Microphysics in Goddard Multi-scale Modeling Systems

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Abstract

Advances in computing power allow atmospheric prediction and general circulation models to be run at progressively finer scales of resolution, using increasingly more sophisticated physical parameterizations. The representation of cloud microphysical processes is one of key components of these models. In addition, over the past decade both research and operational numerical weather prediction models have started using more complex microphysical schemes that were originally developed for high-resolution cloud-resolving models (CRMs).

In the paper, we described different microphysics schemes that are used in Goddard Multi-scale Modeling System. There are three major models, Goddard Cumulus Ensemble (GCE), NASA Unified Weather Research Forecast (NU-WRF) and Multi-scale Modeling Framework (MMF) model, in this modeling system. The microphysics schemes are Goddard three class ice (3ICE) and four class (4ICE) scheme, Morrison two moments (2M) 3ICE, Colorado State University Regional Atmospheric Modeling System (RAMS) 2M five class ice (5ICE) and spectral bin microphysics schemes. The performance of these schemes are examined and compared with radar and satellite observation. In addition, the inter-comparison with different microphysics schemes are conducted. Current and future observations needed for microphysics schemes evaluation as well as major characteristics of current microphysics are discussed.

1. Introduction

The microphysics is one of key physical processes in the in Earth system science (see Fig. 1). For example, its associated latent heat is released or absorbed by the atmosphere as a result of phase changes in water (e.g., condensation or evaporation of cloud droplets and raindrops, freezing of raindrops, melting of snow and graupel/hail, and the deposition or sublimation of ice particles). Cloud microphysics affects the vertical distribution of cloud substances (or hydrometeors) and size distributions (i.e., from small cloud water droplets and ice particles, to medium-sized snow, to large precipitating rain- drops and graupel/hail), aspects of which affect active (i.e., radar reflectivity) and passive (i.e., brightness temperature) remote sensing measurements. Since precipitation can be in the form of light rainfall, heavy rainfall, snow, or mixed phase, it influences surface properties (i.e., soil moisture, runoff, albedo, and emissivity) and the energy and water cycles. Convective transport affects the vertical redistribution of chemical species and, in turn, radiative forcing and atmospheric electrification (see a review by Cotton *et al*., [1995] and Thompson *et al*., [1997]).

Cloud-resolving models (CRMs) are a type of numerical model wherein mathematical equations are applied at discrete points to simulate the evolution of physical processes over a spatial area. Many CRMs have been developed over the past five decades. They have been applied to improve our understanding of micro-scale to cloud-scale and mesoscale as well as their interactions with radiation, aerosol and surface processes. The basic characteristic of CRMs is that their governing equations are non-hydrostatic since the vertical and horizontal scales of atmospheric convection are similar. The CRMs use sophisticated and physical realistic cloud microphysical processes with very fine spatial and temporal resolution. They represent the interaction between clouds and radiation (and aerosol) with greater fidelity than global models since the spatial and temporal distributions of water substances (vapor, liquid, and ice) are explicitly coupled to the atmosphere circulation at cloud system scale. Another advantages of using CRMs are their ability to quantify the effects of each physical process upon convective events by means of sensitivity tests (e.g., eliminating a specific process such as evaporative cooling, ice formation and its associated processes, planetary boundary layer (PBL), and their detailed dynamic and thermodynamic budget calculations. Figure 2 shows a schematic of the main characteristics of typical CRMs. Review of CRMs including its history and their applications can be found in Tao [2003, 2007] and Tao and Moncrieff [2009].

The Goddard Cumulus Ensemble (GCE) model is a CRM that has been developed and improved at NASA Goddard Space Flight Center (GSFC) over the past three and a half decades. It has been used for studying precipitation processes and their impact on rainfall as well as support NASA satellite missions [i.e., Tropical Rainfall Measurement Mission (TRMM) and Global Precipitation Measurement (GPM)]. One of key developments of GCE model is the cloud-microphysical processes (microphysical schemes). However, the cloud-microphysical processes (nucleation, diffusion growth and collision among cloud and precipitation particles) still need to be parameterized in GCE (and other CRMs as well). Note that all cloud-microphysical schemes have their own set of unique assumptions and capabilities. It is critical therefore to sample and evaluate model performance for a comprehensive range of precipitation systems. Observations are crucial to verify model results and improve the initial and boundary conditions as well as the aforementioned physics processes.

The GCE model was recently enhanced to simulate the impact of atmospheric aerosol concentrations on precipitation processes and the impact of land and ocean surface processes on convective systems in different geographic locations [Tao *et al.,* 2007, 2016a; Li *et al.,* 2009a; Zeng *et al.,* 2007, 2009]. The GCE model has also been coupled with the Goddard Satellite Data Simulator Unit (SDSU), which allows us to scrutinize the performance of the microphysics by analyzing discrepancies between the simulated and observed radiances from remote sensing measurements [Matsui *et al.,* 2009; Li *et al.,* 2010].

Recently, the GCE model has been coupled with a global circulation model (GCM) by replacing the one-dimensional cumulus parameterization scheme with two-dimensional GCE model [called super parameterization or multi-scale modeling framework (MMF)]. In addition, the GCE microphysical scheme and its interactions with radiation and surface processes have also been implemented into NASA Unified WRF (NU-WRF). The performance of Goddard microphysics scheme can be tested from local, regional to global and for different types of cloud/cloud systems developed in different environments by using these three modeling systems (GCE, NU-WRF and Goddard MMF or GMMF). These new modeling developments are called Goddard multi-scale modeling system with unified physics [Tao *et al.,* 2009].

The objectives of this paper are to provide a review of developments, improvements and applications of Goddard microphysics schemes. The Goddard multi-scale systems with unified physics and the Goddard microphysics schemes will be descripted, respectively, in Section 2 and 3. The results will be presented in Section 4. Summary and future model developments will be presented in section 5.

2. Multi-Scale Modeling Systems with Unified Physics

Recently, a multi-scale modeling system with unified physics was developed at NASA Goddard. It consists of (1) the GCE model, a CRM; (2) the NU-WRF, a region-scale model; and (3) the coupled GCM-GCE, the GCE coupled to a general circulation model (or known as the Goddard MMF or GMMF). The same cloud-microphysical processes, long- and short-wave radiative transfer and land-surface processes are applied in all of the models to study precipitation processes, cloud-radiation and cloud-surface interactive processes in this multi-scale modeling system. This modeling system has been coupled with a multi-satellite simulator for comparison and validation with NASA high-resolution satellite data. Figure 3 shows the multi-scale modeling system with unified physics. The same GCE physics will also be utilized in the GMMF. The GCE model and NU-WRF share the same Goddard microphysical and radiative transfer processes (including the cloud-interaction) as well as Land Information System (LIS). The same GCE physics is utilized in the GMMF. The idea behind having a multi-scale modeling system with unified physics is to be able to propagate improvements made to a physical process in one component into other components smoothly and efficiently [Tao *et al*., 2009]. The followings will provide descriptions of GCE mode, NU-WRF, Goddard GCM and GMMF.

2.1 The Goddard Cumulus Ensemble model (GCE)

The GCE has been developed and improved at NASA Goddard Space Flight Center over the past three and a half decades. A review on GCE model application to better understand precipitation processes can be found in Simpson and Tao [1993] and Tao [2003]. Its development and main features were published in Tao and Simpson [1993] and Tao *et al.* [2003, 2014]. The three-dimension (3D) version of the GCE is typically run using 256 x 256 up to 4096 x 4096 horizontal grid points at 1 km resolution or better (i.e., 250 m). In typical multi-day to multi-week integrations, the model has performed reasonably well in terms of rainfall, latent heating (LH) profiles and moisture budget structure compared to observations when driven with observed large-scale forcing derived from sounding networks.

The GCE model's advection scheme uses a multi-dimensional Positive Definite Advection Transport Algorithm [Smolarkiewicz and Grabowski, 1990]. The positive definite advection scheme also produces more light precipitation, which is in better agreement with observations [Johnson *et al*., 2002]. Solar and infrared radiative transfer processes [Chou and Suarez, 1999 and Chou *et al*., 1999] have been included [Tao *et al*., 1996]. A sophisticated seven-layer soil/vegetation land process model has also been implemented into the GCE model [Lynn *et al*., 1998; Lynn and Tao, 2001 and Lynn *et al.*, 2001]. Subgrid-scale (turbulent) processes in the GCE model are parameterized using a scheme based on Klemp and Wilhelmson [1978], and the effects of both dry and moist processes on the generation of subgrid-scale kinetic energy have been incorporated [Soong and Ogura, 1980]. Table 1 shows the major characteristics of the GCE model.

The GCE model has been used to understand the following[1] (see Table 2 for more formation on GCE model developments and applications):

- The role of the water and energy cycles in the tropical climate system,
- The redistribution of ozone and trace constituents by individual clouds and well-organized convective systems over various spatial scales,
- The relationship between the vertical distribution of latent heating (phase changes of water), surface rainfall and the large-scale (pre-storm) environment,
- Climate hypotheses of deep convection related to global warming,
- The precipitation processes (i.e., precipitation efficiency),
- Aerosol impact on precipitation and rainfall in different environments,
- Impact of the surface process on precipitation and rainfall,
- The assumptions used in the representation of cloud and convective processes in climate and global circulation models, and
- The representation of cloud microphysical processes and their interaction with radiative forcing over tropical and mid-latitude regions.

Recently, the GCE was adapted to interface with the single (1M) and two-moment (2M) versions of Colorado State University's Regional Atmospheric Modeling System's (RAMS's) bulk microphysical scheme [Meyers *et al.*, 1997; Saleeby and Cotton, 2004], the Morrison 2M scheme [Morrison *et al.*, 2005, 2009], as well as a spectral bin microphysics (SBM) scheme [Khain *et al.*, 2004; Tao *et al.*, 2007; Li *et al.*, 2009a,b]. The GCE's own 1M bulk microphysics, especially ice processes, have been significantly improved, starting with the reduction of excessive graupel [Lang *et al.*, 2007] and unrealistically high dBZs aloft [Lang *et al.*, 2011] and culminating in the new 4ICE scheme [Lang *et* al., 2014; Tao *et al.*, 2016] capable of simulating a wide range of precipitation systems better than previous generations of the Goddard bulk microphysics. These schemes will be described in Section 3.

