Improvement of a Cloud Microphysics Scheme for a Global Nonhydrostatic Model Using TRMM and a Satellite Simulator

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ABSTRACT

The cloud and precipitation simulated by a global nonhydrostatic model with a 3.5-km horizontal resolution, the Nonhydrostatic Icosahedral Atmospheric Model (NICAM), are evaluated using the Tropical Rainfall Measuring Mission (TRMM) and a satellite simulator. A previous study by Roh and Satoh evaluated the single-moment bulk microphysics and established the modified microphysics scheme for the specific tropical open ocean using a regional version of NICAM. In this study, the authors expanded the evaluation over the entire tropics and parts of the midlatitude areas (20°S–36°S, 20°N–36°N) using a joint histogram of the cloud-top temperature and precipitation echo-top heights and contoured frequency by altitude diagrams of the deep convective systems. The modified microphysics simulation improves the joint probability density functions of the cloud-top temperatures and precipitation cloud-top heights over not only the tropical ocean but also the land and midlatitude areas. Compared with the default microphysics simulation, the modified microphysics simulation shows a clearer distinction between the land and ocean in the tropics, which is related to the contrast between the shallow and the deep clouds. In addition, the two microphysics simulation methods were also compared over the tropics using joint histograms of the cloud-top and precipitation cloud-top heights on the basis of CloudSat measurements. It was found that the microphysics scheme that was modified for the tropical ocean displayed general cloud and precipitation improvements in the global domain over the tropics.

1. Introduction

The evaluation of clouds and precipitation is important in high-resolution models such as cloud-system-resolving models (CSRMs). CSRMs are generally defined as nonhydrostatic models with horizontal grid spacing that is sufficiently fine to explicitly simulate individual cloud systems. CSRMs more realistically represent microphysical processes of precipitation and calculate the time evolution, structure, and life cycle of cloud systems than general circulation models (GCMs).

Cloud microphysics plays an important role in the distribution of clouds and precipitation in CSRMs. Two different types of cloud microphysics schemes (i.e., bulk schemes and bin schemes) have been developed and used to represent size distributions. Bulk microphysics schemes represent the hydrometeor size for each class with a distribution function, such as an exponential function or a gamma-type function. Bin microphysics schemes represent the actual size spectra of cloud condensation nuclei (CCN) as well as different hydrometeor particles, where the size distribution comprises

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many bins of a mass or number concentration. However, bin schemes are not suitable to simulate large-domain or long-term cases because they require large amounts of computation time and memory. Therefore, bulk microphysics schemes are typically used to simulate large three-dimensional (3D) domains.

Bulk microphysics schemes are subdivided into single-moment and multimoment schemes on the basis of a number of prognostic variables. Recently, double-moment bulk schemes have been widely used to calculate the mass and number concentrations of hydrometeors (Morrison et al. 2005; Seifert and Beheng 2006; Lim and Hong 2010; Seiki and Nakajima 2014). The double-moment approach in a bulk microphysics scheme allows greater flexibility in size distribution in contrast to the single-moment approach; this enables the mean diameter of hydrometeors to evolve. However, it has been reported that double-moment schemes do not offer improved results over single-moment bulk microphysics schemes in some cases. For example, Van Weverberg et al. (2013) evaluated mesoscale convective system (MCS) simulations using three different bulk microphysics schemes over the tropical western Pacific and found that the performance of complex double-moment schemes was not superior to the simpler single-moment schemes. They found the simulation of MCSs was very sensitive to the parameterizations of microphysical processes. In this study, we focus on the evaluation and improvement of a single-moment bulk microphysics scheme.

Various single-moment bulk microphysics schemes have been developed based on the one proposed by Lin et al. (1983). Such schemes have been used and improved over several decades (Rutledge and Hobbs 1984; Hong et al. 2004; Lin and Colle 2011; Tomita 2008a; Lang et al. 2014). For example, Lang et al. (2007, 2011) reduced the biases of the single-moment bulk scheme for simulated radar reflectivities by improving the microphysical process and the size distributions of graupel and snow. Even though single-moment schemes have been continuously improved by previous studies, there still exist inherent cloud and precipitation biases such that the schemes require further refinement via evaluations with observations.

