Characteristics of Ice Clouds Over Mountain Regions
Detected by CALIPSO and CloudSat Satellite Observations

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Abstract This study examines the characteristics of orographic ice clouds in steep mountain regions using 3 years of CloudSat and CALIPSO satellite products. A combination of radar and lidar cloud fraction data is used to identify ice cloud systems. Additionally, the retrieved ice water content (IWC) and ice number concentration (NI) are used to analyze the dominant ice cloud microphysics in convective- and cirrus-type clouds. The analysis shows that temporally averaged values of the IWC and NI are larger in mountain regions than in land and ocean regions. For convective clouds over mountains, both the IWC and NI have larger values at atmospheric temperatures warmer than 250 K, suggesting a dominant role for the freezing of supercooled liquid water. For cirrus clouds over mountains, however, only the NI has larger values at atmospheric temperatures colder than 240 K, indicating the importance of homogeneous ice nucleation. These characteristics of ice-phase clouds in terms of the IWC and NI in mountain regions are distinct, with a horizontal scale smaller than 300 km. This study suggests that it is useful to categorize ice clouds in mountain regions in addition to ocean and land regions to evaluate the microphysical properties (mass and number) of such ice clouds in atmospheric models.

Plain Language Summary Ice clouds are frequently observed over mountain ridges. However, little is known about how cloud-ice particles develop over mountain regions. Thus, a number of cloud vertical profiles were sampled from satellite observations, which allowed the mechanisms of cloud-ice particle development to be inferred. These observational insights into cloud-ice particle development over mountain regions are useful for improving weather forecasting and climate projection models.

1. Introduction

General circulation models (GCMs) participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) are known to have a large ice cloud distribution bias (Jiang et al., 2012; Li et al., 2012; Waliser et al., 2009). Since the ice cloud bias results in shortwave and longwave radiation biases (Li et al., 2013) and the related uncertainties in simulating precipitation, hydrological cycle, and circulation (e.g., Su et al., 2013; Su et al., 2014; Su et al., 2017), continuous improvement of ice cloud modeling is needed for climate simulations. Ice cloud microphysics includes phase changes between liquid and ice hydrometeors; hence, the interactions among various hydrometeors make model evaluations more difficult than do warm cloud microphysics. Recently, the phase partitioning temperature between liquid and ice hydrometeors detected by the Cloud-Aerosol Lidar with Orthogonal Polarization on the CALIPSO satellite has been used for model evaluation (Cesana et al., 2015; Hu et al., 2010). Tan et al. (2016) indicated that improvement in the phase partitioning for ice cloud simulations using CALIPSO products could reduce climate projection uncertainties. Their results imply the importance of reliable ice microphysics modeling and the evaluation of ice clouds using satellite observations. Recently, detailed ice cloud microphysical models have been developed and tested to attain more realistic global ice cloud simulations (e.g., Eidhammer et al., 2017; Gettelman et al., 2008; Hashino et al., 2013, 2016; Lang et al., 2011; Lang et al., 2014; Morrison & Gettelman, 2008; Roh & Satoh, 2018, 2014; Roh et al., 2017; Seiki et al., 2014; Seiki, Kodama, Noda, et al., 2015; Seiki et al., 2015). Satellite observations enable the evaluation of ice microphysics in various cases and perspectives. This study is aimed at illustrating the microphysical structure of ice clouds using a fine-resolution global data set from the CloudSat and CALIPSO satellites. Such active sensors enable the vertical structures of
cloud systems to be analyzed (Mace et al., 2009). By combining radar and lidar observations from the CloudSat and CALIPSO satellites, both thin cirrus clouds and deep convective clouds can be more accurately detected than with passive imagers such as MODIS (Hagihara et al., 2010; Mace et al., 2009). In addition, the hydrometeor phase can be clearly partitioned with the depolarization ratio and backscattering coefficient from the CALIPSO products (Yoshida et al., 2010). Accordingly, microphysical properties of ice are more precisely retrieved with less contamination from warm clouds compared to satellite products using passive imagers (Deng et al., 2010; Mitchell et al., 2018; Okamoto et al., 2010). A large sample from these satellite observations can complement intensive field observation campaigns with aircraft or video sondes.

After launching the CloudSat and CALIPSO satellites, the characteristics of deep convective clouds were analyzed intensively because of their uncertainty in climate projection. For example, Igel et al. (2014) examined the deep convective cloud geometric response to sea surface temperature anomalies over the tropics by a morphology analysis using CloudSat products. As a proxy for convective activity, the anvil productivity of deep convection was analyzed over the tropical ocean by combining CloudSat and CALIPSO products (Deng et al., 2016). Luo et al. (2014) and Takahashi et al. (2017) aimed at retrieving information about inner deep convective cloud dynamics by combining CloudSat, CALIPSO, and ECMWF reanalysis of the atmospheric state as well as other A-Train satellite products. These research studies successfully illustrate the characteristics of deep convective clouds by defining distinctively intense or organized cloud systems. Thus, it is expected that various microphysical characteristics of ice can be highlighted by suitably choosing different types of cloud systems.

In this study, two distinct cloud types, convective and cirrus clouds, were selected from various ice cloud categories, and the difference in such ice clouds among ocean, land, and mountain regions is analyzed and discussed. Orography is known to have strong effects on precipitating clouds by triggering convective initiation (e.g., blocking and forcing unstable low-level air upward; Houze, 2012). These effects vary by case and region. Observationally, the general aspects of rainfall cloud vertical profiles were investigated using radar echoes observed by the Tropical Rainfall Measuring Mission Precipitation Radar (TRMM PR) sensor (Shige et al., 2013; Shige & Kummerow, 2016; Yamamoto & Shige, 2015). These studies revealed that orographic clouds in the Asian monsoon region were generally characterized by a bottom heavy structure and lower cloud tops. It is therefore expected that ice microphysical cloud properties induced by orography can be characterized by CloudSat and CALIPSO. Since the TRMM PR sensor can detect relatively large precipitating hydrometeors, an analysis using CALIPSO, which is sensitive to smaller cloud particles near the cloud top (e.g., Hagihara et al., 2014), will provide complementary microphysical characteristics of ice. Specifically, the ice water content (IWC) and ice number concentration (NI) in different regions (ocean, land, and mountain) were analyzed.

The IWC and the ice effective radius (REI) have been widely used for model evaluation (e.g., Chen et al., 2011; Chen et al., 2018; Seiki, Kodama, Satoh, et al., 2015; Waliser et al., 2009). van Diedenhoven et al. (2016) developed an advanced technique to analyze the REI vertical profile within clouds and indicated the mechanisms for vertical REI variability in convective clouds. The present study is different from previous studies since it is aimed at revealing which microphysical processes dictate the differences between regions and cloud types. The final goal is to obtain an ice cloud microphysical characterization that can be used for ice cloud evaluations in climate model simulations.