2.2 The NASA Unified Weather Research and Forecasting model (NU-WRF)

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[1] More the last three and a half decades and more than 150 refereed papers using the GCE model have been published in

NASA-Unified Weather Research Forecasting (NU-WRF) combines the capabilities of the Advanced Research WRF (ARW, Michalakes *et al*., [2001]) with various modules developed at NASA-GSFC: the Land Information System (LIS, Kumar *et al.,* [2006]), the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model [Chin *et al.* 2002], the Goddard microphysics [Lang *et al.,* 2014; Tao *et al.,* 2016] and Goddard radiation [Chou and Suarez, 1999, 2001; Matsui and Jacob, 2014], and ensemble data assimilation (EDA) system [Zhang *et al.*, 2017]. In addition to traditional reanalysis and global forecasting data, NU-WRF supports high-resolution initial and boundary conditions from the Modern-Era Retrospective analysis for Research and Applications 2 (MERRA2, Bosilovich *et al.,* [2015]); LIS land surface model (LSM) spin-up, and various aerosol emissions databases, including dynamic 1-km dust erosion maps [Kim *et al.,* 2017]. These packages enable fully coupled aerosol-cloud-precipitation-land surface simulations and satellite-based model evaluation at satellite-resolvable scales [Peters-Lidard *et al.,* 2015]. Figure 4 shows the physical processes and applications of NU-WRF.

NU-WRF has been used to provide real-time forecasts for GPM field campaigns (i.e., MC3E, IFloodS, and IPHEX). It has also been used to simulate a variety of precipitation systems: e.g., C3VP [Shi *et al.,* 2010; Iguchi *et al.,* 2012a], LPVEx [Iguchi *et al.,* 2014], NAMMA [Shi *et al.,* 2014], MC3E [Iguchi *et al.,* 2012b; Tao *et al.,* 2013, 2016] and IFloodS [Wu *et al.*, 2015].

2.3 Goddard finite-volume GCM (fvGCM)

The fvGCM has been constructed by combining the finite-volume dynamic core developed at Goddard [Lin, 2004] with the physics package of the NCAR Community Climate Model CCM3, which represents a well-balanced set of processes with a long history of development and documentation [Kiehl *et al.,* 1998]. The unique features of the finite-volume dynamical core include: an accurate conservative flux-form semi-Lagrangian transport algorithm (FFSL) with a monotonicity constraint on sub-grid distributions that is free of Gibbs oscillation [Lin and Rood, 1996, 1997], a physically consistent integration of the pressure gradient force for a terrain-following Lagrangian control-volume vertical coordinate [Lin, 1997], and a mass-, momentum-, and total-energy-conserving vertical remapping algorithm. The physical parameterizations of the fvGCM have been upgraded by incorporating the gravity-wave drag scheme of the NCAR Whole Atmosphere Community Model (WACCM) and the Community Land Model version 2 [CLM-2; Bonan *et al.*, 2002].

2.4 Goddard Multi-scale Modeling Framework (GMMF)

The Goddard MMF is based on the Goddard fvGCM and the GCE model. The fvGCM provides global coverage while the GCE allows for the explicit simulation of cloud and microphysical processes and their simulated profile of cloud properties provides to fvGCM for radiation calculation.

Goddard MMF typically is conducted using fvGCM with 2.5^o x 2^o horizontal grid spacing with 32 layers from the surface to 0.4 hPa, and the two-dimensional (2D) GCE using 32 horizontal grids (in the east-west orientation) and 32 levels with 4 km horizontal grid spacing and cyclic lateral boundaries[2]. The time step for the GCE is 10 seconds, and the fvGCM-GCE coupling interval is one hour (which is the fvGCM physical time step). Because the vertical coordinate of the fvGCM (a terrain-following coordinate) is different from that of the GCE [a height (z) coordinate], vertical interpolations are needed in the coupling interface. An interpolation scheme, based on a finite-volume piecewise parabolic mapping (PPM) algorithm, has been developed to conserve mass, momentum and moist static energy between the two coordinates. The coupling between fvGCM and GCE is shown in Fig. 5.

2.5 Goddard Satellite Data Simulator Unit (G-SDSU)

Modern multi-sensor satellite observations provide a more complete view of land, cloud, precipitation and aerosols processes from space; meanwhile, it is becoming a challenge for remote sensing and modeling communities to harness these observation simultaneously due to inconsistent physics assumptions and spatial scales between satellite retrievals and CRM physics. To this end, a unified system of multi-sensor simulators, the G-SDSU, has been developed through multi-institutional collaborations [*Matsui et al.*, 2013, 2014]. The G-SDSU is the end-to-end satellite simulator, which computes satellite-consistent Level (L1) measurements (e.g., radiance/brightness temperature or backscatter), from outputs the GCE, NU-WRF, and GMMF simulations through radiative transfer, antenna gain patterns, and satellite orbit/scan simulators for passive microwave and visible-IR sensors, radar, lidar, and broadband and hyper-spectral sensors (see Fig. 6). In addition to the satellite sensors, recent polarimetric radar simulator was included for supporting ground-based polarimetric weather radars [Matsui *et al.*, 2017].

All radiative transfer modules consistently treat CRM's microphysics assumptions (phase, size, and effective density) to calculate single-scattering properties and

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[2] Please see Table 1 in Tao and Chern [2017] for other MMFs' configurations.

backscatter/radiance. G-SDSU-simulated L1 signals can be directly compared with the satellite-observed L1 signals; therefore G-SDSU bridges model and satellite remote sensing through following paths: i) radiance-based model evaluation and development [*Matsui et al.,* 2009; *Li et al.,* 2010], ii) an operator of radiance-based data assimilation system [*Zhang et al.,* 2017], and iii) development of synthetic satellite observations for future satellite missions [Matsui *et al.,* 2014] and retrieval algorithm database [Kidd *et al.,* 2016].

3. Microphysics

3.1 Goddard one-moment (1M) 3-Classes Ice Scheme (3ICE)

The Goddard Cumulus Ensemble (GCE) model's 1M bulk microphysical scheme is mainly based on Lin *et al.* [1983] with additional processes from Rutledge and Hobbs [1984]. However, the Goddard microphysics scheme, known as 3ICE, contains several configuration options. One option allows the user to choose either graupel or hail as the third class of ice [McCumber *et al.,* 1991]. Graupel has a relatively low density and a high intercept value (i.e., more numerous small particles). In contrast, hail has a relatively high density and a low intercept value (i.e., more numerous large particles). These differences can affect not only the description of the hydrometeor population and formation of the anvil-stratiform region, but also the relative importance of the microphysical-dynamical-radiative processes. The Goddard microphysics scheme has been modified to reduce un-realistic cloud water in the stratiform region [Tao *et al.*, 2003]. In addition, the GCE model's own microphysics – especially its ice processes – have been improved to reduce un-realistically high dBZs aloft [Lang *et al.*, 2007, 2011]. Also, ice crystal concentration can be introduced as an independent factor into the scheme to increase the cloud ice (or anvil) significantly so that the modeled clouds are close to observations [e.g., Zeng *et al.,* 2009a,b, 2011].

The GCE's Rutledge and Hobbs [1983, 1984]-based 3-class ice scheme was further improved via the following processes: a snow-density mapping was added whereby snow densities are increased with decreasing size in a more realistic fashion, a rain evaporation correction based on bin-model results was used to remap the rain sizes below cloud base where the fixed intercept in the bulk scheme leads to excessively small rain sizes at smaller rain mixing ratios and hence excessive evaporation, the saturation adjustment scheme was further modified to allow for cloud ice to persist in sub-saturated conditions and for a small amount of ice super saturation to exist even at extremely cold temperatures, a simple two-tier graupel density scheme was added wherein graupel densities are increased to a higher value at higher mixing ratios to mimic the effect of pro-longed riming, and finally the snow/graupel size mapping scheme was adjusted to reduce particle sizes for higher mixing ratios as the addition of hail reduced the need for snow/graupel to produce peak reflectivity values aloft.

All WRF microphysics schemes (more than 20) only considered 3ICE scheme (either cloud ice, snow and graupel or cloud ice, snow and hail). In general, 3ICE-hail scheme is needed to simulate / predict local thunderstorm, tornado and other severe weather in midlatitude in summer season. On the other hand, 3ICE-grauple is needed to simulate/predict tropical cyclones, frontal systems and Tropical oceanic convective systems [McCumber *et al*., 1991; Tao and Simpson, 1989].

