Evaluations of the Thermodynamic Phases of Clouds in a Cloud-System-Resolving Model Using CALIPSO and a Satellite Simulator over the Southern Ocean

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ABSTRACT

A new evaluation method for the thermodynamic phases of clouds in cloud-system-resolving models is presented using *CALIPSO* observations and a satellite simulator. This method determines the thermodynamic phases using the depolarization ratio and a cloud extinction proxy. For the evaluation, we introduced empirical parameterization of the depolarization ratio of ice and water clouds using temperatures of a reanalysis dataset and total attenuated backscatters of *CALIPSO*. We evaluated the mixed-phase clouds simulated in a cloud-system-resolving model over the Southern Ocean using single-moment and double-moment bulk cloud microphysics schemes, referred to as NSW6 and NDW6, respectively. The NDW6 simulations reproduce supercooled water clouds near the boundary layer that are consistent with the observations. Conversely, the NSW6 simulations failed to reproduce such supercooled water clouds. Consistencies between the cloud classes diagnosed by the evaluation method and the simulated hydrometeor categories were examined. NDW6 shows diagnosed water and ice classes that are consistent with the simulated categories, whereas the ice category simulated with NSW6 is diagnosed as liquid water by the present method due to the large extinction from the ice cloud layers. Additional analyses indicated that ice clouds with a small effective radius and large ice water content in NSW6 lead to erroneous values for the fraction of the diagnosed liquid water. It is shown that the uncertainty in the cloud classification method depends on the details of the cloud microphysics schemes. It is important to understand the causes of inconsistencies in order to properly understand the cloud classification applied to model evaluations as well as retrievals.

KEYWORDS: Satellite observations; Cloud parameterizations; Clouds; Model evaluation/performance; Nonhydrostatic models

1. Introduction

The phases of hydrometeors are an important factor in determining the radiative effects of clouds over the

Southern Ocean. The simulation of mixed-phase clouds is difficult in general circulation models (GCMs) and cloud-system-resolving models (Bodas-Salcedo et al. 2014; Cesana et al. 2015). It is known that the poor representation of mixed-phase clouds in models is a possible cause of radiation biases over the Southern Ocean and that a significant fraction of the bias is due to the underprediction of supercooled water or mixed-phase cloud tops (Bodas-Salcedo et al. 2014; Williams et al. 2013).

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This bias is accompanied by the excessive transmission of solar radiation to the sea surface, which is related to the development of large biases of sea surface temperature in coupled atmosphere–ocean models of phase 5 of the Climate Model Intercomparison Project (Jones et al. 2016). This bias is also one of issues of a radiation balance in a cloud-system-resolving simulation with an explicit cloud microphysics scheme. For example, Kodama et al. (2015) demonstrated that the reflected shortwave radiation is underestimated over the Southern Ocean similarly to the results obtained with GCMs (Bodas-Salcedo et al. 2014).

A microphysics scheme plays an important role to reproduce mixed-phase clouds. There have been several studies attempting to understand the cloud microphysical process for simulations of supercooled cloud water by sensitivity tests in numerical models. Forbes and Ahlgrimm (2014) showed that a reduction in the ice deposition rate at the cloud top significantly improves the occurrence of supercooled water clouds and their radiative impacts. Furtado and Field (2017) found that a modification of the riming parameterization improves the mean-state biases of clouds over the Southern Ocean.

The satellite data are useful to evaluate the thermodynamic phases of clouds (e.g., Deschamps et al. 1994; Platnick et al. 2003). Active sensors are particularly powerful tools to investigate the vertical structure of the thermodynamic phases of clouds. Several retrieval algorithms have been developed using observations by the *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (CALIPSO; Winker et al. 2007) satellite (Delanoë and Hogan 2008; Hu et al. 2006; Yoshida et al. 2010, hereafter Y2010; Cesana and Chepfer 2013).

To evaluate numerical models via comparisons to satellite observations, a prospective approach is to calculate the radiances from the numerical model outputs using a satellite simulator. Satellite simulators establish the same assumptions in cloud microphysical schemes regarding hydrometeors, such as their thermodynamic phases, size distributions and densities. Therefore, an evaluation of a numerical model using a satellite simulator avoids inconsistent assumptions between the numerical model and the retrieval algorithms used in satellite remote sensing. There are several satellite simulators being developed; the Satellite Data Simulator Unit (SDSU; Masunaga et al. 2010), the Goddard SDSU (Matsui et al. 2014), the Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP; Bodas-Salcedo et al. 2011), the Earth Cloud, Aerosols, and Radiation Explorer (EarthCARE; Illingworth et al. 2015) simulator (ECSIM), and the Joint Simulator for Satellite Sensors (Hashino et al. 2013; hereafter referred to as the Joint Simulator). These satellite

simulators have been used to evaluate numerical models (e.g., Matsui et al. 2009; Inoue et al. 2010; Satoh et al. 2010; Masunaga et al. 2010; Bodas-Salcedo et al. 2011; Hashino et al. 2016). Moreover, it has been shown that satellite simulators can be used to improve and evaluate the cloud microphysics schemes used in cloud-system-resolving models (e.g., Li et al. 2010; Roh and Satoh 2014; Roh et al. 2017; Roh and Satoh 2018).

To classify the thermodynamic phases of clouds using satellite observations, Cesana and Chepfer (2013) developed a cloud phase identification method based on CALIPSO data. Their method is based on the different characteristics between ice and water clouds, with respect to their perpendicular attenuated backscatter and attenuated total backscatter, and classifies clouds into water, ice, and unknown cloud types. They developed a consistent diagnostic with their cloud phase identification in a lidar simulator, and evaluated the thermodynamic phases of clouds in a GCM using their methodology.

Y2010 also developed a method that enables the discrimination of vertically resolved cloud particle types using CALIPSO data. They used the depolarization ratio and an extinction proxy to classify the cloud particle types and introduced ice cloud types with two- and three-dimensional geometries, as well as liquid and unknown types. However, there is no evaluation study of numerical models based on Y2010 using depolarization ratio and their cloud phase identification method. Cesana et al. (2016) found three CALIPSO cloud products are different each other, especially cloud detections. It is needed to develop a satellite simulator for the CALIPSO product based on Y2010, which are consistent to their diagnostics of cloud identification and phases.