Uncertainty in ice cloud modeling in GCMs originates not only from ice cloud microphysics but also from insufficient GCM spatial resolution. Seiki, Kodama, Satoh, et al. (2015) indicated that artificial bias arises in tropical cirrus clouds when using coarse vertical grid spacing in GCMs. For example, cirriform clouds have a typical thickness of 1 to 2 km (e.g., Mace et al., 2009), whereas GCMs in CMIP5 generally have a vertical resolution of approximately 1 km in the upper troposphere (see Appendix 9A, Flato et al., 2013). Seiki, Kodama, Satoh, et al. (2015) found that a vertical grid spacing of 400 m or less substantially reduced the high cloud fraction and improved the negative bias in the outgoing longwave radiation over the tropics and subtropics, where CMIP5 GCMs commonly have negative outgoing longwave radiation biases (cf. Li et al., 2013). However, no consensus exists for the appropriate horizontal resolution to obtain reliable ice cloud simulations in terms of a global radiation budget. One may speculate that resolving the characteristic scale of ice cloud systems improves the simulated ice cloud radiative forcing. Thus, the horizontal size of ice clouds was also analyzed in addition to ice cloud microphysics.
The structure of this paper is as follows. In section 2, the satellite data set used in this study is described. The analyzed results on the horizontal size of ice clouds and ice cloud microphysics are shown in the subsections of section 3. The summary and discussion are given in section 4.

2. Satellite Data Set

2.1. Definition of Ice Clouds

To analyze ice clouds observationally, we used CALIPSO, CloudSat, and ECMWF ancillary atmospheric state data sets from “the EarthCARE Research A-Train Product Monitor” (http://www.eorc.jaxa.jp/EARTHCARE/research_product/ecare_monitor_e.html), which is based on Kyushu University products (Hagihara et al., 2010, 2014). The data set has a vertical resolution of 240 m and a horizontal resolution of 1.1 km. Okamoto et al. (2007, 2008) and Hagihara et al. (2010) defined four types of cloud masks: radar only (C1); lidar only (C2); radar and lidar (C3), in which both sensors detect clouds; and radar or lidar (C4), in which at least one of the sensors detects clouds. The cloud mask schemes were originally developed for and tested on ship-borne cloud radar and lidar observations by Okamoto et al. (2007) in the midlatitudes and by Okamoto et al. (2008) in the tropics. The cloud mask schemes were modified to apply CloudSat and CALIPSO data (Hagihara et al., 2010).

The ice cloud detection product in the data set was originally developed by Yoshida et al. (2010) for vertically resolved cloud particle type discrimination. It uses a ratio of attenuated backscattering coefficients for two vertically consecutive cloud layers ($x$) in addition to the depolarization ratio ($\delta$). Based on the criteria for $x$-$\delta$ relationships estimated from statistics for observations and theoretical simulations by the Monte Carlo method, their method can discriminate five types of cloud particles independent of atmospheric temperature: (1) cloud water, (2) randomly oriented ice crystals (3-D ice), (3) horizontally oriented plates (2-D plates), (4) a mixture of 3-D ice and 2-D ice, and (5) unknown ice particles (Yoshida et al., 2010). In addition, readers can find the capabilities of this ice cloud product and differences in the cloud phase detection among CALIPSO satellite products in Cesana et al. (2016).

The ice cloud microphysical properties product in the data set was originally developed by Okamoto et al. (2010) and Sato and Okamoto (2011). The retrieval algorithm used the radar reflectivity factor from CloudSat and the attenuated coefficient and depolarization ratio from CALIPSO. Hence, the algorithm was applied to C3 clouds after phase partitioning. The algorithms can handle the coexistence of 2-D plates and 3-D ice categories. The 3-D ice was further modeled as a mixture of 50% 2-D columns and 50% 3-D bullet rosettes and was also mixed with the 2-D plates (see Sato & Okamoto, 2011, for details). The algorithm was applied to cloud regions that show either 2-D plate, 3-D ice, or unknown types by the cloud particle type algorithm described above. The retrieved ice cloud microphysical properties are the effective radius of ice particles, IWC, and mass mixing ratio of the 2-D plate category to total IWC for each layer. Retrieval errors of the cloud microphysical properties are described in Appendix A. We analyzed the 3-year data set, which started from 1 January 2008.

Figure 1 shows an example of the vertical profiles of the C4 cloud mask, IWC, and NI around the Tibetan Plateau. The C4 cloud mask captures both thin and deep convective clouds. Note that the NI and IWC cannot be detected through a whole vertical column, so the sampled NIs and IWCs used in our analyses mainly contain cloud-top information.

Before any analysis, the data set was quality controlled to remove retrieval noise. Anomalously high values of the NI ($>10^{15}$ m$^{-3}$) and IWC ($>10^5$ g/m$^3$) can be estimated near the ground: Radar and lidar signals from the ground surface were considered contaminated. In such cases, REI = 3.0 $\mu$m is always estimated. Therefore, for soundness, observation grids with REI values less than 5.0 $\mu$m were removed from the analysis. This preprocessing step does not affect the conclusion of this study.

2.2. Definition of Cloud Systems

In our analyses, we combined a series of observed vertical cross-section granules between 80°S and 80°N into an atmospheric curtain. Each cloud system was defined within every atmospheric curtain following three steps.

1. Cloud types (ice, convective, or cirrus clouds) were defined for each atmospheric column.
2. Neighboring columns were matched and then merged into one cloud system if cloud pixels of the same cloud type were in contact with each other.

3. Each cloud system was labeled, and its geolocation, ground surface type, cloud length, average cloud thickness, and vertical profiles of the IWC, NI, REI, and atmospheric temperature were stored. Figure 2a shows a sample of cloud systems defined by our method. Labels were used for categorizing cloud systems into ocean, land, or mountain regions. Here two types of cloud systems were defined using the atmospheric temperature as follows: Cirrus clouds were defined by C4 cloudy pixels with cloud-base temperatures colder than 253.15 K (−20 °C), and convective clouds were defined by C4 cloudy pixels with cloud-top temperatures colder than 273.15 K (0 °C) and cloud-base temperatures warmer than 273.15 K. This definition of cirrus clouds contains both cirrus clouds floating near the tropopause and anvil clouds at the edge of organized convective clouds (Figure 2b). For example, cirriform clouds are frequently observed around the 240 to 220 K temperature range over the midlatitudes (e.g., Mace et al., 2006), and anvil cloud bases are typically observed around the 262 to 258 K temperature range over the tropics (Igel et al., 2014). The definition of cirrus clouds captures the major portion of cirriform clouds. The definition for convective clouds consists of deep convective clouds and organized clouds lifted along mountain surfaces.

2.3. Definition of Mountain Region

In this study, a mountain region is defined where the product of the mountain height and gradient is in the upper tenth percentile. Figure 3a shows the horizontal map of topography from GTOPO 30 (https://lta.cr.usgs.gov/GTOPO30) and the defined mountain regions. The edges of major mountains, such as the Himalayas, the Rockies to the Sierra Madres, the Andes, and those in Greenland, are detected using this definition.
According to a linear theory of orographic gravity waves (Durran, 1990; Holton, 1992; Nappo, 2013), a sinusoidal solution of vertical velocity \( w \) is derived as follows:

\[
\begin{align*}
    w &= -w_M \sin(kx + mz),
\end{align*}
\]

where \( w_M \) is the amplitude of the vertical velocity, \( k \) is a horizontal wave number, and \( m \) is a vertical wave number. The amplitude of the vertical velocity is proportional to the perpendicular component of the background horizontal velocity \( u_B \), the mountain height \( h_M \), and the mountain horizontal wave number (here the wave number is the same as \( k \)). The gradient of topography is approximately the same as \( k \), so the product of \( k \) and \( h_M \) represents the strength of orographic effects above mountain regions. Thus, ice clouds are expected to be influenced by orographic gravity waves above mountain regions (e.g., Joos et al., 2008). In addition, convective clouds can also be triggered above such mountain regions when the vertical velocity induced by the topography gradient lifts an air parcel above the level of free convection.

