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The Goddard Multi-Scale Modeling System with Unified Physics

W.-K. Tao[1], J. Chern[1,2], T. Iguchi[1,3], S. Lang[1,4], C. Peters-Lidard[5], X. Li[1,2],
T. Matsui[1,3], K. Mohr[1], B.-W. Shen[1,3], J. J. Shi[1,2], and X. Zeng[1,2]

[1]*Laboratory for Atmospheres, NASA/Goddard Space Flight Center, Greenbelt, Maryland*
[2]*Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Maryland*
[3]*Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland*
[4]*Science Systems and Applications Inc., Greenbelt, Maryland*
[5]*Laboratory for Hydrospheric Processes, NASA/Goddard Space Flight Center, Greenbelt, Maryland*

1. Introduction

The foremost challenge in parameterizing subgrid convective clouds and cloud systems in large-scale models is the many coupled physical processes (*i.e.*, radiation and surface processes) that interact over a wide range of scales, from microphysical scales to the meso-scale. This makes the comprehension and representation of convective clouds and cloud systems one of the most complex scientific problems in earth science. On one hand, clouds and cloud systems owe their origin to large-scale dynamic and thermodynamic forcing, radiative cooling in the atmosphere, and turbulent transfer processes at the surface (*e.g.*, the transfer of heat and moisture from the ocean to the atmosphere). On the other hand, clouds and cloud systems serve

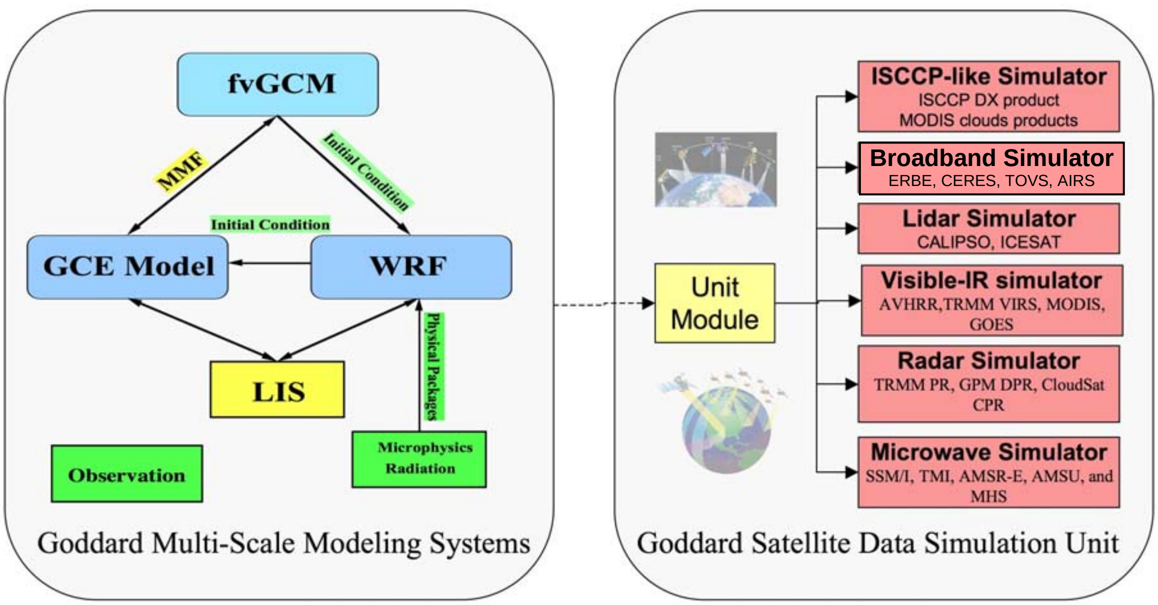

Fig. 1 Schematic diagram of the Goddard Multi-scale Modeling System with unified physics coupled with the Goddard Satellite Data Simulation Unit (SDSU). The coupling between the fvGCM and GCE is two-way [termed a multi-scale modeling framework (MMF)], while the coupling between the fvGCM and WRF and WRF and the GCE is only one-way. LIS is the Land Information System developed in the Goddard Hydrological Sciences Branch. LIS has been coupled interactively with both WRF and the GCE. Additionally, WRF has been enhanced by the addition of several of the GCE model's physical packages (i.e., microphysical scheme with four different options and short and long-wave radiative transfer processes with explicit cloud-radiation interactive processes). Observations (obtained from satellite and ground-based campaigns) play a very important role in providing data sets for model initialization and validation and consequently improvements. The Goddard SDSU can convert the simulated cloud and atmospheric quantities into radiance and backscattering signals consistent with those observed from NASA EOS satellites.

Correspondence to: W.-K. Tao, Laboratory for Atmospheres, NASA/Goddard Space Flight Center, Greenbelt, Maryland; E-mail: wei-kuo.tao-1@nasa.gov

as important mechanisms for the vertical redistribution of momentum, trace gases (including the greenhouse gas, CO2), aerosols, and sensible and latent heat on the large-scale. It is also generally accepted that the proper representation of physical cloud processes in GCMs (general circulation models) is vital to advancing their predictive skill of the water and energy cycles.