The first purpose of this study is to propose an evaluation method based on Y2010 for the thermodynamic phases of clouds in numerical models using a satellite simulator. The second is an evaluation of two different microphysics schemes for the mixed-phases clouds using this evaluation method. We extend the Joint Simulator (Hashino et al. 2013) to simulate the depolarization ratio of clouds by introducing empirical lookup tables. Our method calculates the depolarization ratio of liquid clouds using the total attenuated backscatter and the extinction proxy, and the depolarization ratio of ice clouds using the total attenuated backscatter and the temperature. Then, we apply the evaluation method to clouds simulated by a cloud-system-resolving model. Two types of cloud microphysics schemes, single- and double-moment bulk microphysics schemes, are used. We evaluate thermodynamics phases of the simulated clouds over the Southern Ocean using the two cloud microphysics schemes.

In [section 2](#), the evaluation method and parameterization of the depolarization ratio are described. In [section 3](#), the experimental design and evaluation results are described, and the uncertainty of the method is investigated. In [section 4](#), the simulated results over the Southern Ocean are discussed with an extinction proxy and sensitivity studies using the Joint Simulator. The summary and conclusions are given in [section 5](#).

2. Observation of the thermodynamic phases by CALIPSO and parameterization of the depolarization ratio

a. Observation of cloud classifications from CALIPSO observations

The criterion for cloud detection affects the sampling of clouds in the observation and simulations. For the observation and simulation cloud detections, we followed the cloud-masking algorithm of [Hagihara et al. \(2010\)](#). They used a threshold of the total attenuated backscattering coefficient to detect the cloud signals from the aerosols and clear sky of the merged CALIPSO and CloudSat interpolated with 240-m vertical and 1.1-km horizontal resolutions. We used this threshold $\beta_{th}(R_i)$ for the observation and simulations to distinguish the clouds and clear sky, where $z(R_i)$ is the altitude of the target bin and R_i denotes the range of the center of the layer i :

$$\beta_{th}(R_i) = \frac{\beta_{th,aerosol} + \beta_{th,noise}(R_i)}{2} - \frac{\beta_{th,aerosol} - \beta_{th,noise}(R_i)}{2} \tanh[z(R_i) - 5], \quad (1)$$

where

$$\beta_{th,aerosol} = 10^{-5.25} \quad (\text{m}^{-1} \text{ sr}), \quad (2)$$

and

$$\beta_{th,noise}(R_i) = [P_m(R_i) + P_n + \sigma_n]^2. \quad (3)$$

Here, P_m indicates the volume molecular backscattering coefficient derived from ECMWF data ([Hostetler et al. 2006](#)), P_n indicates the residual of the noise from the satellite sensor, and σ_n is the standard deviation.

The cloud type classification algorithm developed by [Y2010](#) was used for the clouds detected by CALIPSO. To discriminate the cloud particle type, two parameters, the depolarization ratio (δ) and the proxy for the extinction of the target layer (x), are calculated.

The depolarization ratio (δ) is

$$\delta = \frac{\beta_{perp}}{\beta_{parallel}} \times 100 (\%), \quad (4)$$

where β_{perp} is the 532-nm attenuated backscattering coefficient for the perpendicular channel and $\beta_{parallel}$ is the backscattering coefficient for the parallel channel. It is known that the depolarization ratio is sensitive to ice shapes. And depolarization ratio increases by multiple scattering associated with the presence of water clouds ([Y2010](#); [Hirakata et al. 2014](#)). A horizontally oriented ice plate has a low depolarization ratio, while a randomly oriented ice crystal has a large depolarization ratio ([Sassen and Benson 2001](#); [Okamoto et al. 2010](#)). The other parameter, the proxy to the extinction of the target layer (x), is defined as

$$x(R_i) = \log_{10} \left[\frac{\beta_{total}(R_i)}{\beta_{total}(R_{i+1})} \right], \quad (5)$$

where $\beta_{532}(R_i)$ is the backscattering coefficient for the 532-nm wavelength and $x(R_i)$ is proportional to the optical thickness of layer i when the two neighboring vertical layers are homogeneous ([Y2010](#)). The variable x is proportional to the extinction of the target layer when we assume that the microphysical properties of the two vertically successive layers are homogeneous ([Hirakata et al. 2014](#)). Because liquid clouds are known to have a larger extinction than ice clouds, the thermodynamic phases of the clouds can be determined using x .

Using δ and x , [Y2010](#) and [Hirakata et al. \(2014\)](#) classified six cloud types for the thermodynamic phases and ice shapes, i.e., three-dimensional (3D) ice, two-dimensional (2D) plate ice, a mixture of 2D plate ice and 3D ice, warm water, supercooled water, and unknown. [Figure 1](#) shows an example of a global classification diagram for January 2007 over all temperature ranges, as observed by CALIPSO (hereafter the [Y2010](#) diagram). In [Y2010](#), 2D plate ice refers to quasi-horizontally oriented ice plates with a low depolarization ratio, while 3D ice refers to randomly oriented ice crystals with a large depolarization ratio. While ice clouds have $x \sim 0$, water clouds have a linear relationship between x , and the depolarization ratio with large x in the [Y2010](#) diagram. The occurrence of 3D ice is dominant compared to the other categories, because the penetration depth of the lidar signals is limited to a cloud optical depth of less than approximately 3 from the cloud top (e.g., [Heymsfield et al. 2008](#)). The penetration depth depends on the attenuation from the ice shapes and the thermodynamic phases. The penetration depths within a 2D plate ice cloud and water cloud are thinner than that within a 3D ice cloud.