Satellite data are useful to evaluate cloud microphysics schemes because of their large coverage in space and time. Satellite simulators are being developed to evaluate CSRsMs, such as the satellite data simulator unit (SDSU; Masunaga et al. 2010); the Goddard SDSU (http://cloud.gsfc.nasa.gov/index.php?section=14); the Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP; Bodas-Salcedo et al. 2011); the Earth Clouds, Aerosols, and Radiation Explorer (EarthCARE) simulator (ECSIM; Voors et al. 2007); and the Joint Simulator for Satellite Sensors (J-simulator; Hashino et al. 2013). Satellite simulators calculate radiances from the numerical model results, and the simulated radiances are then directly compared with those of the satellite observations (e.g., Inoue et al. 2010; Satoh et al. 2010; Masunaga et al. 2010; Bodas-Salcedo et al. 2011; Hashino et al. 2013). Satellite simulators establish the same microphysical assumptions regarding hydrometeors, such as their size distributions and densities, as those assumed in cloud microphysical schemes. Therefore, an evaluation of numerical models using satellite simulators avoids inconsistent assumptions between the numerical models and the retrieval algorithms in satellite remote sensing.

The large-domain simulations of CSRsMs have benefits for evaluations with satellite data because of the large sampling numbers, especially for satellites with a narrow scan area, such as the Tropical Rainfall Measuring Mission (TRMM) satellite data and the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data. As computational speed and storage memory rapidly increase, CSRsMs can be extended to the global domain using global nonhydrostatic models. Recently, the Nonhydrostatic Icosahedral Atmospheric Model (NICAM; Tomita and Satoh 2004; Satoh et al. 2008; Satoh et al. 2014) has been shown to reproduce realistic cloud systems across the globe with a sub-kilometer horizontal mesh size (Miyamoto et al. 2013, 2015). High-resolution global nonhydrostatic models can consistently represent 3D hydrometeor fields for both convective and stratiform clouds using a cloud microphysics scheme without cumulus parameterizations. In addition, because the horizontal resolutions of the numerical models and the satellite observations have become comparable, direct comparisons and evaluations of observations and simulations are possible.

A number of NICAM studies have been conducted to evaluate simulated clouds using satellite observations (Masunaga et al. 2008; Inoue et al. 2010; Satoh et al. 2010; Nasuno and Satoh 2011; Kodama et al. 2012; Hashino et al. 2013). Sato et al. (2008) studied the characteristics of diurnal precipitation over the entire tropical region using TRMM. Hashino et al. (2013) examined the vertical structure of clouds using NICAM with a 3.5-km horizontal mesh for the 82°S–82°N latitudes using the merged CloudSat and CALIPSO data and retrieved microphysics data based on Hagihara et al. (2010).

Even though high-resolution simulations over the global domain are achievable with NICAM, it is still not
Table 1. Descriptions of the two microphysics schemes. Here, LWC\textsubscript{r} and IWC\textsubscript{r} indicate the liquid water content of the rain and the ice water content of the cloud ice (kg m\textsuperscript{-3}). The process and the size and density parameter nomenclatures follow Tomita (2008a).

<table>
<thead>
<tr>
<th>Process</th>
<th>CON</th>
<th>MODI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pgacs</td>
<td>Turned off (Lang et al. 2007)</td>
<td>Ice nucleation and ice deposition (Hong et al. 2004)</td>
</tr>
<tr>
<td>Pgaci</td>
<td>Turned off (Lang et al. 2007)</td>
<td>No terminal velocity</td>
</tr>
<tr>
<td>Saturation adjustment</td>
<td>Saturation adjustment (Tomita 2008a)</td>
<td>Saturation adjustment for only warm clouds (Tomita 2008a)</td>
</tr>
<tr>
<td>Terminal velocity of cloud ice</td>
<td>$V_p = -3.29(IWC)^{0.16}$ m s\textsuperscript{-1} (Heymsfield and Donner 1990)</td>
<td>Bimodal size distribution (Field et al. 2005) and $\rho_s = 0.15D^{-1}$ kg m\textsuperscript{-3}</td>
</tr>
<tr>
<td>Snow size and density</td>
<td>$N_{bs} = (3.0 \times 10^5$ m\textsuperscript{-4}) and $\rho_b = 100$ kg m\textsuperscript{-3}</td>
<td>$N_{bs} = (4.0 \times 10^5$ m\textsuperscript{-4}) and $\rho_b = 400$ kg m\textsuperscript{-3}</td>
</tr>
<tr>
<td>Graupel size and density</td>
<td>$N_{bg} = (4.0 \times 10^5$ m\textsuperscript{-4}) and $\rho_g = 400$ kg m\textsuperscript{-3}</td>
<td>Below 1 m s\textsuperscript{-1} of vertical wind for each grid, and over 0.001 g m\textsuperscript{-3} of ice water content of snow or graupel in the melting layer: $N_{bg} = 7.106 \times 10^9(10^5 \times LWC_{r})^{0.68}$ m\textsuperscript{-4} (Zhang et al. 2008)</td>
</tr>
<tr>
<td>Rain size and density</td>
<td>$N_{br} = 8.0 \times 10^6$ m\textsuperscript{-4}</td>
<td>Other conditions: $N_{br} = 8.0 \times 10^6$ m\textsuperscript{-4}</td>
</tr>
</tbody>
</table>