As such, the highest science priority identified in the Global Change Research Program (GCRP) is the role of clouds and their interaction with radiation in climate and hydrological systems. For this reason, the Global Energy and Water Cycle Experiment (GEWEX) formed the GEWEX Cloud System Study (GCSS) to address such problems. Cloud ensemble models [CEMs, also called cloud-resolving models (CRMs) or cloud-system resolving models (CSRMs)] were identified as the primary means for carrying out these studies. CRMs now provide statistical information useful for developing more realistic statistics- or physics-based parameterizations for climate models. A CRM, typically, is not a global model and can only simulate cloud ensembles over a relatively small domain (*i.e.*, 500-1000 x 500-1000 km^2). To better represent convective clouds and cloud systems in large-scale models, a GCM coupled with CRMs (termed a *super-parameterization* or *multi-scale modeling framework*, *MMF*) is required given the feasible computational power. The use of a GCM enables global coverage, while the CRMs allow for better and more sophisticated physical parameterizations (*i.e.*, CRM-based physics). In addition, the MMF can utilize current and future satellite programs that provide cloud, precipitation, aerosol and other data at very fine spatial and temporal scales over the entire globe.

Type of Model (Spatial Scale)	**Strengths**	**Weaknesses**
GCMs (10^2 km)	Global Coverage Climate Change Assessment	Coarse Resolution Cumulus Parameterization
Regional Scale Models (10^1 - 10^0 km)	Regional Coverage – Regional Climate Better parameterization (nesting technology)	No Feedback to Global Circulation Case Study
Cloud Resolving Models (10^0 – 10^{-1} km)	Better physics Better Treatment of Cloud-Radiation Interaction	Small Domain No Feedback to Global Circulation Case Study (Field Campaign)
Coupled GCM-CRM (MMF) (10^2 – 4 km)	Global Coverage CRM-Based Physics	Computational Cost 2D CRM Embedded (4 km grid)
Global Cloud Resolving Model (0^0 km)	Global Coverage CRM-Based Physics	Computational Cost Data Management/Analyses

Table 1 A brief summary of the strengths and weaknesses of different modeling approaches

The traditional CRM, however, needs large-scale advective forcing in temperature and water vapor from intensive sounding networks deployed during major field experiments or from large-scale model analyses to be imposed as an external forcing. The advantage of this approach is that the simulated rainfall, temperature and water vapor budget are forced to be in good agreement with observations (see Tao and Moncrieff 2003; Tao 2003, 2007 for review). But, there is no feedback from the CRM to the large-scale model (*i.e.*, the CRM environment). In contrast, an MMF allows explicit interactions between the CRM and the GCM. With the traditional approach, CRMs can only examine the sensitivity of model grid size or physics for one type of cloud/cloud system at a single geographic location. MMFs, however, could be used to identify the optimal grid size and physical processes (*i.e.*, microphysics, cloud-radiation interaction) on a global scale. For example, MMFs can be used to identify the optimal grid size and physical processes (*i.e.*, microphysics, cloud-radiation interactions) needed for non-hydrostatic global CRMs (Satoh *et al.* 2005; Nasuno *et al.* 2008[1]).

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[1] This model is intended for high-resolution climate simulations and has been performed on an aqua planet setup with grid intervals of 7 and 3.5 km for seasonal simulation (due its extensive computation requirement and data storage).

Regional forecast models (*i.e.*, the Weather Research and Forecasting Model or WRF) can also be conducted in CRM mode and could cover large domains (*i.e.*, a tropical channel model) through a two-way interactive nesting technique. The physical processes developed/tested for CRMs could be also used for regional scale models from idealized research to operational forecasting. It is expected that a close collaboration between CRMs, regional scale models, MMFs and non-hydrostatic high-resolution regional and global cloud resolving models can enhance our ability to simulate realistic weather and climate in the near future. The strengths and weaknesses of different modeling approaches are summarized in Table 1.

2. The Goddard Multi-Scale Modeling System

Recently, a multi-scale modeling system with unified physics was developed at NASA Goddard. It consists of (1) the Goddard Cumulus Ensemble model (GCE), a cloud-resolving model (CRM), (2) the NASA unified Weather Research and Forecasting Model (WRF), a region-scale model, and (3) the coupled fvGCM-GCE, the GCE coupled to a general circulation model (MMF). The same cloud microphysical processes, long- and short-wave radiative transfer and land-surface processes are applied in all of the models to study explicit 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 1 shows the multi-scale modeling system with unified physics. The GCE and WRF share the same microphysical and radiative transfer processes (including the cloud-interaction) and land information system (LIS). The same GCE physics will also be utilized in the Goddard MMF.

The idea to have a multi-scale modeling system with unified physics is to be able to propagate improvements made to a physical process in one component into the other the components smoothly and efficiently. In addition, this model system has been coupled to a *Satellite Data Simulation Unit* that can compute satellite-consistent radiances or backscattering signals from simulated atmospheric profiles and condensates consistent with the unified microphysics within the multi-scale modeling system (Fig. 1).

