A Goddard Multi-Scale Modeling System with Unified Physics

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Popular Summary

Numerical cloud resolving models (CRMs), which are based the non-hydrostatic equations of motion, have been extensively applied to cloud-scale and mesoscale processes during the past four decades. Recent GEWEX Cloud System Study (GCSS) model comparison projects have indicated that CRMs agree with observations in simulating various types of clouds and cloud systems from different geographic locations. Cloud resolving models now provide statistical information useful for developing more realistic physically based parameterizations for climate models and numerical weather prediction models. It is also expected that Numerical Weather Prediction (NWP) and regional scale model can be run in grid size similar to cloud resolving model through nesting technique.

Current and future NASA satellite programs can provide cloud, precipitation, aerosol and other data at very fine spatial and temporal scales. It requires a coupled global circulation model (GCM) and cloud-scale model (termed a *super-parameterization* or *multi-scale modeling framework, MMF*) to use these satellite data to improve the understanding of the physical processes that are responsible for the variation in global and regional climate and hydrological systems. The use of a GCM will enable global coverage, and the use of a CRM will allow for better and more sophisticated physical parameterization. NASA satellite and field campaign can provide initial conditions as well as validation through utilizing the Earth Satellite simulators.

At Goddard, we have developed a multi-scale modeling system with unified physics. The modeling system consists a coupled GCM-CRM (or MMF); a state-of-the-art weather research forecast model (WRF) and a cloud-resolving model (Goddard Cumulus Ensemble model). In these models, the same microphysical schemes (2ICE, several 3ICE), radiation (including explicitly calculated cloud optical properties), and surface models are applied. In addition, a comprehensive unified Earth Satellite simulator has been developed at GSFC, which is designed to fully utilize the multi-scale modeling system. A brief review of the multi-scale modeling system with unified physics/simulator and examples is presented in this article.

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The foremost challenge in parameterizing convective clouds and cloud systems in large-scale models is the many coupled, physical processes (e.g., radiation and surface processes) that interact over a wide range of scales, from microphysical to regional (or mesoscale). This makes the comprehension and representation of convective clouds and cloud systems in general circulation models (GCMs) and climate models one of the most complex scientific problems in earth science. . It is generally accepted that properly representing physical cloud processes in GCMs is central to significantly advance their water and energy cycle prediction skill.

Cloud-resolving models [CRMs, also called cloud ensemble models, or cloud-system resolving models (CSRMs)] are based on the non-hydrostatic equations of motion and have been extensively applied to cloud-scale and mesoscale processes over the past four decades. Recent Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) model comparison projects have indicated that CRMs agree with observations in simulating various types of clouds and cloud systems from different geographic locations. CRMs now provide statistical information useful for developing more realistic physically based parameterizations for climate models and numerical weather prediction (NWP) models. Currently, NWP and regional-scale models can be run at grid sizes of a few km or better (similar to CRMs) through nesting techniques.

A CRM, however, 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 coupled GCM and CRM (termed a *super-parameterization* or *multi-scale modeling framework, MMF*) is required. The use of a GCM enables global coverage, while the CRM allows 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.

A multi-scale modeling system with unified physics has been developed at NASA Goddard Space Flight Center (GSFC). The system consists of an MMF, the coupled NASA Goddard finite-volume GCM (fvGCM) and Goddard Cumulus Ensemble model (GCE, a CRM); the state-of-the-art Weather Research and Forecasting model (WRF) and the stand alone GCE. These models can share the same microphysical schemes, radiation (including explicitly calculated cloud optical properties), and surface models that have been developed, improved and tested for different environments. Figure 1 shows a schematic of the Goddard multi-scale modeling system[1].

