Cloud Microphysics in Global Cloud Resolving Models

Tatsuya Seiki[1,1], Woosub Roh[2,2], and Masaki Satoh[2,2]

[1]Japan Agency for Marine-Earth Science and Technology
[2]Atmosphere and Ocean Research Institute, The University of Tokyo

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Abstract

Global cloud resolving models (GCRMs) are a new type of general circulation model that explicitly calculates the growth of cloud systems with fine spatial resolutions and more than 10 GCRMs have been developed at present. This chapter of the monograph reviews cloud microphysics schemes used in GCRMs with introductions to the recent progress and researches with GCRMs. Especially, research progress using a pioneer of GCRMs, Nonhydrostatic ICosahedral Atmospheric Model (NICAM), is focused. Since GCRMs deal with climatology and meteorology, it is a challenging issue to establish cloud microphysics schemes for GCRMs. A brief history of the development of cloud microphysics schemes and cloud-radiation coupling in NICAM is described. In addition, current progress in analytical techniques using satellite simulators is described. The combined use of multi-optical sensors enables us to constrain uncertain processes in cloud microphysics without artificial tuning. As a result, cloud microphysics schemes used in the NICAM naturally represent cloud systems, and hence, the radiative budget is well balanced with little optimization. Finally, a new satellite and a ground validation campaign are introduced for future work.

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Tatsuya Seiki[1], Woosub Roh[2], Masaki Satoh[2]

1: Japan Agency for Marine-Earth Science and Technology

Yokohama Institute for Earth Sciences

2: The University of Tokyo, Atmosphere and Ocean Research

Institute

Corresponding Author: Masaki Satoh (satoh@aori.u-tokyo.ac.jp)

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Abstract

Global cloud resolving models (GCRMs) are a new type of general circulation model that explicitly calculates the growth of cloud systems with fine spatial resolutions and more than 10 GCRMs have been developed at present. This chapter of the monograph reviews cloud microphysics schemes used in GCRMs with introductions to the recent progress and researches with GCRMs. Especially, research progress using a pioneer of GCRMs, Nonhydrostatic ICosahedral Atmospheric Model (NICAM), is focused. Since GCRMs deal with climatology and meteorology, it is a challenging issue to establish cloud microphysics schemes for GCRMs. A brief history of the development of cloud microphysics schemes and cloud-radiation coupling in NICAM is described. In addition, current progress in analytical techniques using satellite simulators is described. The combined use of multi-optical sensors enables us to constrain uncertain processes in cloud microphysics without artificial tuning. As a result, cloud microphysics schemes used in the NICAM naturally represent cloud systems, and hence, the radiative budget is well balanced with little optimization. Finally, a new satellite and a ground validation campaign are introduced for future work.

1. Introduction

This chapter of the monograph reviews cloud microphysics schemes used in global cloud resolving models (GCRMs) with introductions to the recent progress and researches with GCRMs. Section 1 briefly introduces the background and design of GCRMs. Cloud microphysics schemes in GCRMs are reviewed in Section 2 and model evaluation using optical sensors are reviewed in Section 3. Especially, research progress using a pioneer of GCRMs, Nonhydrostatic ICosahedral Atmospheric Model (NICAM), is focused. Finally, Section 4 summarizes this chapter. Acronyms of numerical models, satellites, and optical instruments are described in Table 1.

1.1 Global cloud resolving models

Climatology and meteorology have separated spatiotemporal scales and hence have been individually investigated in separate research communities (see Figure 1). However, ongoing climate change increases social risks such as record breaking intense precipitation, intense tropical cyclones, and extensive flood damage. Recent extreme events have been intensively analyzed around the world and have been edited as a special issue for “Explaining Extreme Events from a Climate Perspective” for the Bulletin of the American Meteorological Society every year starting in 2011 (e.g., Herring et al., 2019). To meet social demands, the World Climate Research Programme (WCRP) has promoted research on “weather and climate extremes” as one of the current grand challenges (https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview). The two research communities have started to work together to tackle this issue across spatiotemporal scales.

For the next decade, the WCRP has newly proposed lighthouse activities (https://www.wcrp-climate.org/wcrp-ip-la), in which a “digital twin of Earth” is to be utilized for modeling earth systems more realistically (e.g. Bauer et al., 2021). Recent advances in parallel computing have enabled us to achieve global atmospheric simulations with finer horizontal resolution (e.g., Wedi, 2014; Satoh et al., 2017; Schär et al., 2020). Thus, motivation and research infrastructure are now prepared for global cloud resolving simulations that fill the scale gap between climate research and weather forecasting.

In the UK, for example, the UPSCALE (UK on PRACE: weather-resolving Simulations of Climate for globAL Environmental risk) project was organized for global weather prediction using a general circulation model (GCM) with a horizontal resolution of up to 25 km (Mizielinski et al., 2014). In Europe, multi-high-resolution GCMs have been used for predicting regional climate as the PRocess-based climate sIMulation: AdVances in high-resolution modelling and European climate Risk Assessment (PRIMAVERA) project (https://www.primavera-h2020.eu/). In the Pan-Pacific region, the International laboratory for High-resolution Earth System Prediction (iHESP) project has started to examine intense cyclones for decadal prediction by using a 25-km atmosphere and 10-km ocean-coupled GCM (Zhang et al., 2020; Chang et al., 2020). Finally, the High Resolution Model Intercomparison Project (HighResMIP) was coordinated as a part of the Coupled Model Intercomparison Project Phase 6 (CMIP6) for examining the capability of capturing mesoscale phenomena using GCMs only by increasing the horizontal resolution up to 25 km (Haarsma et al., 2016; Roberts et al., 2018). However, in HighResMIP, most participants are conventional GCMs, which do not predict precipitating hydrometeors (e.g., rain, snow, graupel, and hail) [cloud microphysics in CMIP6 models are described in the ES-DOC Explorer (https://explore.es-doc.org/)] and rely on parameterizations for representing convective clouds, although some GCMs have recently incorporated explicit calculations for rain and snow [ARPEGE-Climat (Roehrig et al., 2020), CAM (Morrison and Gettelman, 2008; Song et al., 2012; Gettelman and Morrison, 2015), ECHAM/ICON-A (Posselt and Lohmann, 2008; Sant et al., 2015), IFS (Forbes et al., 2011), MIROC (Michibata et al., 2019), and UM-Global Atmosphere (Boutle et al., 2014; Walters et al., 2019)]. Explicit (grid-scale) representations of convective clouds are necessary for seamlessly simulating the interaction between a mesoscale convective system and its environmental state at finer resolutions (e.g., Miyakawa et al., 2012; Takasuka et al. 2015). Climate models without convective parameterizations can successfully better represent some aspects of climate states than those with convective parameterizations by increasing horizontal resolution even if the climate models cannot fully resolve convective clouds (e.g., Senf et al., 2020; Stevens et al., 2020; Vergara-Temprado et al., 2020; Wedi et al., 2020).

In the era of global simulations with horizontal resolutions of a few kilometers, nonhydrostatic dynamical cores (e.g., Saito et al., 2007) are required for resolving convection in an environmental state (e.g., Kato and Saito, 1995; Weisman et al., 1997; Yang et al., 2017). In addition, cloud microphysics for precipitating hydrometeors should be explicitly calculated as is done in mesoscale models. Global atmospheric models that explicitly calculate the growth of cloud systems are a new type of GCM and are now called global cloud resolving models (Satoh et al., 2019). In particular, explicit representation of smaller clouds is a great advantage of GCRMs compared to conventional GCMs even if the cloud microphysics in GCMs become sophisticated (details are described in Section 3.2). Global cloud resolving models are now practically available for various research fields in many countries thanks to prevailing massive parallel computers and advanced network environments. For example, Nakano et al. (2017) demonstrated that forecasts of tropical cyclones generally improve by using three GCRMs with the horizontal resolution of less than 10 km. In contrast to operational global numerical weather prediction models (e.g., Kalnay et al., 1990; Zhang et al., 2019), GCRMs are not restricted by operating time and hence can be used for challenging issues in terms of spatiotemporal resolution and complexity of physics.

Currently, the first international intercomparison project for GCRMs, the initiative DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND), has been organized (Stevens et al., 2019) and GCRMs are becoming established (See Figure 2). Table 2 summarizes the GCRMs that have been developed at present. Note that multimodel framework (MMF) is another approach to modeling convective cloud systems in GCMs (e.g., Tao et al., 2009).

1.2. A baseline for spatial resolutions

Cloud microphysics schemes for GCRMs are designed to work with horizontal resolutions from 1 to 15 km based on 15 years of experience with global high-resolution simulations using the NICAM. Similarly, a common cloud microphysics scheme is used in a unified system for weather-to-seasonal prediction developed in the United States of America that uses a horizontal resolution of 13 km for medium-range weather prediction and a horizontal resolution of 3 km for global cloud resolving simulations [The geophysical fluid dynamics laboratory (GFDL) System for High-resolution prediction on Earth-to-Local Domains (SHiELD), Harris et al., 2020]. In addition, IFS has been well evaluated with a horizontal resolution of 9 km, and its results are comparable to IFS with a horizontal resolution of 1.4 km in many aspects (Wedi et al., 2020). Thus, IFS with a horizontal resolution of 9 km works for research purpose in terms of practical use, although Wedi et al. (2020) emphasized the advantages of using a 1 km resolution for resolving deep convection by IFS.

As a pioneer of GCRMs, the NICAM was developed in the early 2000s (Tomita et al., 2001; Satoh, 2002; Satoh, 2003; Tomita and Satoh, 2004) and has been improved over the past twenty years (Satoh et al., 2008a; Satoh et al., 2014; Kodama et al., 2021). NICAM developers first conducted cloud resolving simulations with horizontal resolutions of up to 3.5 km on an Aqua-

Planet (Tomita et al., 2005) and then achieved cloud resolving simulations with realistic land-ocean distributions (Miura et al., 2007a; 2007b). Miyamoto et al. (2013) finally attained the world's first global simulations with a subkilometer horizontal resolution (Figure 3) on the K computer with 20,480 nodes (163,840 cores).

Global statistics of convective cores from subkilometer simulations have shown that the number of convective cores does not converge, even at a 870 m resolution (Miyamoto et al., 2013; Kajikawa et al., 2016). Sueki et al. (2019) further investigated the resolved size of convective cores over the tropics and found similar results at a horizontal resolution of 50 m. In general, convective cores were found to become resolved at a horizontal resolution of 1/6 of their sizes (Miyamoto et al., 2013; Miyamoto et al., 2015; Kajikawa et al., 2016) and to become fully resolved at horizontal resolutions of 1/40 to 1/20 of their sizes (Sueki et al., 2019).

On the other hand, it has been found that individual convective cores are not necessarily resolved for capturing large-scale convective systems that last longer than the daily scale (cf. Figure 1) or some aspects of climate states as mentioned above. For example, in practice, a NICAM with a horizontal resolution of 14 km is widely used for Madden-Julian oscillation (MJO), tropical cyclones, and extratropical cyclones. A NICAM with a horizontal resolution of 14 km successfully shows the top-performing skill score of the MJO prediction (Miyakawa et al., 2014). Similarly, a NICAM with a horizontal resolution of 14 km successfully reproduces tropical cyclones (e.g., Oouchi et al., 2009; Taniguchi et al., 2010; Yanase et al., 2010; Nakano et al., 2015), as was done using a NICAM with finer horizontal resolutions (e.g., Fudeyasu et al., 2008; Yamada et al., 2016; Nakano et al., 2017). In particular, the eyewall structure has been clearly captured for intense tropical cyclones (Yamada et al., 2010; Yamada and Satoh, 2013; Yamada et al., 2017), although the detailed wind structure of tropical cyclones was not sufficiently resolved even at a horizontal resolution of 7 km (Miyamoto et al., 2014 and see also Figure 3).

We conclude that a horizontal resolution of 14 km, which roughly captures meso-beta-scale (20 - 200 km) cloud systems according to Sueki et al. (2019), is a baseline for global cloud (system) resolving simulations without cumulus parameterizations provided by the NICAM. In terms of the response of clouds to global warming, the response of clouds smaller than 40 to 100 km is found to be very different from the response of larger clouds (Noda et al., 2014; Noda et al., 2016). In terms of the radiative budget, the global mean values almost converged at a horizontal resolution of 3.5 km and did not significantly differ at horizontal resolutions equal to or finer than 14 km (Kajikawa et al., 2016), whereas global simulations with horizontal resolutions of 28 km or 56 km suffer from nonnegligible radiation biases (Seiki et al., 2015b; Kodama et al., 2021). The radiative budget (cloud amount) is found to be affected by the numerical settings of physical processes rather than horizontal resolution (Seiki et al., 2014; 2015a; Roh et al., 2017; Kodama et al., 2021), as was shown in other GCMs (e.g., Meehl et al., 2019). Therefore, we efficiently optimize a cloud microphysics scheme at a horizontal resolution of 14 km in a strategic way and then fine-tune cloud microphysics at finer objective horizontal resolutions because of their high computational cost.

1.3. How to evaluate cloud microphysics

Explicit coupling between radiation and cloud microphysics enables us to evaluate cloud microphysics through cloud radiative forcing (e.g., Hashino et al., 2016). Moreover, the use of a consistent assumption between the radiative transfer model and cloud microphysics represents cloud radiative forcing depending on the particle shape and growth stage of cloud systems (Seiki et al., 2014; 2015a; Thompson et al., 2016; Matsui et al., 2018). In addition, the coupling reduces the freedom of tunable model parameters. This substantially reduces efforts for model optimization and hence provides model developers an insight into the improvements in model performance (e.g., Kodama et al., 2021).

Satellite simulators push forward the idea of cloud-radiation coupling for the purpose of model evaluation, data assimilation, and observing system simulation experiments (e.g., Masunaga et al., 2010). Satellite simulators compile forward radiative transfer models that use model results as an atmospheric environment to match remote sensing (Figure 4). Thanks to satellite simulators, various types of cloud systems and their dominant cloud microphysics can be evaluated from various aspects by using multisensor analyses. Model evaluations using satellite simulators are reviewed in Section 3 in greater detail.

1.4. Benefits to optimizing Cloud Radiative Forcing

Cloud radiative forcing (CRF) is considered the most important parameter to optimize in the performance of cloud microphysics in GCRMs, whereas initialization and reproducibility of specific events are important for mesoscale models. Climate states are realized in the semiequilibrium condition of the energy balance; it is difficult to understand the causal relationship in the balanced state (e.g., Stevens and Feingold, 2009; Morrison et al., 2012). Therefore, one may design a cloud microphysics scheme that represents correct physical mechanisms with few tuning parameters and then optimize the CRF. Uncertainties in CRF significantly affect climate projection through various pathways of cloud feedback (e.g., Meehl et al., 2020; Sherwood et al., 2020). In terms of practical use for long-term simulations, CRF should be optimized because climate drift is inevitable because of energy imbalance (e.g., Stockdale, 1997).