FIG. 1. Cloud classification diagram using the x and δ plane. The color denotes the occurrence frequencies of the observations for January 2007 at all temperatures.

b. Parameterizations of the depolarization ratios of clouds

In this study, we extended the Joint Simulator developed by Hashino et al. (2013) to simulate *CALIPSO*-like signals for a cloud-system-resolving model (CSRM). We introduce an empirical parameterization of the depolarization ratio to evaluate the cloud classifications using the Y2010 diagram. Our approach can quickly determine the utility of the depolarization ratio for the model evaluation using the empirical lookup tables in term of temperatures and total attenuated backscattering coefficients. Other approaches can be used to explicitly calculate the depolarization ratio. The T matrix (Mishchenko et al. 1997), the discrete dipole approximation (Okamoto 2002; Sato and Okamoto 2006), and the backscattering Mueller matrix (Borovoi et al. 2012) are often used to estimate the depolarization ratio of ice particles. The Monte Carlo method (Ishimoto and Masuda 2002) is used to estimate lidar multiple scattering, which is primarily relevant for optically thick water clouds. Because nonspherical shapes are not explicitly treated in typical bulk microphysics schemes, the Monte Carlo method calculations may not be directly possible. In addition, note that Monte Carlo simulations require extensive computation time; therefore, this method is also not applicable to large domains. Recently, there has been progress in the fast simulation of lidar multiple scattering, e.g., the fast lidar and radar multiple-scattering models (Hogan and Battaglia 2008; Hogan 2008), the backscattering intensity by the physical model (Sato et al. 2018), and the depolarization ratio of the water clouds by the vectorized physical model (Sato et al. 2018, 2019).

It may be possible to implement such methods in future experiments with CSRMs.

We constructed a database using a merged *CloudSat* radar and *CALIPSO* lidar (Hagihara et al. 2010) (hereafter referred to as the KU data) dataset for the empirical parameterization. We used nocturnal *CALIPSO* data to avoid noises associated with solar irradiance. These signal data were gridded with 240-m vertical and 1.1-km horizontal resolutions. The tilt angle of CALIOP changed from 0.3° (the nadir case) to 3.0° (the off-nadir case) in November 2007 (Hirakata et al. 2014). The database for the nadir case was obtained from December 2006 to November 2007, while the off-nadir database was obtained from December 2007 to November 2008.

For water clouds, the parameterization is based on the slope between x and the depolarization ratio for three bins of the backscatter coefficients (Fig. 2). According to the Monte Carlo calculation conducted by Y2010, depolarization ratios are affected by the cloud penetration depths, the number of cloud layers, and the extinction coefficients. Therefore, for the empirical parameterization, we divided the samples into the cloud-top-layer group and the other-layer group. We further divided the water clouds based on temperature: warm clouds are designated for temperatures warmer than 0°C , while supercooled water clouds are designated for temperatures colder than 0°C . The mean depolarization ratio in the first cloud layer increases less rapidly with x than the ratios in the other layers for $0.5 < x < 1.2$ (in the blue boxes in Figs. 2a and 2c, the water clouds have x values larger than 0.5 according to Y2010). There are increases in the slopes in the other layers, except for the cloud-top layer, due to the increasing sensitivity to the multiple scattering impact. These results correspond to the numerical results of Y2010. The slopes of the supercooled water clouds are lower than the slopes of the warm water clouds for $0.5 < x < 1.2$ (the blue boxes in Fig. 2a vs Fig. 2b or in Fig. 2c vs Fig. 2d).

Figure 3 shows the standard deviations of the depolarization ratios. The standard deviations are nearly 20% for warm clouds and are even larger for supercooled water clouds. We speculate that such large variability in the depolarization of the supercooled water clouds is related to the mixing of ice particles in this category. In particular, the small lidar backscatter bin of less than -6 for $\log_{10}(\beta_{532})$ has large standard deviations (see the yellow lines in Figs. 3b,d). Because water clouds generally have larger backscatter than ice clouds, the small backscatter bin in the supercooled water cloud category consists of more ice particles than water droplets.

Compared to water clouds, the parameterization of the depolarization ratio for ice clouds is more difficult because the depolarization ratio is affected by many factors including the ice shapes and the orientation of

FIG. 2. The parameterization of the depolarization ratio using x and the backscatter regime for (a),(b) the cloud-top layer and (c),(d) the other layers excluding the cloud-top layer in nocturnal data; (a) and (c) show the warm water clouds, and (b) and (d) show the supercooled water clouds. The $\log b_{532}$ means the logarithm of the 532-nm attenuated backscattering coefficient ($\text{m}^{-1} \text{sr}^{-1}$).

the ice particles. We assume that the depolarization ratio of the ice particles depends on the ice shapes. According to chamber experiments (Magono and Lee 1966; Bailey and Hallett 2009), the ice shapes (the habit) can be classified by the temperature and relative humidity with respect to the ice in the absence of sedimentation. We use the relationships between the temperature and the backscatters to simulate the depolarization ratio (Fig. 4). Four bins are defined with the backscatter coefficient for the ice clouds. Two types of parameterizations for the nadir and off-nadir cases were developed. The depolarization ratio above -20°C , where plates generally grow, increased by nearly 40% after the tilt angle was increased, demonstrating the impact of tilting on the horizontally oriented plates.

The standard deviations of the depolarization ratio for ice particles are larger than those for water clouds (Fig. 5). The standard deviation of the depolarization ratio is relatively small in temperature regions warmer than -40°C ; however, large standard deviations occur at colder temperatures. This means that large uncertainties

exist for simulations of the depolarization ratios in temperatures colder than approximately -40°C . In this study, we focus on the thermodynamic phases of clouds in the temperature regime warmer than -40°C and, in particular, discuss the fraction of supercooled water clouds by classifying the ice and water clouds. We will not evaluate the ice shapes in the colder temperature regime because the uncertainties in the classification of ice particles by Y2010 are even larger than those in the cloud phase.

Detailed descriptions of how to calculate the attenuated perpendicular backscattering coefficient for the liquid and ice particles using the lookup tables are given in the appendix.

3. Numerical results

a. Experimental design and data

We evaluated cloud fields simulated by the non-hydrostatic icosahedral atmospheric model (NICAM;

FIG. 3. Standard deviations of the depolarization ratio of the supercooled water clouds for (a),(b) the cloud-top layer and (c),(d) the other layers excluding the cloud-top layer; (a) and (c) show the warm water clouds, and (b) and (d) show the supercooled water clouds.

Satoh et al. 2014). We followed the approach of Roh and Satoh (2014) and used NICAM as a regional model by transforming the icosahedral grid system to focus on a region of interest with high spacing (stretched NICAM;

Tomita 2008a). Here the center of the focus was set to 0° , 55° S; a model domain from 170° E to 170° W and from 65° to 45° S, in which the horizontal grid resolution was less than approximately 5 km, was analyzed. The vertical

FIG. 4. The parameterization of the depolarization ratio using the temperature and the backscatter regime for (a) the nadir case and (b) the off-nadir case.

