Evaluation of Rain Microphysics Using a Radar Simulator and Numerical Models: Comparison of Two-Moment Bulk and Spectral Bin Cloud Microphysics Schemes

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Abstract This study extended a method to evaluate rain microphysics in a shallow cumulus regime using space-borne radar observational data with a forward simulator of satellite measurements. We compared a two-moment bulk scheme with a two-moment bin scheme. A dynamic-kinematic model was used to isolate cloud microphysics processes from their interactions with dynamics. The relationship between horizontally averaged reflectivity $Z_m$ and optical depth from the cloud top $\tau_d$, that is, the $Z_{m} - \tau_{d}$ relationship, was similar between the bulk and the bin schemes for clouds with large updraft velocity and clean cloud condensation nuclei (CCN). However, the differences in the $Z_{m} - \tau_{d}$ relationship between the two schemes became more apparent for clouds with smaller updraft velocity or polluted CCN. For these clouds, the differences resulted from differences in the autoconversion rate. We increased the autoconversion rate by decreasing the shape parameter of the cloud droplet size distribution in the bulk scheme. This reduced the differences in the $Z_{m} - \tau_{d}$ relationship between the two schemes, indicating that for these clouds, the autoconversion rate of a cloud microphysics scheme can be evaluated by the $Z_{m} - \tau_{d}$ relationship derived from satellite observations. Although the clouds with the smaller updraft velocity or the polluted CCN did not contribute to the rainfall amount significantly, the lifetime of these clouds greatly affected the radiation budget. Thus, the improvement in the autoconversion rate for such weak cumulus clouds provides a better representation of precipitation efficiency and is important for global climate evaluations.

Plain language summary We investigated how space-borne radar observations can improve the bulk cloud microphysics schemes used in regional and global numerical models. We conducted numerical experiments using the bulk and bin schemes. The results allowed us to calculate the radar reflectivity and optical thickness of clouds using a forward simulator of satellite measurements. The two schemes were compared, and we tested the sensitivity of the radar reflectivity and optical thickness of clouds to parameters in the bulk scheme. We found that the parameters in the bulk scheme could be constrained by space-borne radar observations, provided that the observed data are classified by specific atmospheric conditions, such as cloud condensation nuclei, updraft velocity in clouds, and others.

1. Introduction

Although warm liquid clouds play a substantial role in Earth’s climate by affecting radiation and precipitation, large uncertainties remain in the representation of warm liquid clouds in climate models (Bony & Dufresne, 2005; Noda et al., 2010). In particular, the effects of cloud condensation nuclei (CCN) and updraft velocity on warm clouds need to be better represented in numerical models to adequately capture warm liquid cloud processes and their effect on the radiation budget in climate models (other effects are also important, such as turbulence, liquid water path). At the same time, the representation of rain formation in warm clouds needs to be improved to better reflect the hydrological cycle and precipitation efficiency. Warm clouds have been simulated with cloud microphysics schemes implemented in high-resolution cloud system models or large eddy simulation (LES) models by directly resolving circulations associated with cloud formation (Sato et al., 2015; vanZanten et al., 2011); they have also been represented in cloud macrophysics schemes by parameterizing the cloud fraction in climate models (e.g., Mellor & Yamada, 1974; Smith, 1990). Although such cloud-resolving models reduce the uncertainties related to cloud macrophysical assumptions, there are still uncertainties associated with the assumptions made in cloud microphysics schemes. Most cloud-resolving models use bulk methods in cloud microphysics schemes, in which the size distributions
of cloud droplets and raindrops are assumed. Such bulk schemes have been tested against satellite and field observational data (Roh & Satoh, 2014; Suzuki et al., 2011; Suzuki et al., 2015; vanZanten et al., 2011).

Seifert and Beheng (2001) compared bulk schemes with more sophisticated spectral bin schemes. More recently, several studies have used LES to investigate different microphysical schemes. For example, VanZanten et al. (2011) showed that the difference among the results of spectral bin schemes was as large as that among the results of one- or two-moment bulk schemes. The differences in precipitation were caused by differences in the macrostructure of clouds. Sato et al. (2015) compared a one-moment bulk scheme, a two-moment bulk scheme, and a one-moment bin scheme using LES to consider the feedback from cloud microphysics processes on dynamics. They showed that the precipitation amount calculated with the two-moment bulk scheme was much smaller than with the one-moment bin scheme or with the one-moment bulk scheme.

Khain et al. (2015) surveyed one-moment bulk, two-moment bulk, three-moment bulk, and spectral bin microphysics schemes in detail for a wide range of atmospheric conditions. They demonstrated four different approaches to compare microphysics schemes (1) by the rates of separate microphysical processes, (2) by the utilization of same dynamic-kinematic model with prescribed velocity field, (3) by the utilization of the same dynamical framework taking into account all mutual influences of microphysics and dynamics, and (4) by the utilization of different model simulating the same well-documented case study. One study that used the fourth approach is Naumann and Seifert (2016). They compared a two-moment bulk scheme and Lagrangian drop scheme using LES. They showed that the shape parameter of the gamma distribution assumed as the size distribution of raindrops in the two-moment bulk scheme varied in time and space.

In general, LES models including a complex feedback from cloud microphysics processes on dynamics produce more realistic results than simple kinematic models. However, detailed comparisons among the different schemes implemented in LES are not straightforward. Therefore, in many studies, evaluations were limited to the statistical averages in time and space (Sato et al., 2015; vanZanten et al., 2011).

Instead of using a high-resolution cloud system or LES model, a simpler framework with a kinematic driver model has also been widely used to study the dependency on cloud microphysics schemes (the second approach outlined by Khain et al., 2015). Hill et al. (2015) compared a one-moment bulk scheme, a two-moment bulk scheme, and a two-moment bin scheme, using the kinematic driver model “KiD” developed by Shipway and Hill (2012). A kinematic driver model isolates dependencies on the cloud microphysics processes without interaction of the dynamics or flow fields, as the feedback from cloud microphysics processes to dynamics is turned off. Kuba et al. (2014, 2015) applied a similar approach via a kinematic model to evaluate cloud processes simulated with a two-moment bin scheme using satellite observation data.