Figure 2. The same as Figure 1 except for (a) indices of cloud systems and (b) category of cloud types. In the upper figure, different colors indicate different cloud systems. In the lower figure, blue indicates cirrus clouds, yellow indicates convective clouds, and gray indicates other ice clouds detected by the C4 cloud mask.
In the following analyses, we used the ocean, land, and mountain map coarsened into a resolution of $2^\circ \times 2^\circ$ to categorize cloud systems (Figure 3b). A cloud system region is categorized as a certain type if at least one pixel exists within a $2^\circ \times 2^\circ$ grid box. Thus, in a $2^\circ \times 2^\circ$ grid box, ocean, land, and mountain regions can overlap, and cloud systems can overlap over neighboring regions.

3. Results

3.1. Horizontal Distributions of Ice Clouds

Figure 4 shows the 3-year mean values of cirrus and convective cloud fractions from the CloudSat and CALIPSO data sets over the $2^\circ \times 2^\circ$ latitude-longitude grid. Here multilayer clouds were first isolated using the C4 mask and then counted individually. The number of observations was approximately 10,000 within each grid in 1 year. Since polar orbiting satellites observe more frequently in higher latitudes, we used the inverse of the sample size in a grid box as a weighing coefficient in calculating the appropriate statistics (sections 3.2 and 3.3).

The distribution of cirrus clouds is similar to that of convective clouds; hence, the definition of the cloud types captures the spread of anvil cirrus clouds from the tops of convective clouds. The cloud fractions over the ocean, land, and mountain regions are summarized in Table 1. The ice cloud fraction is larger over mountain regions than ocean and land regions, although these values are close to each other. Over land, the cirrus cloud fraction is larger, and the convective cloud fraction is smaller. In contrast, the convective cloud fraction is not so small over mountain regions. This phenomenon suggests that orography triggers convective clouds over mountain regions.

Figure 5 shows a global map of the temporal average values of the NI and IWC from 2008 to 2010. The global average values of the NI and IWC are summarized in Table 1. The NI and IWC values at each vertical layer in a column are calculated individually for the average. For the global average, the IWC over mountain regions is approximately 14% (21%) larger than the IWC over land (ocean) regions, and the NI over mountain regions is approximately 36% (75%) larger than the NI over land (ocean) regions. Larger NI values over mountains are also observed by another CloudSat-CALIPSO satellite product called DARDAR (Gryspeerdt et al., 2018; Sourdeval et al., 2018) and the CALIPSO satellite product (Mitchell et al., 2018).

In terms of the geographical distribution, the NI and IWC values over mountains appear larger than those over surrounding regions (Figure 5). Therefore, Student’s $t$ test was calculated to confirm the local differences of NI and IWC. NI and IWC values averaged over $2^\circ \times 2^\circ$ gridded mountain regions were compared to those over the surrounding $10^\circ \times 10^\circ$ grids with different regional categories. Here we used the original resolution for detecting the surrounding grids with different regional categories because most mountain regions are surrounded by mountain regions when analyzing a $2^\circ \times 2^\circ$ resolution data set. Note that Student’s $t$ test does not strictly confirm the confidence level here because the statistical populations of the observed NI and IWC are not normal distributions but bimodal distributions as shown in the following section. Therefore, the test was calculated just for reference.

Figure 6 shows the horizontal distribution of mountain regions where the NI and IWC are significantly large at a confidence level of 95%: Approximately 60% of the mountain regions are considered to be significantly large. The significant regions are distributed globally without clear geographical differences. Thus, the test indicates that larger NI and IWC values over mountain regions are common microphysical characteristics. Note that the ratio of the significant mountain area to the total analyzed mountain area increases up to approximately 70% when mountain regions that contain mountain subregions that are less than 10% are excluded in the calculation (not shown).

3.2. Ice Cloud Microphysics

First, the probability density functions (PDFs) of the IWC and NI and the PDFs weighted by the IWC and NI values are calculated from the 3 years of the original orbital data set. Here the NI and IWC values at each vertical layer in a column are calculated individually in the same manner as the temporal average. It was found that the IWC and NI have mono-modal PDFs (Figures 7a and 7b) but bimodal weighted PDFs (Figures 7c and 7d). The difference in the value between the smaller and larger modes is 2 orders of magnitude in the weighted IWC PDF and three digits in the weighted NI PDF. This finding means that the larger mode in the weighted PDF does not frequently occur but has a nonnegligible contribution to the temporal
average. In particular, the larger mode contribution to the temporal average value (i.e., the integrated value of the weighted PDF) is distinct over the mountain regions, whereas the weighted PDFs from land and ocean are almost identical to each other. Thus, regional differences originate from this larger mode observed in the weighted PDFs for the NI and IWC.

Typical ranges of the NI and IWC from past field observations are cited in Table 2. We note that the instruments used for the aircraft measurements varied among measurement campaigns; hence, the detectable ranges of ice particle sizes are not consistent with each other. In addition, some observations were suspected to be affected by the shattering of large ice crystals, which artificially increases tiny ice crystals (e.g., Field et al., 2006; Heymsfield, 2007; Jensen et al., 2009). From these evaluations, the IWC can be overestimated by 20% to 30% due to shattering, and the NI is likely to be overestimated by up to a factor of 4, particularly as the effective particle size increases. Here we briefly summarize that past studies showed that typical ranges of the mean NI and IWC are from $10^3$ to $10^6$ m$^{-3}$ and from 0.001 to 0.1 g/m$^3$, respectively. These NI and IWC values within the typical ranges correspond to the smaller mode in Figures 6c and 6d.

Interestingly, unusually large NI and IWC values as shown in the larger mode in Figures 7c and 7d were very occasionally observed in the field observations (e.g., Gayet et al., 2012; Heymsfield et al., 2009). In one such rare case, high NI values in wave cirrus clouds were reproduced by numerical simulations, and physical mechanisms to produce such high NI values were investigated (Hoyle et al., 2005). The simulation study indicated that high-frequency temperature fluctuations from gravity waves or turbulences induced strong cooling rates, and consequently, large NIs ($>10^7$ m$^{-3}$) were produced by homogeneous ice nucleation. In the CIRCLE-2 case, unusually large NI and IWC values (the mean NI was 54 cm$^{-3}$, and the mean IWC was 0.44 g/m$^3$) were observed at the top of an overshooting convective cloud (Gayet et al., 2012). The NI and IWC over the overshooting cloud are approximately 10 times as large as the NI and IWC within the surrounding cirrus clouds. As a result, the observed IWC had distinct bimodal distributions in the statistical population. The Cloud Particle Imager instrument detected that cloud layers with such large NI and IWC values contain a number of chain-like aggregates of small frozen droplets, which means that a large amount of supercooled liquid droplets was lofted by strong updrafts in convective clouds and then frozen in the middle troposphere. Thus, the bimodal distribution observed in our analysis could have originated from such physical processes.