One can strategically evaluate cloud microphysics schemes by using in situ observations or remote sensing whose objective is a specific type of cloud (details are described in Section 2). Cloud radiative forcing differs by cloud type (e.g., Hartmann et al., 1992): distributions of cloud types are climatologically determined by region and season (Rossow and Schiffer, 1999). In general, longwave CRF is dominated by high clouds; shortwave CRF is dominated by high thick clouds and low clouds; both longwave and shortwave CRF are effective over the intertropical convergence zone. In particular, cirrus generally has a strong long CRF even with a small optical thickness (Liou, 1986; Ackermann et al., 1988; Fu and Liou, 1993; Jensen et al., 1994) and extensively covers the upper troposphere (e.g., Liou, 1986; Rossow and Schiffer, 1999; Sassen et al., 2008; Haladay and Stephens, 2009; Hagihara et al., 2010) and hence has a strong influence on a broad range of atmospheric layers. In addition, low-level clouds are commonly biased as "too few and too bright" among GCMs (Nam et al., 2012) and have been a major source of uncertainties in climate sensitivity (e.g., Bony and Dufresne, 2005; Zhang et al., 2013; Andrews et al., 2015). In particular, a negative bias in low-level clouds strongly increases the downward shortwave radiative flux to the sea surface and consequently affects atmospheric circulation through ocean feedback (e.g., Kang et al., 2009; Trenbirth and Fasullo, 2010; Kay et al., 2016; Hyder et al., 2018). On the other hand, in the Arctic region, supercooled liquid water in low-level clouds strongly contributes to the longwave CRF to enhance sea ice (land surface ice) melting (e.g., Curry et al., 1993; Shupe et al., 2004; Francis et al., 2005; Bennartz et al., 2013; Kapsh et al., 2013; 2016). Recently, these strong impacts of CRF from various cloud types on climate states have been used for making a scale to measure the reliability of climate projections as "emergent constraints on future climate change" (e.g., Hall et al., 2019). Current progress in understanding climate sensitivity and cloud feedback is comprehensively reviewed in Sherwood et al. (2020).

Improvements in cloud radiative forcing evidently have positive feedback to improvements in model performances through cloud radiation interactions (e.g., Tao et al., 1996). For instance, satellite observations indicate that cirrus clouds generally support invigoration of convective clouds over the tropics through longwave CRF (Masunaga and Bony, 2018; Masunaga and Mapes, 2020). More specifically, the longwave component of the CRF has strong impacts on the structure and track of tropical cyclones (Fovell et al., 2010; Bu et al., 2014; 2017) and the onset of MJO (Takasuka et al., 2018). Thus, a cloud microphysics scheme, which is evaluated in terms of CRF, is expected to also work for case studies (e.g., Arakane et al., 2014; Sato et al., 2015; Yamada et al., 2016), regional weather prediction (e.g., Miyoshi et al., 2016; Nasuno et al., 2017; Harris et al., 2020), and regional climate research (e.g., Adachi et al., 2017; 2019; Adachi and Tomita, 2020).

1.5. Global and regional simulations

The hybrid use of a GCRM for global and regional simulations accelerates the evaluation of cloud microphysics using in situ measurements (see Figure 5 and details are described in Section 2). The use of in situ measurements [e.g., the Atmospheric Radiation Measurement (ARM)] will greatly contribute to improvements in GCRMs, as was done for GCMs (e.g., Randall et al., 2016). However, it is not efficient to perform global high-resolution simulations for comparison to in situ observations. Therefore, the NICAM employs two types of regional settings that are easily switched with a namelist in the running configuration. One is a stretched grid system on a global domain [so-called stretched NICAM (Tomita, 2008a; Uchida et al., 2016; Shibuya et al. 2016), see Figure 5b]. The other picks up one diamond panel of the icosahedron and uses the panel as the regional domain [so-called diamond NICAM (Uchida et al., 2017), see Figure 5c]. Both grid systems share icosahedral grid data, numerical operators, and physical packages with the original global settings. In addition, the single-column model has also been prepared (Seiki and Roh, 2020).

This kind of regional setting is also used in other GCRMs [ICON (Zängl et al., 2014; Stevens et al., 2020), FV3 (Harris et al., 2019; 2020); MPAS (Skamarock, 2012; 2018); and UM (Davies et al., 2005)].

In addition, portable usage of cloud microphysics among GCRMs, mesoscale models, and LES models will complement the evaluation of cloud microphysics and will develop the application of cloud microphysics. Cloud microphysics schemes in the NICAM are shared with SCALE (Nishizawa et al., 2015; Sato et al., 2015), which works as a mesoscale model and a large eddy simulation model. SCALE is highly optimized for massive parallel supercomputers with codesign by researchers in computational science and computer science (https://scale.riken.jp/) and hence can be used for ultrafine atmospheric simulations with a grid resolution of finer than 10 m (Sato et al., 2018) and for experimental applications such as prediction of the electric field by solving the Poisson equation (Sato et al., 2019). In addition, one can examine the performance of the cloud microphysics schemes in the NICAM in comparison to more complex schemes such as a spectral bin cloud microphysics scheme or a Lagrangian particle model by using SCALE (e.g., Sato et al., 2015; 2018). This common usage of cloud microphysics is also found between ICON and COSMO and between MPAS and WRF. In addition, one can use common packages for cloud modeling to obtain widely used cloud microphysics schemes [e.g., Kinematic Driver (Shipway and Hill, 2012); and libcloudph++ (Arabas et al., 2015; Jaruga and Pawlowska, 2018)].

2. Cloud microphysics in the NICAM

A brief history of the development of cloud microphysics schemes and related processes is described in this section. The NICAM has various options for bulk cloud microphysics schemes that assume particle size distribution (PSD) as specific analytic functions. Single-moment bulk cloud microphysics schemes (SMBs) predict the total mass concentration, and double-moment bulk cloud microphysics schemes (DMBs) predict the total number concentration in addition to the total mass concentration to represent the time evolution of PSDs of hydrometeors. Spectral bin cloud microphysics schemes have not yet worked for global simulations with the NICAM because of the difficulty of tuning with their expensive computational cost. Single-moment bulk cloud microphysics schemes are widely used for GCRMs because of their simplicity and cheaper computational cost. Table 3 summarizes the cloud microphysics schemes used in the DYAMOND GCRMs. Most cloud microphysics in the DYAMOND GCRMs have not yet been comprehensively evaluated for global simulations and some GCRMs have individually started to analyze elemental variables such as surface precipitation (e.g., Arnold et al., 2020; Dueben et al., 2020; Hohenegger et al. 2020). Therefore, performances of cloud microphysics in GCRMs other than NICAM have not yet been sufficiently documented. Hereafter we focus on cloud microphysics in NICAM.

Thermodynamics in cloud microphysics schemes are modified to match the NICAM. In particular, the total air density and the moist internal energy are exactly conserved in common procedures such as diagnosis of the saturated vapor pressure (see Satoh 2003 and Satoh et al., 2008a, for details). Gravitational sedimentation is commonly solved using a semi-Lagrangian scheme, which is conservative and positive definite (Xiao et al. 2003).

2.1. Single-moment bulk cloud microphysics scheme with five water categories

The NICAM team began realistical global cloud resolving simulations with a SMB with five water categories proposed by Grabowski (1998) (hereafter G98). This scheme predicts the specific water content of vapor, cloud water and rain (*qv*, *qc*, and *qr*, respectively) and diagnoses the specific water content of cloud ice and snow (*qi* and *qs*, respectively) by using temperature. The concept of G98 is to represent different latent heat between the ice phase and liquid phase (e.g., latent heat of vaporization Lv = 2.50e6 J kg^{-1} and latent heat of sublimation Ls = 2.83e6 J kg^{-1} at atmospheric temperature Ta = 273 K) and different terminal velocities between rain and snow (typically 3 to 7 m s^{-1} for rain and at most 1 m s^{-1} for snow in G98), although G98 cannot deal with melting and freezing due to the diagnosis. The diagnosis of ice categories is also used in other SMBs for weather prediction (e.g., Lopez, 2002; Khairoutdinov and Randall, 2003). As G98 is simple, there are only four tunable processes: auto-conversion and accretion of cloud water, auto-conversion and accretion of cloud ice, terminal velocity of rain, and terminal velocity of snow. Therefore, radiative fluxes of G98 were optimized by modifying the terminal velocity of snow (Iga et al., 2007) with the assumed effective radii of cloud ice and snow as 40 μm.

These five category types of cloud microphysics do not separate dense ice (graupel and hail) and light ice (snow) and hence do not capture differences in dominant growth processes between convective precipitation systems (riming and accretion) and stratiform precipitation systems (aggregation). In addition, the diagnosis of cloud ice and snow results in the absence of the melting layer (freezing layer). These characteristics are apparently observed in the vertical structure of radar echo by reference to satellite observations (Satoh et al., 2008b; Masunaga et al., 2008). Nevertheless, G98 sufficiently worked to capture deep convective systems over the tropics, such as tropical cyclones (e.g., Fudeyasu et al., 2008; Oouchi et al., 2009; Taniguchi et al., 2010; Yanase et al., 2010) and MJO (e.g., Miura et al., 2007; Nasuno et al., 2009; Taniguchi et al., 2010; Miyakawa et al., 2012).

2.2. Single-moment bulk cloud microphysics scheme with six water categories

The NICAM contains a SMB with six water categories referred to as NSW6 (NICAM single-moment bulk cloud microphysics with six water categories). This scheme predicts the specific water content of vapor, cloud water, rain, cloud ice, snow, and graupel (*qv*, *qc*, *qr*, *qi*, *qs*, and *qg*, respectively). Tomita (2008b) simplified a six-category type based on Lin et al. (1983) and Rutledge and Hobbs (1984) by omitting hail production and replacing the interaction between cloud water and cloud ice with a saturation adjustment to reduce the computational cost. These simplifications allow NSW6 to be similar to G98 except for microphysical processes involving graupel. Kodama et al. (2012) optimized the longwave CRF by modifying the timescale of the auto-conversion of cloud ice to snow. The 2012 version of the NICAM (NICAM.12), which was generally used for published works from 2012 to 2019 [e.g., an atmospheric model intercomparison project (AMIP) type experiment (Kodama et al., 2015)], was established based on this version of NSW6. The reproducibility and forecasting skills for tropical cyclones, MJO, and boreal-summer intra-seasonal oscillation improved by using NSW6 (e.g., Miyakawa et al., 2014; Miyakawa and Kikuchi, 2018; Nakano et al., 2015; 2017; Nakano and Kikuchi, 2019; Kikuchi et al., 2017).

Major revision of microphysical processes involving rain, snow, and graupel in NSW6 was accomplished by Roh and Satoh (2014) using the stretched NICAM by reference to TRMM satellite observations. The objectives of the revisions were to capture the vertical structure of convective systems over the tropics and to separately capture different types of cloud systems. Specifically, a rescaled bimodal shape of snow particle size distribution and variable bulk snow density were assumed following Field et al. (2005) and Thompson et al. (2008); excessive graupel was suppressed by switching off accretion of snow and cloud ice by graupel following Lang et al. (2007) and by changing the intercept parameter of the graupel particle size distribution following

Gilmore et al. (2004); and a variable formulation of the intercept parameter of the rain particle size distribution was incorporated to represent stratiform rain systems following Zhang et al. (2008). In addition, the saturation adjustment for cloud ice was replaced with vapor deposition and sublimation to solve well-known issues (e.g., Gettelman et al., 2010). These modifications significantly increased cloud ice and snow globally, and decreased graupel in the mid-latitudes. As a result, vertical profiles of ice water content from this version of NSW6 more closely approximated the satellite observations compared with those from NSW6 in NICAM.12 (Figure 6a-6c).

Finally, the cloud radiative forcing was successfully improved by explicitly coupling cloud microphysics and radiative transfer using the coupling procedure provided by Seiki et al. (2014) [Kodama et al., (2021); details are described in Section 2.4]. The 2016 version of the NICAM (NICAM.16), which has been used for published works after 2020 [e.g., production for HighResMIP (Kodama et al., 2021)], was established based on this version of NSW6.

The next version of NSW6 is now under development. Global simulations with NSW6 were found to suffer from the underestimation bias in low-level mixed-phase clouds in the midlatitudes to polar regions (Kodama et al., 2015; Hashino et al., 2016; Roh et al., 2020). Recently, Seiki and Roh (2020) improved the bias by replacing rain-production terms with the auto-conversion and accretion parameterizations by Khairoutdinov and Kogan (2000), an ice nucleation term with heterogeneous ice nucleation by Phillips et al. (2007), and suppressing vapor deposition and riming with reasonable thresholds. These modifications successfully prolonged the lifetime of mixed-phase low-level clouds by sustaining supercooled liquid water. A similar approach was used to improve low-level mixed-phase clouds by Furtado and Field (2017) with UM and Engdahl et al.

(2020) with AROME. The improvements were made using a single-column model, and hence, the new settings are now tested for long-term global simulations.

2.3. Double-moment bulk cloud microphysics scheme with six water categories

The NICAM contains a DMB with six water categories referred to as NDW6 (NICAM double-moment bulk cloud microphysics with six water categories). This scheme predicts the specific water content of vapor, cloud water, rain, cloud ice, snow, and graupel (*qv*, *qc*, *qr*, *qi*, *qs*, and *qg*, respectively) and the number concentration of each hydrometeor category (*nc*, *nr*, *ni*, *ns*, and *ng*, respectively). Seiki and Nakajima (2014) developed NDW6 based on Seifert and Beheng (2001; 2006) and Seifert (2008) (hereafter SB) with minor modifications (e.g., saturation adjustment of cloud water is replaced with condensation/evaporation). The SB scheme was evaluated in terms of surface precipitation but not for CRF (e.g., Seifert et al., 2006). As a result, large biases in outgoing longwave radiation at the top of the atmosphere (OLR) were found in global simulations with NDW6 (Figure 7a). This version of NDW6 is referred to as NDW6-SN14.

Seiki et al. (2014) elaborated ice modeling of NDW6 to improve the OLR biases originating from cirrus clouds: the heterogeneous ice nucleation scheme was replaced with the scheme based on Phillips et al. (2007), who referred to experimental data from field campaign observations by Demott et al. (2003); nonsphericity was incorporated into ice cloud microphysics assuming power-law relationships between the projected area and the particle mass and between the maximum dimension and the particle mass based on Mitchell (1996); and nonsphericity was incorporated into CRF based on Fu (1996) and Fu et al. (1998) (details are described in Section 2.4). These improvements were examined using a stretched NICAM by reference to in situ sonde observations. These modifications significantly improved the OLR biases in global simulations (Figure 7b). This version of NDW6 is referred to as NDW6-S14.