We chose this approach for our study because it allows comparison under the same dynamical conditions. Many other studies have used this approach (Hill et al., 2015; Morrison & Grabowski, 2007; Shipway & Hill, 2012; Szumowski et al., 1998). As noted by Khain et al. (2015), the agreement between the bulk and bin schemes in the case of prescribed dynamics (the second approach) does not guarantee the same agreement when considering all mutual influences of microphysics and dynamics in the dynamical framework (the third approach).

There have been many attempts to evaluate cloud microphysics schemes using observational data. In particular, satellite remote sensing data have become more popular recently as a way of reducing uncertainties due to clouds. Additionally, multisensor satellite measurements are now available to study clouds and precipitation processes. Such multisensor satellite observational data have been used to evaluate numerical simulations of clouds and precipitation (Hashino et al., 2013; Hashino et al., 2016; Masunaga et al., 2008; Matsui et al., 2016; Roh et al., 2017; Roh & Satoh, 2014). The use of multisensor satellite observations provides a better representation of cloud microphysics processes used in numerical models.

Suzuki et al. (2015) examined the warm rain formation process in global models using satellite observations. They used the methodologies developed to analyze CloudSat and Moderate Resolution Imaging Spectroradiometer (MODIS) products and a forward simulator for satellite sensors. Radar reflectivity profiles as a function of in-cloud optical depth were used to compare model results and satellite observations; these satellite data can constrain key parameters of autoconversion process in cloud microphysics schemes. The probability of radar reflectivity in terms of the vertical profile of cloud optical depth is portrayed as a contoured frequency by an optical depth diagram (CFODD), whose observational results were examined by
Suzuki et al. (2010). Kuba et al. (2014, 2015) analyzed cloud properties of numerical models with a two-moment bin scheme, following the approach using multisensor satellite measurements proposed by Suzuki and Stephens (2008) and Suzuki et al. (2010). This method distinguishes among the condensational growth of cloud droplets, the autoconversion process, the accretion process, and the initiation of rainfall in the diagram between radar reflectivity and cloud optical depth.

The aim of this study was to extend the methodology proposed by Kuba et al. (2015) to the evaluation of rain microphysics processes using multisensor satellite data for comparing a two-moment bulk scheme and a two-moment bin scheme. This should help to constrain parameters in the bulk scheme using satellite observable data. We used a two-dimensional kinematic driver model to produce cloud profiles of the two schemes without interaction with dynamics. Forward simulators of satellite sensors were used to evaluate numerical results against satellite observations. We used the spectral bin scheme to investigate the relationships between satellite observational data and processes of cloud microphysics in this study, although we should note that the results with a spectral bin scheme are not necessarily regarded as truth, as indicated by vanZanten et al. (2011).

We focused on the size distributions of cloud droplets and raindrops, which are represented by analytic functions (e.g., the gamma distribution, Berry & Reinhardt, 1974a) in bulk schemes. The two parameters in the gamma distribution were calculated using the number and mass of particles, while fixed values were used as shape parameters representing the width of the gamma distribution in many two-moment bulk schemes (e.g., Harrington et al., 1995; Ikawa et al., 1991; Morrison et al., 2005; Phillips et al., 2007; Seifert & Beheng, 2006). The shape parameter affects rain water production (Berry & Reinhardt, 1974b). It is not evident that the two-moment bulk schemes developed for regional models are useful for global models. However, detailed cloud microphysics schemes have been implemented in high-resolution cloud system models (Stevens et al., 2019). Therefore, we investigated ways by which to evaluate the shape parameters in bulk schemes using satellite data.

The structure of this paper is as follows. Section 2 describes the methodology. A two-moment bulk cloud microphysics scheme, a two-moment bin cloud microphysics scheme, a kinematic framework of the numerical model, and the evaluation procedure using a satellite simulator are described. Sections 3 and 4 present the results of the study. Section 5 describes the discussion, and section 6 summarizes the paper.

2. Methodology

2.1. Cloud Microphysics Schemes

Two cloud microphysics schemes were compared in this study. One was a two-moment bin scheme developed by Kuba and Fujiyoshi (2006) based on Chen and Lamb (1994). In the two-moment bin scheme, the number and mass of droplets included in each bin are variables (notably, this is one of the schemes introduced by Tzivion et al., 1987, the microphysics method of moments). This bin scheme adopts a bin-shift method (Chen & Lamb, 1994) to estimate the condensation and coalescence processes of cloud droplets and raindrops. It uses a semi-Lagrangian method and allows the distribution of each bin to account for only a part of the bin width (explained by Figure 3 in Chen & Lamb, 1994). Therefore, the number and mass of droplets in the bin are not always transported to adjacent bins at every time step. This method can suppress the numerical diffusion of droplet size distribution. The bin scheme with the bin-shift method was verified in Chen et al. (1997) and Chen and Lamb (1999) by comparison with observational data. Kuba and Murakami (2010) improved the two-moment bin scheme developed by Kuba and Fujiyoshi (2006) to properly estimate multicoalescence within one time step using both a general stochastic coalescence scheme for rarely occurring coalescence and a continuous coalescence scheme for frequent coalescence. This improvement avoids underestimation of multicoalescence within one time step. The details are described in Appendix A in Kuba and Murakami (2010). Cloud microphysics processes of condensation, coalescence, and breakup of droplets were estimated using the semi-Lagrangian framework, with a 0.5-s time step. This time step is small enough to evaluate the supersaturation rate as a diagnostic variable, except when the activation of CCN is estimated. The number of activated CCN was estimated by the parameterization shown as equation (3) in Kuba and Fujiyoshi (2006), and the initial cloud droplet size distribution was approximated by a gamma distribution modified to satisfy the number of activated CCN and the cloud water mixing ratio for the range of radius larger than 1 μm. From this size distribution, the initial number and mass
of droplets in each bin were calculated. Under the simple condition assumed in this study, activation of CCN occurs at the cloud base. In the present study, we used 73 bins to express a range of radii (1 μm to 4 mm) for the activated cloud droplets and raindrops following Kuba et al. (2015). Sedimentation was estimated using an Eulerian spatial framework, with a 0.5-s time step. The collision efficiency was calculated using Table 1 in Hall (1980). The falling velocity was computed using the code distributed by Bott (1998). In addition, the coalescence efficiency proposed by Seifert et al. (2005) and a breakup scheme based on Feingold et al. (1988) were used to estimate the collision breakup of raindrops as in Kuba et al. (2015). The details are described in Kuba and Murakami (2010).