3.2 Goddard 1M four-classes Ice Scheme (4ICE)

Almost all microphysics schemes are 3ICE (cloud ice, snow and graupel). Very few 3ICE schemes have the option to have hail processes (cloud ice, snow, graupel or hail) and see Table 1 in Tao *et al.* [2016]. Both hail and/or graupel can occur in real weather events simultaneously, therefore a 4ICE scheme (cloud ice, snow, graupel and hail) is required for real time forecasts (especially for high-resolution prediction of severe local thunderstorms, mid-latitude squall lines and tornadoes). In addition, current and future global high-resolution cloud-resolving models need the ability to predict/simulate a variety of weather systems from weak to intense (i.e., tropical cyclones, thunderstorms) over the globe; this requires the use of a 4ICE scheme

A new 1M 4-class ice (cloud ice, snow, graupel, and frozen drops/hail) microphysics scheme (4ICE) was recently developed for the GCE [Lang *et al.,* 2014]. Hail processes from the GCE's 3ICE scheme based on Lin *et al.* [1983] were added to the improved 3ICE graupel scheme [Lang *et al.*, 2007, 2011] and further refined to create a 1M 4ICE scheme [Lang *et al.*, 2014] capable of simulating a wide range of convective systems, from weak to intense. Its key features include no dry collection of ice species by hail, resulting in realistic narrow hail cores as well as peak echoes that monotonically decrease with height, a SBM-based rain evaporation correction [Li *et al.*, 2009a,b], which reduces excessive evaporation and up-shear tilted convective cores, and a refined snow size (and density) mapping scheme with an enhanced aggregation effect. The scheme was then further modified to include the effects of snow breakup by graupel/hail while further improving the snow aggregation effect, resulting in improved radar structures (i.e., a transition region and more horizontally stratified stratiform features), and a simple hail size mapping, which eliminates the need to select the hail intercept *a priori* [Tao *et al.*, 2016]. The Goddard 4ICE scheme was first validated in the GCE where it outperformed 3ICE graupel schemes in terms of peak intensity and overall echo distributions vs observations for both moderate and intense convection [Lang *et al.,* 2014]. It was then added to NU-WRF with the additional modifications where it was similarly shown to be superior to 3ICE schemes, including a hail scheme [Tao *et al*., 2016]; it was also tested in two-year long global GMMF simulations, where it produced improved global cloud ice distributions [Chern *et al.,* 2015] and reflectivity/TB relations over land and ocean [Matsui *et al.,* 2015].

Table 4 shows the evolution of Goddard microphysics scheme during the last three decades. The performance of Goddard 3ICE and 4ICE microphysics schemes will be discussed in Section 4.

3.3 Spectral Bin Microphysics (SBM)[3]

The SBM includes the following processes: (1) nucleation of droplets and ice particles [Pruppacher and Klett, 1997; Meyers *et al*., 1992], (2) immersion freezing [Bigg, 1953], (3) contact freezing [Meyers *et al.,* 1992], (4) ice multiplication [Hallett and Mossop, 1974; Mossop and Hallett, 1974], (5) detailed melting [Khain *et al.,* 2004], (6) condensation/ evaporation of liquid drops [Pruppacher and Klett, 1997; Khain *et al.,* 2000], (7) deposition/sublimation of ice particles [Pruppacher and Klett, 1997; Khain *et al.,* 2000], (8) drop/drop, drop/ice, and ice/ice collision/coalescence [Pruppacher and Klett, 1997; Pinsky *et al.,* 2001], (9) turbulence effects on liquid drop collisions [Pinsky *et al.*, 2000], and (10) collisional breakup [Seifert and Beheng, 2001; Seifert *et al.*, 2005]. In the first process, ice nucleation includes both condensation-freezing and homogeneous nucleation. The Meyers' formula is applied in a semi-Lagrangian approach [see Khain *et al.,* 2000]. The concentration of newly nucleated ice crystals at each time step is calculated by the increase in the value of super-saturation. Sedimentation of liquid and ice particles is also considered. SBM are specially designed to take into account the effect of atmospheric aerosols on cloud development and precipitation formation. The activation of aerosols in each size bin is explicitly calculated in this scheme [Khain *et al.*, 2000]. This added level of sophistication will improve our understanding of microphysical processes and positively influence the development of TRMM and GPM rain/snowfall retrieval algorithms.

The bulk-microphysics Drop Size Distribution (DSD) assumptions have been evaluated against explicitly-simulated DSDs using the SBM scheme, because SBM simulations yield much more realistic radar echo profiles than the bulk one-moment microphysics

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[3] The same SBM has been implemented into the GCE model [Tao *et al.*, 2007; Li *et al.*, 2009a,b and 2010].

(e.g., Fig. 6**,** Li *et al.,* [2009a]). The results suggest that SBM-simulated DSDs are more dependent on temperature than mass mixing ratio. In addition, the numerical results are in good agreement with observations, indicating the microstructure of clouds depends strongly on cloud-aerosol interactions [Tao *et al.,* 2007; Li *et al.,* 2009a, b; Li *et al.,* 2010].

The SBM has also been used to improve bulk schemes. For example, the raindrop size distribution assumption in the bulk microphysical scheme artificially enhances rain evaporation rate by assuming an exponential size distribution, artificially increasing smaller raindrops that evaporate faster than larger ones. The cooling produced by rain evaporation largely determines the cold pool strength, which is crucial for storm regeneration and propagation [e.g., Rotunno *et al.,* 1988]. In the bulk simulation shown in Li *et al.* [2009a], the strong cold pool circulation dominates near-surface environmental wind shear, producing pulsating updraft cores that tilt rearward and propagate into the stratiform region. This is in contrast to the near-balance between the cold pool and the wind shear simulated in the bin scheme, which results in upright, steady updraft cores and a homogeneous stratiform region. Rain evaporation in the bulk scheme is reduced according to an empirical formula derived from the bin scheme [Li *et al.,* 2009b]; the resulting radar reflectivity agrees better with both the observations and the bin simulation [Lang *et al.,* 2014].

3.4 The Morrison 2-moment (2M) microphysics scheme

Morrison 2M microphysical scheme [Morrison *et al*., 2005a, 2009] predicts number concentrations and mass mixing ratios of five hydrometeor types (cloud droplets, ice crystals, raindrops, snow particles, and graupel particles). The particle size distributions are assumed to be gamma distributions. The precipitating hydrometeor types (rain, snow, and graupel) are fully prognostic in the CRM. Droplet activation is calculated at each CRM grid cell, based on the parameterization of Abdul-Razzak and Ghan [2000]. The convective updraft strengths for calculating droplet activation is related to the resolved vertical velocity and the turbulent kinetic energy with a minimum vertical velocity of 0.1 m s^{-1}. A resolved droplet activation scheme with prognostic aerosol (serving as CCN) activation and advection is also included in the Morrison scheme and tested using both GCE and WRF model (e.g., Li *et al*., [2017]; Fridlind *et al*., [2017]). The scheme also includes prognostic equations for both the mass mixing ratio and number concentration for ice nucleation (both homogeneous and heteorogeneous); ice multiplication; auto-conversion of droplets to form rain and ice to form snow; accretion of droplets by rain and snow, of rain by snow, and of ice by snow; freezing; melting; self-collection; condensation/deposition and evaporation/sublimation. A modified Morrison 2-moment scheme was also implemented in the Community Atmosphere Model (CAM5), where the cloud droplet and cloud ice mixing ratio and number concentrations are solved prognostically, whereas the rain and snow are diagnosed [Morrison and Gettelman, 2008]. The sub-grid variability for cloud water is also included in the global model version.

3.5 The Colorado State University Regional Atmospheric Modeling System

The Colorado State University Regional Atmospheric Modeling System (RAMS) two-moment (2M) bulk cloud microphysical scheme [Meyers *et al.*, 1997; Cotton *et al.*, 2003; Saleeby and Cotton, 2004, 2008; Lee *et al.*, 2009] has been implemented in the GCE model. The RAMS 2M scheme assumes gamma particle size distributions for three species of liquid (small and large cloud droplets and rain) and five species of ice (small and large vapor grown crystals, aggregates, graupel, and hail). Consistent with observations of bimodal cloud droplet size distributions, the cloud droplet spectrum is decomposed into two modes; one for droplets up to about 50 microns in diameter, and the second for droplets 50 to roughly 100 microns in diameter. Ice crystal habit is allowed to vary as a function of temperature and humidity. The scheme accounts for mass and number changes of each hydrometeor specie owing to cloud and ice nucleation, vapor diffusion, evaporation, droplet self-collection (auto-conversion), collision-coalescence, freezing, melting, sedimentation, and secondary ice production. In addition, the RAMS bulk aerosol module [Saleeby and van den Heever, 2013] is incorporated for explicit simulation of cloud droplet activation from sub- and super-micron sulfate, sea salt and dust aerosols, wet/dry deposition, and aerosol regeneration upon hydrometeor evaporation. Ice nucleation follows either Meyers *et al*. [1992] or Demott *et al.* [2010] based on user specification. A species-dependent soluble fraction parameter, ε, accounts for aerosol hygroscopicity in a manner analogous to the κ-parameter [Petters and Kreidenweis, 2007 and 2008; Sullivan *et al.*, 2009]. User-specified aerosol profiles are initialized horizontally homogeneously within the model domain, although aerosol mass is tracked within hydrometeors, and non-activated aerosols are advected with the model-predicted flow fields. Collection is simulated using stochastic collection equation solutions, facilitated by bin-emulating look-up tables that incorporate size-dependent collection kernels for liquid species, rather than by continuous accretion approximations. The philosophy of bin representation for collection is extended to calculations of hydrometeor sedimentation [Feingold *et al.*, 1998; Loftus *et al.*, 2014] and riming [Saleeby and Cotton, 2008] melting, shedding (hail only) [Meyers *et al.*, 1997]. The scheme also includes explicit prediction of supersaturation, a critical consideration for conducting aerosol-cloud interaction studies, and has the ability to keep track of microphysical budgets. The Goddard radiation scheme [Chou and Suarez, 1999; Chou *et* *al*., 2001] fully interacts with all eight hydrometeor species and accounts for changes in particle size distributions as cloud systems develop and evolve.

Lee *et al.* [2009a] used the GCE with RAMS 2M microphysics to examine the effects of enhanced aerosol loading on thin marine stratocumulus clouds in environments characterized by different cloud top relative humidity (RH) values. For greater aerosol loading, the authors noted increases in cloud droplet number concentrations (CNDC), along with increased reflection and absorption of downward SW radiation owing to smaller droplet sizes, although changes in cloud liquid water path (LWP) were found to depend on RH near cloud top as well due to feedbacks among CDNC, condensation, and dynamics (i.e., vertical velocities, cloud-top entrainment and evaporative cooling below cloud base).

Table 5 shows the main characteristics of Goddard 4ICE, Morrion, RAMS and spectral bin microhysical schemes. The similarities and differences between these schemes are also shown.