Parameters/Processes	GCE Model
Dynamics	Anelastic or Compressible 2D (Slab- and Axis-symmetric) and 3D
Vertical Coordinate	Z (height)
Microphysics	2-Class Water & 3-Class Ice 2-Class Water & 2-Moment 4-Class Ice Spectral-Bin Microphysics
Numerical Methods	Positive Definite Advection for Scalar Variables; 4th-Order for Dynamic Variables
Initialization	Initial Conditions with Forcing from Observations/Large-Scale Models
FDDA	Nudging
Radiation	k-Distribution and Four-Stream Discrete-Ordinate Scattering (8 bands) Explicit Cloud-Radiation Interaction
Sub-Grid Diffusion	TKE (1.5 order)
Surface Energy Budget	Force-Restore Method 7-Layer Soil Model (PLACE), Land Information System (LIS) TOGA COARE Flux Module
Parallelization	OPEN-MP and MPI

Table 2 Major characteristics of the Goddard Cumulus Ensemble (GCE) Model

2.1 Goddard Cumulus Ensemble (GCE) Model.

The GCE model, a CRM, has been developed and improved at NASA Goddard Space Flight Center over the past two and a half decades. The ability of the GCE model to simulate the impact of atmospheric aerosol concentrations on precipitation processes was recently enhanced (Tao *et al.* 2007) as were its abilities to account for the effects of land (Zeng *et al.* 2007) and ocean surface processes on convective systems in different geographic locations (Wang *et al.* 2003; Tao *et al.* 2004; Zeng *et al.* 2008). The GCE model's bulk microphysical scheme were recently modified to reduce the over-estimated and unrealistic amount of graupel in the stratiform region (Tao *et al.* 2003; Lang *et al.* 2007), to better address saturation issues (Tao *et al.* 2003) and to obtain more realistic ice water contents for longer-term simulations (Zeng *et al.* 2008, 2009). Recently, the GCE model has been adapted to interface with a couple of other bulk microphysical schemes, namely the single and double moment versions of the Colorado State University (CSU) Regional Atmospheric Modeling System's (RAMS's) bulk microphysical scheme (Meyers *et al.* 1997; Saleeby and Cotton 2004), and a spectral bin microphysical scheme (Khain *et al.* 2004; Tao *et al.* 2007; Li *et al.* 2009a&b). The development and main features of the GCE model were published in Tao and Simpson (1993) and Tao *et al.* (2003). A review on the application of the GCE model to better understand precipitation processes can be found in Tao (2003). Table 2 shows the major characteristics of the GCE model.

2.2 *Goddard Unified Weather Research and Forecasting Model (WRF)*

The second component of the modeling system is WRF (Michalakes *et al.* 2004), a next-generation mesoscale forecast model and assimilation system developed at NCAR along with several NOAA and DOD partners. The model is designed to support research advancing the understanding and prediction of mesoscale precipitation systems. It incorporates advanced numerics and data assimilation techniques and has a multiple re-locatable nesting capability as well as improved physics. WRF will be used for a wide range of applications, from idealized research to operational forecasting, with an emphasis on horizontal grid sizes in the range of 1-10 km.

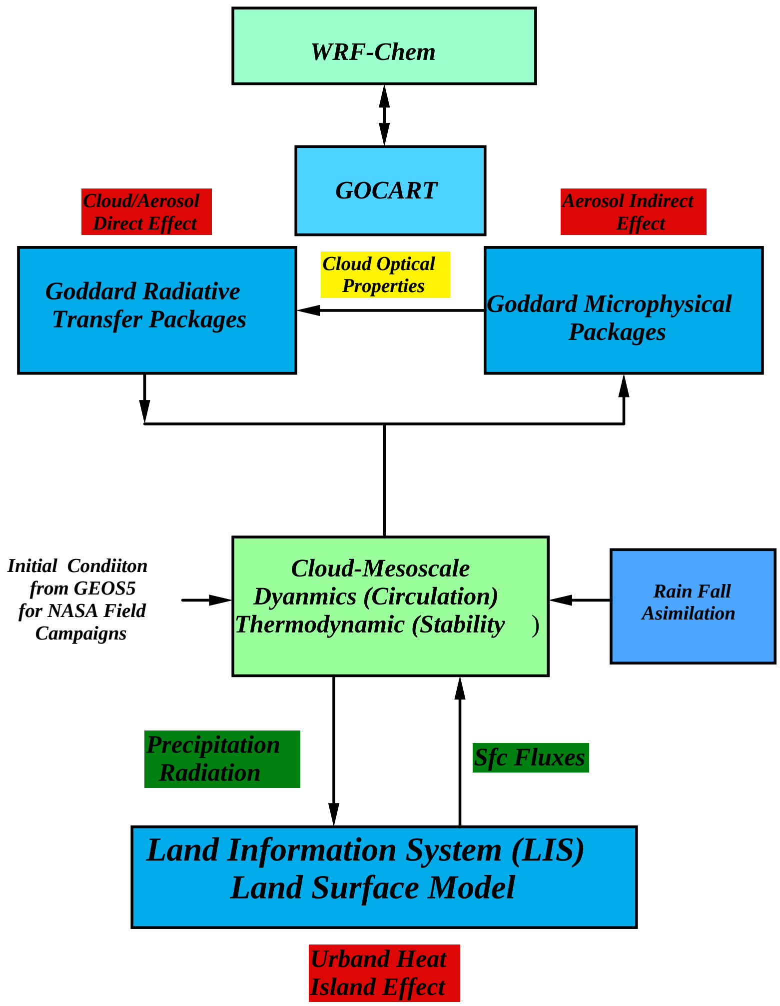

Fig. 2 Schematic diagram showing planned components of the NASA unified WRF. The blue boxes represent physical processes (packages) developed by NASA scientists. The light green boxes represent the WRF dynamical core and others (*i.e.*, NCAR) developed outside of NASA. GOCART stands for Goddard Chemistry Aerosol Radiation and Transport model.