Table 2. Categorization of cloud types based on Matsui et al. (2009).

<table>
<thead>
<tr>
<th>Shallow</th>
<th>Congestus</th>
<th>Midcold</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBB</td>
<td>Above 260 K</td>
<td>Above 245 K</td>
<td>Under 245 K</td>
</tr>
<tr>
<td>PTH</td>
<td>Under 4 km</td>
<td>Between 4 and 7 km</td>
<td>Between 4 and 7 km</td>
</tr>
</tbody>
</table>

Easy to improve a cloud microphysics scheme and the cloud properties by multiple sensitivity tests because of the high computational cost. Satoh et al. (2010) suggested the use of a regional version of NICAM (LCRM in their paper; Tomita 2008b) with the same physics schemes and dynamics as those in NICAM to evaluate and improve the microphysics schemes and to obtain better cloud properties in NICAM simulations. Following the concept of Satoh et al. (2010), Roh and Satoh (2014, hereafter RS14) improved the cloud properties, such as the horizontal cloud size distributions and the precipitation cloud statistics [based on Matsui et al. (2009)], over the tropical Pacific Ocean using a regional version of NICAM and a satellite simulator, in order to improve high-resolution simulations over the global domain. They found biases in the cloud statistics, in terms of cloud-top temperatures and precipitation-top heights (PTHs), and in contoured frequency by altitude diagrams (CFADs) of radar reflectivities using TRMM and a satellite simulator. They improved the single-moment bulk microphysics scheme using the preferred size distributions from the sensitivity tests to reproduce realistic cloud statistics, accumulated precipitation, and outgoing longwave radiation (OLR). Continuously, it is needed to expand evaluations of single-moment bulk microphysics using the global version of NICAM, which were established by RS14 for the specific tropical region. In this study, we investigate the effect of microphysics on regional differences among land, ocean in the tropics, and parts of the midlatitude areas (20°–36°S, 20°–36°N) using two microphysics schemes. Additionally, we analyze the cloud statistics in terms of cloud-top temperatures and PTHs from CloudSat.

In section 2, the experimental design and observational data are described. In section 3, the horizontal distributions of cloud-top temperature and accumulated precipitation are evaluated. We also compare the vertical structure of the Tropical Cyclone (TC) Fengshen of the joint histogram patterns of the cloud-top temperature and PTHs in the entire tropical region and some midlatitude areas are evaluated. In addition, further analyses are discussed using CloudSat and OLR. The summary and conclusions are given in section 4.

2. Experimental design and data

a. Experimental design

The simulations were conducted using NICAM with 3.5-km horizontal spacing and the Earth Simulator at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The integration time was from 0000 UTC 15 June to 0000 UTC 20 June 2008. The first day was discarded as spinup, and the subsequent 4-day simulations from 1200 UTC 16 June to 1000 UTC 20 June 2008 were analyzed. The NICAM simulations were initialized...
with European Centre for Medium-Range Weather Forecasts (ECMWF) Year of Tropical Convection (YOTC) data with a 0.5° resolution for wind, temperature, relative humidity, and geopotential data. Further, the sea surface temperature (SST) was calculated using a slab ocean scheme and nudged to a Reynolds weekly SST with a 5-day relaxation time; other variables were integrated without the nudging process. The bucket model was used for the land surface model. Other physics schemes and vertical resolutions were as in RS14.