Seiki et al. (2015b) incorporated homogeneous ice nucleation into NDW6 based on Ren and McKenzie (2005) and Kärcher et al. (2006) to alleviate the underestimation bias in *ni* found by Seiki et al. (2014). In addition, the lower limit of the sticking efficiency was incorporated into ice aggregation because of a lack of experimental evidence at atmospheric temperatures colder than 253 K (Pruppacher and Klett, 1997). Uncertainties in the sticking efficiency were also discussed in Li et al. (2010). The impacts of the former change on OLR, which caused a significant decrease in OLR, were cancelled by the latter change, and thus, OLR did not significantly change in this latest version of NDW6 (Figure 7c). This version of NDW6 is referred to as NDW6-S15 and is implemented in NICAM.16. Ice water content from NDW6-S15 (NDW6 in NICAM.16) is a little bit underestimated, especially just above the freezing level (Figure 6a, 6d). Ice cloud microphysics in winter snowfall systems, in which interaction between cloud ice and snow dominated, are well represented by NDW6-S15 (Kondo et al., 2021), and hence, hydrometeor interactions between rain and graupel might be problematic. The bias in IWC and higher OLR over the tropics indicate that NDW6-S15 underestimate high-density ice (graupel) originated by convection.

The remaining biases in OLR were found to originate from the spatial resolution of the NICAM (Seiki et al., 2015b). Specifically, negative biases in OLR over the subtropical regions originated from insufficient vertical resolution for capturing thin cirrus layers, and positive biases in OLR over the tropics originated from insufficient horizontal resolution for capturing convective organization. Both biases clearly diminish as vertical layers increase (Figure 7d) and horizontal resolution increases (Figure 7e). Therefore, NDW6 does not need extensive tuning in terms of CRF. In the current status of the NICAM (e.g., Stevens et al., 2019), 78 vertical layers with a layer thickness of approximately 400 m in the free troposphere are used as a standard setting based on Seiki et al. (2015b).

2.4. Coupling procedure between cloud microphysics and radiative transfer

Cloud radiative forcing significantly differs based on the assumption of single-scattering properties (SSPs). For example, the nonsphericity of ice particles had an impact on outgoing solar radiation at the top of the atmosphere (OSR) by more than 100 W m^{-2} in a cirrus case [Seiki et al. (2014) and see Figure 8], and an invalid assumption of effective radii as a globally fixed value, which was used in NICAM.12, caused nonnegligible biases in both OLR and OSR [10 to 20 W m^{-2} from the tropics to mid-latitudes (Seiki et al., 2015a; Kodama et al., 2021), and see Figure 9]. These biases in CRF are comparable to or greater than the biases originating from uncertainties in cloud microphysics. Thus, it is better to optimize cloud microphysics after explicitly coupling cloud microphysics and radiative transfer. Importance of cloud-radiation coupling for numerical weather prediction was discussed also using other models (e.g., Thompson et al., 2016; Matsui et al., 2018).

Cloud microphysics is coupled with radiative transfer through SSPs of hydrometeors. The single-scattering properties strongly depend on the ratio of particle size to wavelength (e.g., Hansen and Travis, 1974); hence, SSPs are generally prepared as a look-up table of effective radii at each wavelength band in radiative transfer models. In the NICAM, radiative transfer is calculated with a broadband model mstrnX (Sekiguchi and Nakajima, 2008), which requires the extinction coefficient per unit volume of hydrometeor particles, scattering coefficients per unit volume of the hydrometeor particles, and moments of the phase function (asymmetry factor and truncation factor) used for the delta two-stream approximation (Nakajima et al., 2000). Thus, input data to the coupling procedure are the volume of the hydrometeors and effective radii derived from cloud microphysics.

In the latest version of the NICAM [NICAM.16 (Kodama et al., 2021)], nonsphericity is newly assumed for the SSP of ice hydrometeors because nonsphericity has been found to have a strong impact on both shortwave radiation (e.g., Pollack and Cuzzi, 1980; Takano and Liou, 1989, 1995; Stephens et al., 1990; Macke, 1993; Yang and Liou, 1995; MacFarquhar et al., 1999; Fu, 2007) and longwave radiation (e.g., Ackerman and Stephens, 1987; Mitchell and Arnott, 1994; Mitchell et al., 1996). A nonspherical database provided by Fu (1996) and Fu et al. (1998) was compiled for the wavelength bands used in mstrnX, and then the SSP look-up table was prepared in the range of effective radii from 1 μm to 1 mm (Seiki et al., 2014). One may choose another nonspherical SSP database that has options to choose specific shapes, such as Yang et al. (2013) [e.g., NU-WRF (Matsui et al., 2018); MIROC (Tatabe et al., 2019)]. Seiki et al. (2014) found that the dependence of the asymmetry factor on the effective radii, which vary by particle shape, is key to determining the cloud albedo of cirrus, as shown in Figure 8.

The definition of the effective radii of nonspherical ice particles is another issue for nonspherical modeling because the "effective" size is not obvious for irregular shapes in contrast to a sphere. Therefore, the concept of "effective distance", which is defined by the ratio of the volume to the projected area, was proposed by Mitchell and Arnott (1994). The concept was confirmed by Fu (1998) by reference to light scattering calculated using the finite difference time domain method. Following equations (3.11) in Fu (1996) or (2.5) in Fu et al. (1998), the effective radii of ice hydrometeors *re* are defined as follows:

$$re_j \equiv \frac{3}{4\rho_{\mathrm{ice}}} \frac{\rho_a q_j}{\int_0^\infty A_j(x) f_j(x) dx}, \ (j = i, s, g) \qquad (1)$$

where ρ_a is the air density, ρ_{ice} = 916.7 kg m^{-3} is the ice density, A is the projected area, x is the particle mass, and f is the particle mass distribution.

Equation (1) is analytically integrated with the power-law relationship between A and x for each hydrometeor category ($A = \gamma x^{\sigma}$). In NDW6, particle models compiled by Mitchell (1996) are used: hexagonal columns for cloud ice, assemblages of planar polycrystals in cirrus clouds for snow, and lump graupel for graupel (Seiki et al., 2014). In NSW6, sponge-like spherical ice is assumed for cloud ice and graupel, and two-dimensional fractal shapes (e.g., $A \propto D^2$ and $x \propto D^2$) are assumed for snow (Roh and Satoh, 2014; Kodama et al., 2021). Thus, the effective radii of snow are assumed to be constant (res = 125 μm). The cloud radiative forcing of NSW6 significantly decreases with this assumption for the effective radii (see NSW6, NSW6-Mie, and NSW6-Mie-ReFIX in Figure 9).

2.5. Impact of precipitating hydrometeors on the radiation budget

The impacts of precipitating hydrometeors on CRF can be examined by means of the new look-up table. CMIP3 and CMIP5 GCMs commonly have large biases in CRF over the ITCZ region (Li et al., 2013). Past studies suggested that these biases originated from the lack of CRF by precipitating hydrometeors in conventional GCMs (e.g., Waliser et al., 2011; Li et al., 2014; 2016). Chen et al. (2018) analyzed the role of precipitating hydrometeors by using an off-line radiation model with NICAM results and found that the layering structure of snow underlying cloud ice had impacts on OLR over the tropics and storm-track regions up to 2 W m^{-2} Similarly, snow has strong impacts on OSR up to 3 W m^{-2} in the summer hemisphere.

The degree of the possible biases related to precipitating hydrometeors could differ by model (Matsui et al., 2018; Michibata et al. 2019), but it is evident that the systematic effect of precipitating hydrometeors on radiation is nonnegligible in terms of climate projection. Recently, precipitating hydrometeors have been found to have important indirect effects on aerosol-cloud interactions (so-called buffering effects) with MIROC (Michibata and Suzuki, 2020; Michibata et al., 2020).

2.6. Differences between SMBs and DMBs

Representation of changing number concentrations is essential for representing realistic cloud growth. Figure 10 shows the typical cloud microphysical processes used in SMBs and DMBs. It is clearly seen that most processes change the number concentrations in addition to the mass concentration. SMBs generally deal with this issue by assuming PSD functions (qj and nj relationship) based on observations. Thus, the performance of SMBs relies on the diagnosis technique of PSDs.

The complexity and dependence of cloud microphysical processes inevitably differ between DMBs and SMBs regardless of the diagnosis technique of PSDs. For example, condensation increases only qr, but evaporation decreases both qr and nr (e.g., Morrison and Grabowski, 2008). In addition, larger liquid droplets are more likely to freeze [heterogeneous and homogeneous freezing of supercooled liquid water (e.g., Bigg 1953; Fukuta and Schaller, 1982; Khvorostyanov and Curry, 2009)], but smaller ice crystals more easily melt away. This kind of asymmetry between a pair of growth and decay processes (see the pairs of arrows in Figure 10) induces hysteresis, and hence, cannot be represented by SMBs. As a result, SMBs necessarily simplify these processes and modify the balance among the hydrometeor interactions. The ratio of the tendency between the mass concentration and the number concentration [$(\partial qj/\partial t)/(\partial nj/\partial t)$] differs by process, and hence, these inconsistencies in the tendency result in bias in the mean particle mass $\overline{xj} = (\rho_a qj/nj)$ or mean particle diameter $\overline{Dj}$ when using SMBs.

Biases in the mean particle mass (diameter) feedback to the performance of cloud microphysics schemes through the dependence of particle-growth equations (e.g., Igel et al., 2015;

Seiki et al., 2015; Seiki and Roh, 2020). The dependences of cloud-related processes on bulk cloud microphysical parameters are summarized in Table 4. For example, in collisional processes, the collisional cross section is proportional to the square of the particle diameter. In addition, in evaporation (sublimation) and condensation (deposition), vapor flux onto the particles is proportional to their surface area (square of the particle diameter). Moreover, terminal velocity, which is contained in many microphysical processes, is mostly determined by the particle diameter (Bohm, 1989; 1992; Mitchell, 1996). In terms of CRF, the extinction efficiency is represented as a function of the size parameter, and the extinction cross-section is proportional to the square of the particle radii as mentioned in Section 2.4. Thus, strong feedbacks of xj (or Dj) to cloud microphysics and CRF imply that cloud microphysics can potentially be evaluated by monitoring xj (or Dj) from observations. Specifically, optical sensors, which are sensitive to various moments of particle radii, are powerful tools to define the growth mode of clouds. Evaluation of cloud microphysics in the NICAM using satellite observations is described in Section 3.

3. Model evaluation using optical sensors

3.1 Sensitivity of optical sensors

There are two kinds of optical sensors to observe clouds and precipitating hydrometeors. Passive sensors can observe the radiance from clouds and precipitation and have more spatial coverage than active sensors. Active sensors have a transmitter and a receiver and can detect the vertical profiles of clouds and precipitation, but they have a smaller swath than passive sensors. Thus, the combined use of the two types of optical sensors can complementarily reveal the nature of cloud systems in detail. In addition, satellite sensors have different characteristics depending on the wavelength of the sensor. The major satellites used for model evaluation are summarized in Table 5.

Visible (Vis) channels can observe optically thick clouds, and the observations are limited during daytime. Visible channels have been widely used for estimating warm-cloud optical properties [e.g., optical thickness and effective radius (Nakajima and King, 1990)]. The infrared (IR) channels, especially from 10 to 13 μm wavelength, are sensitive to cloud-top temperature and can detect even very thin cirrus clouds. Infrared channels have also been utilized for detecting cloud optical properties (e.g., Iwabuchi et al., 2016; 2018). The combined use of VIS and IR channels has been used for categorizing cloud systems using the cloud optical thickness and cloud-top temperature [e.g., the International Satellite Cloud Climatology Project cloud category proposed by Rossow and Schiffer (1999)].

Passive microwaves are sensitive to precipitating hydrometeors. Low frequency microwaves (<20 GHz) are used to capture the emissions from the path-integrated water content of rain over the ocean. On the other hand, high-frequency microwaves (>80 GHz) are used for capturing scattering signals of large ice particles such as snow and graupel over land and ocean. These various frequencies of microwave observations enable us to obtain integrated column information about precipitating hydrometeors, particularly in deep convective systems.

Active microwave observations referred to as radar are now available at 94 GHz/3.2 mm (so-called cloud radar) and at 13.6 GHz/2.2 cm and 35.5 GHz/8.5 mm (so-called precipitation radar). In addition, lidar with wavelengths of 532 and 1064 nm is available. In general, the backscattering coefficient rapidly decreases at size parameters ($2\pi r/\lambda$) smaller than 1 according to Mie theory, and hence, the detectable particle size differs by the frequency/wavelength. In addition, too strong backscattering results in strong attenuation of return signals. The Cloud Profilin Radar (CPR) on

CloudSat can clearly detect vertical profiles of nonprecipitating and light-precipitating clouds and slightly detect intense precipitating clouds due to attenuation (Stephens et al. 2008). CALIOP on CALIPSO can detect optical thin cirrus and the thermodynamic phase of clouds using the depolarization ratio (Winker et al., 2009). The precipitation radar on TRMM and GPM core satellites can detect the vertical profiles of precipitating clouds but cannot detect nonprecipitating clouds (Hou et al., 2014). Even when using GPM satellite observations, it is difficult to accurately capture extreme precipitation systems such as hail storms due to strong attenuation, multiple scattering, and spatial inhomogeneity (e.g., Mroz et al., 2018). Thus, the combined use of lidar, cloud radar, and precipitation radar enables us to integrate an understanding of cloud organization from shallow clouds to deep convective clouds.

Consistency in the assumption of cloud microphysics between a model and a satellite retrieval algorithm is an important issue. For example, so-called *Z*-*R* and *k*-*Z* relationships, which implicitly assume a PSD, are used in the retrieval of precipitation flux using PR (Iguchi et al., 2009). However, the assumptions are generally not used in cloud microphysics schemes. In contrast, some cloud microphysics schemes (e.g., Milbrandt and Yau, 2005; Seifert, 2008) have more degrees of freedom to represent PSDs than these retrieval algorithms. In addition, satellite products inherently suffer from contamination: a product consists of a major portion of an objective physical parameter and a minor portion of other physical parameters. For example, in the past, it was difficult to separate cloud water paths from liquid water paths in the retrieval of microwaves (Elsaesser et al., 2017). It is still difficult to retrieve snowfall over sea ice or land ice using microwaves. Thus, we need to understand the characteristics of optical sensors in comparing model results to satellite observations.

Satellite simulators solve the issue by directly comparing emulated satellite signals from model results to level 1 satellite data (see Figure 4). This comparison method enables us to share microphysical assumptions between a model and satellite simulators. On the other hand, it is difficult to interpret radiance-based comparisons to find biases in cloud microphysics schemes. Current progress in analytical techniques using satellite simulators is described in the following sections. Note that the accuracy of emulated satellite signals depends on the forward radiative transfer calculation method used in a satellite simulator and hence it needs to be examined, especially in data assimilation (e.g., Okamoto, 2017; Okamoto et al., 2019). At present, various satellite simulators (optical sensor simulators) have been developed [e.g., COSP (Bodas-Salcedo et al., 2011; Swales et al., 2018), CRTM (Chen et al., 2008; Ding et al., 2011), ECSIM (Voor et al., 2007; Reverdy et al., 2015), Joint-Simulator (Hashino et al., 2013; Satoh et al., 2016), POLARRIS (Matsui et al., 2019), RTTOV (Saunders et al., 2018), SDSU (Masunaga et al. 2010), and Goddard-SDSU (Matsui et al., 2013; 2014)].