The temperature dependence of microphysical properties is examined to investigate the dominant ice microphysics in ice clouds. Figure 8 shows the joint PDF of the IWC and the atmospheric temperature weighted by the IWC values. As shown in Figure 7, the weighted joint PDF has a bimodal structure (Figure 8a). The IWC values in the smaller mode increase as the atmospheric temperature increases. This characteristic was also found in previous works using satellite and aircraft observations (e.g., Heymsfield et al., 2017). The temperature dependence of the IWC values can be interpreted as the dependence of the water vapor pressure on the atmospheric temperature: The available water vapor for depositional growth of ice
particles decreases exponentially as temperature decreases. In contrast, the larger mode has almost no
dependence on atmospheric temperature. The difference between the weighted joint PDFs over the ocean
and over mountains is distinct for atmospheric layers warmer than 250 K (Figure 8b). In terms of cloud
type, the difference mainly originates from convective clouds (Figures 8c and 8d). These results indicate
that the larger mode originates from the vertical transport of frozen droplets (freezing of supercooled
liquid water) in the updrafts.

This explanation was also supported by observational evidence. Heymsfield et al. (2009) analyzed aircraft
measurements in seven field campaigns and showed that most liquid water contents (LWCs) disappeared
at temperatures colder than 253 K in strong updrafts (w > 2 m/s), suggesting that the IWC grew by consum-
ing LWCs at atmospheric temperatures warmer than 253 K. In the CIRCLE-2 measurement campaign, a
number of chain-like aggregates of quasi-spherical frozen droplets with sizes of approximately 15 to 20 μm
were observed in overshooting clouds with unusually large NI and IWC values (Gayet et al., 2012). Such
small frozen droplets indicate that supercooled liquid cloud droplets were lifted in strong updrafts.

Similarly, the weighted joint NI PDF is shown in Figure 9. Compared to the weighted joint IWC PDF, the
larger mode contribution to the total value is more distinct. Interestingly, the difference between the
weighted joint PDFs over the ocean and over mountains is distinct at two atmospheric temperature ranges:
warmer than 250 K and colder than 240 K (Figure 9b). In terms of cloud type, the former signal is found in
convective clouds (Figure 9d), and the latter is found in cirrus clouds (Figure 9c).

NI values within the larger mode, which are on the order of 10^8 m^{-3}, are typical values for cloud condensa-
tion nuclei in warm clouds. Therefore, the increase in the weighted joint PDF in the warmer temperature
range, which is also observed in the weighted joint PDF of the IWC, is likely to originate from the freezing

Figure 5. Global map of (a) the ice number concentration (l^{-1}) and (b) the ice water content (mg/m^3) from the CloudSat and CALIPSO satellite observation product from 2008 to 2010.

Figure 6. Horizontal distribution of the mountain regions for which (a) the ice number concentration (NI) or (b) the ice water content (IWC) is significantly larger than those of the surrounding regions at a confidence level of 95%. For reference, the mountain regions without distinct confidence levels are also shown in gray. The longitudinal integrated values of such mountain grid numbers are shown in (c).
of cloud water. This finding is consistent with the characteristics of the IWC. Such high NI values (~10^8 m^−3) produced by the freezing of supercooled liquid water are supported by past aircraft measurements. Stith et al. (2004) found that most LWCs were removed at temperatures from 268 to 256 K in tropical updrafts, and correspondingly, such high NIs (~10^8 m^−3) with circular 2-D images (spherical shape) were observed at temperatures from 257 to 250 K.

![Figure 7](image_url)

**Figure 7.** Probability density functions (PDFs; a,b) and weighted PDFs (c,d) of the ice number concentration (NI) and ice water content (IWC) on a logarithmic scale.

| Table 2 | Observed Ranges of the NI and IWC From Aircraft and Sonde In Situ Observations |
|---------|--------------------------------------------------------------------------------|
| NI (m^−3) (NI) | IWC (g/m^3) (IWC) | Cloud types | Campaign/instruments (reference) |
| 10^3 to 10^5 | 10^−3 to 0.14 | Midlatitudinal cirrus | The 1986 First International Satellite Cloud Climatology Project Regional Experiment Intensive Field measurements (Heymsfield et al., 1990) |
| 10^3 to 7 × 10^5 | 10^−4 to 0.02 | Midlatitudinal wave cirrus | The Subsonic Clouds and Contrails Effects Special Study (Jensen et al., 1998) |
| 10^2 to 10^5 | 10^−4 to 0.02 | Various cloud systems with a temperature range from 210 to 235 K | The INterhemispheric differences in Cirrus properties from Anthropogenic emissions measurement campaign (Gayet et al., 2002; Kärcher & Ström, 2003) |
| (1.2 × 10^6 to 5.3 × 10^6) | 10^−4 to 0.02 | Midlatitudinal cirrus | The first Egret Microphysics with Extended Radiation and Lidar experiment (EMERALD-1) measurement campaign (Gallagher et al., 2005) |
| 10^4 to 10^5 | (5 × 10^−4 to 3.5 × 10^−3) | Tropical anvil cirrus | The Cirrus Regional Study of Tropical Anvils and Cirrus Layers Florida Area Cirrus Experiment measurement campaign (Garrett et al., 2005) |
| (6.4 × 10^5 to 1.7 × 10^6) | (0.1 to 1.3) | Tropical anvil cirrus | The Emerald-II measurement campaign (Gallagher et al., 2012) |
| (2.5 × 10^5 to 2.5 × 10^6) | 10^−4 to 0.02 | Midlatitudinal cirrus | The Japanese Cloud and Climate Study and post-Japanese Cloud and Climate Study measurement campaigns (Orikasa et al., 2013) |
| (1.7 × 10^7 to 5 × 10^7) | (0.05 to 0.44) | Midlatitudinal cirrus | The Tropical Composition, Cloud, and Climate Coupling measurement campaign (Jensen et al., 2009) |
| (2.5 × 10^6 to 5 × 10^7) | 5 × 10^6 to 5.4 × 10^7 | Midlatitudinal deep convective cloud | The coordinated German French CIRus Cloud Experiment (CIRCLE-2) measurement campaign (Gayet et al., 2012) |

Note. The mean values of the measurements are shown in parentheses in the first and second columns from the left (the median values are shown in Orikasa et al., 2013). Note that these ice number concentration (NI) and ice water content (IWC) values are not those given in the original database but are from the reference papers.
Cloud water usually does not exist in cirrus clouds. Thus, we speculate that an increase in the weighted joint PDF in the colder temperature range is dominated by homogeneous ice nucleation. The ice nucleation process is enhanced by strong orographic lift over mountain regions because the NI produced by homogeneous ice nucleation is known to strongly depend on the vertical velocity (see Appendix B). Interestingly, an increase in the NI in the colder temperature range was not observed in convective clouds (Figure 9d). In theory, existing ice particles can depress subsequent homogeneous ice nucleation by consuming supersaturation (e.g., Ren & MacKenzie, 2005; Spichtinger and Cziczo, 2010). Thus, in convective clouds, a large NI in the warmer temperature range results in an insensitivity in the colder temperature ranges.

3.3. Ice Cloud Size

We analyzed the relationship between the ice cloud size and cloud microphysical parameters in different regions. The cloud size is expected to be affected by the topography wave number over mountain regions. Here all ice clouds were analyzed to calculate the cloud size.

Figure 10 shows the cumulative size distribution of ice clouds over the ocean, land, and mountain regions. Differences in the ice cloud size between the ocean and the mountain regions are clearer than those between the ocean and land regions. In general, the median ice cloud size is largest over the ocean regions and is smallest over mountain regions. In a more detailed evaluation, ice clouds smaller than 20 km are more frequently observed over the mountain regions.