The other scheme was a two-moment bulk scheme based on Seiki and Nakajima (2014). This scheme is implemented in the Non-hydrostatic Icosahedral Atmospheric Model (Tomita & Satoh, 2004; Satoh et al., 2008, 2014) and is referred to as the Non-hydrostatic Icosahedral Atmospheric Model double-moment scheme with six water categories (NDW6; Seiki & Nakajima, 2014). This scheme estimates the activation of CCN, condensation, coalescence, breakup, and sedimentation of droplets, with a 0.5-s time step. In this scheme, the size distributions of cloud droplets and raindrops are represented by the generalized gamma distributions as follows:

\[
    f_a(x) = \alpha_a x^{\gamma_a} \exp(-\lambda_a x^{\nu_a}),
\]

where \( a \) represents cloud droplets (c) or raindrops (r) and \( x \) is the mass of a cloud droplet or a raindrop. Seifert (2008) used a modified gamma distribution as follows:

\[
    n_a(D) = N_a D^{\nu_a} \exp(-\lambda_a D),
\]

where \( D \) is the diameter of a cloud droplet or a raindrop. Equations 1 and 2 are equivalent if \( \nu_a \) in equation 1 is 1/3. The default values of \( (\mu_c, \mu_r) \) in the generalized gamma distributions are (1, 1/3) based on Seifert and Beheng (2006) and Seiki and Nakajima (2014). The shape parameters \( \nu_c \) and \( \gamma_c \), equations 1 and 2, respectively, represent the width of the size distribution. \( \nu_c \) and \( \gamma_c \) are related as follows:

\[
    \gamma_c = 3\nu_c + 2.
\]

The default values of the shape parameters \( (\nu_c, \nu_r) \) in equation 1 are (1, –1/3) based on Seifert and Beheng (2006) and Seiki and Nakajima (2014); thus, \( (\gamma_c, \gamma_r) = (5, 1) \). Autoconversion and accretion processes were estimated based on Seifert and Beheng (2001, 2006) and Seifert (2008). \( \nu_r \) is used to estimate the autoconversion process, and \( \nu_r \) is used to estimate a mass-weighted mean falling velocity and evaporation rate of raindrops. Therefore, \( \nu_r \) and \( \nu_r \) affect the vertical distribution and generation rate of rain water; the effect of \( \nu_r \) and \( \nu_r \) will be investigated in this paper. In NDW6, the number of activated CCN was approximated by the aerosol nucleation scheme (Rogers & Yau, 1989) at the cloud base. Self-collection and collisional breakup of raindrops were estimated based on Seifert and Beheng (2006) and Seifert (2008) so that the coalescence-breakup equilibrium was formed. The details are described in Appendices A and B of Seiki and Nakajima (2014). Note that we used the corrected form of the breakup function derived by Seifert and Beheng (2006) in this study. This correction is detailed in Appendix A of this study.

### 2.2. Kinematic Framework for Warm Cloud Evolution

To compare the two microphysics schemes described above, the schemes were installed in the kinematic driver model, “KiD” (version 2.3.2625). KiD was developed by Shipway and Hill (2012) as a community tool to facilitate the comparison of cloud microphysics schemes. A kinematic flow was prescribed as a time-dependent function, and the advection of cloud microphysics variables such as water vapor, cloud droplets, and raindrops was calculated using the prescribed flow. Effects of turbulence on humidity and the feedback to the dynamics and temperature fields from cloud microphysics processes were not considered. Temperature was calculated at each time step without the effect of condensation/evaporation to clearly compare the distinction between the two microphysics schemes. This approach, which isolates each effect of the cloud microphysics processes, has been applied in several previous studies: Szymowski et al. (1998), Morrison and Grabowski (2007), Shipway and Hill (2012), Hill et al. (2015), and Kuba et al. (2015).
The size of the domain was 9 km in horizontal distance and 3 km in vertical distance. The grid spacing was 50 m in the horizontal and vertical directions. The time step for advection was 0.5 s. We chose the case of a shallow warm cloud following Suzuki et al. (2015) and Kuba et al. (2015). Flow pattern is shown in Figure 1. Three types of evolution of a single shallow warm cloud (thin, middle, and thick clouds) were simulated for a duration of 120 min by changing the maximum updraft velocity. The vertical profiles of the updraft velocity at the center of the clouds at 15 min are shown in Figure 2a. The temporal changes in the maximum updraft velocity at the centers of the clouds are shown in Figure 2b. The updraft velocity was terminated at 30 min; otherwise, an unrealistically long cloud would be generated, as simulated by Kuba et al. (2015). For example, the time evolutions of simulated liquid water path for the thin, middle, and thick clouds are shown in Figures 2c and 2d. The flow pattern, vertical profile of updraft velocity, and change in the maximum updraft velocity of the middle cloud (red lines in Figures 2a and 2b) were the same as in Kuba et al. (2015). The effect of latent heat on temperature is neglected, so the temperature and flow fields are the same between the two schemes.

The initial vertical profiles of temperature, potential temperature, and relative humidity are shown in Figure 3. These profiles are based on aircraft data from 10 August 1990 during the Hawaiian Rainband Project (Szumowski et al., 1998). For each cloud (thin, middle, or thick), we chose five cases from numerous cases with different CCN input data, varying between clean and polluted CCN conditions. Table 1 lists 30 cases and their cloud droplet number concentrations near the cloud base at about 15 min. For each thin, middle, or thick cloud, the chosen five numbers of cloud droplets were the same between the cases with the bin scheme and the bulk scheme (NDW6); this was done to minimize the influence of the differences in activation schemes between the two schemes and to focus, instead, on the influence of cloud droplet number on the conversion process from cloud droplets to raindrops and rain processes.

### 2.3. Horizontally Averaged Radar Reflectivity and Optical Depth

We evaluated the results in the observable space by forward simulating satellite remote sensing observations in a manner similar to that in Kuba et al. (2014, 2015). Vertical profiles of radar reflectivity in clouds and optical thickness can be observed by cloud radars on CloudSat (Stephens et al., 2008) and MODIS or those on the future satellite mission, EarthCARE (Earth Clouds, Aerosols and Radiation Explorer; Illingworth et al., 2015). The footprint size of pixel-level data from the CloudSat radar is 1.75 km, and the horizontal resolution of MODIS cloud product is about 1 km. These data can be used to compare the products between the observation and simulation.