3.2 Evaluation of the size distribution of cloud systems

The horizontal resolution of GCRMs that is comparable to satellite observations is a milestone for the evaluation of cloud representation. For example, infrared channels on a geostationary satellite MTSAT, which were frequently used for capturing cirrus clouds (e.g., Inoue, 1987; Mapes and Houze, 1993), had a footprint size of approximately 4 km. Thus, cloud size can be newly evaluated by the advent of GCRMs, whereas cloud fraction is derived from macrophysics in conventional GCMs (e.g., Watanabe et al., 2009; Park et al., 2014). Horizontal inhomogeneity in cloud distribution develops as the cloud regime changes (Kawai and Teixeira, 2010; 2012), and hence, explicit representation of cloud systems is the unique approach of GCRMs. One can use

GCRMs' cloud distribution to evaluate sub-grid inhomogeneity assumed in conventional GCMs (e.g., Watanabe et al., 2009; Hotta et al., 2020).

The split-window technique, which uses brightness temperature of 11 μm and 12 μm, is generally applied to classify high clouds (e.g., Inoue, 1987; Liou, 2002). In addition, OLR or IWP can also be applicable to classifying relatively thick high clouds over the subtropics to tropics (e.g., Inoue and Ackerman, 2002; Inoue et al., 2006; 2008; 2010). The size distribution of high clouds derived from MTSAT was well reproduced by the NICAM with a horizontal resolution of 3.5 km (Inoue et al., 2008), and smaller clouds are likely to be underestimated as the horizontal resolution decreases to 7 km or 14 km (Inoue et al., 2008; Noda et al., 2014). Recently, CloudSat and CALPSO satellite observations have also been available for estimating cloud sizes with the categorization of cloud types (e.g., Seiki et al., 2019)

A new issue arises from the NICAM simulations: formation processes of smaller high clouds, which are not well represented in GCRMs or conventional GCMs. Even small clouds make a large contribution to the total CRF over the tropics due to their large population. This is true for the response of high clouds to global warming (Noda et al., 2014; 2016). Simulated results from the NICAM indicated that the response of high clouds with cloud radii smaller than 50 km to global warming significantly differs from the response with cloud radii larger than 100 km (Noda et al., 2014; 2016). In particular, the robustness of the fixed anvil temperature (FAT) hypothesis (Hartmann and Larson, 2002; Zelinka and Hartmann, 2010) is found to depend on cloud sizes (Noda et al., 2016). Figure 11 shows an example of the different responses of high clouds to global warming by cloud size. The OLR change under global warming attributes to a change in emissivity, a change in cloud top temperature, and a change in clear sky radiation. A reduction in the emissivity is found to be dominant in the response of smaller thin cirrus whereas an increase in the cloud top temperature is dominant in the response of larger clouds as was established by conventional GCMs with the FAT hypothesis. Moreover, Noda et al. (2019) argued that convective self-aggregation (e.g., Wing et al., 2017) does not sufficiently work to reduce CRF over the tropics from cloud-size analysis using global high-resolution simulations. Note that cirrus clouds contain very small-scale structures, such as uncinus and streak structures (e.g., Heymsfield, 1975), which can be captured by using large eddy simulation models (e.g., Sölch and Kärcher, 2011). Thus, the response of smaller cirrus formations to climate change is an underdeveloped issue.

3.3 Evaluation of vertical structure of cloud systems

The vertical structures of precipitating cloud systems from NICAM simulations have been evaluated using active sensors: TRMM-PR, CloudSat-CPR, and CALIPSO-CALIOP. In particular, TRMM-PR has a footprint of 5 km, and hence, rain microphysics is directly evaluated without assuming subgrid variability. TRMM-PR enables us to evaluate the difference in the vertical structure of precipitation flux between convective cloud systems and stratiform cloud systems (Takayabu, 2002; Satoh et al., 2008b). Here, the physical parameter "precipitation flux" has inconsistency in the terminal velocities of precipitating hydrometeors between the NICAM and TRMM algorithms. Therefore, the evaluation of models using retrieved products is not an apple-to-apple comparison. After Satoh et al. (2008b), we generally used satellite simulators to evaluate the vertical structures of cloud systems.

The contoured frequency by altitude diagram (CFAD), which illustrates the probability density function of the radar reflectivity at each vertical level, is frequently used for evaluating the vertical structure of cloud systems (e.g., Marchand et al., 2009; Matsui et al., 2016). Atmospheric temperature is also used as the vertical axis of the CFAD to capture differences in the freezing level and the tropopause level by latitude. The shape of the CFAD is sensitive to cloud microphysics or assumptions of particle shapes (e.g., Masunaga et al., 2008; Satoh et al., 2010; Hashino et al., 2013). In addition to the CFAD, a cloud-top beta-temperature radar-conditioned diagram was also proposed by Hashino et al. (2013) to analyze the relationship between ice water content and ice effective radii. The sensitivity of cloud microphysics to the CFAD was clearly observed within only 7 days from NICAM simulations (e.g., Satoh et al., 2010; Roh and Satoh, 2014; Roh et al., 2017). Therefore, we did not require longer simulations (e.g., seasonal to annual simulations) to evaluate cloud microphysics schemes using satellite observations.

Nakajima et al. (2010) proposed a contoured frequency by using the optical depth diagram (CFODD), which uses the cloud optical depth from the cloud top (COD) as the vertical axis, by using Aqua and CloudSat satellite observations. This alternative diagram successfully captures the transition of the droplet growth mode from condensational growth to collisional growth by means of the characteristics that the COD is directly related to the liquid water path and effective radius (Suzuki et al., 2010; 2011). Auto-conversion and accretion in warm clouds have been globally evaluated by using the CFODD (Suzuki et al., 2013; 2015). Kuba et al. (2015) analyzed the detectable cloud microphysics in the CFODD using a spectral bin cloud microphysics scheme.

In terms of the evaluation of cloud microphysics schemes in the NICAM, Kuba et al. (2020) found that the CFODD is sensitive to the shape parameters assumed in the PSD function from the comparison between NDW6 and a spectral bin cloud microphysics scheme. The contoured frequency by optical depth diagram can also be utilized for the evaluation of vertical structures of cirrus clouds by combining CloudSat and CALIPSO satellite observations (Seiki et al., 2015b). One can easily analyze the CFODD for cirrus clouds by using the EarthCARE Research Product

Monitor (https://www.eorc.jaxa.jp/EARTHCARE/research_product/ecare_monitor.html) provided by the Japan Aerospace Exploration Agency.

3.4 Evaluation of cloud organization

Masunaga et al. (2005) proposed an analytical method to categorize cloud systems using cloud-top temperature and radar echo top height from TRMM satellite observations (see Figure 12a). The categorized cloud systems were found to be closely related to large scale circulation (Masunaga and Kumerrow, 2006). Thus, the cloud-top and rain-top diagrams can be used for the evaluation of cloud organization in GCRMs (e.g., Masunaga et al., 2008). Recently, Roh and Satoh (2018) proposed a method to extend the observable coverage by using the polarization-corrected brightness temperature at 89 GHz (PCT89) instead of radar echo to detect the rain-top height.

Matsui et al. (2009) further established a method to systematically evaluate the cloud microphysics scheme [Triple-Sensor Three-Step Evaluation Framework (T3EF)]: comparisons of 1) the cloud-top and rain-top diagram from IR radiance and radar echo, 2) CFAD from radar echo, and 3) cumulative probability distribution of PCT85 from a high-frequency microwave imager. T3EF clearly revealed problematic processes in a cloud microphysics scheme (Li et al., 2010). NSW6 was successfully revised by using T3EF (Roh and Satoh, 2014; Roh et al., 2017, and see Figure 12).

3.5 Evaluation of hydrometeor classes

Global observations of the depolarization ratio from CALIOP enable us to discriminate the thermodynamic phase of hydrometeors and the shape of ice particles (Hu et al., 2009; 2010; Yoshida et al., 2010; Saito et al., 2016). Recently, the GCM-Oriented CALIPSO Cloud Product

(CALIPSO-GOCCP) was released for easy comparison between models and CALIPSO satellite observations (Chepfer et al., 2010). One can evaluate the frequency of occurrence of liquid and ice clouds to evaluate the freezing process in cloud microphysics schemes using GOCCP (Cesana and Chepfer, 2012). The GCM results were more consistently evaluated by satellite observations with the aid of a satellite simulator (Cesana and Chepfer, 2013; Cesana et al., 2015). Note that hydrometeor classification using CALIOP is limited to nonprecipitating particles near the cloud top due to the limitation of attenuation (e.g., Hagihara et al., 2014).

Roh et al. (2020) developed a single parameterization to diagnose the depolarization ratio from the backscattering coefficient and then evaluated NSW6 and NDW6 using the hydrometeor discrimination method proposed by Yoshida et al. (2010) (see Figure 13). NSW6 underestimated mixed-phase low-level clouds over the Southern Ocean due to poor representation of supercooled liquid water, whereas NDW6 reproduced mixed-phase low-level clouds well. The bias in NSW6 was successfully alleviated by Seiki and Roh (2020), as described in Section 2.2.

Large particles can be evaluated using cloud radar and precipitation radar. Kikuchi et al. (2017) proposed a hydrometeor classification method using only CPR radar echo and atmospheric temperature based on the CloudsSat-CALIPSO combined dataset. Recently, hydrometeor classification using GPM-DPR satellite observations has been developed. Snow, rain, and mixed-phase clouds are categorized by using Ku-band radar echo and the dual-frequency ratio (Liao and Meneghini, 2011; 2016; Liao et al., 2020). In addition, the hail detection method was newly proposed by Seiki (2021). Future work should evaluate the microphysics of precipitating hydrometeors using CPR and DPR.

3.6 Challenging issues in satellite simulators

A challenging new satellite project is now underway: The Earth Clouds, Aerosol and Radiation Explorer (EarthCARE, Illingworth et al. 2015) satellite, which is a joint mission by the European Space and Japanese Aerospace Exploration Agencies. The EarthCARE satellite has multiple passive and active sensors (Figure 14): Cloud Profiling Radar (CPR), ATmospheric LIDar (ATLID), Multi Spectral Imager (MSI), and Broad Band Radiometer (BBR). The CPR on EarthCARE has a Doppler capability to provide information on the terminal velocity of rain and ice and convective motions. Multiple sensors have synergy to understand the interaction between clouds and aerosols and to provide new insights into cloud microphysics related to vertical motion for evaluating GCRMs. It is confirmed that the EarthCARE satellite will be launched in 2023.

Global cloud resolving models can be used for the observing system simulation experiments (OSSE) to evaluate retrieval algorithms for optical sensors at the planning stage of new satellite projects. A NICAM with a Joint-Simulator was used to create the EarthCARE-like radiances to estimate the accuracy of the retrieved Doppler velocity. In particular, OSSE using the NICAM were helpful to investigate the noise of Doppler velocity of CPR depending on the instrument setting (pulse repetition frequency) before the launch (Hagihara et al., 2021).

There are ongoing challenging issues in the development of satellite simulators. First, satellite simulators will be utilized to estimate a range of uncertainties from the observations, as was done by Hagihara et al. (2021). Second, the sensitivity of the nonspherical assumption to cloud representation is also a challenging issue. Several satellite simulators consider the nonspherical shapes of ice from a database using the discrete dipole approximation (DDA) and T-matrix (e.g., Hashino et al. 2013; Matsui et al. 2019). In addition, the application of depolarization provides insight into nonspherical modeling (Matsui et al., 2019). Finally, the 3D radiation of clouds is a long-standing issue (e.g., Benner and Evans 2001; Okata et al. 2017), whereas radiative transfer is generally calculated in the vertical dimension. Three-dimensional scattering from cloud sides will be nonnegligible when the horizontal resolution of GCRMs increases to finer than 1 km (global LES). Monte Carlo simulations or other 3D techniques will be introduced into satellite simulators.

3.7 Ground validation for satellites and models

The ULTra-sIte for Measuring Atmosphere of Tokyo metropolitan Environment (ULTIMATE) project has started to validate satellite observations and cloud microphysics schemes in numerical models by using intensive ground observation data in Japan. The ULTIMATE project obtained several active sensors to detect the vertical distributions of clouds and precipitation. For example, polarimetric Doppler radars were set to derive information about the size distributions, hydrometeor types, and terminal velocity of hydrometeors. In addition, several weather radars (c-band polarimetric radars, x-band phased array polarimetric radar, and w-band cloud radar) work in cooperation around the Tokyo metropolitan area (Figure 15). Wind profiler network and data acquisition system (WINDAS, Ishihara et al. 2006) data are also available to observe the vertical profiles of wind. To utilize these ground radar networks, the POLArimetric Radar Retrieval and Instrument Simulator (POLARRIS, Matsui et al. 2019) is newly introduced into the Joint-Simulator. The synergy of intensive ground, remote-sensing observations and satellite data will contribute to the understanding of microphysical processes and improvements of microphysics in GCRMs.

4. Summary

This chapter reviewed the cloud microphysics in GCRMs and the way to improve cloud microphysics. From the twenty-year history of NICAM development, we recognized that the combined use of multi-optical sensors enables us to constrain uncertain processes in cloud microphysics without artificial tuning. As a result, cloud microphysics schemes used in the NICAM naturally represent cloud systems, and hence, the radiative budget is well balanced with little optimization. On the other hand, some cloud systems have not yet been evaluated because of the diversity of cloud systems in Earth and the limited sensitivity of spaceborne optical sensors. The evaluation method using satellite simulators is underdeveloped, and new satellites will be continuously planned and launched. In addition, intensive ground observation systems and satellite observations are complementary to each other. Thus, a new frontier for cloud microphysics development is still spreading toward the future.

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Figure Captions and Tables

Figure 1. Typical spatiotemporal scales of some examples of weather and climate phenomena. The numerical weather prediction model (NWP), general circulation model (GCM), and global cloud resolving model (GCRM) cover different but partially overlapping scales.

Figure 2. Cloud images calculated by the GCRMs in the DYAMOND project and from the geostationary satellite Himawari-8 (After Fig. 2 in Stevens et al., 2019). From left to right: IFS with a horizontal resolution of 4 km, 9 km, and NICAM (top row); ARPEGE-NH, Himawari-8, and ICON (second row); FV3, GEOS5, and UM (third row); and SAM and MPAS (bottom row).

Figure 3. Cloud images calculated by the NICAM with horizontal resolutions of 14 km, 3.5 km and 0.87 km (after Kajikawa et al., 2016). Zoom images of a tropical cyclone are shown in the right column.

Figure 4. A schematic image of the comparison between models and satellites using satellite simulators. From Masunaga et al. (2010), © American Meteorological Society. Used with permission.

Figure 5. Sample images of (a) the default NICAM with the global quasi-uniform icosahedral grid system, (b) stretched NICAM, and (c) diamond NICAM (after Uchida et al., 2017, © American Meteorological Society. Used with permission.).