Various Goddard physical packages (*i.e.*, CRM-based microphysics, radiation and land-surface hydrology processes) as well as a real-time forecast system using Goddard Earth Observing System (GEOS) global analyses that have been developed at NASA have recently been implemented into WRF (Fig. 2). The CRM-based packages have improved forecasts (or simulations) of convective systems [*e.g.*, a linear convective system in Oklahoma (International H2O project, IHOP-2002), an Atlantic hurricane (Hurricane Katrina, 2005), high latitude snow events (Canadian CloudSat CALIPSO Validation Project, C3VP 2007), and a heavy orographic-related precipitation event in Taiwan (Summer 2007)]. In addition, two other GSFC modeling components have been coupled to the GSFC WRF representing the land surface (*i.e.*, the Land Information System or LIS) and aerosols [*i.e.*, the WRF Chemistry Model and Goddard Chemistry Aerosol Radiation and Transport Model (GOCART)].

2.3 Goddard Multi-Scale Modeling Framework (MMF)

The third component of the modeling system couples the NASA Goddard finite volume GCM (fvGCM) with the GCE model (known as the Goddard MMF)[2]. The use of the fvGCM allows for global coverage and the use of the GCE for the explicit simulation of subgrid cloud processes and their interaction with radiation and surface processes. This modeling system has been applied to the study of climate scenarios such as the 1998 El Nino and 1999 La Nina. The new coupled modeling system results in the more realistic propagation and intensity of tropical rainfall systems and intra-seasonal oscillations and an improved diurnal variation of precipitation; all are difficult to capture using even state-of-the-art GCMs with subgrid convection schemes. The new Goddard MMF is the second MMF developed worldwide following the one at CSU. Despite differences in model dynamics and physics between the Goddard and CSU MMFs, both simulate stronger MJOs, better cloudiness (high and low), single ITCZs and more realistic diurnal rainfall patterns than traditional GCMs. Both MMFs also have similar biases, such as a summer precipitation bias (relative to observations and to their parent GCMs) in Asian monsoon regions. However, there are notable differences between the two MMFs. For example, the CSU MMF simulates less rainfall over land than its parent GCM, which is why it simulates less global rainfall than its parent GCM. The Goddard MMF simulates more global rainfall than its parent GCM because of a high contribution from its oceanic component. Please see Tao *et al.* (2009) for a detailed discussion.

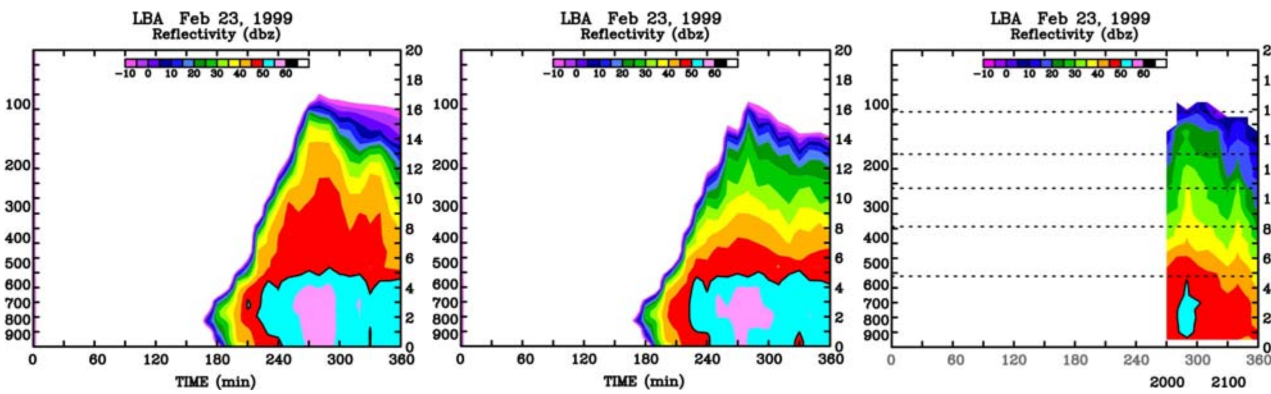

Fig. 3 Time-height cross sections of maximum radar reflectivity obtained from 3D simulations of the 23 February 1999 easterly regime event observed during TRMM LBA (Large Scale Biosphere-Atmosphere Experiment in Amazonia) using the original Rutledge and Hobbs (1984) based bulk microphysics formulation (left panel), an improved version (midde panel) and observed (right panel). Climatologically, 40-dBZ penetrations above 10 km are rare even over land (Zipser *et al.* 2006; Li *et al.* 2008). Ground-based radar data for this case indicated 40-dBZ echoes reached to approximately 8 km.