We tested two microphysics schemes: the first was the original NICAM Single-Moment Water (NSW6) scheme [herein CON, as in RS14 and Tomita (2008a)], and the second was the modified NSW6 scheme (herein MODI, as in RS14), which was developed to better represent the microphysics in the tropical open ocean.

Table 1 lists the changes in the microphysics from MODI to CON, which are explained below. CON was based on Lin et al. (1983) and Rutledge and Hobbs (1984). Nucleation and deposition processes of cloud ice
were introduced (Hong et al. 2004), and the accretion processes of graupel with snow and cloud ice were turned off in MODI (Lang et al. 2007). The increase in the amount of snow increased stratiform precipitation and anvil clouds relative to CON. Further, MODI reproduced the OLR closer to observations than CON. However, these changes did not improve the bias of the cloud statistics in terms of the cloud-top temperatures and the PTH and CFADs of deep clouds. RS14 found the preferable size distribution of precipitating hydro-meteors using sensitivity tests of size distribution parameterizations. The snow size distribution of Field et al. (2005) was applied, and the size–density relationship of snow was based on the empirical equation of Fabry and Szyrmer (1999) in MODI. The interceptor parameter of the graupel was increased 100 times (Gilmore et al. 2004; Van Weverberg et al. 2011). The Zhang et al. (2008) method was used to obtain the rain size distribution in the stratiform precipitation areas, and the Marshall–Palmer distribution was used in the convective and other precipitation areas in MODI. Stratiform precipitation areas in this model were classified so that the vertical wind was $<1 \text{ m s}^{-1}$ and the ice water content was $>0.001 \text{ g m}^{-3}$ in the melting layer (the highest vertical grid above $0^\circ \text{C}$).

The difference in the microphysical setting, compared with RS14, is that the terminal velocity of the cloud ice is only considered in CON (Heymsfield and Donner 1990). The terminal velocity of cloud ice was not considered for CON or MODI in RS14. When we tested the terminal velocity of cloud ice using a regional version of NICAM over the tropical open ocean, the terminal velocity was not important to the improvements in the precipitating cloud statistics and the CFADs of deep clouds in CON.

**FIG. 2.** Comparison of the horizontal distribution of the averaged accumulated precipitation (mm h$^{-1}$) from (a) TRMM 3B42 and the (b) CON and (c) MODI simulations using NICAM from 0000 UTC 16 Jun to 0000 UTC 20 Jun 2008 with 0.25° resolution and 3-hourly data.
b. Observational data and the satellite simulator

To evaluate the simulated results, we used the globally merged infrared equivalent blackbody temperatures (TBBs) of the geostationary satellites (Global IR) and the TRMM 3B42 products to compare the observed and simulated TBBs and the precipitation across the globe. Global IR contains 11-μm infrared channels with approximately 4-km resolution. It is compiled by the National Centers for Environmental Prediction/Climate Prediction Center (NCEP/CPC) and is available every 30 min (Janowiak et al. 2001). The TRMM 3B42 provides 3-hourly precipitation retrieved from microwave channel data and infrared data from geostationary satellites with 0.25° × 0.25° grids.

The infrared 11-μm TBBs from the TRMM 1B01 product and the 13.8-GHz reflectivities from TRMM 2A25 were used in the TRMM Triple-Sensor Three-Step Evaluation Framework (T3EF) method (Matsui et al. 2009). The T3EF has three steps. First, the joint histograms of the TBBs and PTHs are built, and cloud types are classified into four categories—shallow, congestus, midcold, and deep clouds—using histograms (Table 2 and Fig. 5a). Second, CFADs of the PR reflectivities are constructed for each cloud type. Third, the cumulative probability distributions of the TRMM Microwave Imager (TMI) 85-GHz brightness temperatures are constructed for each cloud type. The PTH is identified as the highest altitude of the layer above the 17-dBZ PR reflectivity. The TBB on the PR instantaneous field of view is used, and every data point is interpolated to 0.0315° (~3.5 km) in horizontal spacing for comparison with the NICAM data. Following RS14, we focused on the joint histograms and CFADs of the deep clouds.