FIG. 5. Standard deviations of the depolarization ratio of the ice clouds for (a) the nadir case and (b) the off-nadir case.

grid has 40 layers, which increases intervals from the bottom of the atmosphere to the top (Table 1). The integration time was from 0000 UTC 1 January to 0000 UTC 8 January 2007. The first day was assumed to be the spinup period, and the last 7 days were analyzed.

The NICAM simulations were initialized with the National Centers for Environmental Prediction (NCEP 2011) data with a 1° resolution for the wind, temperature, relative humidity, and geopotential data. The sea surface temperature was fixed. We conducted simulations with two types of bulk cloud microphysics schemes; these were the NICAM single-moment scheme with six water categories (Tomita 2008b) with modifications by Roh and Satoh (2014) (hereafter referred to as NSW6), and the NICAM double-moment scheme with six water categories (Seiki and Nakajima 2014; Seiki et al. 2014; Seiki et al. 2015; hereafter referred to as NDW6).

For the model evaluation, the simulated results were processed using satellite simulators and then were compared to the satellite observation; the EarthCARE Active Sensor Simulator (EASE; Okamoto et al. 2007, 2008; Nishizawa et al. 2008) and the visible-infrared channel simulator (Nakajima et al. 2003) in the Joint Simulator were used. Note the vertical resolution affects the simulation of depolarization ratio (e.g., Cesana and Chepfer 2013). The lidar and radar signals are simulated with the 240-m vertical resolution using vertically interpolated NICAM data. The assumed size distributions and thermodynamic phases of the hydrometeors were consistent between the NICAM simulation and the Joint Simulator. Note that the size distribution functions for cloud ice and cloud water are not defined in NSW6. Therefore, monodisperse size distributions were assumed for the cloud ice and cloud water in the Joint Simulator. In addition, effective radii of 40 and $8\mu\text{m}$ were used for the cloud ice and cloud water, respectively. We calculated

single scatterings of ice hydrometeors as spherical shapes with Mie theory for lidar and radar signals. We discuss about nonspherical shape assumptions in the discussion part.

In the comparison, the W-band radar reflectivity, the total attenuated backscattering coefficients, the depolarization ratio at the 532-nm channel, and the hydrometeor particle types (see section 2) were analyzed. Because the KU data are an orbital dataset, the sample size during the simulation period was smaller than that of the global simulations. Therefore, a 1-month dataset during January 2007 was analyzed to obtain more robust statistical cloud characteristics. To illustrate the horizontal cloud distribution, the merged $11\text{-}\mu\text{m}$ brightness temperature product observed by geostationary satellites (Janowiak et al. 2001) was also used.

b. Horizontal and vertical cloud structures

Figure 6 compares the horizontal distribution of the observed $11\text{-}\mu\text{m}$ brightness temperature with those of the NICAM simulations with NSW6 and NDW6 in the analysis domain (the Southern Ocean). The observation shows convective systems with a bow shape associated with an extratropical cyclone in the northern part of the analysis domain. Both simulations reproduced the convective systems in the observation. The horizontal coverages of the upper clouds of the convective systems are similar for the simulations with NSW6 and NDW6. NSW6 shows higher brightness temperatures for lower clouds in the southern part of the analysis domain ($60^\circ\text{--}65^\circ\text{S}$) compared to NDW6.

Next, we investigated the vertical structure of the clouds by comparing the observation with CALIPSO and CloudSat. We show the cross section along the yellow lines in Fig. 6 for the observation and the simulations. Figure 7a shows the backscatters from CALIPSO.

TABLE 1. Heights of the model layers. These layers are interfaces of control volumes of the model. Hydrometeors are defined at the middle levels of the control volumes.

Level number	Height (m)
1	162
2	336
3	524
4	726
5	945
6	1180
7	1433
8	1707
9	2001
10	2319
11	2661
12	3030
13	3428
14	3856
15	4318
16	4816
17	5353
18	5932
19	6556
20	7228
21	7952
22	8733
23	9575
24	10 483
25	11 461
26	12 515
27	13 652
28	14 877
29	16 197
30	17 620
31	19 154
32	20 807
33	22 590
34	24 511
35	26 581
36	28 813
37	31 219
38	33 812
39	36 608
40	39 620

There are two cloud systems in the cross section; the first consists of the low clouds in the south between 52° and 65°S, and the second consists of the high clouds in the north between 45° and 52°S.

The area of the high clouds can be seen in Fig. 6 as the low brightness temperature distribution region. Both the NSW6 and NDW6 simulations capture the structures of the two cloud systems and show a clear contrast between the low clouds and the high clouds. However, NSW6 underestimates the cloud top of the low clouds compared to the observation and NDW6. For the high clouds, both simulations show a higher cloud top for the convective regions than observed. Figure 7a shows that

strong backscatters ($\beta > 10^{-4} \text{ m}^{-1} \text{ sr}^{-1}$) are observed at the tops of the low clouds (2–3 km in altitude) and in the middle layer (6–7 km in altitude) of the high cloud regions. NDW6 reproduces the strong backscatters at the tops of the low clouds (Fig. 7g), while NSW6 fails to do so (Fig. 7d). It is known that water clouds have relatively larger backscatters than ice clouds. We compare the depolarization ratios of the observation, NSW6, and NDW6 in Figs. 7b, 7e, and 7h, respectively. The simulated depolarization ratio shows good agreement with the observation of a depolarization ratio close to 20% between the altitudes of 5 and 10 km. Both simulations show depolarization ratios above 20% for the high clouds (9–12 km) and are larger than the observed ratio. This is related to the overestimation of the cloud-top height by NSW6 and NDW6 compared to the observation because the parameterization of the depolarization ratio is a function of the temperature for ice clouds. For boundary layer clouds, the cloud depths simulated by NSW6 and NDW6 are shallower than the observation and the simulated depolarization ratios are underestimated.