2.4 Goddard Satellite Data Simulation Unit (GSSU)

The Goddard SDSU is a multi-satellite simulator unit. It has six simulators at present: passive microwave, radar, visible-infrared spectrum, lidar, ISCCP type, and broadband (see Fig. 1). The SDSU can compute satellite-consistent radiances or backscattering signals from simulated atmospheric profiles and condensates consistent with the unified microphysics within the multi-scale modeling system (Fig. 1). These simulated radiances and backscattering signatures can be directly compared with satellite observations, establishing a satellite-based framework for evaluating the cloud parameterizations. This method is superior to the traditional method of validating models with satellite-based products, since models and satellite products often use different assumptions in their cloud microphysics (Matsui *et al.* 2009). Once the cloud

[2] The typical configuration for the Goddard MMF consists of the fvGCM run with 2.5° x 2° horizontal grid spacing with 32 layers from the surface to 0.4 hPa and the two-dimensional (2D) GCE using 64 horizontal grids (in the east-west orientation) and 32 levels with 4 km horizontal grid spacing and cyclic lateral boundaries. The time step for the 2D GCE is 10 seconds, and the fvGCM-GCE coupling interval is one hour, which is the fvGCM physical time step.

model reaches satisfactory agreement with the satellite observations, simulated clouds, precipitation, atmospheric states, and satellite-consistent radiances or backscattering will be provided to the science community as an *a priori* database for developing physically-based cloud and precipitation retrieval algorithms. Thus, the SDSU coupled with the multi-scale modeling system can lead to a better understanding of cloud processes in the Tropics as well as improved precipitation retrievals from current and future NASA satellite missions [*i.e.*, TRMM, the A-Train, GPM (Global Precipitation Measurement), and the ACE mission].

3. Results

3.1 The improvements of the microphysics scheme

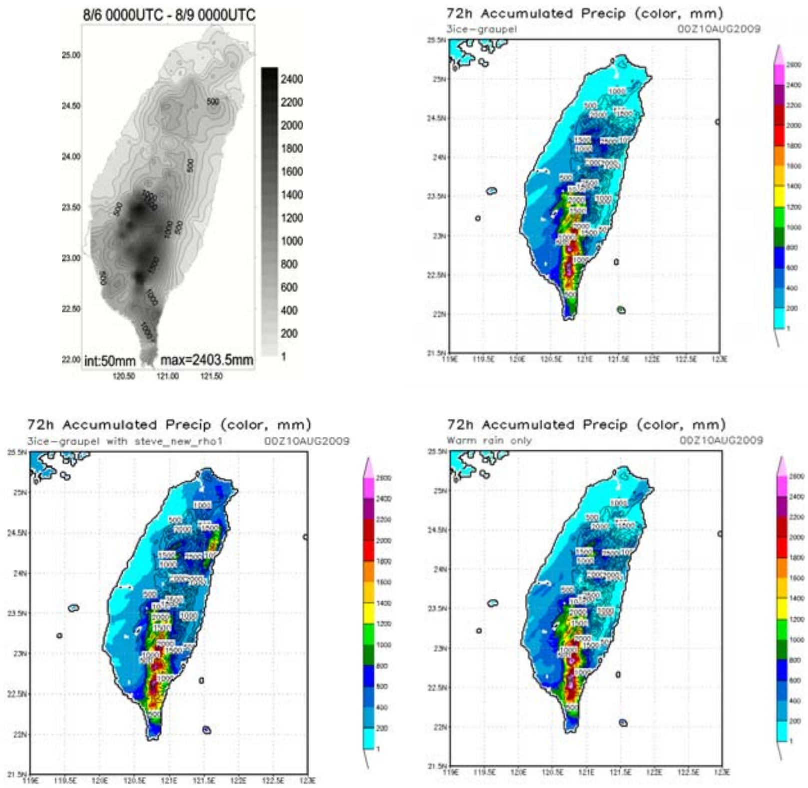

Fig. 4 Observed (left-top) and model simulated accumulated rainfall from August 6 0000UTC to August 9 0000UTC 2009. The original (right-top), improved (left-bottom) and warm rain only (right-bottom) are shown for comparison with observation.