We also used vertical profiling data from the 94-GHz radar reflectivities in 2B-GEOPROF CloudSat data with 1-km horizontal resolution for additional analysis. The CloudSat data are more sensitive to small cloud ice particles and snow than the TRMM PR data because of the smaller minimum detectable signal and shorter wavelength. Therefore, it is useful to analyze the vertical structures of nonprecipitating ice-phased clouds using the CloudSat data.

Four days of TRMM and CloudSat observations do not contain enough spatial samples to make a statistically significant comparison. Therefore, we sampled observation data from the period of 1 June–31 July 2008 to provide sufficient statistical data for the comparison.

To compare satellite observations and simulated data in signal space, we used SDSU (Masunaga et al. 2010) version 2.14 as a satellite simulator. This was the same approach taken in RS14. Recently, the use of satellite simulators has become a common approach to evaluate numerical models in signal space (Masunaga et al. 2010; Bodas-Salcedo et al. 2011; Hashino et al. 2013). For the size distributions of rain, snow, and graupel for SDSU, we used the same assumptions as in NICAM. We set the effective radius of the cloud ice to 30 μm and used a lognormal distribution of the cloud water (the median diameter was 20 μm, and the dispersion was 0.35) in the radar simulator and the visible/infrared channel simulator of SDSU.

3. Results

a. Horizontal and vertical structure of the clouds and precipitation

The observed 11-μm TBBs were compared with the TBBs simulated by CON and MODI at 1200 UTC 18 June (Fig. 1). Compared with the observations, both simulations had similar horizontal distributions of their synoptic cloud systems. In both the simulations and the observations, convective systems corresponding to the intertropical convective zone (ITCZ) were aligned in the Pacific Ocean near the equator. The high clouds were also well simulated near the equator in Africa and on the American continent. TC Fengshen located near the Philippines was reproduced in both simulations, albeit with more clouds in MODI. In general, MODI produced a greater coverage of upper clouds (TBB < 240 K) than CON.

Figure 2 shows the averaged accumulated precipitation of TRMM 3B42, CON, and MODI for the 4-day simulations. The overall distributions of the two
simulated precipitation fields are comparable to the observations; however, the accumulated precipitation amounts are overestimated. Interestingly, the simulated precipitation distributions are nearly the same. This indicates that the large-scale precipitation distributions are not sensitive to the different microphysics of CON and MODI during a simulation of a few days. These results are somewhat different from RS14, in which organizational characteristics were very different between CON and MODI (Fig. 14 in RS14). Figure 3 shows the zonal average of the accumulated precipitation for 4 days. The total amount of accumulated precipitation in the simulations is overestimated compared with the observations at nearly all latitudes. This difference in zonal averaged accumulated precipitation is largest near the ITCZ region at approximately 8°N. The modification of the microphysics scheme in RS14 results in an alteration of the horizontal distributions of the accumulated precipitation. However, Fig. 3 shows that the effect of the modification is not significant for the accumulated horizontal distribution or the zonally averaged precipitation on a global scale. It suggests that the large-scale distribution of precipitation is controlled by the initial conditions and large-scale forcing (such as the sea surface temperature distribution) rather than the cloud microphysics scheme.

The TCs constitute MCSs, which comprise convective and stratiform precipitation. First, we examined TC Fengshen by directly comparing the vertical profiles of the radar reflectivities to understand the differences in the simulated signals. Figure 4 shows the observed 11-μm TBBs and a cross section of the 13.8-GHz radar reflectivities at 1700 UTC 19 June for TC Fengshen. We have 3-hourly snapshot outputs to compare with the observations at 1800 UTC 19 June, which are the closest times to the observations. CON simulated a more isolated precipitation pattern than seen in the observations. Hashino et al. (2013) also reported that global NICAMs reproduce more isolated convective cells and less spread of detraining than seen in the observations. In

![Figure 4](http://journals.ametsoc.org/jas/article-pdf/74/1/167/3866025/jas-d-16-0027_1.pdf)
addition, CON shows greater radar reflectivity frequencies above 10-km altitude than the TRMM data. The 13.8-GHz radar reflectivities of the TRMM observations show that most of the maximum heights of the deep convective systems are below an altitude of 10 km. MODI has precipitation systems that are well organized with better cross-sectional profiles and low signal frequencies above 10 km (as in the observations). When we
consider several tests related to the cross sections with various angles and locations in CON and MODI, the characteristics are similar to Fig. 4—that is, the radar reflectivity frequencies above an altitude of 10 km (not shown).