The horizontally averaged radar reflectivity $Z_m$ and the optical depth from the cloud top $\tau_d$ were calculated using the radar simulator developed by Masunaga and Kummerow (2005) in the Joint Simulator for Satellite Sensors (hereafter referred to as Joint-Simulator) (Hashino et al., 2013; Satoh et al., 2016). For input data, we used the directly simulated cloud droplet size distributions for the bin scheme and the generalized gamma distribution with the chosen shape parameter simulated in the bulk scheme. The Joint-Simulator reproduced the data observed by CloudSat and MODIS. The cloudy grid boxes were defined as those with radar reflectivity $Z > -27$ dBZ (95 GHz). First, we calculated the radar reflectivity $Z$ by considering the attenuation caused by cloud droplets and raindrops above and within the layer. $Z_m$ was calculated by averaging radar reflectivity $Z_0$ (mm$^6$ m$^{-4}$) at a cloudy grid point over each layer (grid size: 50 m). Second, we calculated the optical thickness, $\tau$, using a wavelength of 0.64 $\mu$m at each grid on the ground. Finally, we calculated the effective optical thickness by averaging $e^{-\tau}$ over the cloud. In addition, the optical depth from the cloud top $\tau_d$ was calculated under the assumption of adiabatic condensational growth following Suzuki et al. (2010) (equations (1)–(4) in Suzuki et al., 2010) from the effective optical thickness. The horizontal size of the simulated cloud in this study (1–2 km) was comparable to the resolution of data used in Suzuki et al. (2010) (~1 km). We compared the $Z_m$-$\tau_d$ relationships between the two cloud microphysics schemes. Suzuki et al. (2010) generated a CFODD by accumulating the $Z_m$-$\tau_d$ relationships derived from satellite observations statistically to discuss cloud properties. In satellite observations, a CFODD is a probability distribution that includes different stages of a cloud lifetime and different types of atmosphere (updraft velocity,
Figure 2. (a) Vertical profiles of the updraft velocity at the centers of the three types of cloud at 15 min. (b) Time evolutions of the maximum updraft velocity at the centers of the three types of cloud. (c) Time evolutions of liquid water path averaged near the center of the three types of cloud for the cases in which the cloud droplet number at 15 min near the cloud base is about 160 cm$^{-3}$ for the bulk cases (W1Bulk160, W2Bulk160, and W3Bulk160). (d) Same as (c), except for the bin cases (W1Bin160, W2Bin160, and W3Bin160). Black, red, and green lines show the thin, middle, and thick clouds.

Figure 3. Initial vertical profiles of potential temperature (black) and temperature (red) (a) and relative humidity (b) in a cloud.
CCN number density, etc.). We calculated the $Z_m \tau_d$ relationships for each of our simulated cases with three types of cloud and five CCN conditions. These differed from probability distributions, because a CFODD includes the statistical effect of temporal evolution and cannot be compared directly to the probability distribution by the satellite observation. However, our method isolates the characteristics of the $Z_m \tau_d$ relationship of each cloud type. Following this, the shape in the $Z_m \tau_d$ relationship can be examined using observable data, provided they can be sorted by cloud type and atmospheric condition.

### 3. Basic Results

The evolutions of the mixing ratio of cloud water were almost the same for both schemes for the first 20 min (not shown here). This means that both schemes estimated the conversion process from water vapor to cloud water similarly. The calculated rates of condensation and the change in vapor saturation were similar between the two schemes. Before rain water was produced, cloud water amounts were roughly the same for cases with a small number and those with a large number of cloud droplets, except for the layer near the cloud base where supersaturation of vapor occurs (not shown here). When rain water was produced after around 30 min, differences arose because the efficiencies of rain production were different between the two schemes and between cases with a different number of cloud droplets. The evolution of rainwater for the middle cloud and clean CCN condition for both schemes (W2Bin80 and W2Bulk80) is shown in Figure 4. Figure 5 is the same as Figure 5 but for the polluted CCN cases (W2Bin1000 and W2Bulk1000). We define a raindrop in the bin scheme as a droplet whose radius is larger than 40 $\mu$m. Rainwater fell faster in the bulk cases than in the bin cases (Figures 4 and 5). The maximum values of the rainwater mixing ratio during the lifetime of a cloud were larger in the bulk schemes than in the bin schemes regardless of the cloud droplet number. The amount of rainwater in the clean CCN case (Figure 4) was greater than that in the polluted CCN case (Figure 5) for both the bin scheme and bulk scheme, as expected. Figure 6a clearly shows this tendency for the 30 cases listed in Table 1.

### Table 1
Names of 30 Cases

| Bin      | Bulk   | $W_{\text{max}}$ (m s$^{-1}$) | Cloud | $N_d$ (cm$^{-3}$) |
|----------|--------|-------------------------------|-------|------------------|
| W1Bin50  | W1Bulk50 | 0.8                           | thin  | 50               |
| W1Bin80  | W1Bulk80 | 0.8                           | thin  | 80               |
| W1Bin160 | W1Bulk160 | 0.8                          | thin  | 160              |
| W1Bin220 | W1Bulk220 | 0.8                          | thin  | 220              |
| W1Bin350 | W1Bulk350 | 0.8                          | thin  | 350              |
| W2Bin80  | W2Bulk80  | 1.6                          | middle| 80               |
| W2Bin160 | W2Bulk160 | 1.6                          | middle| 160              |
| W2Bin400 | W2Bulk400 | 1.6                          | middle| 400              |
| W2Bin800 | W2Bulk800 | 1.6                          | middle| 800              |
| W2Bin1000 | W2Bulk1000  | 1.6                        | middle| 1,000            |
| W3Bin80  | W3Bulk80   | 3.2                          | thick | 80               |
| W3Bin160 | W3Bulk160  | 3.2                          | thick | 160              |
| W3Bin400 | W3Bulk400  | 3.2                          | thick | 400              |
| W3Bin900 | W3Bulk900  | 3.2                          | thick | 900              |
| W3Bin1100 | W3Bulk1100 | 3.2                        | thick | 1,100            |

*Note.* $W_{\text{max}}$ is the maximum updraft velocity. $N_d$ is the approximate cloud droplet number concentration at 15 min near the cloud base.