There is a well-known bias common to many of the bulk microphysics schemes currently being used in cloud-resolving models. It involves the tendency for these schemes to produce excessively large reflectivity values (*e.g.*, 40 dBZ) in the middle and upper troposphere in simulated convective systems and is primarily due to excessive amounts and/or sizes of graupel (*e.g.*, Lang *et al.* 2007; Li *et al.* 2008). This bias is also related to a bias in excessive simulated ice scattering. The Rutledge and Hobbs (1983, 1984) based bulk microphysics scheme within the GCE model (Lang *et al.* 2011 and Fig. 3) and WRF (Tao *et al.* 2011 and Fig. 4) is modified to reduce this bias. Systematic evaluation of the scheme resulted in the following changes to individual processes: the efficiencies for snow and graupel riming and snow accreting cloud ice were lowered or made dependent on collector particle size, thresholds for converting rimed snow to graupel were tightened, snow and graupel were allowed to sublimate out of cloud, simple rime splintering, immersion freezing and contact nucleation parameterizations were added, the Fletcher (1962) curve for the number of activated ice nuclei was replaced with the Meyers *et al.* (1992) formulation throughout, the saturation adjustment scheme was relaxed to allow water saturation at colder temperatures and the presence of ice super saturation, ambient relative humidity and cloud ice size were accounted for in the "Bergeron" growth of cloud ice to snow, cloud ice fall speeds following Hong *et al.* (2004) were added and accounted for in the sweep volumes of processes accreting cloud ice, and the threshold for snow auto-conversion was changed to physical units. In addition, size-mapping schemes for snow and graupel were added whereby the characteristic size (*i.e.*, inverse of the slope parameter for the inverse exponential distributions) was specified based on temperature and mixing ratio, effectively lowering the size of particles at colder temperatures while still allowing particles to become larger near the melting level and at higher mixing ratios.

3.2 WRF simulated Typhoon Morakot case

In recent years, heavy rainfall associated with severe weather events (*e.g.*, typhoons, local heavy precipitation events) has caused significant damage to the economy and loss of human life throughout Taiwan. For example, Typhoon Morakot struck Taiwan on the night of Friday August 7th, 2009 as a Category 2 storm with sustained winds of 85 knots (92 mph). Although the center made landfall in Hualien county along the central east coast of Taiwan and passed over the central northern part of the island, it was southern Taiwan that received the worst effects of the storm where locally as much as 2400 mm of rain were reported, resulting in the worst flooding there in 50 years. The enormous amount of rain resulted in massive flooding and devastating mudslides. More than 600 people were confirmed dead (including hundreds of people in Shiao Lin Village, which was buried by a large mudslide).