Figure 6. Comparison of the vertical profiles of annual mean ice water content (IWC) [mg m-3] from (a) CloudSat satellite observations [2B-CWC-RO product (Austin and Stephens 2001; Austin et al., 2009)], (b) NSW6 in NICAM.12, (c) NSW6 in NICAM.16, and NDW6 in NICAM.16. The solid lines represent 273-K isotherms. The global simulation data with horizontal resolution of 14 km and 38 vertical layers were provided by courtesy of C. Kodama and A. T. Noda.

Figure 7. Comparison of outgoing longwave radiation at the top of the atmosphere (OLR) from CERES satellite observations (solid lines with points) and NICAM simulations with various versions of NDW6 (solid lines) (after Satoh et al., 2018).

Figure 8. The vertical profiles of (a) downward shortwave radiation and (b) upward shortwave radiation (after Seiki et al., 2014). Thick lines indicate observations by radiometer sonde, thin solid lines indicate NICAM simulations using NDW6 with spherical SSPs, and thin dashed lines indicate NICAM simulations using NDW6 with nonspherical SSPs. The dashed rectangles indicate the location of a cirrus layer.

Figure 9. Comparison of (a) OLR and (b) outgoing shortwave radiation at the top of the atmosphere (OSR) from CERES satellite observations (solid lines) and NICAM.16 simulations with various settings of cloud and radiation coupling. NSW6 uses full coupling between cloud and radiation (dashed lines), NSW6-Mie assumes variable effective radii but spherical SSPs (long dashed short dashed lines), and NSW6-Mie-ReFIX assumes constant effective radii and spherical SSPs (dotted lines). The global simulation data were provided by courtesy of C. Kodama.

Figure 10. Cloud microphysical processes and cloud interaction among water classes (after Satoh et al., 2018). Solid lines indicate the processes that change the number and mass concentration of hydrometeors, while dashed lines indicate the processes that change only the mass concentration of hydrometeors. Hom/het indicates homogeneous/heterogeneous, respectively.

Figure 11. Breakdown of OLR change under global warming simulated by the NICAM (after Noda et al., 2016). An OLR change ΔF is attributed to a change in emissivity $\Delta\varepsilon$, a change in cloud-top temperature ΔT_{CT}, and a change in clear sky radiation ΔF^{CLR}. The breakdown was calculated by cloud size. Sum shows the summation of the contributions and the difference between ΔF and Sum indicates the error of the analysis.

Figure 12. The cloud-top and rain-top diagram using Ku-band radar echo and infrared brightness temperature from (a) satellite observations, (c) NSW6 in NICAM.12, and (e) NSW6 in NICAM.16. CFAD using Ku-band radar echo from (b) satellite observations, (d) NSW6 in

NICAM.12, and (f) NSW6 in NICAM.16. Here, simulated results were processed by a Joint-Simulator. From Roh et al. (2017), © American Meteorological Society. Used with permission.

Figure 13. Joint probability density function of the depolarization ratio δ and the ratio of attenuated backscattering coefficients for successive layers x from (a) satellite observations, (b) NSW6 in NICAM.16, and (c) NDW6. Low-level clouds behind a frontal cloud system were sampled over the Southern Ocean. Signals of supercooled liquid water are highlighted by circles. From Roh et al. (2020), © American Meteorological Society. Used with permission.

Figure 14. Observation geometry of the EarthCARE satellite (from https://directory.eoportal.org/web/eoportal/satellite-missions/e/earthcare).

Figure 15. Overview of the ground observations used in the ULTIMATE project around the Tokyo metropolitan area.

Table 1. List of acronyms of models, satellites, and instruments.

Table 2. List of GCRMs. Short names and references to the model-frameworks and recent settings are summarized.

Table 3. GCRMs and cloud microphysics used for the DYAMOND project. The subscripts v, c, r, i, s, and g indicate vapor, cloud water, rain, cloud ice, snow, and graupel categories, respectively.

Table 4. Dependences of cloud-related processes on bulk cloud microphysical parameters.

Table 5. Optical sensors and corresponding sensitive physical parameters.

1 Table 1. List of acronyms of models, satellites, and instruments.

Acronym	Long name
AMSR-E	Advanced Microwave Scanning Radiometer-EOS
AROME	Applications of Research to Operations at Mesoscale
ARPEGE-NH	Action de Recherche Petite Echelle Grande Echelle-NonHydrostatic version
CALIPSO/CALIOP	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations/Cloud-Aerosol LIdar with Orthogonal Polarization
CAM	Community Atmosphere Model
COSP	The cloud feedback model intercomparison project Observation Simulator Package
CPR	Cloud Profiling Radar
CRTM	Community Radiative Transfer Model
DFSM	Double Fourier Series Model
EarthCARE	Earth Clouds, Aerosols and Radiation Explorer
ECHAM	European Centre Hamburg model
ECSIM	EarthCARE Simulator
FV3	Finite-Volume Cubed-Sphere Dynamical Core
GCOM-C/SGLI	Global Change Observation Mission-Climate/ Second-generation Global Imager
GEOS	Goddard Earth Observing System
GOES	Geostationary Operational Environmental Satellite
GPM/DPR/GMI	Global Precipitation Measurement mission/Dual-frequency Precipitation Radar/GPM Microwave Imager
GRIST	Global-to-Regional Integrated forecast SysTem
ICON	ICOsahedral Non-hydrostatic atmospheric model
IFS	Integrated Forecasting System
MIROC	Model for Interdisciplinary Research on Climate
MODIS	Moderate Resolution Imaging Spectroradiometer
MSSG	Multi-Scale Simulator for the Geoenvironment
MPAS	Model for Prediction Across Scales
MTSAT	Multi-functional Transport Satellite
NICAM	Nonhydrostatic ICosahedral Atmospheric Model
NOAA/AVHRR	National Oceanic and Atmospheric Administration /Advanced Very High Resolution Radiometer
POLARRIS	POLArimetric Radar Retrieval and Instrument Simulator
RTTOV	Radiative Transfer for the TIROS Operational Vertical Sounder
SAM	System for Atmospheric Modeling
SCALE	Scalable Computing for Advanced Library and Environment
SDSU	Satellite Data Simulator Unit
TRMM/PR/VIRS/TMI	Tropical Rainfall Measuring Mission/Precipitation Radar/ Visible Infrared Scanner/ TRMM Microwave Imager
UM	Unified Model
WRF	Weather Research and Forecasting Model

Table 2. List of GCRMs. Short names and references to the model-frameworks and recent settings are summarized.

Model name	References
ARPEGE-NH	Bubnová et al. (1995) Voldoire et al. (2017)
DFSM	Yoshimura (2012)
FV3	Lin and Rood (1997) Lin (2004), Zhou et al. (2019)
GEOS5	Putman and Lin (2007), Putman and Suarez (2011), Arnold et al. (2020)
GRIST	Zhang et al. (2019; 2020)
ICON	Zängl et al. (2014), Hohenegger et al. (2020)
IFS	Malardel et al. (2016), Dueben et al. (2020), Wedi et al. (2020)
MSSG	Takahashi et al. (2008), Sasaki et al. (2016), Ohnishi et al. (2019)
MPAS	Skamarock et al. (2012)
NICAM	Satoh et al. (2014), Kodama et al. (2021)
SAM	Khairoutdinov and Randall (2003), Satoh et al. (2019)
UM	Wood et al. (2014), Walters et al. (2019)

Table 3. GCRMs and cloud microphysics used for the DYAMOND project. The subscripts v, c, r, i, s, and g indicate vapor, cloud water, rain, cloud ice, snow, and graupel categories, respectively.

Model name	Cloud microphysics schemes
ARPAGE-NH	SMB with five categories (v, c, r, i, and s) Roehrig et al. (2020)
FV3	SMB with six categories (v, c, r, i, s, and g) Lin et al. (1983), Zhou et al. (2019)
GEOS	SMB with six categories (v, c, r, i, s, and g) Lin et al. (1983), Zhou et al. (2019)
ICON	SMB with six categories (v, c, r, i, s, and g) Lin et al. (1983), Baldauf et al. (2011)
IFS	SMB with five categories (v, c, r, i, and s) Forbes et al. (2011)
MPAS	Hybrid of SMB and DMB with six categories [v, c, r, i, s, and g (the number concentrations of rain and cloud ice are predicted with prescribed aerosols)] Thompson et al. (2008) modified for WRF 3.8.1.
NICAM	SMB with six categories (v, c, r, i, s, and g) Lin et al. (1983), Tomita (2008b), Roh and Satoh (2014)
SAM	SMB with six categories [v, c, r, i, s, and g (ice categories are diagnosed)] Khairoutdinov and Randall (2003)
UM	SMB with four categories [v, c, r, and i (cloud number concentration is diagnosed with climatological distribution of aerosols)] Wilson and Ballard (1999), Boutle et al. (2014), Walters et al. (2019)

Table 4. Dependences of cloud-related processes on bulk cloud microphysical parameters.

Processes	Dependences	References	Assumptions
Auto-conversion ($c \rightarrow r$)	$\rho \frac{\partial q_c}{\partial t} \propto (\rho q_c)^2 \overline{D_c}^6$	Seifert and Beheng (2001)	Long's kernel (Long, 1974) is used for the collection efficiency.
Auto-conversion ($i \rightarrow s$)	$\rho \frac{\partial q_i}{\partial t} \propto \rho q_i n_i \overline{D_i}^4$	Seiki et al. (2015)	Cloud ice is assumed to be spherical and sufficiently small to satisfy Stoke's law. $v_{t,i} \propto D^2$
Riming ($c \rightarrow j$) ($j = i, s, g$)	$\rho \frac{\partial q_j}{\partial t} \propto \rho q_c n_j \overline{D_j}^{2+d}$	Seiki and Roh (2020)	Power law is assumed between v_t and D as follows: $v_t \propto D^d$ with d typically ranging from 0.1 to 0.5 (e.g., Locatelli and Hobbs, 1974).
Condensation Evaporation Vapor Deposition Sublimation Melting	$\rho \frac{\partial q_j}{\partial t} \propto n_j \overline{D_j}$	Igel et al. (2015) Seiki and Roh (2020)	Spherical shape is assumed for ice particles.
Immersion freezing	$\rho \frac{\partial q_r}{\partial t} \propto \rho q_r \overline{D_r}^3$	Bigg (1953)	The equation is derived from experiment.
Cloud optical thickness τ_c	$\tau_c \propto n_c \overline{D_c}^2$	Liou (2002)	Extinction efficiency is assumed to be approximately constant (2) for most particles.
Visible cloud albedo R_c	$R_c = \frac{\sqrt{3}(1-g)\tau_c}{2+\sqrt{3}(1-g)\tau_c}$	Liou (2002) Fu (2007)	Two-stream approximation is used with the asymmetry factor g typically ranging from 0.75 to 0.9 (e.g., Fu, 2007)
Infrared emissivity of cirrus ε_{IR}	$\varepsilon_{IR} = 1 - \exp(-0.79\tau_c)$	Fu and Liou (1993)	The function is derived by fitting to results from a numerical model with experimental data.

Table 5. Optical sensors and corresponding sensitive physical parameters.

Optical sensors	Satellites/instruments	Physical parameters
Visible/near-infrared imager (0.3 to 4 μm)	Geostationary meteorological satellites (e.g., GOES, Himawari, Meteosat), NOAA/AVHRR, Aqua, Terra/MODIS, GCOM-C/SGLI, TRMM-VIRS	Cloud optical thickness, Cloud-top effective radius
Infrared imager (8 to 12 μm)		Cloud-top temperature, Ice cloud optical thickness Ice cloud-top effective radius
Microwave imager (10 to 20 GHz)	Aqua/AMSR-E, GCOM-W/AMSR2, TRMM/TMI, GPM/GMI	Liquid water path, Precipitation flux,
Microwave imager (80 to 90 GHz)		Ice water path
Lidar (532 nm, 1064 nm)	CALIPSO/CALIOP	Thermodynamic phase, Ice shape, Optical thickness
Cloud radar (94 GHz)	CloudSat/CPR	Ice water content, Liquid water content
Precipitation radar (13.6 GHz, 35.5 GHz)	TRMM/PR, GPM/DPR	Precipitation flux, Hydrometeor class

Figures and Tables

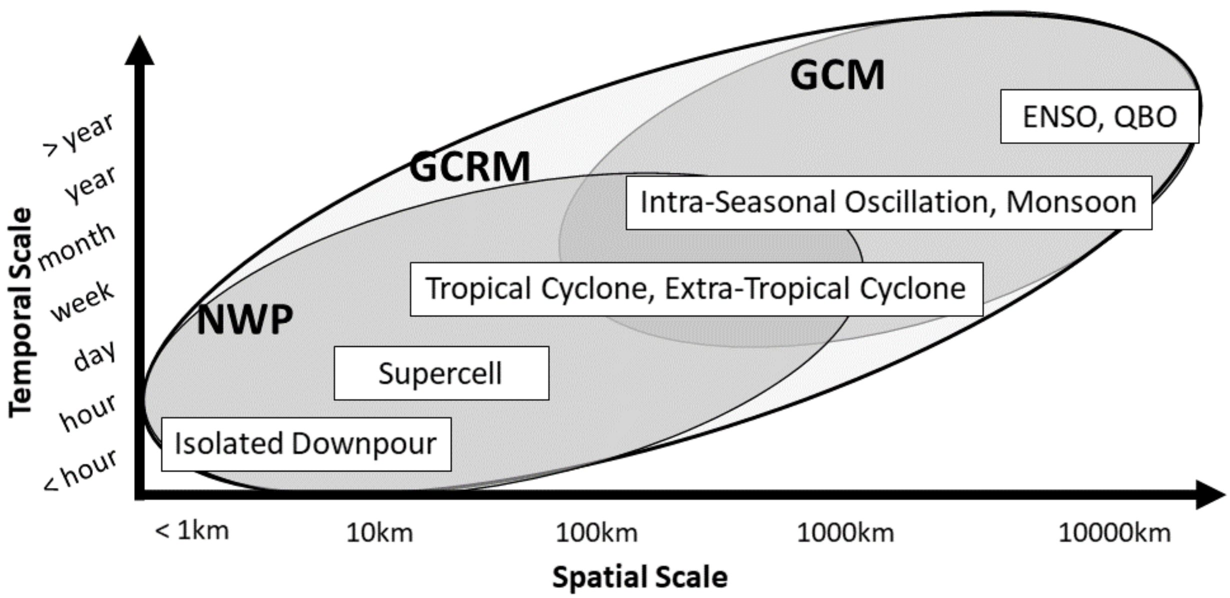

Figure 1. Typical spatiotemporal scales of some examples of weather and climate phenomena. The numerical weather prediction model (NWP), general circulation model (GCM), and global cloud resolving model (GCRM) cover different but partially overlapping scales.