**b. Evaluations using TRMM statistics**

In RS14, the analysis domain was limited to the central Pacific Ocean and used the joint histograms and CFADs of deep clouds. We extended the target evaluation domain to the entire tropics to validate the impact of modifying the RS14 cloud microphysics.

Figure 5 (left panels) shows the joint histograms of the cloud top and PTHs in the TRMM observations, CON, and MODI for the entire tropical area (20°S–20°N). CON shows similar biases in RS14, such as high frequencies of PTH near 14 km and low frequencies of PTH between 5 and 10 km; according to RS14, these are related to the size distribution parameterizations of snow and rain. The results of MODI are improved compared with those of CON; for example, the increase in the midcold clouds and the reduction in the bias over 12-km PTH originated from the size distribution parameterizations of the snow. This result is similar to those obtained for the central Pacific case in RS14, except for the underprediction of the ratio of deep clouds in MODI. CON has better deep cloud statistics than MODI, whereas MODI has shallow and midcold cloud statistics that are closer to the observations than those of CON (Table 3).

The right panels of Fig. 5 show that the CFADs of deep clouds for the entire tropical region are also similar to the CFADs described in RS14. For example, CON overestimates the average and maximum radar reflectivities in the CFADs (Fig. 5d). MODI does a better job of reproducing the average radar reflectivities over the melting layer, whereas the maximum radar reflectivities are underestimated by nearly 5 dBZ (Fig. 5b and 5f). One of the possible causes for the underestimation of the maximum radar reflectivities is that MODI better simulates the smaller particle sizes of graupel than CON because of its larger intercept parameter in the negative exponential distribution. The convective systems in the extreme precipitation cases accompany large ice particles with high density, such as hail. However, MODI does not have hail categories with which to reproduce these extreme cases. Lang et al. (2014) reported that the introduction of a hail category reproduced the maximum radar reflectivity in the case of the Midlatitude Continental Convective Clouds Experiment (MC3E).

We divided the land and ocean areas in the tropics to investigate the effect of the surface conditions (Fig. 6). The joint histogram for the ocean area has shallower precipitation clouds than does the land area; this result is consistent with the KWAJEX case in Matsui et al. (2009). However, the congestus, midcold, and deep clouds have greater frequencies than the shallow clouds over the land areas. The strongest convective systems, with 16-km PTH, occurred over land areas rather than ocean areas. Differences in shallow clouds between the land and ocean areas can be found in the results of both simulations. CON shows weaker contrasts than do the observations and MODI, whereas MODI overestimates the fraction of congestus compared with the observations. The CFADs of the land and ocean areas do not show clear differences in the observations (Fig. 7). The maximum radar reflectivities over land areas are larger than those over the ocean areas because of stronger convective systems, with nearly 3 dBZ seen in the observations.

Following Masunaga et al. (2005), we investigated the effects of SSTs on the characteristics of the joint histogram structures over the ocean areas. According to Masunaga and Kummerow (2006) and Masunaga et al. (2005), shallow precipitation in the joint histograms is linked to the SST range over the ocean. Both simulations show that the frequencies of shallow precipitation are sensitive to the SST range (Fig. 8). This reveals a general trend in which shallow clouds have the highest probability of occurrence for relatively cold SSTs, whereas previous studies have shown that deep convective events take their place in the case of warmer SSTs. Compared with the observations in terms of these SST ranges, MODI reproduces similar joint histogram structures for both shallow and deep clouds.