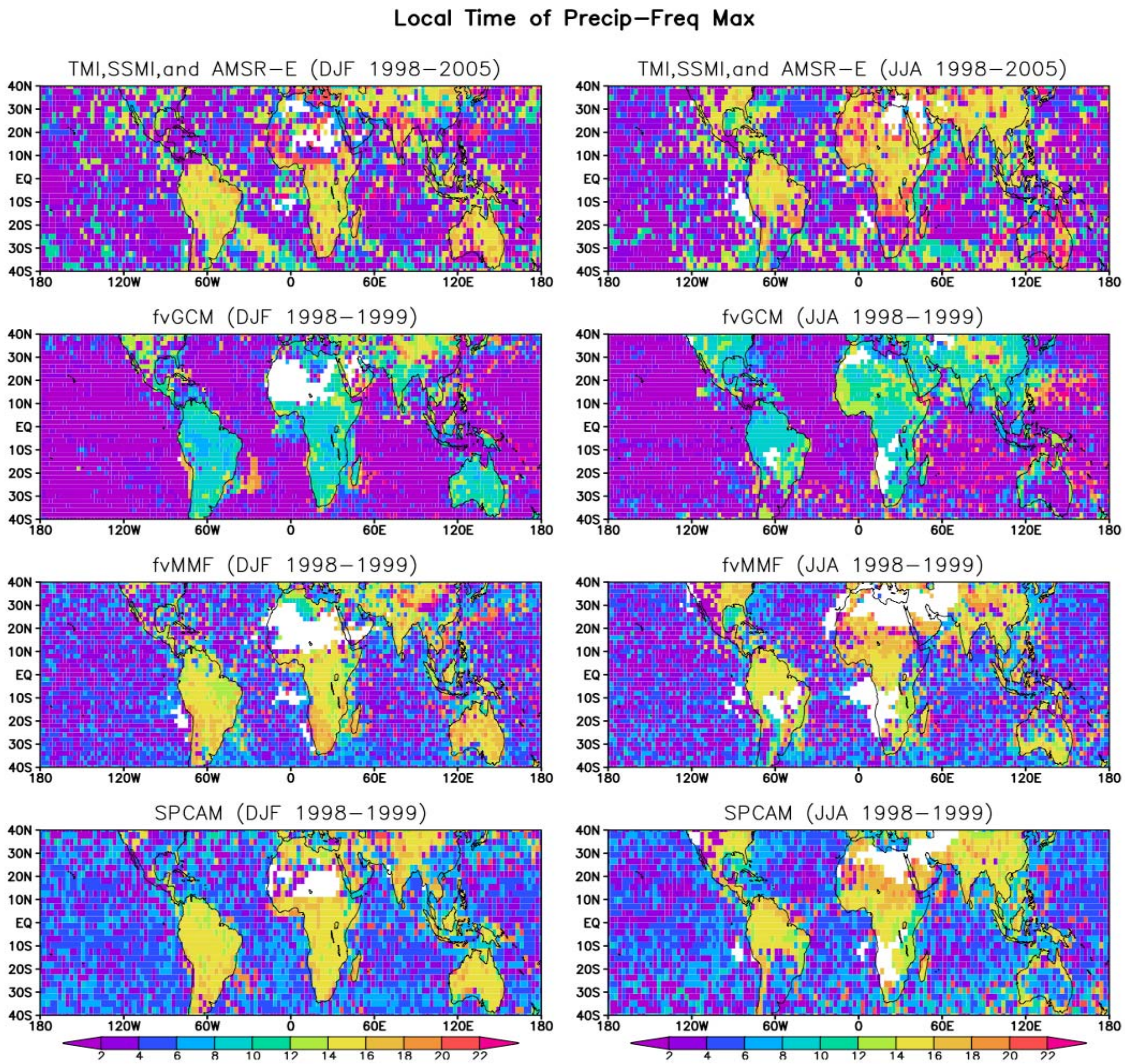

Fig. 5 Geographical distribution of the LST for the non-drizzle precipitation frequency maximum in winter (left panels) and summer (right panels) as observed by satellite from 1998-2005 (upper panels), simulated with the Goddard fvGCM (middle-upper panels) for two years (1998-1999), Goddard MMF (middle-lower panels) and CSU MMF (bottom panels). Blank regions indicate no precipitation. The MMF results are based on detailed 2D GCE model-simulated hourly rainfall output. Satellite retrieved rainfall is based on a 5-satellite constellation including the TRMM Microwave Imager (TMI), Special Sensor Microwave Imager (SSMI) from the Defense Meteorological Satellite Program (DMSP) F13, F14 and F15, and the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) onboard the Aqua satellite.

Figure 4 shows the observed and WRF-simulated rainfall using three different options (improved and original 3ICE-graupel) and warm rain only in the Goddard microphysical scheme. Generally speaking, WRF produced the right distribution of precipitation for this typhoon case despite using different Goddard microphysical options. For example, in all of the runs the main precipitation event is elongated in the southwest-northeast direction and concentrated in a heavy north-south line over southern Taiwan as observed. All options resulted in simulations wherein the main area of precipitation continued over southern Taiwan over the 72-h period. This feature also agrees with observations. The results (with high resolution visualization) show that a persistent (over 48 h) southwesterly flow associated with Morakot and its circulation was able to draw up copious amounts of moisture from the South China Sea into southern Taiwan where it was able to interact with the steep topography in all four microphysical options. These results suggest that the main rainfall distribution in the Morakot case is determined by the large-scale circulation pattern (*i.e.*, the typhoon-induced circulation). The interaction between the terrain and moisture flux was the dominant factor that led to the floods/landslides in this case. All of the options produced more than 2000 mm of accumulated rainfall over southern Taiwan. The improved 3ICE-graupel produced more rainfall over northeastern Taiwan, which may be in better agreement with observations than other schemes (see Fig. 4). In addition, the warm-rain-only produced almost similar results as other two cases in terms of rainfall pattern, maximum rainfall (> 2500 mm) and total amount rain over South Taiwan and whole Island (Fig. 4). These results suggested that the warm rain processes are dominant for precipitation processes.