4. Results

4.1 GCE model results

GCE model has been used for two types of precipitation process studies. The first uses large-scale forcing in temperature and water vapor derived from a sounding network to drive the model. In this mode, the model is typically integrated for multiple weeks to sample and obtain cloud statistics for many systems. The GCE model simulated apparent heating (Q_1) and apparent moisture sink (Q_2) defined in Yanai *et al.* [1973]; and surface rainfall are typically in excellent agreement with the observed (sounding derived). Results using this approach have been used in support of both the TRMM and GPM missions [e.g., Tao *et al*., [2001, 2010]; Lang and Tao, [2017]). The second type of GCE study is the case study, which is used to study cloud processes as well as cloud-radiation, cloud-aerosol and cloud-surface interactions for specific cloud systems, and the GCE model is usually only integrated for a short term (12 – 24 h). In the following sub-section, the performance of the Goddard microphysics for these two types of simulations is presented.

4.1.1 Long Term Integration and Diurnal Variation

The diurnal variation of tropical oceanic convection is one of most important components in tropical variability and plays a crucial role in regulating tropical hydrological and energy cycles. A successful simulation of the diurnal variability of the hydrologic cycle and radiative energy budget provides a robust test of physical processes represented in atmospheric models (e.g., Slingo *et al*., [1987]; Randall *et al.*, [1991; Lin *et al.*, [2000]). The simulation sensitivity (3ICE vs 4ICE) to the cloud microphysics was examined using the 2D GCE model with 512 horizontal grids in 1 km spacing and 43 vertical levels. Large-scale advective tendencies for dry static energy and moisture obtained from the sounding network during the Dynamics of MJO (Madden-Julian Oscillation) (DYNAMO) over Gan Island (Yoneyama *et al.*, [2013]). The 3-hourly forcing was specified during the model integration. The surface fluxes were also specified uniformly over the model domain.

Figure 7 shows the observed and the GCE simulated precipitation rate. Overall, both 3ICE and 4ICE cases can capture observed active period of deep convection associated with the MJO event during 17 – 30 November, and the suppression periods before and after the MJO event. The result also shows that both 3ICE and 4ICE cases simulate very similar temporal variation and rainfall intensity. This feature is better illustrated with the scatter plot of precipitation rate between observation and the two GCE runs with the 3ICE and the 4ICE microphysics schemes (Fig. 8). The correlation with observed precipitation rate is as high as 0.92 in both simulations. This result suggests that the 4ICE scheme can be applied for tropical oceanic convective event that rarely with presence of hail.

The sounding estimated and GCE simulated diurnal variation of precipitation is also examined. Figure 9a shows the observed and the simulated diurnal cycle of precipitation, where the hourly rainfall data were averaged each hour. The observation shows double peaks, one from the midnight to morning (0000 – 0900 LST) and the other in late afternoon (~1800 LST). The nighttime peak is distributed more widely in time, whereas the afternoon peak is centered at 1800 LST. Overall, the nighttime precipitation is more dominant rather than the daytime. This is consistent with the previous observational studies (i.e., Kraus, [1963]; Gray and Jacobsen, [1977]; Randall *et al.*, [1991]; Sui *et al.*, [1997]).

Both 3ICE and 4ICE cases capture the observed diurnal cycle of rainfall fairy well, with the double peaks in the nighttime and late afternoon. There is discrepancy at the timing of minimum precipitation rate between observation (~1200 LST) and the model simulations (~1500 LST), but this may be partly caused by less frequent data sampling of observed precipitation. This study further separated the cases of nighttime and the late afternoon rainfall (Figs. 9b and 9c). Both GCE cases also reproduce the observed variation quit well.

The prevalence of nocturnal rainfall in tropical oceans has been suggested by the cloud-radiation interaction mechanism that emphasizes the dominant role of convective clouds in the nighttime though enhanced IR cooling (Kraus, [1963]; Randall *et al.*, [1991]) and a large-scale dynamic response to the radiational differences between cloudy and clear regions (Gray and Jacobson, [1977]). The simulated cloud-radiation feedback can be affected by the implemented microphysics schemes, particularly by the differences in vertical distribution of ice clouds. Both GCE cases show almost no sensitivity in the simulated diurnal cycle of precipitation (c.f. Fig. 9a). However, the simulation difference becomes relatively larger in the nighttime, suggesting the connection between the ice clouds and long-wave radiation. This aspect should be tested more rigorously for the GCE model.

4.1.2 Short Term Integration – Case Studies

The Goddard 4ICE scheme was used to simulate an intense continental squall line observed during Midlatitude Continental Convective Clouds Experiment (May 20, 2011) to evaluate its ability to simulate intense convection with significant hail, as well as a loosely organized transient line of moderate convection from TRMM Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA, February 23, 1999) to ensure the scheme does not over-predict less intense convection. The MC3E 20 May 2011 case featured an intense squall line that formed over central Oklahoma as a deep, upper-level low over the central Great Basin moved through the central and southern Rockies before lifting into the central and northern plains. 3D GCE model simulations were conducted using 1-km horizontal grid spacing and a 256 km x 256 km horizontal domain with a stretched vertical grid having 70 levels and a top near 23 km. The LBA case was characteristic of the widespread, weaker monsoon-like convection observed within the westerly wind regime during TRMM LBA. For the LBA case, a horizontal domain of 128 km x 128 km with 200 m horizontal grid resolution was used with 70 stretched vertical grids with a top near 23 km. For each case, seven numerical experiments were conducted. Three experiments were made using previous versions of the 3ICE-graupel scheme: the original Tao *et al*, [2003, named 3ice0], Lang *et al*. [2007, named 3ice1], and Lang *et al*. [2011, named 3ice3]. Four variations of the new 4ICE scheme were tested: with smaller-, medium-, and larger-sized hail with a bin rain evaporation correction (4iceb sml, 4iceb med, and 4iceb lrg, respectively) and smaller-sized hail without the evaporation correction (4ice sml). Smaller-, medium-, and larger-sized hail use fixed hail distribution intercepts of 0.020, 0.0020, and 0.0002 cm^{-4}, respectively.

Figure 10 shows vertical profiles of maximum radar reflectivity for the MC3E and TRMM LBA cases. For the MC3E case, all three 3ICE simulations have a pronounced low bias that ranges from about 5 dBZ below the freezing level to as much as 15 dBZ above the freezing level (Fig. 10a). The 4ICE simulations show a marked improvement in the bias at almost all levels except for 4iceb lrg, which produces excessively large reflectivities (~15 dBZ) near the melting level. The medium-hail profile has the smallest overall bias and agrees best with the observed. Though not quite as good, the smaller hail runs are significantly improved over the 3ICE with a consistent low bias of just 5 dBZ at all levels. Peak reflectivity profiles from the LBA case are shown in Fig. 10b; the 4ICE simulations with smaller hail clearly perform the best and show almost no bias (less than ~4 dBZ) through nearly the entire depth of the storm. Remarkably, none of the 4ICE runs produced the over bias evident in runs 3ice0 and 3ice1 in the top part of the storm; furthermore, all of the 4ICE runs produced monotonically decreasing profiles with height in agreement with the observations. However, obviously the medium to larger hail sizes in runs 4iceb med and 4iceb lrg are much too large, producing over biases of up to ~10–15 dBZ around the melting level. These results suggest the new 4ICE scheme is quite capable of responding appropriately to the intensity of the convective environment and can outperform the 3ICE-graupel scheme in terms of peak reflectivities even in a moderate-intensity environment.

In addition, CFADs or contoured frequency with altitude diagrams (Yuter and Houze, [1995]) are used to evaluate the overall reflectivity distributions. For the 20 May MC3E squall line case (Fig. 11a), the observed CFAD has high concentrations of dBZs from 0 to 40 dBZ below the melting level, whereas aloft, a coherent core of even higher echo probabilities (i.e., more concentrated dBZ values) increases from ~10 dBZ near 200 mb to ~25 dBZ just above the freezing level, a signature of increased particle size due mainly to aggregation in the stratiform region. Infrequent but much more intense echoes associated with the convective cores extend out to near ~65 dBZ above and below the freezing level, 50 dBZ at 12 km, and 40 dBZ at 16 km. The improved 3ICE graupel scheme (3ice3, Fig. 11a) cannot reproduce the strong reflectivities over 50 dBZ above the freezing level, and while there is some evidence of an aggregation effect, the highest probabilities (i.e., most abundant echoes) occur at dBZ values that are too weak compared to the observations. In contrast, the 4ICE simulations (represented by the medium hail run) can much more realistically capture the infrequent but intense echoes that arise from hail and, though the proportion of weak echoes (i.e., below 10 dBZ) is still too high, have better distributions of weaker echoes with a better aggregation signature. CFADs for the weaker, less-organized 23 February 1999 TRMM LBA case (Fig. 11b) show that the 4ICE scheme even with medium-sized hail can match the performance of the improved 3ICE graupel scheme (3ice3) for weak echoes. The 4ICE scheme with medium hail is comparable in its ability to replicate the infrequent but more moderate echoes, tending to be slightly too strong versus slightly too weak, but it does eliminate the tendency of the graupel scheme to produce elevated reflectivity maxima above the freezing level. The 4ICE scheme with smaller hail performed the best overall for the 23 February case (Lang *et. al.*, [2014]). The 4ICE scheme was further improved by implementing, among other modifications, a simple hail mapping scheme that eliminates the need to have to choose an appropriate hail intercept value for each case. The improved 4ICE scheme was implemented into both the GCE and NU-WRF (Tao *et al*., [2016]).

4.1.3 Bin Microphysics

The 2D GCE model with the SBM scheme was used to simulate a summer time midlatitude squall line case in central US. This is a case study using the open lateral boundary condition with observed atmospheric conditions ahead of the squall line as the initial condition. There are 1024 horizontal and 33 vertical grid points. The horizontal resolution is 1km at the center of the domain, and is stretched toward the lateral boundaries. The vertical grids are also stretched, with finer resolution (~0.2 km) near the ground and coarser resolution (2 km) at the top. Figure 12 shows a comparison of observed radar reflectivity (Fig. 12a), and simulated radar reflectivity by the SBM scheme (Fig. 12b) and the Goddard 3ICE bulk scheme (Fig. 12c). The SBM simulation compares much better with the observation in that it has an extensive stratiform region that has a horizontally uniform structure. The 3ICE bulk scheme produced a narrower stratiform region that consists of previous convective cells propagating from the leading edge.