### Figure 4
Rainwater mixing ratios (g kg$^{-1}$) for the middle cloud with clean CCN. (a–c) W2Bulk80. (d–f) W2Bin80. Times are 25 min (a and d), 30 min (b and e), and 35 min (c and f).
Moreover, the rainfall amount at 120 min was similar between the bulk and the bin schemes for the thick clouds (green circles in Figure 6a) and a small number of cloud droplets (Figure 6a). Conversely, the rainfall amount was smaller in the bulk scheme than in the bin scheme for clouds with a large number of cloud droplets, particularly for the thin clouds (black circles whose cloud droplet numbers are $160 \text{ cm}^{-3}$ and larger; Figure 5.

Figure 5. Same as Figure 4 except for polluted CCN cases (W2Bulk1000 and W2Bin1000). Times are 35 min (a and d), 40 min (b and e), and 50 min (c and f).

Figure 6. Relationship between the accumulated surface rainfall averaged over the domain at 120 min and the cloud droplet number concentration near the cloud base at about 15 min for thin (black), middle (red), and thick (green) clouds. Closed circles show the bin scheme. Open circles show the bulk scheme with $(\nu_c, \nu_r) = (1, -1/3)$ (a), $(-1/3, -1/3)$ (b), $(1, 1)$ (c), and $(-1/3, 1)$ (d). The 30 circles in (a) correspond to 30 cases listed in Table 1.
they correspond to cases W1Bin160, W1Bulk160, W1Bin220, W1Bulk220, W1Bin350, and W1Bulk350). We focused on the difference for clouds with a large number of cloud droplets, particularly for the thin clouds.

We compared our results to those of Sato et al. (2015) using a sensitivity study; the difference between the bulk and the bin schemes was much smaller in the present study than that reported in Sato et al. (2015) for precipitating clouds (thick and middle clouds in this paper). Sato et al. (2015) used LES to compare the bulk and bin schemes and reported that the two-moment bulk schemes produced a much smaller amount of rainfall than the bin scheme. We used a kinematic framework, in which feedback from cloud microphysical processes to dynamics was neglected. It may be possible that the difference in the rainfall amounts between the bulk and bin schemes in Sato et al. (2015) was enlarged by feedback from cloud microphysics processes to dynamics because they used LES.

Initially, rainwater is produced by an autoconversion process (the production of rainwater by the coalescence between cloud droplets). In the bulk scheme, the autoconversion rate is estimated as a function of the cloud water mixing ratio $Q_c$ and the mean volume radius of cloud droplets $R_c$ based on Seifert and Beheng (2001) as follows:

$$\left(\frac{\partial Q_r}{\partial t}\right)_{aut} = \frac{k_{c}}{20} \frac{(u_{c} + 2)(u_{c} + 4)}{(u_{c} + 1)^2} Q_{c}^2 R_{c}^4 \left[ 1 - \Phi_{aut}(\tau) \right], \tag{4}$$

where $\nu_c$ is the shape parameter of the gamma distribution (equation 1) representing the cloud droplet size distribution near the cloud base in the bulk scheme. The accretion rate (the production rate of rainwater by the coalescence between cloud droplets and raindrops) is estimated by the function of cloud water and rainwater mixing ratios ($Q_c$ and $Q_r$) based on Seifert and Beheng (2001) as follows:

$$\left(\frac{\partial Q_r}{\partial t}\right)_{acc} = k_{c} Q_{c} Q_{r} \Phi_{acc}(\tau), \tag{5}$$

where

$$\tau = 1 - \frac{Q_{c}}{Q_{c} + Q_{r}}. \tag{6}$$

$\nu_r$ is not included in equations 4 and 5; however, $\nu_r$ is used to estimate the mass-weighted mean falling velocity of raindrops. The production of rainwater by the accretion process is related to both the accretion rate and the falling time of raindrops through the cloud layer in the bulk scheme. (Note that the accretion parameterization used in the bulk scheme is not directly related to the falling velocity of raindrops. However, the accretion process is estimated using the falling velocity of each droplet in the bin scheme.) Therefore, both $\nu_c$ and $\nu_r$ affect the generation rate of rainwater. To investigate the effect of the values of $\nu_c$ and $\nu_r$ on the rainfall amount, additional experiments were conducted for the bulk scheme with modified shape parameters $\nu_c$ and $\nu_r$. Figures 6b–6d are the same as Figure 6a, but the shape parameters used in the bulk scheme ($\nu_c, \nu_r$) are $(-1/3, -1/3)$, $(1, 1)$, and $(-1/3, 1)$, respectively. Figures 6a–6d show that the bulk scheme with $(\nu_c, \nu_r) = (1, 1)$ estimates a rainfall amount similar to the bin scheme for the case with a small number of cloud droplets and that the bulk scheme with $(\nu_c, \nu_r) = (-1/3, 1)$ estimates a rainfall amount similar to the bin scheme for the case with a large number of cloud droplets. For the thick cloud, the effect of the shape parameters $\nu_c$ and $\nu_r$ is small (green open circles). Decreasing the shape parameter $\nu_c$ from 1 to $-1/3$ increases the autoconversion rate by a factor of about 3.6. The increase in $\nu_r$ from $-1/3$ to 1 leads to a decrease in the width of the raindrop size distribution and a decrease in the number of large raindrops, leading to a decrease in the falling velocity of raindrops. In addition, the decrease in the falling velocity of raindrops leads to the increase of falling time (but accretion rate is not affected). Therefore, the increase in $\nu_r$ leads to the increase in the rain production. These sensitivity experiments indicate that empirically determined size distribution parameters for both cloud droplets and raindrops affect the rainfall evolution in the bulk scheme. Specifically, the impact of the shape parameter of the cloud droplet size distribution increases as the cloud droplet number increases.