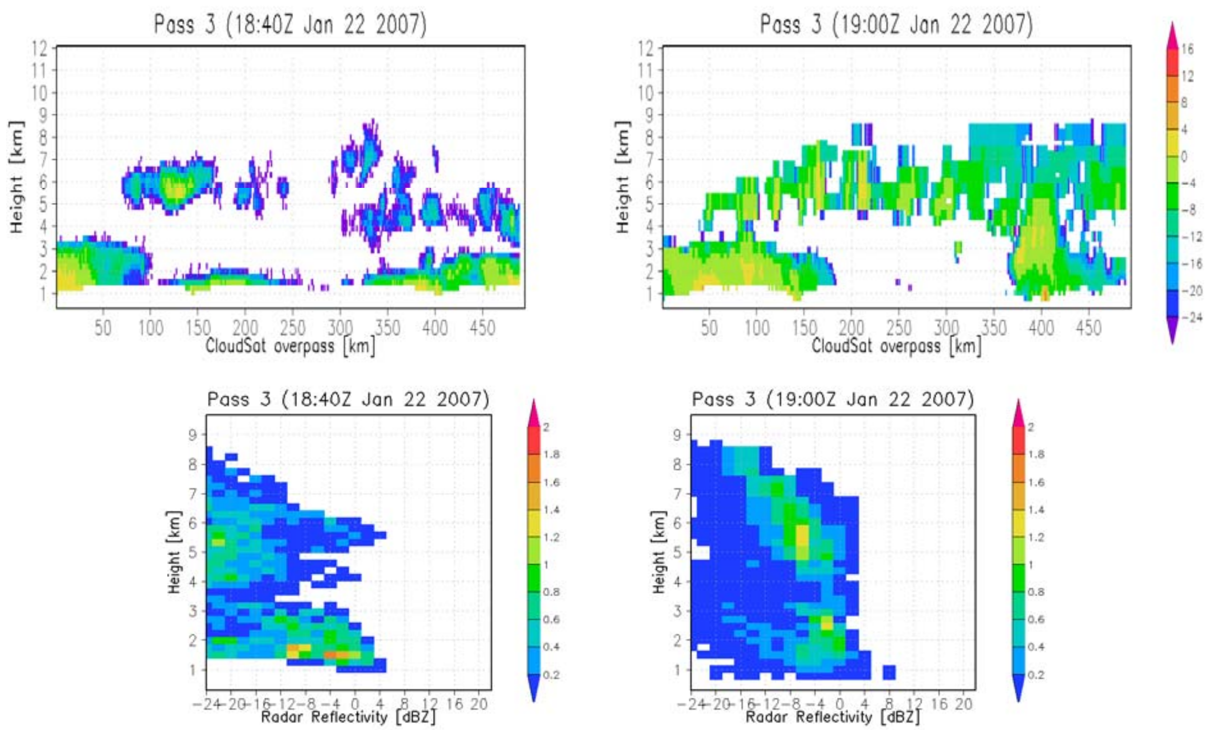

Fig. 6 Instantaneous cross-sectional snap shot (upper panels) and contoured frequency with altitude diagrams (CFADs) (lower panels) of CloudSAT-observed (left) and WRF-SDSU-simulated (right) Cloud Profiling Radar (CPR, 94 GHz) reflectivities.

3.3 MMF simulations of diurnal variation of precipitation systems

The diurnal cycle is a fundamental mode of atmospheric variability. 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 1987, Randall *et al.* 1991, Lin *et al.* 2000). Figure 5 shows the geographical distribution of the local solar time (LST) of the non-drizzle precipitation frequency maximum in winter and summer of 1998 as simulated by the fvGCM, fvMMF, and CSU MMF. Satellite microwave rainfall retrievals from a 5-satellite constellation are analyzed at 1-hour intervals from 1998 to 2005 for comparison. The non-drizzle precipitation is defined as precipitation that occurs such that the 1-hour averaged rain rate is larger than 1 mm/day (see Lin *et al.* 2007).

Satellite microwave rainfall retrievals in general show that precipitation occurs most frequently in the afternoon to early evening over the major continents such as South and North America, Australia, and west and central Europe, reflecting the dominant role played by direct solar heating of the land surface. Over open oceans, a predominant early morning maximum in rain frequency can be seen in satellite observations, consistent with earlier studies (see a review by Sui *et al.* 1997, 2008). The MMF is superior to the fvGCM in reproducing the correct timing of the late afternoon and early evening precipitation maximum over the land and the early morning precipitation maximum over the oceans. The fvGCM, in contrast, produces a dominant morning maximum rain frequency over major continents. Additional and more detailed comparisons between the observed and MMF-simulated diurnal variation of radiation fluxes, clouds and precipitation under different large-scale weather patterns and different climate regimes will be published elsewhere.

3.4 Evaluating model microphysics with the coupled satellite simulator

WRF, configured with the Goddard microphysics and radiation schemes, was used to simulate two snow events (January 20-22, 2007) over the C3VP site in Ontario, Canada (Shi *et al.* 2010). Figure 6 displays 94GHz radar reflectivities from CloudSAT observations and WRF-SDSU simulations. The cross-sectional comparison indicates that WRF successfully captured the spatial distribution of radar reflectivity, while the statistical comparison using contoured frequency with altitude diagrams (CFADs) shows that WRF overestimated radar reflectivity above 4 km. This result demonstrates that WRF was able to capture the cloud macro-structure reasonably well but not the cloud microphysics. An improved version of the microphysics is now being developed based largely on the comparison between model-simulated and satellite-observed cloud and precipitation properties (Matsui *et al.* 2009). Improved microphysics and hence model simulations are necessary to provide consistent 4D thermodynamic and dynamic cloud data sets for future GPM snow retrievals and to improve our understanding of precipitation processes over high-latitude regions.

4. Conclusions

Significant advances in the use of CRMs to simulate and improve our understanding of convective dynamics and its interaction with microphysics, precipitation, clouds, radiation, surface effects and boundary layers across multiple scales have been made over the past four decades. These model simulations are vital for comprehending the interaction between cloud systems and the large-scale circulation and also play a key role in the retrieval of precipitation and latent heating from satellite measurements (*i.e.*, Tao *et al.* 2006). The unified physics in the multi-scale modeling system is mainly based on those developed for the CRMs. However, the enormous dynamic range of modern CRMs presents new challenges for validation. This will involve integrated satellite simulators, satellite datasets, field-campaign analysis, CRMs, high-resolution NWP models (*i.e.*, WRF), and the MMF.

Global CRMs have already been run on an experimental basis, made possible by ever-improving computing power (Satoh *et al.* 2005). It is expected that by incorporating physical packages[3] originally developed for high-resolution process models such as CRMs into NWP models and GCMs along with the continuing development of global CRMs, the ability to simulate realistic weather and climate in the near future will be greatly enhanced (see Tao and Moncrieff 2009 for more discussion).

Acknowledgements. The GCE model and WRF-GCE coupling are supported by the NASA Headquarters Atmospheric Dynamics and Thermodynamics Program and the NASA Tropical Rainfall Measuring Mission (TRMM). The Goddard MMF is supported by NASA MAP (Modeling and Analyses Prediction). The coupling between WRF-LIS and GCE-LIS is supported by the NASA Earth Science Technology Office. We also acknowledge support by the NASA Grant: NNX06AF30G – Global Environmental Change-hazards and regional impacts, and support by the technical officers Don Anderson and Lucia Tsaoussi.

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[3] Note that the microphysics scheme and its interactions with radiation and surface processes are still the major uncertainty and need to be developed, improved and validated.

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