The differences between the SBM and the bulk scheme are also used to improve the Goddard 3ICE bulk scheme. For example, the raindrop size distribution assumption in the bulk microphysical scheme artificially enhances rain evaporation rate. This is because bulk microphysical schemes have to make assumptions on rain drop size distributions. When the exponential assumption is used, rain mass is artificially redistributed to the small-size tail compared with the more realistic SBM model simulation. Smaller raindrops evaporate faster than the larger ones. The cooling produced by rain evaporation largely determines the cool pool strength, which is crucial for storm regeneration and propagation (e.g., Rotunno *et al.*, [1988]). In the bulk simulation shown in Li *et al.* [2009a], the strong cool pool circulation dominates the near-surface environmental wind shear, producing pulsating updraft cores that tilt toward the rear and propagating into the stratiform region, as shown in Fig. 12c. This is in contrast to the near-balance between the cool pool and the wind shear simulated in the bin scheme (Li *et al.*, [2009b]), which results in upright and steady updraft cores and a homogeneous stratiform region (Fig. 12b). In order to improve 3ICE bulk scheme, rain evaporation rate is reduced according to an empirical formula derived from the SBM scheme (Li *et al.*, [2009b]). This resulted in a better agreement in the radar reflectivity comparisons.

The SBM scheme has helped to improve the bulk scheme (see section 2). However, the SBM scheme itself is not perfect. For example, when nine years of TRMM Precipitation Radar (PR) and 85 GHz TRMM Microwave Imager (TMI) data during the late spring and early summer over central US were compiled and compared against an SBM simulation of the PRE-STORM (1985) squall line (Li *et al.*, [2010]). Figure 13 shows the comparisons and the resulted SBM scheme improvements. Comparisons against a surface C-band radar (Fig. 13a) and the TRMM PR radar (Fig. 13b) show an over estimation of radar reflectivity in the original scheme, especially between the height of 5 to 8 km (Fig. 13d and 13e). To improve the simulated radar reflectivity profiles, the temperature dependence of the collection efficiency between ice-phase particles, especially the plate-type, was modified. This modification reduced the coalescence of various ice-phase particles and produced smaller aggregates, resulting in better radar CFAD comparisons in the stratiform region for both C-band radar and TRMM PR, as shown in Fig. 13g and 13h. In addition, the 85 GHz brightness temperature distributions compare reasonably well with the TMI observation (Fig. 13i). We will continue testing and improving the SBM scheme for other precipitating events (especially for convective systems and snow events observed at the aforementioned GPM-related GV sites).

4.1.4 GCE-Morrison

Li *et al.* [2017] have conducted model inter-comparison study to examine the differences ad similarity of precipitation processes between the Goddard 3ICE (graupel version) and Morrison microphysics. DYNAMO case as shown in the previous section 4.1.1 was used and a long-term 3D GCE model integration is performed, with the domain size of 256 x 256 km and 60 vertical levels. Figure 14a shows the comparison of probability distributions of simulated surface rainfall for the 3ICE scheme (blue) and Morrison scheme (orange). Generally, Morrison scheme simulated more light rainfall (< 5 mm h^{-1}) and more heavy rainfall (> 30 mm h^{-1}). On the other hand, GCE 3ICE scheme simulated more moderate rainfall (between 5 and 30 mm h^{-1}).

Figures 14b and 14c show the simulated echo-top height distributions from GCE 3ICE and Morrison scheme, respectively. Generally speaking both schemes captured the variations of the radar echo-top height variations during the MJO event. The clouds transitioned from mainly shallow convection during the MJO suppressed phase (9 to 15 November) to a mixture of convection with different heights during the developing phase (16 to 22 November) to the deep convection dominant during the mature phase (23 to 29

November). Morrison scheme simulated slightly lower echo top heights compared to its GCE 3ICE counterpart (i.e., at the height of 5 km and below, and around November 4, 10 and 14). This is consistent with its simulated rainfall intensity (more light rainfall compared to 3ICE scheme simulated). Morrison scheme also simulated more, higher echo-top heights compared to GCE 3ICE scheme prior to November 24 during the developing stage. –This could explain that Morrison scheme simulated more heavy rainfall compared to 3ICE scheme.

TRMM surface rainfall product 3B42 within the DYNAMO sounding array is used to compare simulated surface rainfall by both Goddard 3ICE and Morrison scheme. 3B42 is a merged multi- satellite, near real-time product with 3-hourly temporal resolution and 0.25 degree spatial resolution. Model simulated surface rainfall rates are sampled every 3 hours and averaged over 28km x 28km grids to match the 3B42 resolution. Figure 14a shows the resulted comparisons. The satellite observations and model simulations compare reasonably well for most of the rainfall rates. However, model simulations overestimate light surface rainfall below 1 mm/hr. They are also missing the extremely strong events of higher than 20 mm/hr rainfall.

4.1.5 GCE-RAMS

Sample results from a 3D GCE simulation using RAMS 2M microphysics with the aerosol module of Saleeby and van den Heever [2013] depict the nighttime development stage of a low-level stratocumulus deck over northern Vietnam (Fig. 15) that was observed on 7-8 April 2013 during the 7-SEAS/BASELInE field campaign (Loftus *et al*., [2016]; Tsay *et al*., [2016]). The model domain was 14x14x13.6 km in the horizontal and vertical directions, respectively, with horizontal grid spacing of 200 m, and vertical grid spacing stretched from 30 m at the lowest model level to 300 m above 13 km. The large and small time steps were 1 and 0.25 s, respectively. For this particular simulation, only sulfate aerosols served as potential CCN, and the model was initialized with an exponentially decreasing aerosol concentration profile with a maximum of 300 mg^{-1} at the lowest model level. The model was initialized horizontally homogeneously using the 12 UTC atmospheric sounding from Hanoi, Vietnam, and a slightly supersaturated (0.05%) layer in the initial sounding forced the cloud layer to form shortly after model startup. With time, the cloud layer thickened by several hundred meters along with gradual increases in LWC (Fig. 15a), cloud droplet sizes (Fig. 15b), and W-band radar reflectivity (Fig. 15c). Peak N_c values exceeded 200 cm^{-3} during the initial cloud development stage, followed by lower N_c values owing to droplet self-collection (Fig. 15d). Notably, depletion of CN within the cloud (Fig. 15e) and the regeneration of CN owing to evaporation along the cloud boundaries (Fig. 15f) is well captured by the model.

Recently, experiments have been performed in which large ensembles of GCE-RAMS simulations of convection are run, and used to test the spectrum of convection – aerosol responses in different environments. Simulations of the aforementioned TRMM LBA 23 February 1999 case were performed with 2 km grid spacing and 72 model levels (c.f. Posselt, [2016] for details). A 9,900 member ensemble was generated by perturbing the 23 February sounding with temperature, water vapor, and wind empirical orthogonal functions (EOFs) generated from eight years of soundings in the Maritime Continent [Bukowski *et al.* 2017]. Six sets of 1665 simulations were generated, each set having a different sulfate aerosol concentration: [150, 300, 500, 1000, 2000, and 5000 cm^{-3}].

Figure 16 shows histograms of GCE output precipitation rate (16a – 16c) and mean upward vertical velocity (16d – 16f) averaged over times corresponding to storm development (16a,d), maturity (16b,e) and dissipation (16c,f), and for clean (150 cm^{-3}; blue) and polluted (5000 cm^{-3}; red) conditions. The largest effect of increases in aerosol is in the precipitation rates, which exhibit the well-known shift in precipitation rate that occurs during squall line evolution. Early in the development (warm rain only) phase, larger CCN concentrations lead to rain suppression (Fig. 16a). There is little difference in the distribution of rainfall at maturity (Fig. 16b), when convective updrafts are strongest (Fig. 16e). Post-maturity, when the majority of the precipitation is stratiform and vertical velocities are relatively weak, rain rates are larger in the more heavily polluted environment. The simulations exhibit little evidence of vertical velocity enhancement in polluted conditions, though the variance in updraft speeds is larger at maturity (Fig. 16e), and mean vertical velocities are larger for the polluted cases in the dissipating phase (Fig. 16f).

4.2 NU-WRF

Both GCE and NU-WRF have been utilized to improve Goddard latent heating retrieval and surface rainfall/snowfall retrieval for TRMM and GPM (Tao *et al.*, [2006,2016]; Simpson *et al.*, [2006]). This section will present the performance of microphysics schemes associated different weather events simulated by NU-WRF.

4.2.1 3ICE vs 4ICE – MC3E

NU-WRF was used at a relatively high horizontal resolution (i.e., 1 km for the innermost domain[4]) to examine the performance of the Goddard 3ICE and 4ICE microphysics schemes. The strong, well-organized MC3E MCS (20 May 2011) with intense leading edge convection and a well-developed trailing stratiform region (the same GCE case presented earlier) was simulated and the different schemes evaluated in terms of their radar reflectivity structures and distributions, propagation, rainfall, and surface rain rate histograms versus NMQ NEXRAD radar data (see details in Tao *et al*., [2016]).