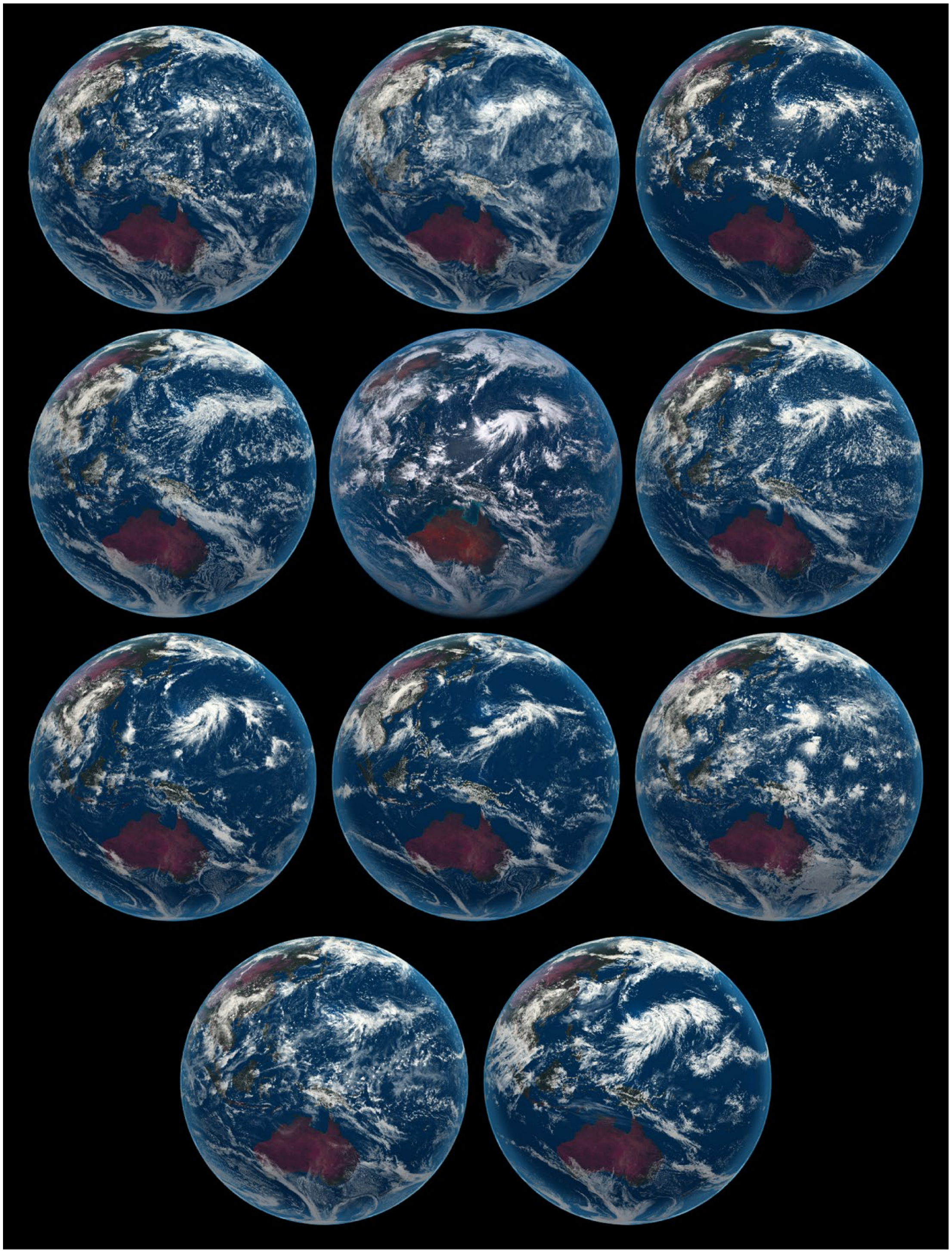

Figure 2. Cloud images calculated by the GCRMs in the DYAMOND project and from the geostationary satellite Himawari-8 (After Fig. 2 in Stevens et al., 2019). From left to right: IFS with a horizontal resolution of 4 km, 9 km, and NICAM (top row); ARPEGE-NH, Himawari-8, and ICON (second row); FV3, GEOS5, and UM (third row); and SAM and MPAS (bottom row).

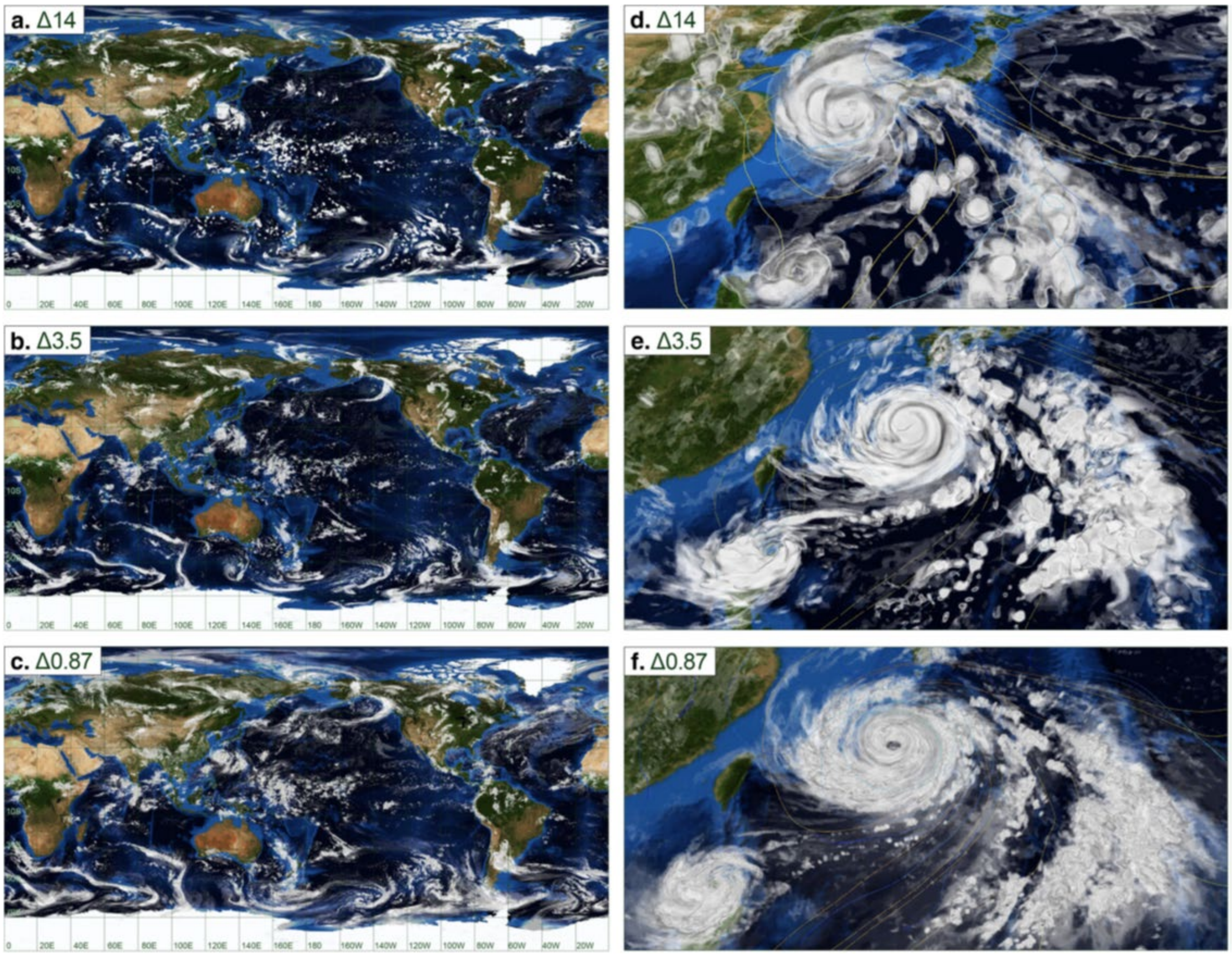

Figure 3. Cloud images calculated by the NICAM with horizontal resolutions of 14 km, 3.5 km and 0.87 km (after Kajikawa et al., 2016). Zoom images of a tropical cyclone are shown in the right column.

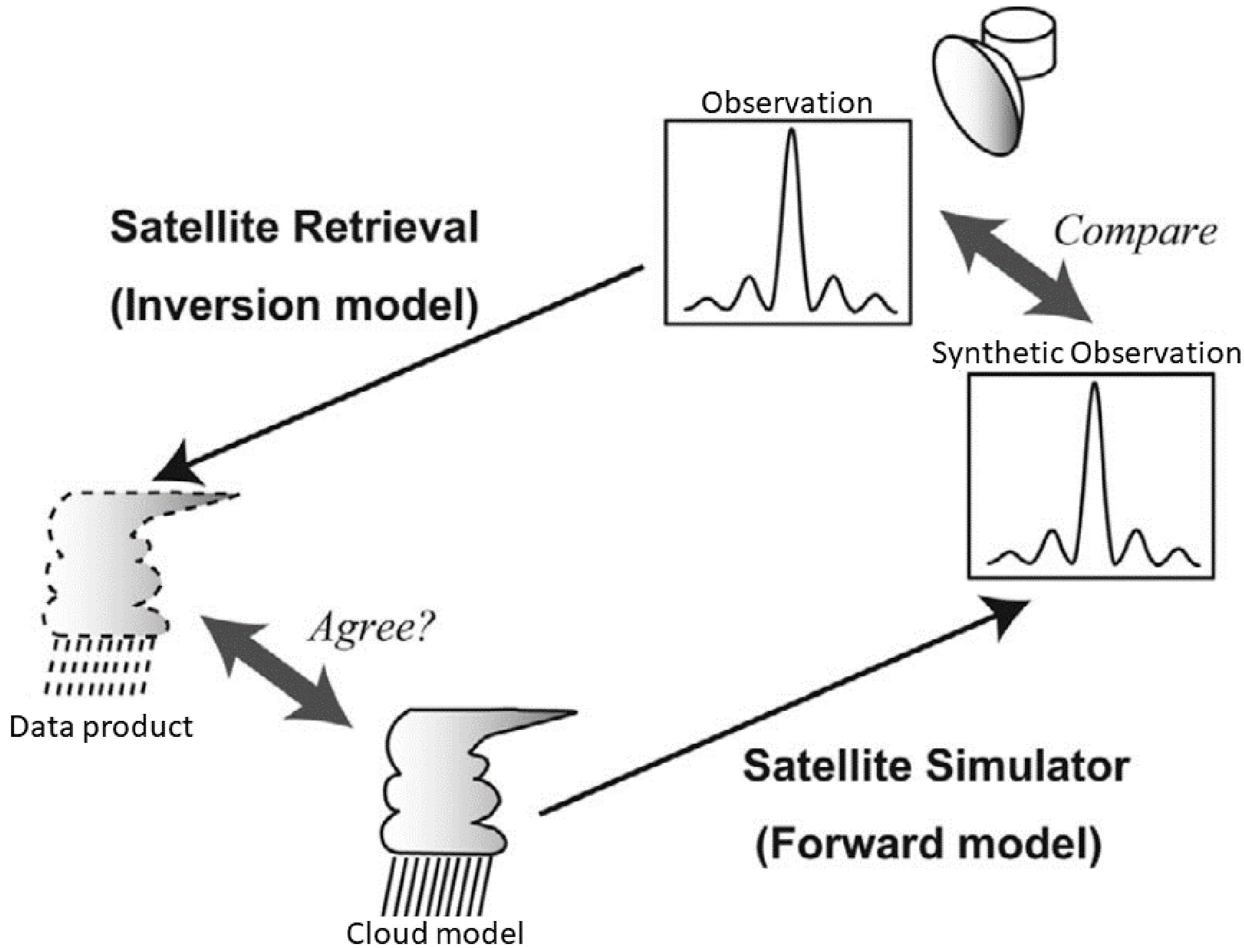

Figure 4. A schematic image of the comparison between models and satellites using satellite simulators. From Masunaga et al. (2010), © American Meteorological Society. Used with permission.

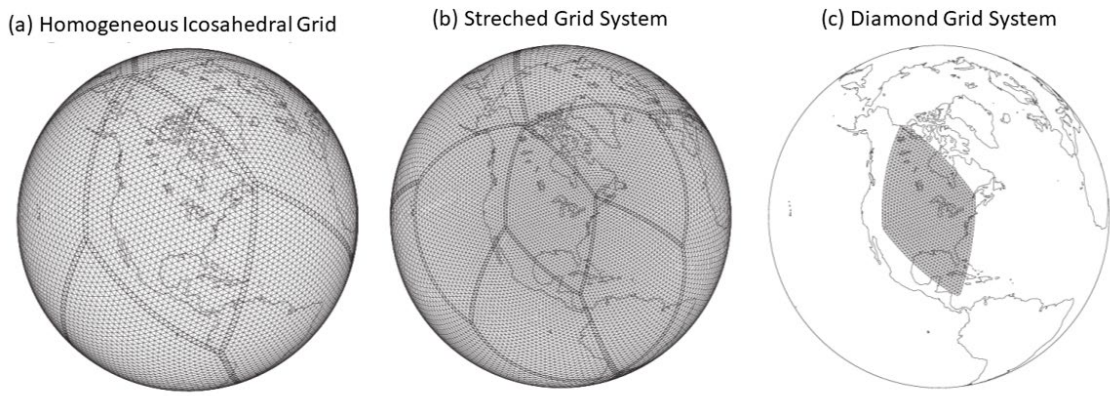

Figure 5. Sample images of (a) the default NICAM with the global quasi-uniform icosahedral grid system, (b) stretched NICAM, and (c) diamond NICAM (after Uchida et al., 2017, © American Meteorological Society. Used with permission.).