To match various types of cloud systems, we categorized cloud sizes into the following five types: (i) sizes from 1 to 30 km, which correspond to meso-gamma cloud systems; (ii) sizes from 30 to 100 km, which correspond to meso-beta cloud systems; (iii) sizes from 100 to 300 km, which correspond to intermediate-scale meso-beta to meso-alpha cloud systems; (iv) sizes from 300 to 1,000 km, which correspond to meso-alpha cloud systems; and (v) sizes larger than 1,000 km, which are generated by synoptic-scale disturbances such as extratropical cyclones. These categories roughly correspond to various types of simulation models. Conventional GCMs

Figure 8. Joint probability density function (PDF) of the ice water content (IWC) and the atmospheric temperature weighted by the IWC values: (a) The weighted joint PDF over the ocean, (b) differences between the weighted joint PDF within total ice clouds over the ocean and over mountains, (c) differences between the weighted joint PDF within only cirrus clouds over the ocean and over mountains, and (d) differences between the weighted joint PDF within only convective clouds over the ocean and over mountains. For reference, the weighted joint PDF for the total ice, cirrus, and deep convective clouds over the ocean are shown by contours in (b), (c), and (d), respectively.

Figure 9. The same as Figure 8 but the weighted joint PDF of the ice number concentration (NI).
only capture Cloud Types (iv) and (v), and high-resolution GCMs are starting to resolve Cloud Types (ii) and (iii). Subgrid parameterizations are necessary to simulate Cloud Type (i) in GCMs.

The contributions of each cloud size to the average IWC and NI values are shown in Figure 11. To calculate the contributions, the cloud systems were first categorized by their sizes, and then the average values of NI and IWC in each cloud system are summed with a weighting factor of the retrievable vertical cross section. Finally, each contribution was derived by dividing the sums by the sample size of the regions (ocean, land, and mountains). Ice clouds smaller than 300 km mostly contribute to increasing NI over the land and mountain regions. In contrast, regional differences in the IWC are small except for 100–300-km ice clouds, although the mountain regions have the largest value in the broad range of cloud sizes. As introduced in section 2.2, steep terrain induces vertical motion with a high horizontal wave number. From our analysis, the steepest and highest terrain in the upper tenth percentile induces atmospheric disturbances smaller than 300 km.

Next, the number of cloud cores in a cloud system were determined; a cloud core is defined as a cloud pixel whose NI exceeds $10^7 \text{ m}^{-3}$ or IWC exceeds 0.3 g/m$^3$ (e.g., Figures 8 and 9). Figure 12 shows the ratio of the average cloud core number to the mean cloud size for each cloud size category. The cloud cores occur infrequently in cloud systems, and hence, the ratio has generally very small values. For example, only a few kilometers of cloud core exist within 1- to 300-km size cloud systems (less than 5–20% of the cloud sizes).

In addition, the ratio decreases as the cloud size increases because anvil clouds formed from organized cloud systems extend more broadly than those from small cumuli. This feature does not change between cloud cores defined by NI or IWC values. Thus, the topographic effect on the NI and IWC is apparent for cloud systems smaller than 300 km.

4. Discussion

The NI and IWC satellite products used in our study have uncertainties. Now the validity of the bimodal characteristics of the weighted PDF of the NI and IWC (cf. Figure 7) is discussed. The retrieval errors of the IWC and NI increase as the IWC and NI increase and reach approximately 100–200% at IWC values larger than 0.3 g/m$^3$ or NI values larger than $10^6 \text{ m}^{-3}$ (Appendix A). Thus, the existence of the large mode is evident from the error analysis, but the true shape of the distribution is very likely to be narrower than the observed shape (cf. Figure 7). The bimodal structure is more clearly captured in Sato and Okamoto (2011), who developed the radar-only retrieval algorithm, although the algorithm has larger errors than the radar and lidar retrieval algorithm used in this study.

Next, the sources of the uncertainties in NI are proposed because retrieved NI values have potentially larger uncertainties that are difficult to evaluate. Given the population of ice particles, the IWC represents the total volume of particles, and the effective radius (REI) represents the cross section of particles, but the NI possibly
has various values depending on the assumed particle models. For example, chain-like aggregates of 10 frozen droplets and 10 separated frozen droplets have the same IWC and REI and similar single scattering properties according to the discrete dipole approximation method, but the NI is different between the two samples. Thus, the estimated IWC values are considered more reliable than the NI values, and the uncertainty in the NI is 1 order of magnitude higher than the IWC. However, we emphasize again that the statistical population of the IWCs also has a bimodal structure; hence, the bimodal structure of the weighted PDF of the NI is acceptable. The NI and IWC values in the larger mode were very rarely observed by aircraft observations (e.g., Heymsfield et al., 2009); hence, using satellite observations has the advantage of being able to analyze such ice clouds with a large sample size. At the same time, the rarity makes it difficult to evaluate satellite products.

Figure 11. Contribution of each cloud size to the global average values of (a) the ice number concentration (NI) and (b) the ice water content (IWC).
To our knowledge, extremely high IWC values and 94-GHz radar echoes were simultaneously observed only once in the CIRCLE-2 measurement campaign (Gayet et al., 2012). Such IWC values were observed in convective overshooting clouds, whereas moderate IWC values were observed in surrounding cirrus clouds: Bimodal distributions were indicated in the IWC-Ze relationships (see the solid and dashed lines in Figure 13a). Unfortunately, the satellite product used in this study (from 2008 to 2014) does not cover the date on which the cloud event occurred (26 May 2007). Instead, we prepared a pair of subsamples for comparison: One subsample consists of cloud systems that do not contain cloud cores (NOCORE), and the other subsample consists of cloud systems that contain cloud cores (CORE). Here the IWC threshold was used to define

Figure 12. The ratio of the average number of cloud cores to the cloud size in each size category where cloud cores are defined by (a) the ice number concentration (NI) threshold and (b) the ice water content (IWC) threshold.
The first $10^6$ samples from 1 January 2008 were detected from the satellite products. Bimodal distributions are only depicted in the IWC-Ze and NI-Ze scatter diagrams derived from the CORE subsample. The regression line for cirrus clouds (the solid line in Figure 13a) lies along the NOCORE subsample and the smaller IWC mode in the CORE subsample. The smaller IWC mode in the IWC-Ze relationships was also observed in past studies (e.g., Gayet et al., 2014). Therefore, the retrieval algorithm used for the satellite product works well for major ice clouds. We now focus on the larger IWC mode in the CORE subsample. The slope of the larger IWC mode is smaller than the regression line for convective overshooting clouds: The IWC values at Ze from $-30$ to $-10$ dBZ are at most 1 order of magnitude larger than those from the regression line, whereas the IWC values at Ze from $-10$ to 10 dBZ are comparable to those from the regression line. The inconsistency in the IWC values at Ze smaller than 10 dBZ indicates that satellite products have potentially large uncertainties for such cloud pixels. Given a certain Ze value, an overestimation of the IWC means an underestimation of the REI and, consequently, an overestimation of the NI. Thus, extremely high values of the NI (greater than $10^7$ m$^{-3}$) at Ze smaller than $-10$ dBZ are potentially 1 order of magnitude overestimated in the CORE subsample.

Past studies using TRMM PR radar echo profiles indicate that orographic clouds are generally characterized by moderate updrafts and the dominance of warm cloud processes (Shige et al., 2013; Shige & Kummerow, 2016; Yamamoto and Shige, 2014). However, our results show that strong updrafts, though infrequent, do impact the weighted PDF for the IWC and NI. In addition, the signal also appears in cirrus clouds that were hardly detected by TRMM PR observations. Thus, one can evaluate model results more fully using CloudSat and CALIPSO observations in combination with TRMM PR observations.