Figure 17 shows the observed and NU-WRF simulated CFADs. The NU-WRF simulated CFADs with several different microphysics schemes (Goddard 3ICE, Goddard 4ICE, and Morrison 3ICE with two different 3rd class ice options, i.e., graupel or hail) are also shown for comparison. For the observed CFAD (Fig. 17a), the highest probabilities follow a coherent pattern with the peak density steadily decreasing with height from between 20 and 35 dBZ near the melting level to between 5 and 15 dBZ above 12 km, indicative of a robust sedimentation/aggregation effect. Maximum reflectivities at the lowest frequency contour of 0.001% are just over 60 dBZ from the surface up to 6 km and drop off steadily aloft to around 45 dBZ at 14 km. The Goddard 3ICE-graupel scheme simulated CFAD (Fig. 17d) has some notable discrepancies with the observed. Similar to the GCE results, it lacks all of the reflectivity values higher than 45 dBZ above the freezing level. Second, although it captures some of the aggregation effect evident in the observed CFAD, it is too weak with too few echoes in the 20–25 dBZ range between 4 and 8 km. In contrast, the 4ICE scheme (Fig. 17b) can simulate the rare high reflectivity values above the freezing level as was observed. It produces a very realistic radar reflectivity CFAD with a more robust and coherent aggregation signature than the 3ICE graupel scheme that much more closely resembles the observed as well as peak reflectivities similar to the observed and which realistically monotonically decrease with height as observed. The Morrison scheme CFAD with the hail option (Fig. 17f) is in better agreement with the observed than when using the graupel option (Figs. 17e). These results (3ICE vs 4ICE and graupel vs hail) suggested that hail processes are essential for this particular case. In addition, the results suggested that the pre-determined hail option in the Morrison 3ICE scheme performed better than the graupel option for this case (Fig. 17f).

Vertical cross sections of the observed NEXRAD and NU-WRF simulated radar reflectivity are shown in Fig. 18 for comparison. This MC3E case shows a classic continental uni-cellular squall line structure [*Rutledge et al.,* 1998; *Johnson and Hamilton,* 1988; see review by *Houze,* 1997] with deep, erect leading convective cell(s)

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[4] A triple nested domain with 9, 3 and 1 km resolution, respectively, was used.

followed by a wide trailing stratiform region, featuring a distinct high radar reflectivity bright band near the melting level separated from the convective core(s) by a transition area with a less prominent bright band. The Goddard 3ICE graupel scheme produced a wide trailing stratiform region as observed but with too much moderate precipitation and leading edge reflectivities that were too weak (Fig. 18b). Without hail, the graupel scheme simply cannot match the intense radar returns associated with such large solid ice particles while too much moderately falling graupel is transported rearward into the stratiform region. The Goddard 3ICE hail scheme is able to replicate the intense echoes in the convective cores, but the cores are too broad, and the structure of the stratiform region is quite different from the observed with dBZs maximized well above the freezing level and their distribution very non-uniform. In contrast the 4ICE scheme, especially the modified version, can reproduce the narrow, but intense convective cores, a broad, uniform stratiform area with radar echoes that are strongly vertically stratified, and a more well-defined transition region separating it from the leading convection (Fig. 18d). All of which are in good or better agreement with the observed.

Figure 19 show PDFs of the total simulated and observed surface rain rate intensities. Both the hail and 4ICE schemes have a higher proportion of heavy precipitation (i.e., > 30 mm h^{-1}) as well as less moderate precipitation (i.e., 10–20 mm h^{-1}) than does the graupel scheme, placing them in better agreement with the bias-corrected Q2 radar estimates in both situations. Overall, the hail scheme is in the best agreement with the observed frequencies despite its unrealistic anvil radar structure.

4.2.2 Bin – C3VP, MC3E, LPVex

The spectral bin microphysics in Hebrew University Cloud Model (HUCM; Khain *et al.*, [2011, 2012]) was coupled with the WRF (Skamarock, [2008]) model. This coupling enabled cloud-resolving simulations using the spectral bin microphysics for hindcast simulations under realistic conditions beyond conventional idealized simulations. It is beneficial particularly to studies based on comparison with various types of measurement for the validation of the model performance and the development of the discussion on the atmospheric processes. The versions of WRF coupled with the spectral bin microphysics (WRF-SBM) model developed in the NASA Goddard Space Flight Center employ advanced parameterizations with the following functions, compared to the community versions of WRF model released by National Center for Atmospheric Research (NCAR): The particle size distributions (PSDs) of atmospheric hydrometeors are represented by 43 doubling mass bins (33 bins in the community versions). The SBM traces changes of bulk density of snow aggregates through explicit prediction of rimed mass fraction on snow. In addition, a time-dependent melting scheme [Phillips *et al*., 2007] in the SBM to calculate liquid water fractions of ice hydrometeors was replaced with an outdated instantaneous melting scheme. These advanced functions were included to conduct cloud resolving hindcast simulations for specific precipitation events to support the NASA Global Precipitation Measurement (GPM) mission. Several precedence publications showed how WRF-SBM demonstrated the characteristics of cloud microphysics captured in remotely sensed measurements as well as in-situ ground-based and aircraft measurements. The followings provide brief reviews of studies based on WRF-SBM simulations.

Iguchi *et al.* [2012a] investigated two distinct snowfall events observed during the field campaign of the Canadian CloudSat/CALIPSO validation project (C3VP) conducted near Toronto, Canada. The first snow event was local intense lake-effect snowfall developed from Georgian Bay of Lake Huron, and the second event was a widely-distributed modulate snowfall caused by the passage of synoptic low-pressure system. The cloud microphysics of these two events was observed by in-situ measurements. Their characteristics were distinguished by different bulk density of solid-phase hydrometeor particles, which were attributable to the presence or absence of the interaction with super-cooled droplets. The WRF-SBM simulations were conducted to analyze these two snowfall events. A double-nesting domain with 3- and 1-km horizontal grid spacing was used, and the vertical domain extending to a height of approximately 20 km was divided into 60 layers with intervals increasing with altitude. The simulations successfully reproduced these distinct characteristics in the two snowfall events. In particular, riming of snow caused by super-cooled droplets was a key factor in the microphysical characteristics observed in the lake-effect snowstorm. Sensitivity experiments with different planetary boundary layer (PBL) schemes showed that PBL process had a large impact on the cloud microphysics of the lake-effect snowstorm through the change in the generation of super-cooled water in the system.

Figure 20 shows comparison between the ground-based C-band radar and aircraft in-situ measurements and the WRF-SBM simulation results. The observed maximum radar reflectivity distribution characterized the lake-effect snowstorm by narrow and straight reflectivity bands and the synoptic-system snowfall by a wide and uniform reflectivity pattern covering the entire domain. The WRF-SBM reproduced the overall reflectivity distribution through the radar reflectivity simulation using the G-SDSU, except for some forecast errors in snowfall spatial distribution and timing. The aircraft in-situ measurements showed the mixture of high-density rimed snow and low-density snow in the lake-effect snowstorm, whereas the measurements for the synoptic-system snowfall exhibited the presence of low-density snow only. The WRF-SBM simulated roughly the difference of the snow bulk density between the two events, but the mixture of high- and low-density snow in the lake-effect snowstorm was not well reproduced. Employment of different PBL schemes could change the variability of the bulk snow density in the lake-effect snowstorm simulation.

WRF-SBM simulated mid-latitude continental convective and shallow cloud system observed at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site in central Oklahoma during the MC3E field campaign [Iguchi *et al*. 2012b]. The configuration of the model grid resolutions is the same as in the C3VP case simulations. Ground-based disdrometer measurements revealed two distinct modes in the observed rainfall variables caused by precipitation from deep convective clouds and from shallow clouds. The WRF-SBM simulation successfully reproduced similar two distinct modes in calculated rainfall variables that were compatible with those from the actual disdrometer measurements. On the other hand, the analysis of the simulated atmospheric fields showed how the cloud physics and the weather condition in the day with the precipitation event were closely interacted in forming the unique rainfall characteristics.

Figure 21 presents the observation and the WRF-SBM simulation results for the precipitation event (25 April 2011) over the ARM SGP site during MC3E. The vertical reflectivity profiles obtained from Ka-band ground zenith radar measurements show that deep convective clouds passed over the site for a limited time and shallow boundary layer clouds hanged over the site intermittently during most of the day. The bulk effective radii of sampled raindrops and the rainfall rates derived from the disdrometer measurements (Fig. 21c) exhibit two distinct modes according to the sampling time of the precipitation in the day. A corresponding scatter plot (Fig. 21e) derived from the WRF-SBM simulation shows the similar two distinct modes. The horizontal distributions of cloud top temperature and surface raindrop radius at 09 UTC in the simulation (Figs. 21b and 21d) exhibit negative correlation between the two quantities. The shallow clouds with higher cloud top temperature moved over the ARM-SGP site after the passage of the deep convective clouds with lower cloud top temperature.

Simulation of radar bright bands caused by ice particles melting is an advantage of the WRF-SBM model compared with conventional cloud microphysics parameterizations employed in typical weather or climate models. Two precipitation events with mixed-phase clouds over the southern part of Finland during the field campaign of the Light Precipitation Validation Experiment (LPVEx) were simulated using the WRF-SBM [Iguchi *et al.*, 2014]. 36-hours hindcast simulations using WRF-SBM were conducted in a double-nesting domain with 3- and 1.5-km horizontal grid spacing, and its vertical domain with a top height of approximately 20 km was divided into 60 layers with intervals increasing with altitude. Two types of WRF-SBM simulation with or without the time-dependent melting scheme were compared to highlight the effects of ice particles melting on the radar reflectivity and Doppler velocity profiles containing bright band structure.

Figure 22 shows observed and simulated radar reflectivity and Doppler velocity profiles in the form of normalized CFTDs in the first precipitation event. CFTD can show the correlation between frequency distribution of a target quantity and temperature that is important for discussion of the ice particles melting, as compared to conventional normalized CFADs. The radar reflectivity CFTD from the observation (Fig. 22a) shows relatively large reflectivity from 0 to 3°C. The WRF-SBM simulation with the time-dependent melting scheme yields the similar CFTD structure (Fig. 22c), whereas the corresponding simulation using an old-style instantaneous melting scheme is not able to reproduce the structure (Fig. 22e). These features are also confirmed in the line graph for the averages (Fig. 22g). The Figs. 22b, 22d, 22f, and 22hshow that the Doppler velocity gradually increases with temperature in the range from 0° to 3°C in both observation and simulation using the time-dependent melting scheme. In contrast, the CFTD of the simulation using the instantaneous melting scheme does not exhibit such a zone with gradual velocity change.