Figure 7a shows the size distributions calculated by the bin scheme for the thin cloud with polluted CCN (W1Bin350) at four different heights. The width of cloud droplet size distribution decreased as altitude
increased. Also, the mode radius of raindrops increased as altitude decreased due to the accretion process. Gamma distributions (equation 1) satisfying the cloud droplet number, cloud water mixing ratio, raindrop number, and rainwater mixing ratio (these four values were calculated in the bin scheme for case W1Bin350) were compared with the size distributions calculated by the bin scheme. Figures 7b and 7c show the comparisons near the cloud top and near the cloud base, respectively. Raindrop (radius > 40 μm) size distributions estimated in the bin scheme (black lines in Figures 7b and 7c) were well approximated by the gamma distribution (equation 1) with $\nu_r = 1$ (blue lines in Figures 7b and 7c). As shown previously (Igel & van den Heever, 2017a; 2017b; Khain et al., 2015), cloud droplet size distributions (radius < 40 μm) are not well approximated by the gamma distribution with a fixed shape parameter $\nu_c$. Near the cloud base, the size distribution of cloud droplets estimated in the bin scheme (black line in Figure 7c) was well approximated by the gamma distribution with $\nu_c = -1/3$ (blue line in Figure 7c). However, near the cloud top, the width of cloud droplet size distribution estimated in the bin scheme (black line in Figure 7b) was approximated by the gamma distribution with $\nu_c = 1$ (red line in Figure 7b) better than that with $\nu_c = -1/3$ (blue line in Figure 7b).

Seifert and Beheng (2001, 2006) assumed that autoconversion and accretion processes could be approximated analytically using cloud base information and that the effect of time-varying size distribution on these processes could be corrected using functions of internal timescale in the collisional growth. Therefore, it is reasonable to optimize the cloud droplet size distribution near the cloud base when using their parameterizations. Figures 6d and 7 verify that the bulk scheme using the shape parameter of cloud droplets, which can represent the cloud droplet size distribution near the cloud base similar to that in the bin scheme, represents the surface rainfall similar to that in the bin scheme. Next, we aimed to derive information about the shape parameter from the vertical structures of radar echo.
Figure 8. Relationships between horizontally averaged radar reflectivity $Z_m$ and optical depth from the cloud top $\tau_d$ at 2.5-min intervals for the thin cloud with clean CCN (a: W1Bin50, b: W1Bulk50 with $(\nu_c, \nu_r) = (1, -1/3)$ (default setting), c: W1Bulk50 with $(\nu_c, \nu_r) = (-1/3, -1/3)$, d: W1Bulk50 with $(\nu_c, \nu_r) = (1, 1)$, e: W1Bulk50 with $(\nu_c, \nu_r) = (-1/3, 1)$) and with polluted CCN (f: W1Bin50, g: W1Bulk350 with $(\nu_c, \nu_r) = (1, -1/3)$ (default setting), h: W1Bulk350 with $(\nu_c, \nu_r) = (-1/3, -1/3)$, i: W1Bulk350 with $(\nu_c, \nu_r) = (1, 1)$, j: W1Bulk350 with $(\nu_c, \nu_r) = (-1/3, 1)$). And those for thick clouds with clean CCN (k: W3Bin80, l: W3Bulk80 with $(\nu_c, \nu_r) = (1, -1/3)$ (default setting), m: W3Bulk80 with $(\nu_c, \nu_r) = (-1/3, -1/3)$, n: W3Bulk80 with $(\nu_c, \nu_r) = (1, 1)$, o: W3Bulk80 with $(\nu_c, \nu_r) = (-1/3, 1)$) and with polluted CCN (p: W3Bin1100, q: W3Bulk1100 with $(\nu_c, \nu_r) = (1, -1/3)$ (default setting), r: W3Bulk1100 with $(\nu_c, \nu_r) = (-1/3, -1/3)$, s: W3Bulk1100 with $(\nu_c, \nu_r) = (1, 1)$, t: W3Bulk1100 with $(\nu_c, \nu_r) = (-1/3, 1)$). Time period is 10.0–35.0 (black), 37.5–62.5 (red), 65.0–90.0 (green), or 92.5–117.5 (blue) min.
Figure 9. Relationship between \( dZ_m/d\tau_d \) and autoconversion rate near the cloud top for the thin cloud. \( dZ_m/d\tau_d \) is calculated in the section (\( \tau_d = 0 \sim \tau_x \); \( \tau_x < 5 \)) in which \( Z_m \) increased linearly. Autoconversion rates are calculated in the same section as \( dZ_m/d\tau_d \) at the center of cloud. Closed circles show the case with polluted CCN at 60, 65, 70, 75, and 80 min (black: W1Bin350, red: W1Bulk350 with (\( \nu_c, \nu_r \)) = (1, -1/3) (default setting), green: W1Bulk350 with (\( \nu_c, \nu_r \)) = (-1/3, -1/3), blue: W1Bulk350 with (\( \nu_c, \nu_r \)) = (1, -1/3) (default setting), green: W1Bulk350 with (\( \nu_c, \nu_r \)) = (-1/3, -1/3), blue: W1Bulk350 with (\( \nu_c, \nu_r \)) = (-1/3, 1)). Open circles show the case with clean CCN at 35, 40, 45, 50, and 55 min (black: W1Bin50, red: W1Bulk50 with (\( \nu_c, \nu_r \)) = (1, -1/3, 1)).

4. Vertical Profiles of Radar Reflectivity

We compared the relationships between horizontally averaged radar reflectivity \( Z_m \) and optical depth from the cloud top \( \tau_d \) (\( Z_m-\tau_d \) relationship) simulated by both schemes using the satellite simulator in Figure 8, where each point corresponds to each layer of Kid (\( \Delta z = 50 \) m) in the cloud. The optical thickness of simulated clouds was between 5 and 40 in Figure 8. This optical thickness range is typical, as observed in previous studies (e.g., Figure 2 in Suzuki et al., 2010).

\( Z_m \) increased as \( \tau_d \) increased (altitude decreased) in the upper part of the cloud. This indicates formation of raindrops caused by the autoconversion and accretion processes. To evaluate these processes, we focused on the slope \( dZ_m/d\tau_d \) near the cloud top. \( dZ_m/d\tau_d \) near the cloud top reached a maximum value earlier in the clean CCN case than in the polluted CCN case and earlier in the thick cloud case than in the thin cloud case (Figure 8).