Figure 7c shows the vertical cross section of the radar reflectivity of *CloudSat* for comparison with the simulated radar reflectivities in Figs. 7f and 7i. The radar reflectivity is sensitive to the large ice particles. NSW6 shows the maximum radar reflectivity at the bottom of the convective systems (Fig. 7f), while NDW6 shows the peak in the radar reflectivity in the middle of the convective systems at an altitude of 6 km (Fig. 7i). The *CloudSat* radar is not sensitive to boundary layer clouds (Fig. 7c, 60°–50°S). NSW6 shows relatively larger radar reflectivities for boundary layer clouds than the observation and NDW6.

c. Evaluations using the Y2010 cloud classification

Figure 8 shows the 2D frequency distributions of a proxy for the cloud extinction x and the depolarization ratio δ from the observations, NSW6, and NDW6. NSW6 and NDW6 do not take into account the change in the nonspherical ice shape for ice clouds. To compare the Y2010 diagnosis and the model representation, we summed up the ice cloud categories of the different 2D or 3D ice shapes of Y2010 into a single ice cloud category and compared the water phase cloud and ice phase cloud categories with those represented by the cloud microphysics schemes. The ice clouds consist of 2D plate ice, a mixture of 2D plate ice and 3D ice, and 3D ice clouds. The distinction between 2D plate ice and 3D ice is not informative for evaluations of the thermodynamic phases of clouds.

NDW6 reproduces the similar fractions of ice and water clouds to the observation comparing to NSW6 (Fig. 1). The water cloud fractions for NSW6 (19.9%) and

FIG. 6. Comparison of the horizontal distribution of the 11- μ m brightness temperatures (K) from the merged brightness temperatures from (a) geostationary satellites at 0100 UTC 3 Jan 2007 and that from (b) the NSW6 simulation and (c) the NDW6 simulation by NICAM at 0000 UTC 3 Jan.

NDW6 (35.8%) are the smaller and larger, respectively, and the observed fraction (32.5%) is in between those of NSW6 and NDW6. Conversely, the ice fraction is the largest for NSW6 (75.4%) and the smallest for NDW6 (61.1%), while that of the observation is in between the two (63.6%).

A linear relationship between x and the depolarization ratio in the diagram can be seen for NDW6 compared to the satellite observation (the blue circles in Fig. 8) but completely missed for NSW6. NSW6 underestimates the maximum depolarization ratio (15%) of the water clouds compared to NDW6 (40%) and the observation (50%).

The observation shows the distinct peak of the ice clouds with low depolarization ratio (2D plate in Y2010) and a higher fraction of water clouds compared to the global analysis of Y2010 (Fig. 1). This means that mixed-phase clouds are dominant in this domain. Note that the temperature of most of the analysis domain (the Southern Ocean) is below 0°C and that supercooled water and 2D plate ice are dominant within the temperature range from -20° to -10° C (e.g., Kobayashi 1957; Y2010; Hirakata et al. 2014). Both simulations reproduce a frequency distribution of ice clouds and water clouds similar to the observation. However, the depolarization

FIG. 7. Latitude–height distributions of the (left) backscatters (β , $\text{m}^{-1} \text{sr}^{-1}$), (center) depolarization ratio (δ , %), and (right) radar reflectivities (dBZ). (a)–(c) The observation (KU data), (d)–(f) the NSW6 simulations, and (g)–(i) the NDW6 simulations. The black lines are isothermal contours for 0°, -10°, -20°, -30°, -40°, and -50°C. The red line indicates an altitude of 10 km.

ratio of ice clouds is overestimated in NSW6 and NDW6. Simulations cannot reproduce the peak frequency of depolarization ratio seen in the observation. NDW6 considers nonspherical ice assumptions for the ice particles in the microphysical processes, e.g., cloud ice as a hexagonal column and snow as aggregates of planar polycrystals (Seiki et al. 2014). In section 4b, the nonspherical ice assumptions are discussed via sensitivity tests using the Joint Simulator.

We investigated the temperature dependencies of the cloud frequencies over the diagram with x and the depolarization ratio (Fig. 9). We defined three different temperature (T) regimes of $T \geq 0^\circ\text{C}$, $-20^\circ \leq T < 0^\circ\text{C}$, and $T < -20^\circ\text{C}$ following Y2010. Both the observation and the simulations show general tendencies in the phase changes of the clouds according to the temperature; water clouds are most frequent for $T \geq 0^\circ\text{C}$, mixed

clouds become more frequent for $-20^\circ \leq T < 0^\circ\text{C}$, and ice clouds are most frequent for $T < -20^\circ\text{C}$.

Table 2 shows the fraction of clouds in each temperature regime to check the dominant temperature regime in the analysis domain. In this analysis domain, the cloud fraction for $T > 0^\circ\text{C}$ is 6.6% in the observation data and below 0.5% in both simulations with NSW6 and NDW6. This means that warm water clouds are relatively rare in this domain. The observation indicates that the cloud fraction for $-20^\circ < T < 0^\circ\text{C}$ is 60.2%. NDW6 reproduces a similar fraction (67.0%) to the observation. NSW6 overestimates the fraction of ice clouds for $T < -20^\circ\text{C}$. NDW6 simulates more realistic occurrences of the depolarization ratio, extinction, and temperature than does NSW6 (Fig. 9 and Table 2).

The warm water clouds for $T > 0^\circ\text{C}$ show a linear relationship between x and the depolarization ratio in

FIG. 8. Joint histograms of the clouds in terms of x and δ for all temperature ranges from (a) the KU data, (b) NSW6, and (c) NDW6. PDFs of the cloud occurrences are shown on the scale below the diagrams.

the observation (Fig. 9a). Even though both simulations basically capture this relationship for warm water clouds, there is an additional linear trend that reaches $(x, \delta) = (1.5, 60)$ in NDW6, which is not seen in the observation. This trend is related to the parameterization of the depolarization for the water clouds; the bin with backscatters of $(-5 < \log b532 < -4)$ indicates δ reaching 60 at $x = 1.5$ (Fig. 2). There are the fractions of ice clouds for $T > 0^\circ\text{C}$ in the observation and simulations. We think it is related to the transportation of ice particles from a cold region (Hirakata et al. 2014). The total fraction of warm water clouds is relatively very low (Table 2) and the most of temperatures are below 5°C in this analysis domain. For clouds in the regime of $-20^\circ < T < 0^\circ\text{C}$, the observation reveals a main mode that is related to supercooled water clouds $(x, \delta) = (1.0, 20)$. NDW6 has a similar structure of

the cloud frequency in this temperature regime, while NSW6 does not reproduce this mode but shows smaller depolarization ratios of less than 10 for $x = 2.0$. For clouds in the regime of $T < -20^\circ\text{C}$, the observation shows a mode along $x \sim 0.0$ with wide variations in the depolarization ratio from 0% to 70%. The simulations capture this mode; however, the depolarization ratios are limited between 10% and 50%. Note that neither simulation reproduces the observed fraction of supercooled water clouds in the regime of $T < -20^\circ\text{C}$.