In this study, mountain regions were defined using the mountain height and gradient. One may choose other indices, such as only the mountain height. As shown in Figure 3b, the mountain regions used in our analysis cover approximately 33% of the total land area after coarsening the map to a 2° × 2° resolution and, hence, include most major mountains. In addition, one may distinguish the analysis domain between the windward and leeward directions to assess the effect of orographic gravity waves. In this study, large analysis domains enabled a large number of ice clouds to be sampled over the mountain regions, allowing for a robust comparison against other regions (i.e., the land and ocean regions). Thus, by focusing on a specific region or phenomenon, the microphysical signals detected by our analyses become clearer.

Our analyses indicate that the regional differences in the IWC and NI are associated with the stronger end of the vertical velocity spectrum in cloud systems. Thus, nonhydrostatic atmospheric models are necessary to reproduce the regional differences because hydrostatic atmospheric models, such as conventional GCMs, cannot represent the vertical wind acceleration. In addition, the difficulty in representing global ice clouds originates from the smallness of each ice cloud system. Conventional GCMs with a grid size of approximately 100 to 300 km (T42 to T106) resolve only half the populations of ice clouds (cf. the median sizes of ice clouds are 241, 207, and 180 km over the ocean, land, and mountain regions, respectively). To resolve the whole population of ice clouds, a horizontal resolution smaller than 5 km is required for GCMs (cf. the 90th
percentile values of the ice cloud sizes are 9, 7, and 6 km over the ocean, land, and mountain regions, respectively). One needs to remove the contribution of cloud cores from the temporal average values of the IWC or NI when comparing model results with the CloudSat-CALIPSO products.

Recently, nonhydrostatic GCMs with a horizontal resolution of approximately 10 km (e.g., the Nonhydrostatic Icosahedral Atmospheric Model, Satoh et al., 2008; 2014; Tomita & Satoh, 2004; the Icosahedral Nonhydrostatic model, Dipankar et al., 2015; Zängl et al., 2014; the Finite Volume Cubed-Sphere Dynamical Core model, Lin, 2004; and the Model for Prediction Across Scales, Skamarock et al., 2012) have been used for practical numerical weather predictions such that the highest resolution GCMs can capture a large portion of ice cloud systems (cloud sizes larger than 30 km).

Note that cloud cores were not frequently observed, even in smaller ice clouds (cf. Figure 12). This result indicates two possibilities for the aspects of ice clouds. One possibility is that the cloud cores have a small size and are concentrated at the center of convection. The other possibility is that the cloud cores exist more frequently in ice clouds but are not frequently detected by either CALIPSO or CloudSat because of a strong attenuation of the lidar signal or insensitivity of the radar signal to smaller ice particles (Hagihara et al., 2014). The latter is more plausible because IWC values greater than 0.3 g/m³ are more frequently observed by using only the CloudSat product (Sato & Okamoto, 2011). An examination of the ice cloud cores using regional models with a very fine horizontal resolution (~100 m) and vertical grid spacing that can resolve orographic effects is the next challenging issue.

5. Summary

Topographic effects on the IWC, NI, ice cloud fraction, and ice cloud size were statistically analyzed over 3 years starting from 2008. The CALIPSO, CloudSat, and ECMWF ancillary atmospheric state data set from the EarthCARE Research A-Train Product Monitor were used to perform the cloud analyses; mountain regions were defined as land regions with the uppermost 10% of values for the product of the mountain height and gradient. To identify topographic effects on various types of ice clouds, convective clouds were categorized as ice clouds with cloud-base temperatures warmer than the freezing level and cloud-top temperatures colder than the freezing level, and cirrus clouds were categorized as ice clouds with cloud-base temperatures colder than 253.15 K.

Ice clouds were observed more frequently over mountain regions than over ocean and land regions. In particular, convective clouds are more active over mountain regions; hence, the IWC and NI are distinctively larger. Ice clouds with sizes smaller than 300 km dominate the regional contrasts in the IWC and NI. We speculate that smaller ice clouds are selectively triggered by steep mountains according to the linear theory of orographic mountain waves. Our results also indicate that orographic effects on the IWC and NI are localized over steep mountains and are unlikely to propagate downwind or upwind within a whole cloud system. Therefore, the effect was attenuated in cloud systems larger than 300 km, and the differences in IWC and NI between the ocean, land, and mountains are not distinct in such larger cloud systems (cf. Figure 11).

The IWC and NI have almost monomodal-shaped PDFs but bimodal-shaped weighted PDFs. The larger mode mostly contributes to the temporal average value, and the contribution becomes more distinct over the mountain regions. Regional differences in the IWC mainly originate from warmer atmospheric temperature regions (T > 250 K) in convective clouds. Regional differences in the NI originate from warmer atmospheric temperature regions (T > 250 K) in convective clouds and colder atmospheric temperature regions (T < 240 K) in cirrus clouds.

The values in the larger mode of the IWC and NI have a weak dependence on the atmospheric temperature and, hence, are likely to be related to vertical transport by strong updrafts in cloud systems. We speculate that the increase in the IWC and NI in the warmer atmospheric temperature regions originates from the freezing of supercooled liquid water in convective cores and that the increase in the NI in the colder atmospheric temperature regions originates from homogeneous ice nucleation in cirrus clouds.

Appendix A.: Retrieval Errors in the Ice Cloud Microphysical Parameters

The satellite products of ice cloud microphysical parameters (IWC and REI) were retrieved using lookup tables for the radar reflectivity factor, radar extinction coefficients, lidar backscattering coefficients, and
The same as Figure 1 except for the estimated errors (%) for (a) the ice water content (IWC; g/m$^3$) and (c) the ice number concentration (NI; m$^{-3}$). The mean values and standard deviations of (b) the IWC errors and (d) the NI errors are shown by solid lines and error bars.

Figure A1 shows the estimated errors in the IWC and NI in the same sample cloud scene as that in Figure 1. The characteristics of the vertical profiles of the IWC errors and NI errors are similar to each other: The errors are relatively small at the cloud top (15−20%) and become larger toward the lower layer (25−35%). Since the occurrence of the IWC (NI) is concentrated at $10^{-3}$−$10^{-2}$ g/m$^3$ ($10^{5}$−$10^{6}$ m$^{-3}$; see Figures 7a and 7b), the retrieval errors of the algorithm are within 30% in most cases. In regard to the larger mode in the weighted PDF (Figures 7c and 7d), the errors reach approximately 100−200%.