There are few TRMM studies concerning the joint histogram at midlatitudes. The reason for this is the limited observed range for midlatitudes in TRMM (36°S–36°N). We defined the following midlatitude areas: the southern region (20°–36°S) and the northern region (20°–36°N). In our case, there was a seasonal difference: the northern region was experiencing summer, and the southern region was experiencing winter. We found that the joint histogram structure is sensitive to seasonal differences due to the related tropopause and melting-layer heights (Fig. 9). In addition, the

**Table 3. Frequencies of cloud types (%) for TRMM, CON, and MODI over the entire tropics.**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Shallow</th>
<th>Congestus</th>
<th>Midcold</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRMM</td>
<td>17.1</td>
<td>18.1</td>
<td>27.9</td>
<td>24.2</td>
</tr>
<tr>
<td>CON</td>
<td>37.3</td>
<td>23.6</td>
<td>5.6</td>
<td>23.2</td>
</tr>
<tr>
<td>MODI</td>
<td>24.1</td>
<td>26.3</td>
<td>26.3</td>
<td>14.4</td>
</tr>
</tbody>
</table>

...
difference between the northern region and southern region is related to the fractions of ocean and land, especially for the shallow clouds (Fig. 6). NICAM reproduces a realistic tropopause height and simulates a realistic minimum TBB in CON and MODI. In the observations and in both simulations, the minimum TBB is nearly 190 K in the northern region and 210 K in the southern region. The cloud structure in the northern
region is similar to the structure in the tropical results. In the southern region, the minimum TBB increases and the maximum PTH is reduced compared with the tropical and northern region results. It is found that the categorization relies on the tropopause and melting-layer heights in the midlatitude areas. Lower tropopause and lower melting-layer levels lead to smaller ranges of PTH and TBB in the diagrams.

FIG. 7. The CFADs of the deep clouds (\% km\(^{-1}\) dBZ\(^{-1}\)) over (a),(c),(e) the land areas and (b),(d),(f) the ocean areas for (top) the TRMM observations, (middle) CON, and (bottom) MODI.
 Evaluations using CloudSat observations

We investigated effects of a different active satellite on the evaluation results using the CloudSat data instead of TRMM data, which were used in the previous section and RS14. First, we compared the vertical radar reflectivity profiles of the 94-GHz radar reflectivities at 2300 UTC 10 June with the simulations at 0000 UTC 20 June (Fig. 10). The 94-GHz signals capture a larger fraction of the deep clouds over 5 km than does TRMM. Therefore, it is possible to investigate anvil cloud characteristics. The CloudSat observations show maximum radar reflectivities, which are larger than 10 dBZ, from 4- to 10-km altitudes; these reflectivities are related to precipitation particles. However, the radar reflectivities in CON are underestimated because of the strong attenuation of the upper clouds. MODI shows larger radar reflectivities than CON but with weaker attenuation. The precipitation systems are well organized, as seen by comparing the observations and CON; this is consistent with the TRMM results (Fig. 4). However, MODI reproduces a larger fraction of the anvil clouds than does CON.

Following Masunaga et al. (2008), we conducted a similar joint histogram analysis using CloudSat. Masunaga et al. (2008) used two thresholds, −28 and 10 dBZ, as conceived by Stephens and Wood (2007), instead of the TBBs and PTH in T3TF. Masunaga et al. (2008)
evaluated the cloud properties of NICAM using this joint histogram for the dry and wet phases of a Madden–Julian oscillation (MJO) system. Note that they analyzed numerical data from Miura et al. (2007), in which a different cloud microphysics scheme (Grabowski 1998) was used, whereas CON used the NSW6 cloud microphysics scheme (Tomita 2008a). They found that NICAM did not reproduce the 94-GHz radar reflectivity
larger than 5 dBZ above an altitude of 6 km. The reason for this is that the signals of 94-GHz tend to be more attenuated by large ice particles, such as snow and graupel, than by the lower-frequency active sensors of TRMM.

Figure 11 shows the structure of the joint histogram by CloudSat over the tropical ocean (20°S–20°N). This result has a similar structure to the joint histogram of TBB and PTH from TRMM; however, the fraction of shallow clouds under the 4-km PTH is smaller than in the TRMM joint histogram. CON shows a closed histogram shape, as seen in Masunaga et al. (2008). MODI shows a larger fraction of deep clouds than CON; however, the midcold clouds are overestimated. The CFADs of the deep clouds (above the 7-km PTH) show a clear difference between CON and MODI. Compared with the observations, CON shows weaker maximum radar reflectivities (by nearly 6 dBZ) caused by attenuation. However, MODI shows maximum radar reflectivities of over 15 dBZ near 10 km and melting layers near 5 km. The attenuated CFAD radar reflectivities in CON are accompanied by the low frequencies of midcold and deep clouds. MODI has two peaks in the radar reflectivity above the altitudes of 5 and 10 km in the CFADs (Fig. 11f) corresponding to the two discrete high frequency modes at 5 and 10 km in the joint histograms (Fig. 11e).