d. Investigation of cloud phases according to Y2010

We analyzed the cloud phases of the simulations using the joint diagram of (x, δ) proposed by Y2010. Figure 10 shows the vertical cross section of the cloud phases diagnosed by Y2010 over the Southern Ocean. The KU

FIG. 9. Joint histograms of the clouds in terms of x and δ over the Southern Ocean in January 2006 for (left) only $T \geq 0^\circ\text{C}$, (center) only $-20^\circ\text{C} \leq T < 0^\circ\text{C}$, and (right) only $T < -20^\circ\text{C}$. (a)–(c) The KU data, (d)–(f) NSW6, and (g)–(i) NDW6. PDFs of the cloud occurrences are shown on the scale below the diagrams.

data show supercooled water clouds near the boundary layer and in the middle layer with cloud tops at 8 km. Even though NSW6 and NDW6 show supercooled water clouds in the boundary layer below 1 km, there are no supercooled water clouds near the middle layers between 5 and 8 km in the simulations.

The Y2010 cloud phase diagnosis and the phase represented in the models can be inconsistent. The simulations possess their own cloud phases categorized by the cloud

microphysics schemes. Both NSW6 and NDW6 have two hydrometeor categories for the water cloud phase (cloud water and rain) and three hydrometeor categories for the ice cloud phase (cloud ice, snow, and graupel). We now examine the consistency between the cloud microphysics scheme and the diagnostics using the joint diagram of (x, δ) by Y2010. Figure 11 shows the cross section of the ice water content and liquid water content simulated by NSW6 and NDW6. NDW6

TABLE 2. Cloud fractions (%) for the three temperature regimes.

	Clouds for only $T > 0^{\circ}\text{C}$	Clouds for only $-20^{\circ} < T < 0^{\circ}\text{C}$	Clouds for only $T < -20^{\circ}\text{C}$
KU data	6.6	60.2	33.2
NSW6	0.2	33.7	60.1
NDW6	0.4	67.0	32.6

reproduces the liquid water content near the boundary layer at altitudes of less than 1 km. NDW6 shows the supercooled water cloud layer in the cloud top and precipitating ice below the top layer consistent to observation studies (e.g., Shupe et al. 2008) (Figs. 11b,d). These lower water clouds in the boundary layer correspond to the water cloud phase diagnosed by Y2010 in Fig. 10c. However, NSW6 shows ice water content in the boundary layer (Fig. 11a) instead of liquid water content (Fig. 11c, bottom right). This differs from the diagnosis by Y2010 (Fig. 10b) in which the boundary layer clouds are identified as water clouds. This indicates that NSW6 miscalculates the fraction of supercooled water clouds in its evaluation method.

For the hydrometeors in the numerical results with the cloud microphysics schemes, both ice and liquid phase clouds generally coexist in any given cloudy grid box. Therefore, we introduced a threshold of 1 mg m^{-3} for the ice water content (IWC) or liquid water content (LWC) so that the cloud characteristics of a grid box could be identified as ice, liquid, mixed, or no clouds. The four categories are ice clouds ($\text{IWC} > 1 \text{ mg m}^{-3}$ and $\text{LWC} < 1 \text{ mg m}^{-3}$), liquid clouds ($\text{IWC} < 1 \text{ mg m}^{-3}$ and $\text{LWC} > 1 \text{ mg m}^{-3}$), mixed clouds ($\text{IWC} > 1 \text{ mg m}^{-3}$ and $\text{LWC} > 1 \text{ mg m}^{-3}$), and no clouds ($0 < \text{IWC} < 1 \text{ mg m}^{-3}$ and $0 < \text{LWC} < 1 \text{ mg m}^{-3}$).

Table 3 shows the fraction of the four categories of clouds based on the IWC and LWC thresholds.

FIG. 10. Latitude–height distributions of the cloud phases over the Southern Ocean from (a) the KU data, (b) NSW6, and (c) NDW6. The yellow color indicates ice clouds, and the blue color indicates supercooled water clouds.

FIG. 11. Latitude–height distributions of the (a),(b) ice water content and (c),(d) liquid water content; (a) and (c) are from the NSW6 simulations, and (b) and (d) are from the NDW6 simulations. The units of the color bar are the logarithm of g m^{-3} .

For NSW6, the fraction of ice clouds is 97.3% and the sum of the liquid, and mixed clouds is nearly 1%. This is very different from the Y2010 classification based on the simulated signals with the Joint Simulator (Fig. 1): in this case, the fraction of water clouds is 19.9% for NSW6. Conversely, for NDW6, the fraction of water clouds (17.1%) and that of mixed clouds (38.2%) are consistent with those classified by the Joint Simulator, that is, the fraction of water clouds (35.8%) from Y2010 (Fig. 1).

Figure 12 shows how consistent the classification between the ice and liquid clouds is for the numerical

results and for the diagnosed results with the Joint Simulator using the method of Y2010. The stacked bars indicate the water and ice clouds according to Y2010, and the stack legend denotes the fraction of ice, liquid, mixed, and no clouds according to the NICAM simulations. The water clouds according to Y2010 primarily consist of ice clouds in NSW6, where as those in NDW6 primarily consist of the liquid and mixed clouds of NICAM. This indicates that the liquid clouds in the results simulated by NDW6 are consistently diagnosed as water clouds by Y2010.

TABLE 3. Fraction (%) of the four categories of cloud characteristics in the NICAM grid boxes using the thresholds of the ice water and liquid water contents of the simulated results for all the cloudy grids defined by the CALIPSO simulator.

	Ice clouds ($\text{IWC} > 1 \text{ mg m}^{-3}$, $\text{LWC} < 1 \text{ mg m}^{-3}$)	Liquid clouds ($\text{IWC} < 1 \text{ mg m}^{-3}$, $\text{LWC} > 1 \text{ mg m}^{-3}$)	Mixed clouds ($\text{IWC} > 1 \text{ mg m}^{-3}$, $\text{LWC} > 1 \text{ mg m}^{-3}$)	No clouds ($0 \text{ mg m}^{-3} < \text{IWC} < 1 \text{ mg m}^{-3}$, $0 \text{ mg m}^{-3} < \text{LWC} < 1 \text{ mg m}^{-3}$)
NSW6	97.3	0.4	0.65	1.7
NDW6	43.4	17.1	38.2	1.4

FIG. 12. Stacked bars for the water, ice, and unknown categories. The stack legend denotes the fraction of model-native ice clouds (red), model-native water clouds (blue), model-native mixed clouds (yellow), and model-native no clouds (green) based on Table 3, which was determined using thresholds on the ice water and liquid water content outputs from NICAM.