In the past, errors in the IWC estimated from the algorithm have been directly evaluated by comparison with 19 aircraft observations in four measurement campaigns (Heymsfield et al., 2008). In the test, the IWC values fell in the range from approximately $10^{-3}$ to 1 g/m$^3$. The mean (standard deviation) and median of the ratio of the retrieved IWC to the measured IWC in the 19 cases were 1.2 ($\pm$0.5) and 1.08, respectively. In regard to IWC values greater than 0.3 g/m$^3$, the ratio is 1.0 $\pm$ 0.4. Thus, the error estimation from the retrieval algorithm applied in this study (Figure A1) is consistent with the past case study and is potentially overestimated in the cases of extremely large IWC values.
Appendix B.: Homogeneous Ice Nucleation

It is known that a key physical mechanism of homogeneous ice nucleation is condensational freezing of deliquescent aerosols (Fukuta & Schaller, 1982; Pruppacher & Klett, 1997). Deliquescent aerosols dissolve by absorbing water vapor in an environment with relative humidity larger than a certain critical value. As the environmental temperature (generally below $-40^\circ C$) decreases, stochastically initiated ice embryos in a liquid droplet become more likely to crystalize the entire droplet (Khvorostyanov & Curry, 2004, 2009; Khvorostyanov & Sassen, 1998). Thus, cooler and more humid conditions favor the process of homogeneous ice nucleation. Ren and MacKenzie (2005) proposed a theory-based parameterization of the homogeneous ice nucleation process with an experimentally determined database from Koop et al. (2000). When assuming an adiabatic ascending parcel with vertical velocity $w_v$, the nucleated NI can be estimated using the ice supersaturation and an assumed aerosol size distribution. Figure B1 shows the dependence of the nucleated ice number concentration on the environmental vertical velocity calculated using a parameterization developed by Ren and MacKenzie (2005) and Kärcher et al. (2006). In the upper troposphere (230–210 K), a strong vertical velocity of more than 4 m/s can produce a NI of more than 10 cm$^{-3}$ (10$^7$ m$^{-3}$), corresponding to the threshold used to categorize the larger mode in the weighted PDF (cf. Figure 8a).

References

Cesana, G., Chepfer, H., Winker, D., Getzewich, B., Cai, X., Jourdan, O., et al. (2016). Using in situ airborne measurements to evaluate three cloud phase products derived from CALIOPSO. *Journal of Geophysical Research: Atmospheres*, 121, 5788–5808. https://doi.org/10.1002/2015JD024334

Cesana, G., Waliser, D. E., Jiang, X., & Li, J.-L. F. (2015). Multimodel evaluation of cloud phase transition using satellite and reanalysis data. *Journal of Geophysical Research: Atmospheres*, 120, 7871–7892. https://doi.org/10.1002/2014JD022932

Chen, W.-T., Woods, C. P., Li, J.-L. F., Waliser, D. E., Chern, J.-D., Tao, W.-K., et al. (2011). Partitioning CloudSat ice water content for comparison with upper tropospheric ice in global atmospheric models. *Journal of Geophysical Research*, 116, D19206. https://doi.org/10.1029/2010JD015179

Chen, Y.-W., Seiki, T., Kodama, C., Satoh, M., & Noda, A. T. (2018). Impact of precipitating ice hydrometeors on longwave radiative effect estimated by a global cloud-system resolving model. *Journal of Advances in Modeling Earth Systems*, 10, 284–296. https://doi.org/10.1002/2017MS001180

Deng, M., Mace, G. G., & Wang, Z. (2016). Anvil productivities of tropical deep convective clusters and their regional differences. *Journal of the Atmospheric Sciences*, 73, 3467–3487. https://doi.org/10.1175/JAS-D-15-0329.1

Deng, M., Mace, G. G., Wang, Z., & Okamoto, H. (2010). Tropical Composition, Cloud and Climate Coupling Experiment validation for cirrus profiling retrieval using CloudSat radar and CALIPSO lidar. *Journal of Geophysical Research*, 115, D00J15. https://doi.org/10.1029/2009JD013104

Dipankar, A., Stevens, B., Heinze, R., Moseley, C., Zängl, G., Giorgetta, M., & Brdar, S. (2015). Large eddy simulation using the general circulation model ICON. *Journal of Advances in Modeling Earth Systems*, 7, 963–986. https://doi.org/10.1002/2015MS000431

Durran, D. R. (1990). Mountain waves and downslope winds. In *Atmospheric Processes over Complex Terrain*, Meteorological Monographs (Vol. 23, pp. 59–81). Boston, USA: American Meteorological Society.

Edhammer, T., Morrison, H., Mitchell, D., Gettelman, A., & Erfani, E. (2017). Improvements in global climate model microphysics using a consistent representation of ice particle properties. *Journal of Climate*, 30, 609–629. https://doi.org/10.1175/JCLI-D-16-0050.1

Field, P. R., Heymsfield, A. J., & Balsbøe, A. (2006). Shattering and particle interarrival times measured by optical array probes in ice clouds. *Journal of Atmospheric and Oceanic Technology*, 23, 1357–1371. https://doi.org/10.1175/JTECH1922.1

Flato, G., Marotzke, J., Abdin, B., Braconnot, P., Chou, S.-C., Collins, W., et al. (2013). Evaluation of climate models. In *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change* (Chap. 9, pp. 741–866). Cambridge and New York: Cambridge University Press.

Fukuta, N., & Schaller, R. C. (1982). Ice nucleation by aerosol particles: Theory of condensation-freezing nucleation. *Journal of the Atmospheric Sciences*, 39, 648–655.

Gallagher, M. W., Connolly, P. J., Crawford, I., Heymsfield, A., Bower, K. N., Choularton, T. W., et al. (2012). Observations and modelling of microphysical variability, aggregation and sedimentation in tropical anvils cirrus outflow regions. *Atmospheric Chemistry and Physics*, 12, 6689–6628. https://doi.org/10.5194/acp-12-6689-2012

Gallagher, M. W., Connolly, P. J., Whiteley, J., Figueras-Nieto, D., Flynn, M., Choularton, T. W., et al. (2005). An overview of the microphysical structure of cirrus clouds observed during EMERALD-1. *Quarterly Journal of the Royal Meteorological Society*, 131, 1143–1169. https://doi.org/10.1012/jglq.01.138.

Garrett, T. J., Navarro, B. C., Twyoh, C. H., Jensen, E. J., Baumgardner, D. G., Bui, P. T., et al. (2005). Evolution of a Florida cirrus anvil. *Journal of the Atmospheric Sciences*, 62(7), 2352–2372. https://doi.org/10.11002/2015JD02495.I

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Figure B1. Dependence of the homogeneously nucleated ice number concentration on the effective vertical velocity under various temperature conditions, assuming an atmospheric pressure of $p = 200$ hPa, and an ice relative humidity of RH$_i = 100\%$ from the box-model calculation.
Li, J.-L. F., Waliser, D. E., Chen, W.-T., Ghan, B., Kubu, T., Stephens, G., et al. (2012). An observationally based evaluation of cloud ice water in CMIP3 and CMIP5 GCMs and contemporary reanalyses using contemporary satellite data. Journal of Geophysical Research, 117, D16105. https://doi.org/10.1029/2012JD017640

Li, J.-L. F., Waliser, D. E., Stephens, G., Lee, S., L'Ecuyer, T., Kato, S., et al. (2013). Characterizing and understanding radiation budget biases in CMIP3/CMIP5 GCMs, contemporary GCM, and reanalysis. Journal of Geophysical Research: Atmospheres, 118, 8166–8184. https://doi.org/10.1002/jgrd.50378

Lin, S. J. (2004). A “vertically Lagrangian” finite-volume dynamical core for global models. Monthly Weather Review, 132, 2293–2307. https://doi.org/10.1175/1520-0493(2004)132<2293:AVLFD>2.0.CO;2

Luo, Z., Ji, Y., Yoshinaga, J., Iwasaki, S., Takahashi, H., & Anderson, R. (2014). Convective vertical velocity and cloud internal vertical structure: An A-Traint perspective. Geophysical Research Letters, 41, 723–729. https://doi.org/10.1002/2013GL058922