4.2.3 NE Storm (4 ice vs other WRF Microphysical Parameterization Schemes)

Nicholls *et al.* [2017] investigated how five bulk microphysics parameterization schemes (BMPSs) affected WRF simulations of seven intense wintertime cyclone events ("nor'easters"). The five evaluated BMPSs include the single moment, six-class Lin (Lin6; Lin *et al.*, [1983]), the WRF single-moment, six-class (WSM6; Hong and Lim, [2006]), the Goddard Cumulus Ensemble (GCE) single-moment, six-class "3 ice" (GCE6; Lang *et al.*, [2007]), the GCE single-moment, seven-class "4 ice" (GCE7; Lang *et al.*, [2014]), and the WRF double-moment, six-class (WDM6; Lim and Hong, [2010]) schemes. WRF was configured with 61-vertical levels, four model domains (45-, 15-, 5-, and 1.67-km grid spacing) and was integrated for seven days starting 24-hours prior the onset of rapid cyclogenesis. Model validation of simulated microphysical properties and radar reflectivity structures focused on the multi-radar, multi-sensor 3D radar reflectivity product (MRMS).

Figure 23 shows the cumulative frequency with altitude diagram (CFAD) for the January 2015 nor'easter event derived from MRMS data and WRF model output, which covers a 24-hour period and is representative of all seven events. The MRMS CFAD in Fig. 23 shows two distinct frequency maxima centered around 2,500 m and 12,000 m above mean sea level (AMSL), respectively. GCE7- and Lin6-based WRF simulations best reproduce the lower frequency maximum value, but only GCE7 correctly produced CFADs of similar frequency and slope as MRMS below 6 km AMSL. All other BMPS shifted toward higher reflectivity values due to comparatively higher graupel mixing ratios. As compared to GCE6, GCE7 mitigates graupel generation by including a new snow size map, including deposition processes, improved aggregation physics, and a general reduction in super-cooled cloud droplets. Approaching cloud top (6,000 - 9,000 m AMSL), all WRF CFADs unrealistically collapse toward lower reflectivity values due to entrainment and underlying aggregation assumptions. Notably, the GCE7-based WRF simulation collapses most rapidly, likely due to its comparatively higher snowfall mixing ratios. No WRF simulation produced the MRMS-based CFAD frequency maximum above 10,000 m AMSL, which is likely a byproduct of weak echo filtering in MRMS data product processing.

Complimentary to Fig. 23, Fig. 24 shows CFAD scores in height and time. A CFAD score measures forecast skill by determining the degree of overlap (0 = no overlap, 1 = identical) between radar reflectivity probability density functions calculated for each height and time between MRMS and each WRF simulation. Results from Fig. 24 show GCE7 and Lin6 have the best forecast skill below 5,000 m AMSL, yet GCE7 forecast skill falls below other BMPSs are higher altitudes, a result consistent with Fig. 23. The hourly timeframe of Fig. 24 (versus daily for Fig. 23) does demonstrate these results to be robust and not a product of outlier points or times throughout the event.

4.3 GMMF

The performances of Goddard new 4ICE scheme have been examined by comparison between GMMF and satellite observation (i.e., CloudSat and TRMM). In addition, GMMF with 4ICE scheme have been compared with a cloud-permitting global circulation model.

4.3.1 MMF vs CloudSat

The embedded CRMs in a MMF make it possible to apply CRM-based cloud microphysics directly within a GCM. However, most such schemes are typically developed and evaluated using special field campaign datasets or short-term case study simulations. How well these schemes perform in a global environment for long-term climate simulations is still uncertain and requires comprehensive evaluation. Four one-moment Goddard microphysical schemes, including three 3ICE class (cloud ice, snow, and graupel) and one 4-ice class (cloud ice, snow, graupel, and hail), are implemented into the Goddard MMF and their results validated against CloudSat/CALIPSO cloud ice products and other satellite data. Four GMMF control experiments (named T2003, L2007, L2011 and L2014) are carried out with four different Goddard microphysical schemes (i.e., Tao *et al*., [2003]; Lang *et al*., [2007]; Lang *et al*., [2011]; and Lang *et al*., [2014]) from 1 January 2007 to 31 December 2008. The GMMF was configured to run with 2° x 2.5° (latitude x longitude) GEOS's horizontal grid and 48 vertical layers stretching from the surface to 0.4 hPa. Within each GEOS grid column there is a 64-column 2D GCE with a horizontal spacing of 4 km and a 10 second time step. The 2-year (2007-2008) global total ice water content (TIWC) from CloudSat/CALIPSO 2C-ICE Release 4 product [Deng *et al.*, 2010] and cloud ice water content (CIWC) derived from 2C-ICE [Li *et al*., 2012] are used as the primary validation. The annual mean zonal-height distribution of TIWC and CIWC from the 2C-ICE observations and the four GMMF experiments are shown in Fig. 25. The GMMF TIWC zonal patterns (Figs. 25b-e) are in good agreement with observation with relatively high values over the tropics and mid-latitude storm tracks (though the magnitudes tend to be too low) and low values over subtropical subsidence regions. The asymmetric patterns with a stronger northern branch in the Tropics are well simulated and the southern mid-latitudes have more ocean surface hence produce more ice condensate than the northern. The vertical distribution of total ice in the GMMF simulations is similar to observations except the model cloud tops are lower in high latitude. This may indicate that the vertical resolution of the model is inadequate for simulating the thin cirrus clouds observed by CALIPSO. The 4ICE scheme is superior in terms of its mean zonal cloud ice vertical structure and amount among the four schemes (Figs. 25e and j). In contrast to the other GMMF simulations, which have high cloud ice bases near 400-500 hPa in the Tropics, CIWCs extend down to the freezing level near 600 hPa in L2014 (Fig. 25j) in good agreement with the 2C-ICE products. The better simulation in L2014 is mainly due to the improvements in cloud ice depositional growth and snow/graupel size mappings as discussed in Chern *et al.* [2016].

4.3.2 TRMM vs MMF

The results from GMMF also compared with multi-sensor radiance composites from the TRMM observation through the G-SDSU. Figure 26 a joint diagram of infrared bright temperature (Tb_{IR}) and radar echo-top height (Het) from the TRMM and the GMMF. The diagram is separated into ocean and land component. It also shows CFADs from the TRMM PR and the GMMF. Based on the joint diagram, four types of cloud classification can be identified (left panel, a, c and e in Fig. 26 and Matsui *et al.*, [2009]). These are (1) shallow ($Tb_{IR} > 260$ K and $H_{ET} < 4$ km), (2) congestus ($Tb_{IR} > 245$ K and 4 km $< H_{ET} < 7$ km), (3) Midcold ($Tb_{IR} > 245$ K and 4 km $< H_{ET} < 7$ km), and (4) Deep ($Tb_{IR} < 260$ K and 7 km $< H_{ET}$ b). For the purpose of model evaluation, this separation method is advantageous in that identical radiance-based separation can be applied to both the TRMM observations and simulator-coupled CRM simulations [Masunaga *et al.* 2008]. Two different Goddard microphysics schemes (4ICE and 3ICE) are evaluated. TRMM PR CFADs shows three distinct transitions of reflectivity distributions (right panel, b in Fig. 26): solid-phase (i.e., > 8000 m), mixed phase (i.e., 5000-8000 m) and liquid-phase zones (i.e., < 5000 m). The 4ICE CFAD simulated three distinct microphysics zones as shown in the TRMM observations. The 4ICE microphysics has improved and is much better than the 3ICE (right panel, d and f in Fig. 26). For the joint Tb_{IR}-H_{et} diagram: the performance of the 4ICE microphysics scheme is not as good shown in the CFADs. But its performance is better than the 3ICE scheme for the deep and the shallow cloud categories. Please see Kidd *et al.* [2016] for more detail discussions.

Matsui *et al.* [2016] applied TRMM Triple-sensor Three-Step Evaluation Framework (T3EF) to evaluate the performance of GMMF and a global cloud permitting (or cloud resolving) model, Nonhydrostatic Icosahedral Cloud Atmospheric Model (NICAM) [Satoh *et al.* 2014, Progress in Earth and Planetary Science (PEPS)[5]]. A month-long integration (June 2008) was conducted for the GMMF with 4-km grid spacing in its embedded GCE. However, only 1-week (starts June 15) was conducted in the NICAM (3.5 km grid spacing?) due to expensive computation and data storage. The GMMF and NICAM used the Goddard 4ICE and the NICAM 1-M Water 6 (NSW6; Tomita, [2008]) microphysics scheme, respectively. In addition, Matsui *et al.* [2016] modified the cloud classifications from four to five types based on joint Tb_{IR}-H_{et} diagram. They are shallow Warm, Shallow Cold, Mid-Warm, Mid-Cold and Deep.

Figure 27 shows a joint Tb_{IR}-H_{et} diagram from the TRMM, the GMMF and the NICAM to identify the land-ocean contrast in characteristics of the convective precipitating cloud.. While both the GMMF and the NICAM simulations capture convective land-ocean contrasts in the warm precipitation to some extent (Fig. 27a, b and c), they found that near-surface conditions over land are relatively moister in the NICAM than the GMMF, which appears to be the key driver in the divergent warm precipitation results between the two models. However, continental convective vigor is not captured by the GMMF probably because the GCE in the GMMF is driven by the homogeneous surface forcing, which does not have realistic see-breeze-driven convective system over islands. Nevertheless, neither model could reproduce a realistic land-ocean contrast in in deep convective precipitation microphysics characterized by the PR CFADs. A realistic

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[5] Please see http://progearthplanetsci.org/

contrast between land and ocean remains an issue in global storm-resolving modeling. Please see Matsui *et al.* [2016] for more details.