4. Discussion

a. The impact of an extinction proxy for the cloud classification

The proxy x is important for determining the cloud phases in Y2010. Ice clouds have smaller x values than water clouds in the Y2010 diagram. The depolarization ratio plays an important role for the ice shape in Y2010. The previous section indicated that there was a mismatch between the water clouds and ice clouds represented in the NICAM cloud microphysics schemes and those in the Y2010 cloud classification based on the signals simulated with the Joint Simulator. Figures 13a and 13b show the joint histograms between the IWCs and x for NSW6 and NDW6, respectively. NSW6 shows a linear relationship between the IWC and x , whereas such NDW6 does not show such a relationship. Figures 13c and 13d show the joint histograms between the effective radius of the ice water and x . This figure indicates that NSW6 simulates a smaller effective ice radius than NDW6. The extinction coefficient $\sigma(R_i)$ in the Mie scattering regime can be estimated by

$$\sigma_{(R_i)} = \frac{3W(R_i)}{2r_{\text{eff}}(R_i)\rho}, \quad (6)$$

where $W(R_i)$ is the ice or LWC, $r_{\text{eff}}(R_i)$ is the effective radius of the clouds, and ρ is the density of the spherical ice or liquid particles. For $x > 1.0$, Fig. 13 indicates that the ice clouds of NSW6 have a smaller effective radius and larger IWC than those of NDW6; therefore, Eq. (6)

implies that the Joint Simulator applied to NSW6 produces a larger extinction coefficient.

The extinctions of ice and water clouds are different. Water clouds result in larger signal extinction due to their smaller effective radius. Figure 14 shows the joint histogram of the LWC and x for the water clouds in the simulations. Both simulations show two slope modes between the LWC and x , which correspond to cloud water (the lower slope) and rain (the upper slope). Water clouds have a more distinct linear relationship between the LWC and x than do ice clouds in the simulations. This means that water clouds have larger extinction for the same water content. Y2010s use of the proxy x makes a distinction between liquid and ice clouds. For NSW6, however, the ice clouds represented in the native NICAM outputs are diagnosed as water clouds due to the large extinction.

b. Impact of the nonspherical ice and multiple scattering assumptions

Simulations of the depolarization ratio are sensitive to ice shape assumptions and the multiple scattering parameterization. The ice particles were assumed to have a spherical shape with Mie theory for the previous results in the Joint Simulator. We estimated the ambiguity in the simulated signals due to the ice shapes using the Joint Simulator. We conducted a sensitivity test to estimate how much the ice shape assumptions affected the fraction of water clouds by changing the cloud parameters in the Joint Simulator.

FIG. 13. Joint histograms in terms of (a),(b) x and the ice water content and (c),(d) x and the effective ice radius; (a) and (c) are from NSW6, and (b) and (d) are from NDW6. PDFs of the cloud occurrences are shown on the scale below the diagrams.

Nonspherical ice shapes are one of the big issues in calculations of radiative properties. We tested nonspherical ice shapes using the single scattering library from six nonspherical ice models calculated using the discrete dipole approximation, which is available in EASE (Sato and Okamoto 2006; Okamoto et al. 2010); in addition to the spherical shape (sphere), we tested bullet rosettes, hexagonal columns, and hexagonal plates oriented randomly in 3D planes, which are referred to as “3D bul.,” “3D col.,” and “3D plt.,” respectively, and hexagonal columns and hexagonal plates oriented in the horizontal plane, which are referred to as “2D col.” and “2D plt.,” respectively, in Table 4. We examined the impact of the ice shape assumption on the water cloud fraction. Table 4 indicates that NSW6 experienced a small impact on the water cloud fraction due to the nonspherical ice assumption. Conversely, NDW6 showed a decrease in the fraction of diagnosed water clouds when nonspherical scattering was assumed. When an ice particle is assumed to be 2D plt. (note that this is different from the 2D plate ice in Y2010), the water cloud fraction is close to the observed values (25.3% in Table 1). This means that one of the possible reasons for the overestimation of the water

phase clouds in NDW6 is related to the nonspherical ice assumption. The assumption of a 2D plt. ice shape decreases the penetration depth of the ice clouds and decreases the water cloud fraction below the ice clouds.

CALIPSO has a footprint size of 90 m at the surface. This induces a multiple scattering effect on the backscatters (Hu et al. 2001). In the default setting of EASE, a single scattering is considered for ice clouds and a multiple scattering parameter η for water clouds is parameterized via an empirical method as a function of the water content and the effective radius (Ishimoto and Masuda 2002). The lidar-attenuated backscattering β_{obs} is calculated with η such that

$$\beta_{\text{obs}}(R) = \beta_{\text{true}}(R) \exp \left[-2 \int_0^R \eta(R) \sigma(R) dR \right], \quad (7)$$

where R is the range and β_{true} is the lidar backscattering without attenuation in units of ($\text{m}^{-1} \text{sr}^{-1}$). We simply changed the fixed η from 1 to 0.5 and 0.7 in EASE for the ice particles. Figure 15b reveals that the penetration depth of the water and ice clouds increases as η decreases. Table 5 shows that the change in the

FIG. 14. Joint histograms in terms of (a),(b) x and the liquid water content and (c),(d) x and the effective liquid radius; (a) and (c) are from NSW6, and (b) and (d) are from NDW6. PDFs of the cloud occurrences are shown on the scale below the diagrams.

parameter η reduces the fraction of water clouds by nearly 5%. However, this is not as significant a change as the effect of the nonspherical ice assumption in NDW6 (Table 4). Cesana and Chepfer (2013) found a similar result when investigating the impacts of these parameters on the water cloud fraction using their satellite simulator and the Institut Pierre Simon Laplace model.