Mace, G. G., Benson, S., & Vernon, E. (2006) Cirrus clouds and the large-scale atmospheric state: relationships revealed by six years of ground-based data. Journal of Climate, 19, 3257–3278. https://doi.org/10.1175/JCLI3786.1

Mace, G. G., Zhang, Q., Vaughan, M., Marchand, R., Stephens, G., Trepte, C., & Winker, D. (2009). A description of hydrometeor layer occurrence statistics derived from the first year of merged CloudSat and CALIPSO data. Journal of Geophysical Research, 114, D06A26. https://doi.org/10.1029/2007JD009755

Mitchell, D. L., Garnier, A., Pelon, J., & Erfani, E. (2018). CALIPSO (IIR-CALIP) retrievals of cirrus cloud ice-particle concentrations. Atmospheric Chemistry and Physics, 18, 17,325–17,354. https://doi.org/10.5194/acp-18-17325-2018

Morrison, H., & Gettelman, A. (2008). A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (CAM3). Part I: Description and numerical tests. Journal of Climate, 21, 3642–3659. https://doi.org/10.1175/2008JCLI2105.1

Nappo, C. I. (2013). An introduction to atmospheric gravity waves. San Diego, USA: Academic Press.

Okamoto, H. (2002). Information content of the 95-GHz cloud radar signals: Theoretical assessment of effects of nonsphericity and error evaluation of the discrete dipole approximation. Journal of Geophysical Research, 107(D22), 4628. https://doi.org/10.1029/2001JD001386

Okamoto, H., Iwasaki, S., Yasui, M., Horie, H., Kuroiwa, H., & Kumagai, H. (2003). An algorithm for retrieval of cloud microphysics using 95-GHz cloud radar and lidar. Journal of Geophysical Research, 108(D7), 4226. https://doi.org/10.1029/2003JD003225

Okamoto, H., Nishizawa, T., Takeamura, T., Kumagai, H., Kuroiwa, H., Sugimoto, N., et al. (2007). Vertical cloud structure observed from shipborne radar and lidar, part I: Mid-latitude case study during the MR01/K02 cruise of the R/V Mirai. Journal of Geophysical Research, 112, D08216. https://doi.org/10.1029/2006JD007628

Okamoto, H., Nishizawa, T., Takeamura, T., Sato, K., Kumagai, H., Ohno, Y., et al. (2008). Vertical cloud properties in the tropical western Pacific Ocean: Validation of the CCSR/NIES/PRCCG GCM by shipborne radar and lidar. Journal of Geophysical Research, 113, D24213. https://doi.org/10.1029/2008JD009812

Okamoto, H., Sato, K., & Hagihara, Y. (2010). Global analysis of ice microphysics from CloudSat and CALIPSO: Incorporation of specular reflection in lidar signals. Journal of Geophysical Research, 115, D22209. https://doi.org/10.1029/2009JD013383

Orikasa, N., Murakami, M., & Heymsfield, A. J. (2013). Ice crystal concentration in midlatitude cirrus clouds: In situ measurements with the balloonborne hydrometeor videosonde (HYVIS). Journal of The Meteorological Society of Japan, 91, 143–161. https://doi.org/10.2151/jmsj.2013-204

Pruppacher, H. R., & Klett, J. D. (1997). Microphysics of clouds and precipitation. Dordrecht, Netherlands: Kluwer Academic Publisher.

Ren, C., & MacKenzie, A. R. (2005). Cirrus parameterization and the role of ice nuclei. Quarterly Journal of the Royal Meteorological Society, 131, 1585–1605.

Roh, W., & Satoh, M. (2018). Extension of a multisensor satellite radiance-based evaluation for cloud system resolving models. Journal of the Meteorological Society of Japan, 96, 55–63. https://doi.org/10.2151/jmsj.2018-002

Roh, W., & Satoh, M. (2014). Evaluation of precipitating hydrometeor parameterizations in a single moment bulk microphysics scheme for deep convective systems over the tropical central Pacific. Journal of the Atmospheric Sciences, 71, 2654–2673. https://doi.org/10.1175/JAS-D-13-0252.1

Roh, W., Satoh, M., & Nasuno, T. (2017). Improvement of a cloud microphysics scheme for a global nonhydrostatic model using TRMM and a satellite simulator. Journal of the Atmospheric Sciences, 74, 167–184. https://doi.org/10.1175/JAS-D-16-0027.1

Sato, K., & Okamoto, H. (2006). Characterization of Ze and LDR of nonspherical and inhomogeneous ice particles for 95-GHz cloud radar: Its implication to microphysical retrievals. Journal of Geophysical Research, 111, D22213. https://doi.org/10.1029/2005JD009695

Sato, K., & Okamoto, H. (2011). Refinement of global ice microphysics using spaceborne active sensors. Journal of Geophysical Research, 116, D20202. https://doi.org/10.1029/2011JD015885

Satoh, M., Matsuno, T., Tomita, H., Miura, H., Nasuno, T., & Iga, S. (2008). Nonhydrostatic icoseahedral atmospheric model (NICAM) for global cloud resolving simulations. Journal of Computational Physics, 227, 3486–3514.

Satoh, M., Tomita, H., Yashiro, H., Miura, H., Kodama, C., Seiki, T., et al. (2014). The Non-hydrostatic Icosahedral Atmospheric Model: Description and development. Prog. Earth and Planetary Science, 1, 18. https://doi.org/10.1186/s40645-014-0018-1

Seiki, T., Kodama, C., Sato, M., Hashino, T., Hagihara, Y., & Okamoto, H. (2015). Vertical grid spacing necessary for simulating tropical cirrus clouds with a high-resolution atmospheric general circulation model. Geophysical Research Letters, 42, 4150–4157. https://doi.org/10.1002/2015GL064282

Seiki, T., Satoh, M., Tomita, H., & Nakajima, T. (2014). Simultaneous evaluation of ice cloud microphysics and nonsphericity of the cloud optical properties using hydrometeor video sounder and radiometer sounder in situ observations. Journal of Geophysical Research: Atmospheres, 119, 6681–6701. https://doi.org/10.1002/2013JD020886

Shige, S., Kida, S., Ashiwake, H., Kubota, T., & Aonashi, K. (2013). Improvement of TMI rain retrievals in mountainous areas. Journal of Applied Meteorology and Climatology, 52, 242–254. https://doi.org/10.1175/JAMC-D-12-074.1

Shige, S., & Kummerow, C. D. (2016). Precipitation-top heights of heavy orographic rainfall in the Asian monsoon region. Journal of the Atmospheric Sciences, 73, 3009–3024. https://doi.org/10.1175/JAS-D-15-0271.1

Skamarock, W. C., Klemp, J. B., Duda, M. G., Fowler, L. D., & Park, S.-H. (2012). A multi-scale nonhydrostatic atmospheric model using centroid Voronoi tessellations and C-grid staggering. Monthly Weather Review, 140, 3099–3105. https://doi.org/10.1175/MWR-D-11-00215.1

Souza e Silva, O., Grynpevtzir, E., Kätner, M., Goren, T., Delanoe, A., Afchine, A., Hemmer, F., & Quaas, J. (2018). Ice crystal number concentration estimates from lidar-radar satellite remote sensing — Part 1: Method and evaluation. Atmospheric Chemistry and Physics, 18, 14,327–14,350. https://doi.org/10.5194/acp-18-14327-2018