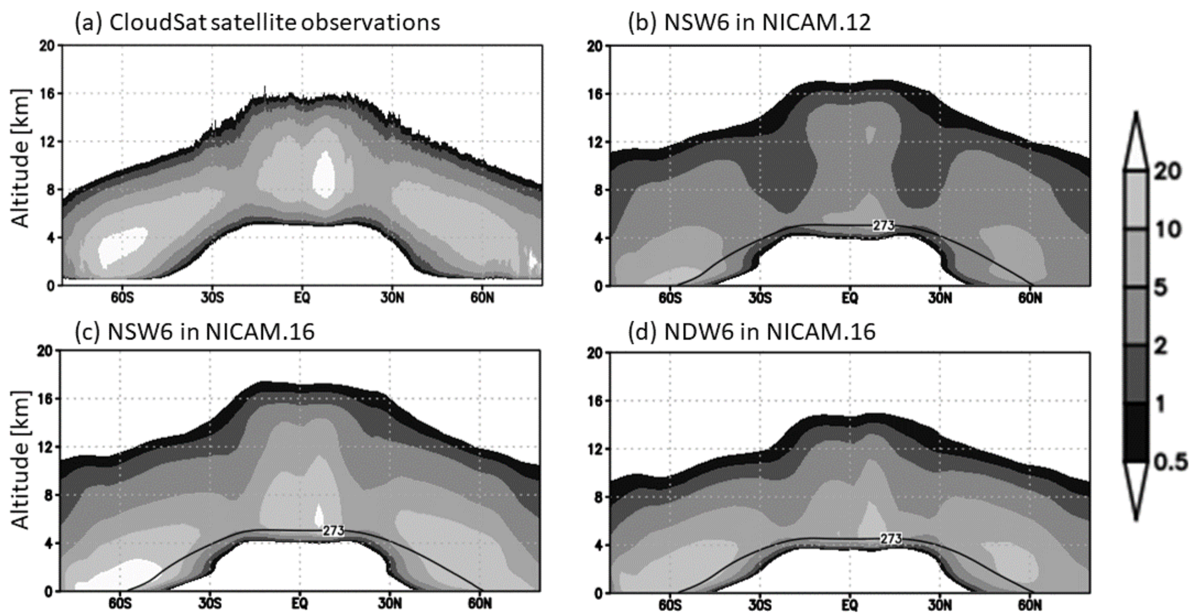

Figure 6. Comparison of the vertical profiles of annual mean ice water content (IWC) [mg m^{-3}] from (a) CloudSat satellite observations [2B-CWC-RO product (Austin and Stephens 2001; Austin et al., 2009)], (b) NSW6 in NICAM.12, (c) NSW6 in NICAM.16, and NDW6 in NICAM.16. The solid lines represent 273-K isotherms. The global simulation data with horizontal resolution of 14 km and 38 vertical layers were provided by courtesy of C. Kodama and A. T. Noda.

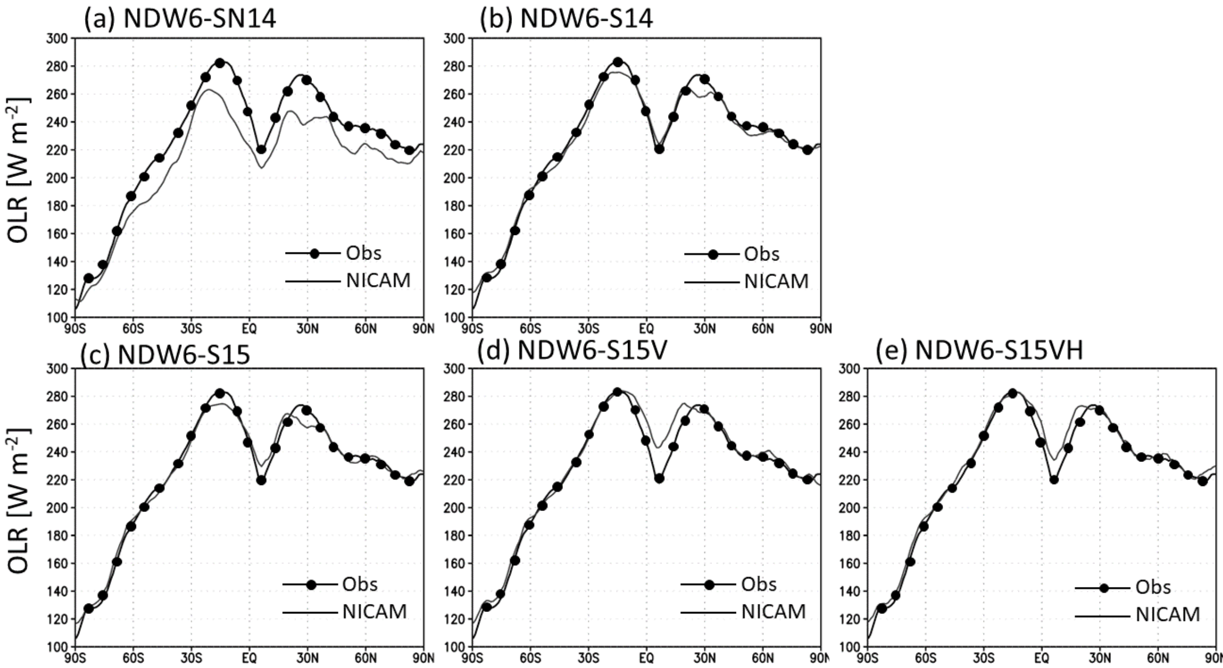

Figure 7. Comparison of outgoing longwave radiation at the top of the atmosphere (OLR) from CERES satellite observations (solid lines with points) and NICAM simulations with various versions of NDW6 (solid lines) (after Satoh et al., 2018).

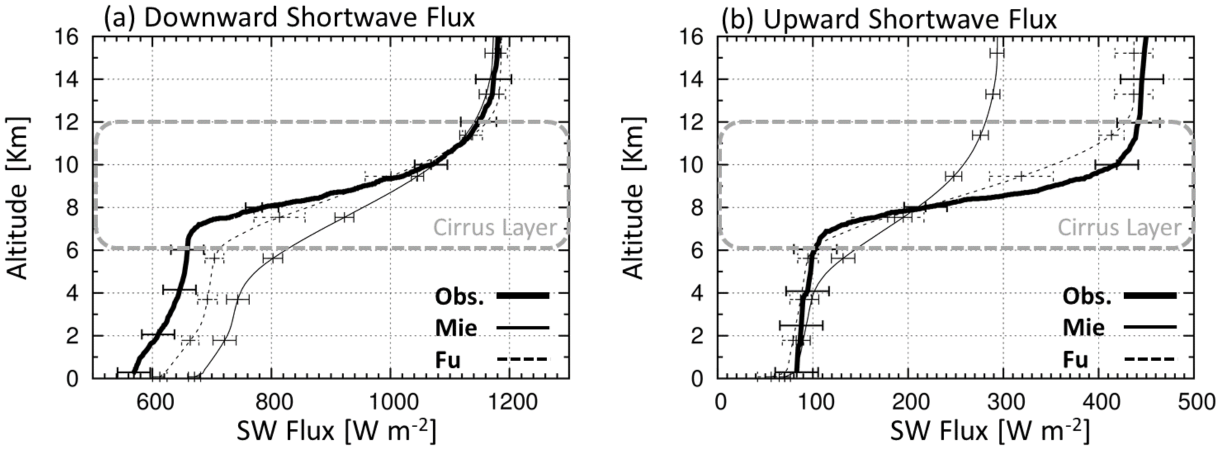

Figure 8. The vertical profiles of (a) downward shortwave radiation and (b) upward shortwave radiation (after Seiki et al., 2014). Thick lines indicate observations by radiometer sonde, thin solid lines indicate NICAM simulations using NDW6 with spherical SSPs, and thin dashed lines indicate NICAM simulations using NDW6 with nonspherical SSPs. The dashed rectangles indicate the location of a cirrus layer.

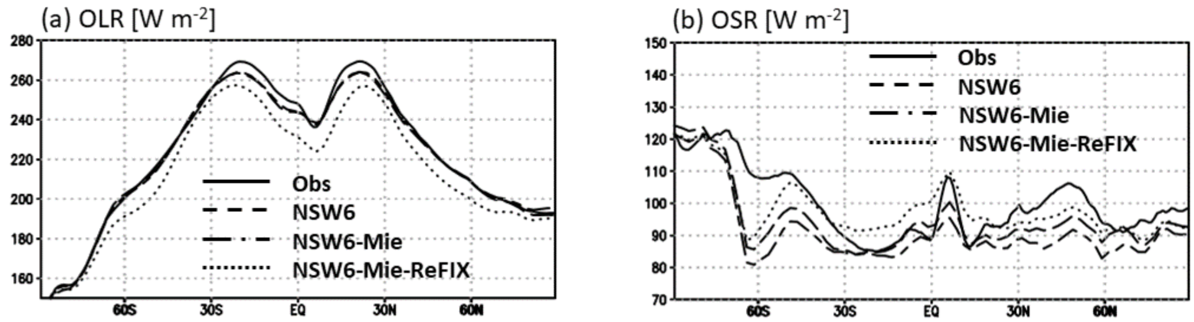

Figure 9. Comparison of (a) OLR and (b) outgoing shortwave radiation at the top of the atmosphere (OSR) from CERES satellite observations (solid lines) and NICAM.16 simulations with various settings of cloud and radiation coupling. NSW6 uses full coupling between cloud and radiation (dashed lines), NSW6-Mie assumes variable effective radii but spherical SSPs (long dashed short dashed lines), and NSW6-Mie-ReFIX assumes constant effective radii and spherical SSPs (dotted lines). The global simulation data were provided by courtesy of C. Kodama.

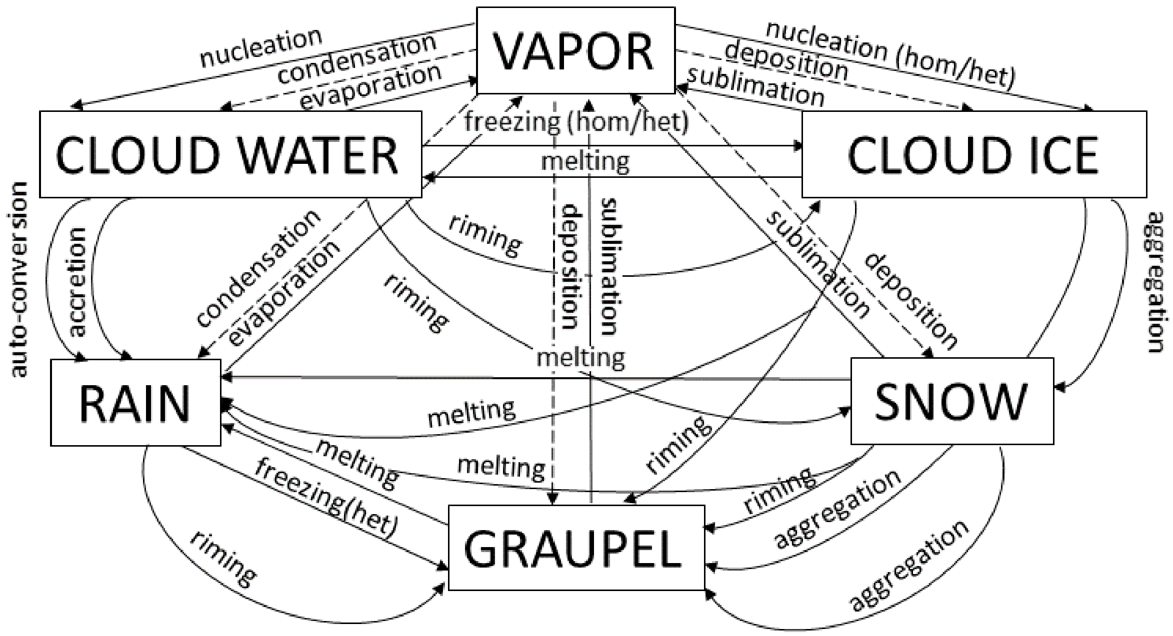

Figure 10. Cloud microphysical processes and cloud interaction among water classes (after Satoh et al., 2018). Solid lines indicate the processes that change the number and mass concentration of hydrometeors, while dashed lines indicate the processes that change only the mass concentration of hydrometeors. Hom/het indicates homogeneous/heterogeneous, respectively.

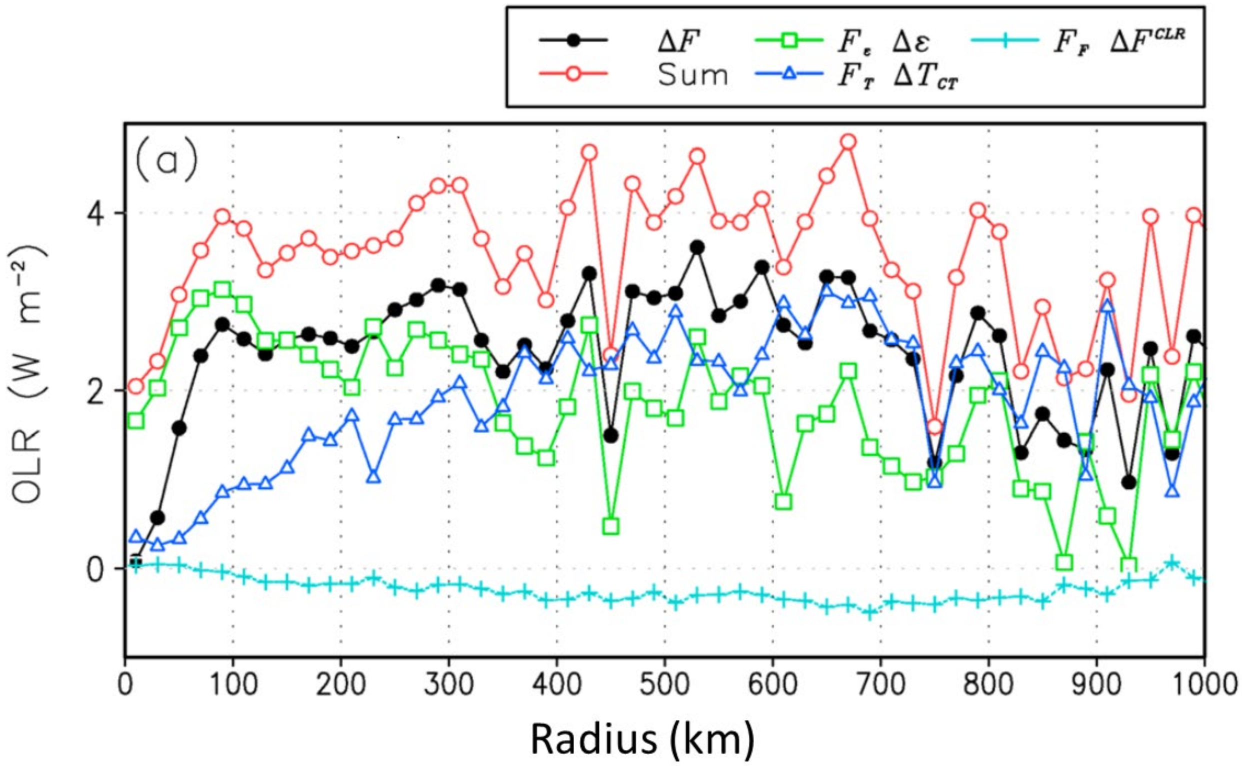

Figure 11. Breakdown of OLR change under global warming simulated by the NICAM (after Noda et al., 2016). An OLR change ΔF is attributed to a change in emissivity $\Delta\varepsilon$, a change in cloud-top temperature ΔT_{CT}, and a change in clear sky radiation ΔF^{CLR}. The breakdown was calculated by cloud size. Sum shows the summation of the contributions and the difference between ΔF and Sum indicates the error of the analysis.