5. Summary and conclusions

We introduced an evaluation method for the thermodynamic phases for a CSRM using *CALIPSO* and a satellite simulator following Y2010. The depolarization ratio and the extinction proxy x are used for the evaluation. We developed an empirical parameterization of the depolarization ratio for water and ice clouds in the Joint Simulator.

We evaluated the cloud fields over the Southern Ocean simulated by a CSRM, NICAM, using two cloud microphysics schemes: a single-moment bulk scheme (NSW6) and a double-moment bulk scheme (NDW6). The fraction of the supercooled water clouds for

NSW6 and NDW6 was obtained using the Y2010 cloud classification.

The consistency of the thermodynamic phases between the model-native outputs and the cloud classification based on the simulated signals was examined. We found that NSW6 shows a mismatch for the supercooled clouds between the simulated LWC and the diagnosed water clouds. The reason for this mismatch is that the ice clouds, with their small effective radius and large IWC, have large extinction values, and are therefore classified as water clouds by this cloud classification.

We also investigated the impacts of the nonspherical ice shape assumption and multiple scattering impacts on the water cloud fraction using the Joint Simulator. The introduction of a nonspherical ice shape would improve the fraction of diagnosed water clouds in NDW6 by

TABLE 4. Dependence of the fraction (%) of diagnosed water clouds on the nonspherical ice scattering models in EASE.

	Sphere	2D col.	2D plt.	3D bul.	3D col.	3D plt.
NSW6	19.9	19.9	19.8	19.8	19.9	19.9
NDW6	35.8	28.4	24.2	29.4	30.1	27.0

FIG. 15. Latitude–height distributions of the NDW6 backscatters over the Southern Ocean with assumption of (a) 2D plt. as the ice shape and (b) $\eta = 0.5$. The units of the color bar are the logarithm of $\text{m}^{-1} \text{sr}^{-1}$.

reducing the fraction of diagnosed water clouds. The assumption of the multiple scattering of ice also reduces the fraction of diagnosed water clouds; however, the impact of this assumption was not as large as that of a nonspherical ice shape.

This study shows that the uncertainties in the evaluation methods for the thermodynamic phases of clouds depend on the details of the cloud microphysics schemes. It is important to understand the reasons for the inconsistencies between the actual simulation results and the diagnosis by an evaluation method. The reasons for the inconsistencies provide hints to understand and improve the microphysics schemes. For example, NSW6 reproduced the fact that ice clouds have large extinction with large IWC and a small effective radius. We can check the impact of these ice clouds on the supercooled water clouds and their microphysical processes. This also provides information to understand retrieval algorithms and some possible uncertainties from ice clouds with large extinction.

In Part II of this study (Seiki and Roh 2020), we investigated the reason for the underestimation of supercooled water clouds in NSW6 using NDW6 and we will improve NSW6 by reducing the inconsistencies found in the present study. Biases in the simulated results and uncertainties in the cloud microphysics schemes can be evaluated using the satellite simulator and the new evaluation method. Improvements to the supercooled

liquid water in the NSW6 simulation are dealt with in the companion paper.

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APPENDIX

A Diagnosis for Only the Liquid and Ice Particles

The EASE simulator was modified to diagnose the depolarization or the perpendicular component of the attenuated backscattering coefficient associated with only the liquid and ice particles, $\beta_{532,\perp}^M(R_i)$. First, we diagnosed whether a cloud liquid layer was the topmost layer of a cloudy column based on the calculated attenuated total backscattering coefficient, the backscatter threshold given by Eq. (1), and the lowest value of

TABLE 5. Dependence of the fraction (%) of diagnosed water clouds on the multiple scattering parameter.

	Default	$\eta = 0.5$	$\eta = 0.7$
NSW6	19.9	19.2	19.6
NDW6	35.8	30.7	30.8

the cloud water content that was regarded as significant (10^{-9} g m^{-3}). Then, to diagnose the depolarization of the liquid particles in a layer, the backscattering coefficient used for the lookup table index was calculated by removing the ice particles in the layer. The backscatter for the layer R_i is denoted $\beta'_{532,\text{liq}}(R_i)$. Similarly, the proxy of extinction with only liquid particles, $x_{\text{liq}}(R_i)$, is calculated as

$$x_{\text{liq}}(R_i) = \log_{10} \frac{\beta'_{532,\text{liq}}(R_i)}{\beta'_{532,\text{liq}}(R_{i+1})} - 2\sigma_{532,\text{ice}}(R_i)\Delta R \log_{10} e,$$

where $\sigma_{532,\text{ice}}(R_i)$ is the extinction coefficient for the ice particles in the layer and ΔR is the vertical resolution. Once the depolarization was linearly interpolated from the lookup tables, then the perpendicular components of the attenuated backscattering coefficient for the liquid particles without gas molecules and aerosol particles, $\beta'^M_{532,\perp,\text{liq}}(R_i)$, were estimated using the depolarization and the parallel component of the attenuated backscattering coefficient associated with the liquid particles such that

$$\beta'^M_{532,\perp,\text{liq}}(R_i) \cong \delta \beta'^M_{532,\parallel,\text{liq}}(R_i).$$

Note that we assume that the left- and right-hand sides of the equation are approximately equal because δ in the lookup tables includes signals from the gas molecules and the aerosol particles. A similar procedure to estimate the depolarization of the ice particles was repeated for the attenuated backscattering coefficient associated with only the ice particles, $\beta'^M_{532,\perp,\text{ice}}(R_i)$, using the air temperatures instead of the proxy $x_{\text{liq}}(R_i)$. Finally, the attenuated perpendicular backscattering coefficient for the cloud layer associated with only the liquid and ice particles, $\beta'^M_{532,\perp}(R_i)$, was calculated by weighting $\beta'^M_{532,\perp,\text{liq}}(R_i)$ and $\beta'^M_{532,\perp,\text{ice}}(R_i)$ with $\beta'_{532,\text{liq}}(R_i)$ and $\beta'_{532,\text{ice}}(R_i)$:

$$\beta'^M_{532,\perp}(R_i) = w_1 \beta'^M_{532,\perp,\text{liq}}(R_i) + w_2 \beta'^M_{532,\perp,\text{ice}}(R_i),$$

$$w_1 = \frac{\beta'_{532,\text{liq}}(R_i)}{\beta'_{532,\text{liq}}(R_i) + \beta'_{532,\text{ice}}(R_i)},$$

$$w_2 = 1 - w_1.$$

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