d. Outward longwave radiation

We compared the zonally averaged OLR between the Clouds and the Earth’s Radiant Energy System (CERES; Wielicki et al. 1996) daily OLR data, CON, and MODI (Fig. 12). The OLR in MODI is underestimated compared to that in the observations and in CON. This underestimation dominates over the tropics and in the Northern Hemisphere.

RS14 focused on the cloud microphyscis of the precipitating hydrometeors (i.e., rain, snow, and graupel). However, the OLR is sensitive to cloud ice. We believe that the OLR underestimation can be controlled by sensitivity tests of cloud microphysics processes related to cloud ice. For example, because the falling speed of cloud...
ice affects OLR (Iga et al. 2011; Satoh et al. 2010), a parameterization of the terminal speed of cloud ice using a formulation, such as that of Heymsfield and Donner (1990), can be investigated. In this study, we did not consider the terminal velocity of cloud ice in MODI. In addition, the OLR is sensitive to the autoconversion process of cloud ice. Kodama et al. (2012) reported that the latitudinal mean OLR of NICAM changes significantly.
from 187 to 266 W m\(^{-2}\) in sensitivity tests of the autoconversion process parameter [Table 3 in Kodama et al. (2012)].

4. Summary and conclusions

An improved cloud microphysics scheme with a regional NICAM was tested with a global NICAM for the entire tropical region and limited midlatitudes covered by TRMM. CON and MODI simulated a realistic horizontal distribution of clouds compared with the observed 11-\(\mu\)m TBB. However, the MODI simulation reproduced larger cloud systems than did the CON experiment. The locations of the accumulated simulated precipitation were well reproduced compared to the TRMM 3B42 data; however, the simulations overestimated the accumulated precipitation sizes and amounts. At a larger scale, the accumulated precipitation distribution was not sensitive to the modifications in the microphysics scheme. The cross section of TC Fengshen was evaluated for CON and MODI using TRMM and CloudSat. The clouds in CON were more isolated than those in MODI. The simulated vertical profiles of the 13.8-GHz signals were improved in MODI, such as the reduction in the radar reflectivity frequencies over altitudes of 10 km.

The joint histogram of TBB and PTH, as well as the CFADs of the deep clouds over the entire tropics, were similar to the regional results described in RS14. For example, the joint histogram of MODI had improved features compared with CON, such as the reduction of high frequencies above the 12-km PTH. The fraction of midcold and shallow clouds was improved in MODI compared with the observations, whereas the fraction of deep clouds was underestimated. Regional differences were seen in the tropics originating from the surface condition of the land and ocean areas in the observations; for example, the fraction of shallow clouds is lower over land areas than ocean areas. The patterns of contrast in the shallow clouds between the land and ocean were similar to the observations for both simulations, even though the contrast is more evident in MODI than in CON. However, MODI underestimates the maximum radar reflectivities.

Seasonal differences between the limited southern (20°–36°S) and northern (20°–36°N) midlatitudes were seen in the observations. The joint histogram of the southern latitudes in the winter season shrinks compared with the tropics and the northern latitudes in the boreal summer season. It means that the differences in the tropopause and melting-layer heights lead to the seasonal differences in the joint histogram. Similar to the observations, we found that the simulation results clearly reproduced the seasonal difference in the joint histogram.

Additional analysis using the 94-GHz signals from CloudSat was carried out. The results of this analysis show that MODI improves the joint histogram and the CFADs calculated for the 94-GHz radar reflectivities. MODI reproduces larger fractions of anvil clouds than do both CON; this yields an underestimation of the OLR compared with the observations. It is necessary to improve the OLR results in MODI by further considering the microphysics of cloud ice.

These results show that improvement in the microphysics scheme in a specific region of the central Pacific Ocean is capable of reproducing statistically realistic vertical structures, not only in the tropics but also in the examined midlatitude areas. These results also demonstrate that the statistics based on CloudSat improved over the tropics when the scheme was improved using the TRMM data.

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