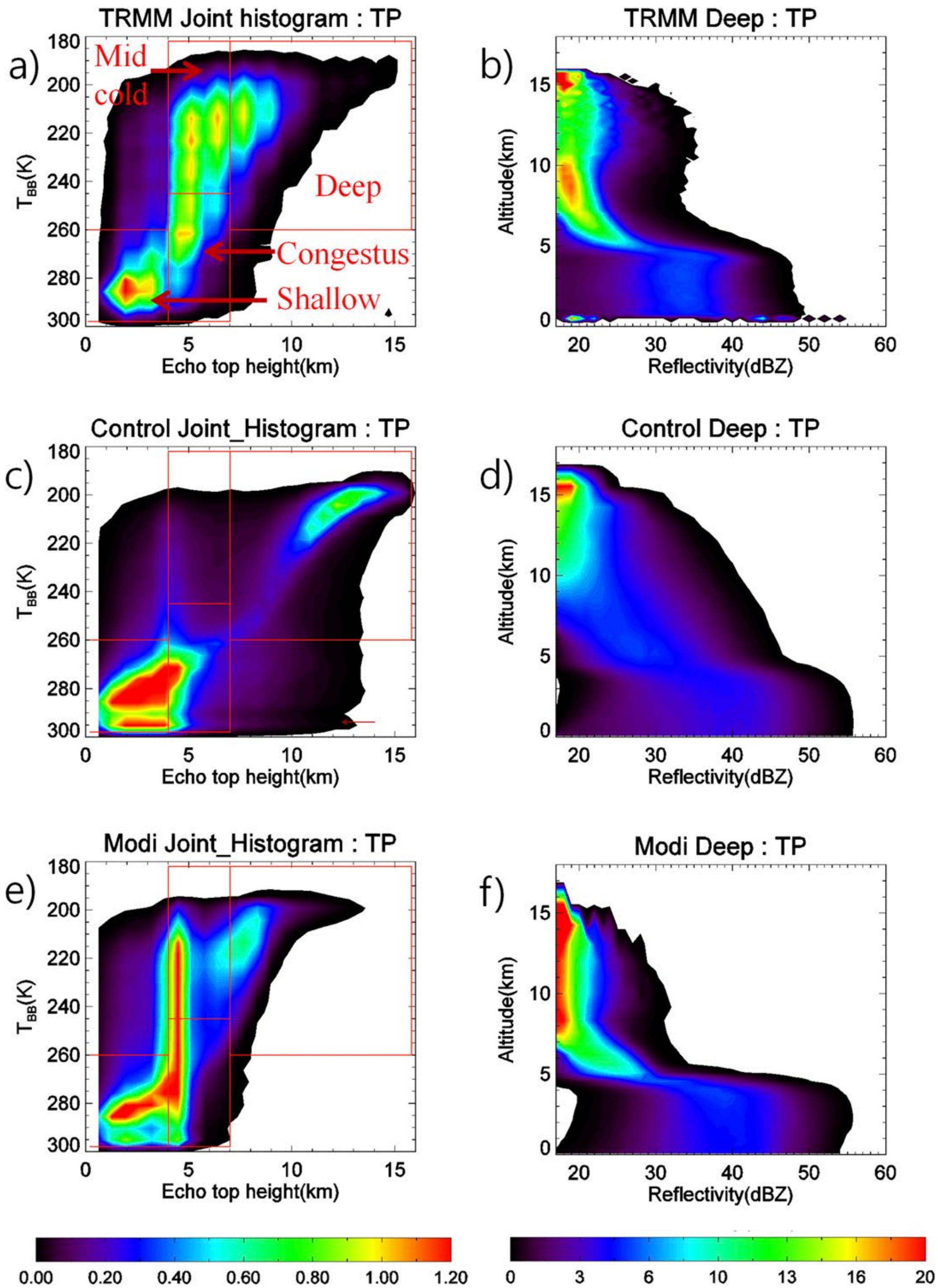

Figure 12. The cloud-top and rain-top diagram using Ku-band radar echo and infrared brightness temperature from (a) satellite observations, (c) NSW6 in NICAM.12, and (e) NSW6 in NICAM.16. CFAD using Ku-band radar echo from (b) satellite observations, (d) NSW6 in NICAM.12, and (f) NSW6 in NICAM.16. Here, simulated results were processed by a Joint-Simulator. From Roh et al. (2017), © American Meteorological Society. Used with permission.

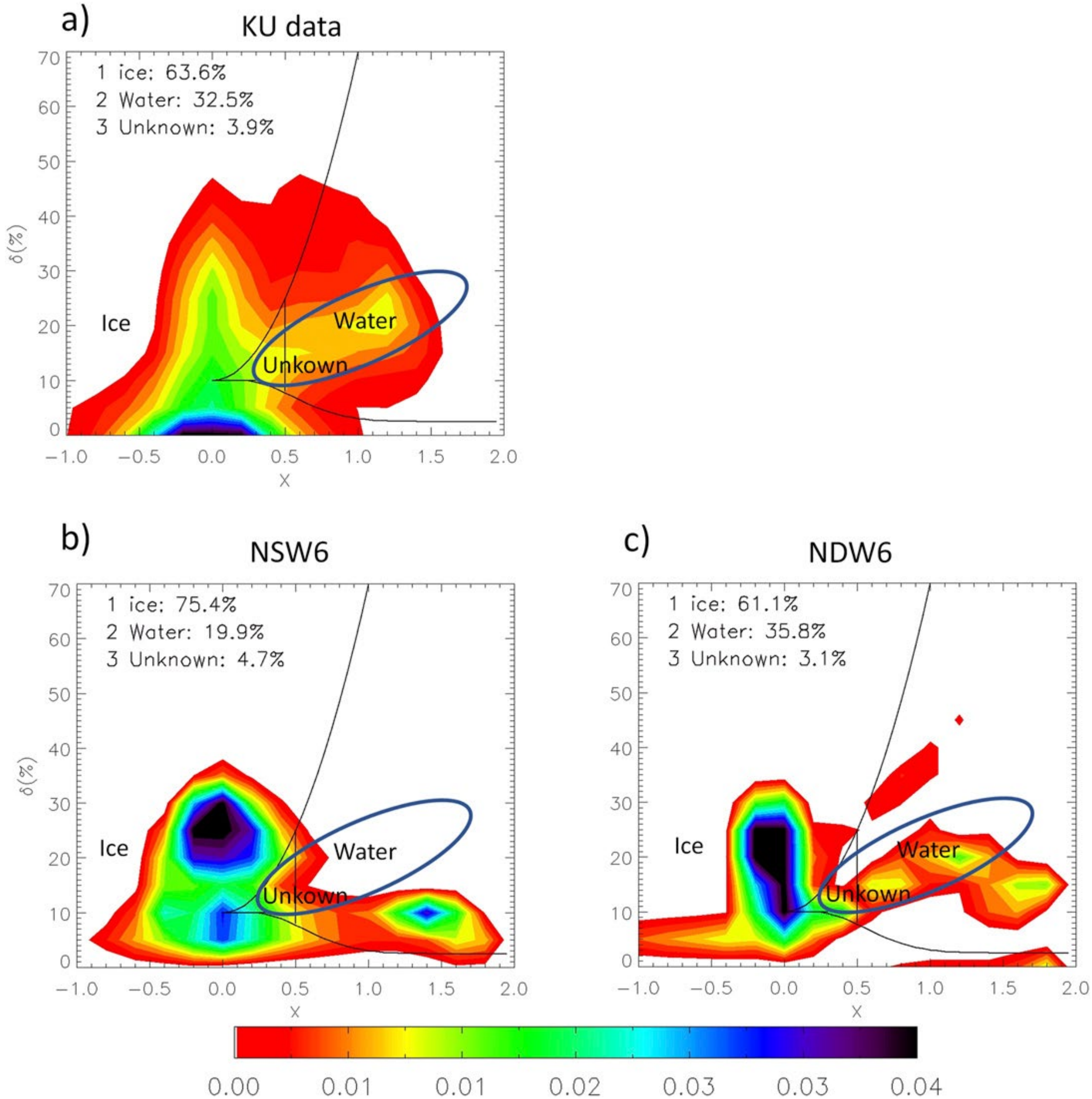

Figure 13. Joint probability density function of the depolarization ratio δ and the ratio of attenuated backscattering coefficients for successive layers x from (a) satellite observations, (b) NSW6 in NICAM.16, and (c) NDW6. Low-level clouds behind a frontal cloud system were sampled over the Southern Ocean. Signals of supercooled liquid water are highlighted by circles. From Roh et al. (2020), © American Meteorological Society. Used with permission.

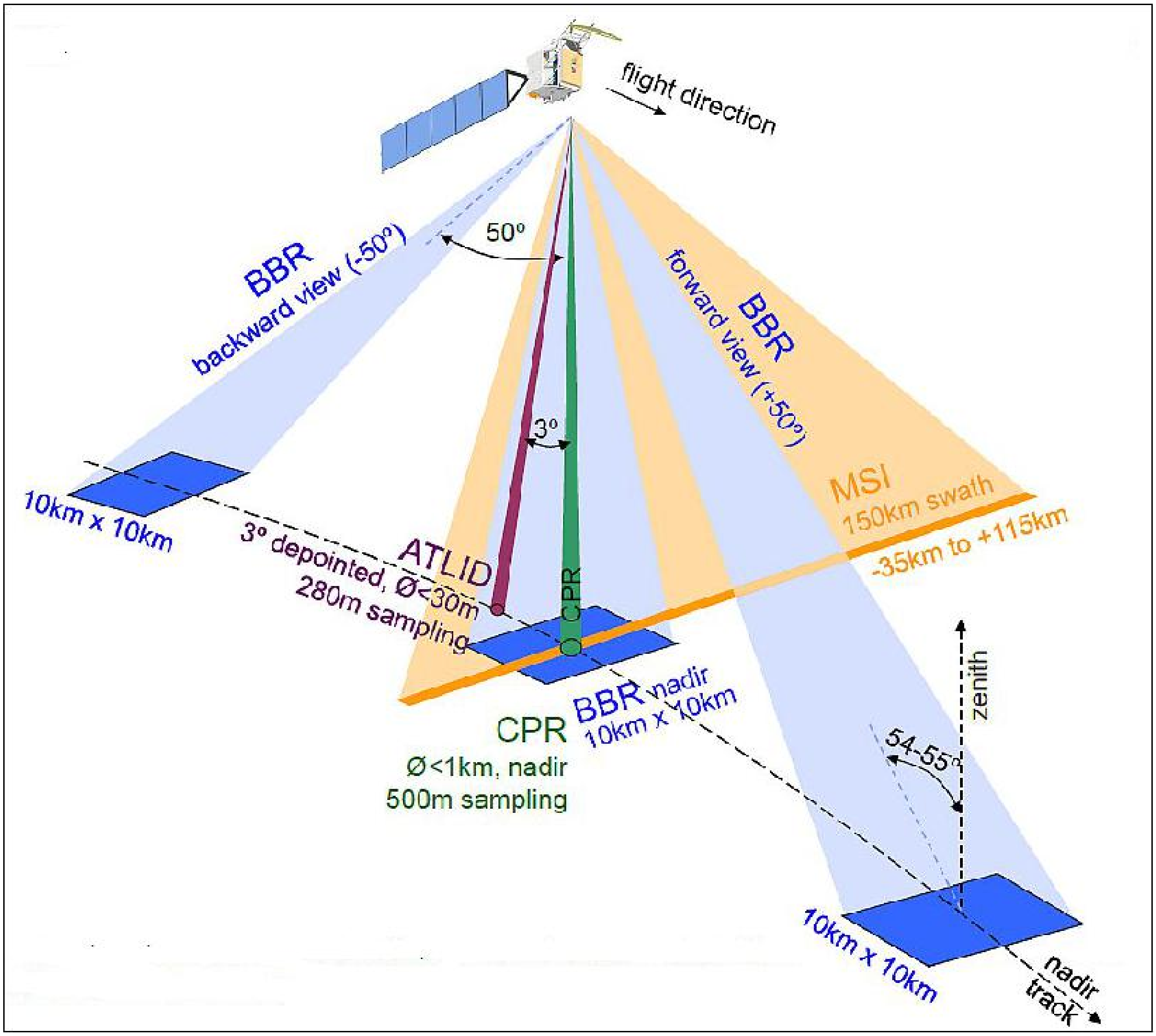

Figure 14. Observation geometry of the EarthCARE satellite (from https://directory.eoportal.org/web/eoportal/satellite-missions/e/earthcare).

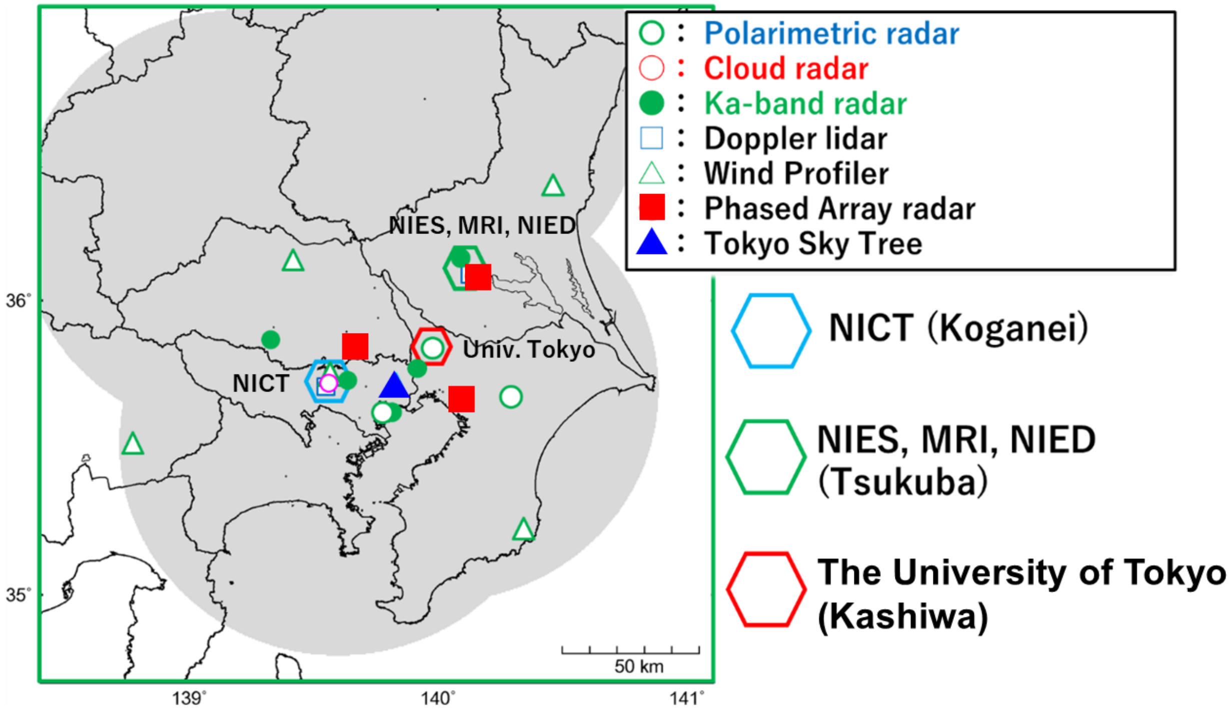

Figure. 15. Overview of the ground observations used in the ULTIMATE project around the Tokyo metropolitan area.