As shown in Figures 8a–8j, the difference in \( dZ_m/d\tau_d \) near the cloud top between the bin scheme and the bulk scheme was smaller for a small number of cloud droplets (clean CCN cases, Figure 8a (W1Bin50) and Figure 8b (W1Bulk50)) than for a large number of cloud droplets (polluted CCN cases, Figure 8f (W1Bin350) and Figure 8g (W1Bulk350)). The effects of \( \nu_c \) and \( \nu_r \) on \( dZ_m/d\tau_d \) near the cloud top were small for a small number of cloud droplets (Figures 8b–8e). Conversely, in Figures 8g–8j (polluted CCN, W1Bulk350), the effects were large (the difference in the slope is shown more clearly in Figure 9). The bulk scheme with (\( \nu_c, \nu_r \)) = (-1/3, 1) (Figure 8j) showed the most similar slope \( dZ_m/d\tau_d \) near the cloud top to that of the bin scheme (Figure 8f) (the difference in optical thickness was still large, as discussed later). The effects of \( \nu_c \) and \( \nu_r \) on \( dZ_m/d\tau_d \) near the cloud top corresponded to the effects of \( \nu_c \) and \( \nu_r \) on rainfall amount for the thin clouds (black circles in Figure 6). For the thin clouds with polluted CCN, the autoconversion rate in the bulk scheme was enlarged by decreasing the shape parameter of cloud droplets \( \nu_r \). However, for the thick clouds, the differences in \( dZ_m/d\tau_d \) near the cloud top between the bulk scheme and the bin scheme were small. In addition, the effects of the shape parameters \( \nu_c \) and \( \nu_r \) on the slope were small, especially for cases with a small number of cloud droplets (Figures 8k–8l).

Figure 9 shows the relationship between \( dZ_m/d\tau_d \) and autoconversion rate near the cloud top for the thin cloud cases. For both polluted and clean cases, bin scheme and bulk schemes with (\( \nu_c, \nu_r \)) = (1, -1/3), (-1/3, -1/3), and (-1/3, 1) are compared. For the cases with polluted CCN (closed circles), \( dZ_m/d\tau_d \) increased as the autoconversion rate increased \( \nu_r \) decreased and became similar to that of bin scheme. On the other hand, the relationship was weak for the cases with clean CCN (open circles). This shows that \( dZ_m/d\tau_d \) depends on the autoconversion rate when the autoconversion rate is small (polluted CCN case) and
the accretion process is not effective. In the case of clean CCN, the autoconversion rate is large and the accretion process is effective, then $dZ_m/d\tau_d$ depends on the production rate by the autoconversion and the accretion processes (not only the autoconversion rate).

Figure 8 also shows that the optical thickness estimated from the bulk scheme was larger than that from the bin scheme. The difference in optical thickness seemed to be a result of the size distributions of cloud droplets and raindrops. Near the cloud top, almost all cloud droplets simulated in the bin scheme were larger than 8 $\mu$m in radius even in the case of polluted CCN (see black line in Figure 7b). However, those simulated in the bulk scheme had many cloud droplets smaller than 8 $\mu$m in radius (see red and blue lines in Figure 7b), because the size distributions of cloud droplets and raindrops were assumed as generalized gamma distributions. The unnaturally small cloud droplets and raindrops tended to cause overestimation of the optical thickness, especially for the polluted CCN cases. To investigate this overestimation of optical thickness, we calculated the optical thickness using the Joint Simulator while removing droplets smaller than 8 $\mu$m in radius. Figure 10 shows that the optical thicknesses of droplets larger than 8 $\mu$m in radius were similar to those of all droplets for case W1Bin350 (see Figures 10a and 10d). This was because almost all droplets simulated in the bin scheme were larger than 8 $\mu$m near the cloud top (black line in Figure 7b). However, the optical thicknesses for droplets larger than 8 $\mu$m in radius were smaller than those for all droplets in W1Bulk350 (see Figures 10b, 10e, 10c, and 10f) and similar to those in W1Bin350.

The $Z_m-\tau_d$ relationship is likely affected by the falling velocity of rain water. In the bin scheme, the falling velocity of a cloud droplet or a raindrop was computed using the code distributed by Bott (1998). In the bulk scheme, the mass-weighted mean falling velocity of rain water is estimated using the gamma distribution (equation 1), which was assumed to represent the raindrop size distribution. An increase in the shape
parameter $\nu_r$ in the gamma distribution results in a decrease in the mass-weighted mean falling velocity of rainwater and an increase in rainfall amount as mentioned in section 3. However, increasing only the shape parameter $\nu_r$ of the raindrop size distribution (from $-1/3$ to 1) in the bulk scheme did not largely affect the $Z_m/\tau_d$ relationships near the cloud top. It is because the accretion process does not occur when the autoconversion process is not effective. Both the decrease in $\nu_r$ (from 1 to $-1/3$) and the increase in $\nu_r$ (from $-1/3$ to 1) made the rainwater production similar to that simulated by the bin scheme for the thin cloud with polluted CCN (see Figures 8–10).

5. Discussion

A larger shape parameter $\nu_r$ led to a smaller mass-weighted mean falling velocity of rainwater in the bulk scheme. This study showed that a value of 1 was appropriate for the shape parameter $\nu_r$ of the gamma distribution assumed as a raindrop size distribution. Seifert (2008) investigated the process of evaporation of raindrops under the cloud base and recommended a value of $-1/3$ as $\nu_r$ (i.e., $\nu_r = 1$ in equation 2). Several values of $\nu_r$ were derived from the observation of raindrops at ground level (e.g., Marshall & Palmer, 1948; Uijlenhoet et al., 2003). Curry (1986) showed that the observed shape parameter of raindrop size distribution varied within a cloud. Khvorostyanov and Curry (1999a; 1999b) also derived a function of the shape parameter or a three-moment bulk scheme. This study confirmed that the shape parameter of the gamma distribution assumed as the raindrop size distribution in the two-moment bulk scheme affected rainwater generation, as shown by Milbrandt and Yau (2005a, 2005b) and Shipway and Hill (2012). The diagnostic function of the shape parameter or the three-moment bulk scheme is ideal as shown by Milbrandt and Yau (2005a, 2005b) and Shipway and Hill (2012). However, our results show that even a fixed value of $\nu_r$ can reproduce surface rainfall similar to the bin scheme for the case of shallow clouds.

