit $Z_e^{0,14\text{G}}$ at a height of 1200 m into $Z_e^{\text{DIS},14\text{G}} A(1200 \text{ m})$, and $Z_e^{0,95\text{G}}$ at a height of 150 m into $Z_e^{\text{DIS},95\text{G}} A(150 \text{ m})$, assuming uniform rainfall. Note Eq. (A1) and Eq. (A2) clearly show the calibration method is independent of N_T and D_m .

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