4.3.3 GMMF and MCS

The importance of precipitating mesoscale convective systems (MCSs) has been quantified from TRMM precipitation radar and microwave imager retrievals. MCSs generate more than 50% of the rainfall in most tropical regions. MCSs usually have horizontal scales of a few hundred kilometers (km); therefore, a large domain with several hundred km is required for realistic simulations of MCSs in cloud-resolving models (CRMs) (i.e., Ooyama, [2001]; Johnson *et al*., [2002]; Petch *et al*., [2001]). Almost all traditional global and climate models do not have adequate parameterizations to represent MCSs. Typical multi-scale modeling frameworks (MMFs) may also lack the resolution (4 km grid spacing) and domain size (128 km) to realistically simulate MCSs.

The impact of MCSs on precipitation is examined by conducting model simulations using GMMF. Figure 28 shows the two-year (2007-2008) annual mean precipitation rate from GPCP and three different GMMF simulations with different MMF embedded CRM configurations (M32: 32 grid points with 4 km grid spacing, M128: 128 grid points with 2 km grid spacing, and M256: 256 grid points with 1 km grid spacing). Overall, the GMMF simulations show very similar surface rainfall patterns and capture the major weather phenomena, such as a single ITCZ and SPCZ and large rainfall over the Indian Ocean, S. America and Eastern Atlantic. However, all of the GMMF simulations over-estimated the total rainfall amount compared to satellite estimates from GPCP (Fig. 28).

However, the GMMF with more CRM grid points and higher resolution (M256) has a lower bias, smaller RMSE and higher correlation versus surface rainfall compared to those with fewer grid points and lower resolution (i.e., M32, M64 and M128). Overall, the M256 and M128 simulations are in better agreement with observations than the M32 and M64 (Fig. 28a and d). The results indicate that models can realistically simulate MCSs with more grid points and higher resolutions compared to those simulations with fewer grid points and low resolution (Fig. 28e and f). The modeling results also show the strengths of the Hadley circulations, mean zonal and regional vertical velocities, surface evaporation, and amount of surface rainfall are weaker or reduced in the GMMF when using more CRM grid points and higher CRM resolution. In addition, the results indicate that large-scale surface evaporation and wind feed back are key processes for determining the surface rainfall amount in the GMMF. Please see Tao and Chern [2017] for more details.

5. Current and Future Research

In this paper, the microphysics schemes used in the Goddard multi-scale modeling systems are reviewed. The performances of these microphysics schemes have been examined by conducting high-resolution model simulations at local (using GCE), regional (using NU-WRF) and global (using GMMF) scales, spanning a wide range of precipitation systems and then validating the results from these model simulations with radar and satellite observations.

There are uncertainties in the cloud and microphysical processes. These uncertainties include the simulated vertical profiles of the cloud/precipitation properties in convective and stratiform regions, the mixed phase processes (melting, riming, ice processes), as well as the life cycle of cloud and precipitation systems. These uncertainties can impact the numerical models across all spatial scales. As the resolutions in general circulation models increase (i.e., NICAM shown in section 4.3.2), explicit cloud and microphysics schemes developed for CRMs are being used for global models (called convection-permitting global models). In this section, current and future research, including the impact of the microphysical schemes on precipitation processes as well as evaluations of their performances using current and future observations, are briefly described.

5.1 Microphysics

All microphysical schemes (including the Goddard 4ICE microphysics schemes) have their own set of unique assumptions and capabilities. Therefore, it is critical to evaluate model performance for a comprehensive range of precipitation systems. Table 6 shows the main characteristics of 1M, 2M, 3M and P3 [Morrison and Milbrandt, 2015] microphysical schemes. For 1M schemes, only mass mixing ratio of cloud hydrometeors (i.e., cloud water, rain, cloud ice, snow, graupel and/or hail) are predicted. In addition to the mass, the total number concentrations of these hydrometeors are also predicted in 2M schemes. For 3M schemes, reflectivities of hydrometeors are also predicted in addition to the mixing ratio and number concentration. The P3 scheme does not differentiate precipitating ice particles (i.e., snow, graupel and hail). It only predicts precipitating solid particles from riming and bulk rime volume for precipitating ice particles. The cloud water, rain and cloud ice are 2M in the P3 scheme[6].

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[6] Note that P3 microphysics scheme will be available in NCAR WRF V3.9. The Goddard 4ICE is currently implementing into NCAR WRF and will be available for WRF community in next version.

The bin microphysical scheme explicitly resolves the hydrometeor size distributions using 43 mass doubling size bins. There is no need to assume any pre-defined particle size distribution. Eight different species, i.e., the aerosols serving as CCN, liquid drops, three types of pristine ice crystals (column, plate, and dendrite), snow aggregates, graupel, as well as hail are included. Riming fractions for aggregates and graupel, and melting fractions for all ice-phase species, are also predicted.

More comprehensive case studies are needed using the different microphysics schemes (i.e., Goddard 3ICE, Goddard 4ICE, Morrison and RAMS). In order for a fair comparison, all common and pre-determined cloud properties and parameters (i.e., densities, intercept, and size distributions) need to be identical (i.e., hail or graupel in the 3ICE scheme as shown in Fig. 16). These inter-comparison studies could identify the "uncertainties" of microphysics schemes by conducting sensitivity tests [i.e., eliminate or reduce/increase some precipitation processes (riming for example) and examining their impact on cloud and precipitation structures and properties]. These comparison studies could also identify the strengths and weaknesses of each scheme by validating their results with observations. The ultimate goal of these comparisons is to reduce uncertainties and improve the performance of each scheme.

5.2 Aerosols and microphysics

Some microphysics schemes require initial CCN (cloud condensation nuclei) and IN (ice nuclei) to activate cloud condensation and ice deposition (see Table 4). These initial CCN and IN distributions (specifications) can have a major impact on the simulated cloud and precipitation properties and surface rainfall (see a review by Tao *et al.*, 2012). Therefore, detailed case studies also need to (1) identify the activation of cloud CCN (and/or giant CCN) and IN in each scheme and set them as close as possible, (2) set the background aerosols identical[7], (3) have all schemes produce common cloud properties and surface rainfall datasets, and (4) couple the radiation explicitly and consistently with the microphysics assumptions and simulated cloud properties (size distributions and optical properties).

5.3 Microphysics evaluation

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[7] The IN and CCN used in the GCE model will be provided by high resolution Goddard Chemistry Aerosol Radiation and Transport (GOCART). The CCN is calculated from the 14 aerosol species predicted by GOCART based on the Koehler curve [Koehler *et al.*, 2006; Andreae and Rosenfeld, 2008], while ice nuclei (IN) is obtained following approach in *DeMott et al.* (2010)

Radar has and will continue to be central to model validation with 3D comprehensive sampling and the ability to profile intense convective cores (see examples shown in section 4). However, simple radar reflectivity (i.e., the sixth moment of particle size distributions) is a necessary but not unique solution; thus, comparisons with additional parameters, including polarimetric radar quantities, can be of great benefit for validating and further refining model physics. As such, in addition to regular radar and microwave signatures, it is planned to compare model-simulated cloud microphysical properties with ZDR, LDR, Kdp, and HID (hydrometeor identification) analyses from polarimetric radar for a variety of different cloud systems. Doppler-derived winds and polarimetric-radar-derived surface rain maps are also critical for model validation.

Specifically, cloud and microphysical schemes can be validated using the following measurements of cloud properties: (1) 3D vertical velocity structures, (2) high temporal resolution aerosol/CCN measurements, (3) vertical hydrometeor particles (ice and liquid droplet spectrum, condensation, size, density) in-situ measurements, and (4) comprehensive Polarmetric radar measurements (i.e., S/C-band ground-based for convective cores and air/space borne or vertically pointing X/K-band for convective/anvil/stratiform characteristics). These measurements can be used to constrain as well as improve the performance of microphysics schemes.

5.4 Cloud and Precipitation Processes Mission (CaPPM, a future satellite mission)

Looking toward the future, global cloud and precipitation process measurements (CaPPM) are needed to provide critical data for fundamental improvements in the understanding of cloud processes and cloud models as described herein. Indeed, in 2017, CRMs are at a roadblock and cannot improve without observational constraints to assess the fidelity of existing microphysical schemes and processes (e.g., Hagos *et al*., 2014, Bassill, 2014, Stephens and Ellis, 2008). This necessitates a paradigm shift away from our current practices that largely observe states to future observing strategies that can deliver information on both states and the processes that govern model physics and prediction skill. Thus, it becomes essential to understand at both the local and global scale the underlying cloud processes (via measurable proxies such as ice microphysics and vertical velocities) that result in precipitation in order to improve the next generation of climate and numerical weather prediction (NWP) models. As the resolutions of these climate models improve over time to be able to explicitly represent cloud and convective processes, it is equally imperative to plan for timely observations to constrain, evaluate and define these processes to produce more accurate predictions of the water cycle. Central to this required knowledge are better predictions of atmospheric water across all spatial scales to know where, when and how clouds form, whether they precipitate or not, and how those patterns may change in a future climate.

As such, a CaPPM mission concept was submitted to the 2017 Earth Science Decadal Survey. The science and application target of the proposed CaPPM concept is the improvement of cloud and precipitation processes in Earth system models through focused global space-borne measurements of cloud and precipitation vertical velocities and hydrometeor microphysical characteristics. These relate directly to microphysical processes that form the key linchpin of uncertainty in Earth system predictive capacities and would bring fundamental insights and essential improvements to the models described herein.

5.5 Data distribution through a cloud library

The Goddard Mesoscale and Dynamics Modeling Group has generated and made available a multi-dimensional (space, time, multivariate, and multiple cloud/cloud system type) cloud database representing different geographic locations/climate regimes to the global modeling community to help improve the representation and performance of moist processes in climate models, and to improve our understanding of cloud and precipitation processes globally. This database is available to modelers and other researchers aiming to improve representations of cloud processes in GCMs and climate models. The cloud dataset is available to the public community via ftp access from a web site created within NASA Goddard (Goddard Cloud Library, http://cloud.gsfc.nasa.gov/).

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7. References