The autoconversion rate in the bulk scheme is underestimated for clouds with polluted CCN, particularly for clouds with a small updraft velocity. This is reasonable, since this scheme has been developed for precipitating clouds. Clouds with a small updraft velocity and polluted CCN do not contribute to the rainfall amount, but the lifetime of these clouds affects the global climate. Therefore, it is important to evaluate the autoconversion rate for these clouds using satellite observational data. The results may depend on cloud type and the method used. The observational data need to be classified by the atmospheric conditions (e.g., CCN number concentration, updraft velocity in the cloud, and liquid water content). It should also be noted that other factors (turbulence and feedback from cloud microphysical processes to dynamics, etc.) not investigated in the present study may affect the $Z_m/\tau_d$ relationship. Investigations including these effects are for future works using the cloud-resolving model (not the kinematic driver model).

6. Summary

We have extended a method proposed by previous studies (Kuba et al., 2014, 2015) to evaluate rain microphysics using space-borne radar observational data with a forward simulator of satellite measurements to compare two-moment bulk and two-moment bin schemes. Our method is useful for constraining parameters in cloud microphysics schemes using observational data from satellite remote sensing. A kinematic driver was used to isolate cloud microphysics processes from their interactions with dynamics. The two-moment bulk scheme, NDW6, based on Seifert and Beheng (2006) and modified slightly by Seiki and Nakajima (2014), was compared with the two-moment bin scheme developed by Kuba and Fujiyoshi (2006) and modified by Kuba and Murakami (2010). We focused on the conversion processes from cloud droplets to raindrops in shallow cumulus clouds.

Sensitivity experiments on the strength of the vertical velocity, CCN concentration, and size distribution parameters were conducted to examine the relationships between horizontally averaged radar reflectivity, $Z_m$, and optical depth from the cloud top, $\tau_d$, (i.e., $Z_m/\tau_d$ relationships). The results of our study are as follows:

1. The differences in the slope $dZ_m/d\tau_d$ of the $Z_m/\tau_d$ relationships near the cloud top between the bin scheme and the bulk scheme were large for the cases of clouds with a large number of cloud droplets.
(polluted CCN cases), particularly for clouds with small updraft velocity (thin clouds). For these clouds, the differences in the slope can be reduced by decreasing the shape parameter of cloud droplets $v_c$ in the bulk scheme, which in turn increases the autoconversion rate. Thus, the autoconversion rate along with $v_c$ in the bulk scheme can be evaluated by the slope $dZ_m/dt_d$ of the $Z_m$ vs $t_d$ relationships near the cloud top derived from satellite observations. This method is useful in cases that the difference in the $Z_m$ vs $t_d$ relationships near the cloud top between observation and simulation with bulk scheme is large for polluted CCN area and small for clean CCN area. For clouds with clean CCN, the slope $dZ_m/dt_d$ depends on several processes.

2. The shape parameter, $v_c$, in the cloud droplet size distribution changes with height above the cloud base. However, the bulk scheme with the fixed shape parameter, $v_c$, approximating the cloud droplet size distribution near the cloud base (rather than cloud top), estimated the rainfall amounts similar to those in the bin scheme, when using the parameterization developed by Seifert and Beheng (2001, 2006).

3. The slope $dZ_m/dt_d$ of the $Z_m$ vs $t_d$ relationships near the cloud top was similar between the bin scheme and the bulk scheme for the cases of clouds with large updraft velocity (thick clouds) and a small number of cloud droplets. Optical thickness in the bulk scheme was likely overestimated due to the assumption that the particle size distributions followed a generalized gamma distribution.

We have shown that the autoconversion rate affected by $v_c$ can be evaluated by the satellite observational data, provided they can be sorted by cloud type and atmospheric condition. The comparison between the $Z_m$ vs $t_d$ relationships observed by satellites and those produced by the results of the bulk scheme simulation is useful, because the results of the bin scheme simulation are not necessarily accurate. We used the bin scheme to investigate the relationships between cloud microphysics processes and the $Z_m$ vs $t_d$ relationships. Further work is needed to improve the parameters in the bulk scheme using real observational satellite data.

Appendix A: The Seifert and Beheng (2006) Correction

The breakup function is introduced as equation (15) in Seifert and Beheng (2006), but it contains a typo. The scales of the vertical axis in Figure 2 in Seifert and Beheng (2006) also contain typos.

The collisional breakup rate $\left( \frac{\delta N_r}{\delta t} \right)_{br}$ and self-collection rate $\left( \frac{\delta N_r}{\delta t} \right)_{sc}$ of raindrops are parameterized as a simple relaxation to an equilibrium mean volume diameter $D_{eq}$ in Seifert and Beheng (2006) as follows (equation (13) in Seifert & Beheng, 2006):

$$\left( \frac{\delta N_r}{\delta t} \right)_{br} = -[\Phi_{br}(\Delta D_r) + 1] \left( \frac{\delta N_r}{\delta t} \right)_{sc}$$

(A1)

where $\Delta D_r = D_r - D_{eq}$, with $D_r$ being the mean volume diameter of raindrops and $D_{eq}$ being the constant equilibrium mean volume diameter of raindrops. The breakup function $\Phi_{br}$ is defined as follows in Seifert and Beheng (2006):

$$\Phi_{br}(\Delta D_r) = \begin{cases} 1 & \text{for } D_r < 350 \mu m \\ k_{br} \Delta D_r & \text{for } 350 \mu m \leq D_r \leq D_{eq} \\ 2\exp(k_{br} \Delta D_r) - 1 & \text{for } D_r > D_{eq}. \end{cases}$$

(A2)

Equations A2 and A3 need to be zero at $\Delta D_r = 0$ (i.e., $D_r = D_{eq}$) (Verlinde & Cotton, 1993), but we found that equation (A3) is not zero at $\Delta D_r = 0$. In this study, we used the corrected form of equation (A3) as follows:

$$\Phi_{br}(\Delta D_r) = \exp(k_{br} \Delta D_r) - 1 \text{ for } D_r > D_{eq}.$$  

(A3)

A different corrected form of equation A3 can be used; the omission of equation A3, as in Seifert (2008), is valid in some cases.

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