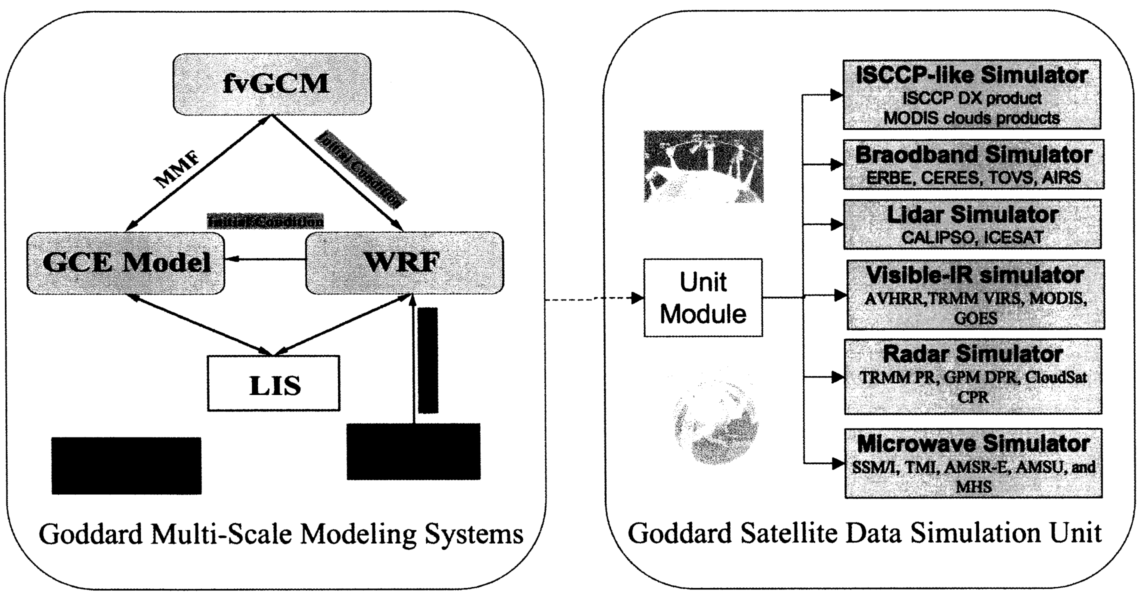

Figure 1. Goddard Multi-scale Modeling System with unified physics. The coupling between the fvGCM and GCE is two-way [termed a Multi-scale Modeling Framework (MMF)], while the coupling between the fvGCM and WRF and WRF and the GCE is only one-way. LIS is the Land Information System developed in the Goddard Hydrological Sciences Branch. LIS has been coupled interactively with both WRF and 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

[1] More information on the multi-scale modeling system and its simulated data sets (or cloud library) can be found at http://atmospheres.gsfc.nasa.gov/cloud_modeling/.

important role in providing data sets for model initialization and validation and consequently improvements. The Goddard Satellite Data Simulation Unit can convert the simulated cloud and atmospheric quantities into radiance and backscattering signals consistent with those observed from NASA EOS satellites.

The new Goddard MMF based on the coupled fvGCM-GCE (Tao *et al.* 2008a) is the second MMF developed worldwide following the one at Colorado State University (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 variation of rainfall than traditional GCMs (Figure 2). Both MMFs also have similar biases, such as a summer precipitation bias (relative to observations and 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. To fully understand the strengths and weaknesses of the MMF approach in climate modeling, a more detailed comparison between the two MMFs for longer simulations (i.e., 10-year integrations or longer), including simulated cloud properties from their CRM components as well as their improvements and sensitivities, is needed.

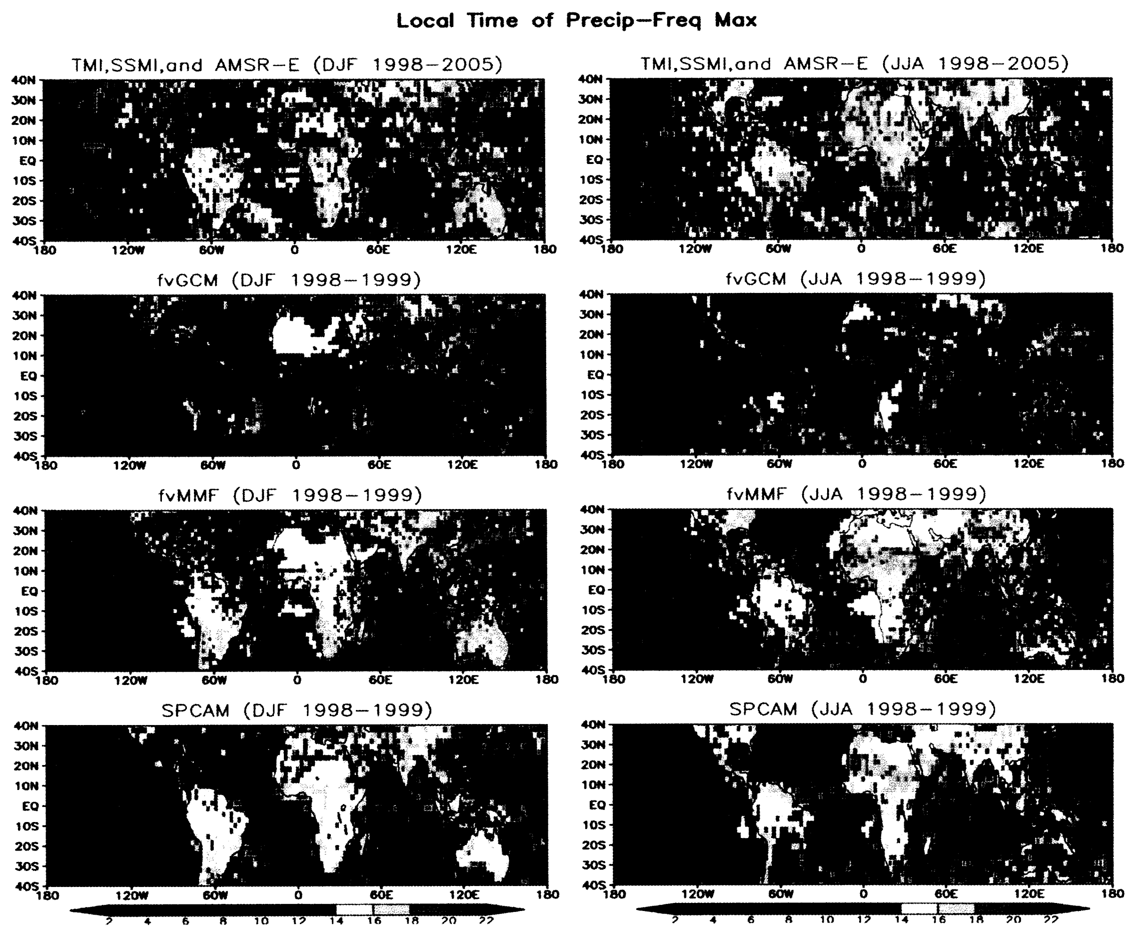

Fig. 2 *Geographical distribution of the local solar time (LST) for the non-drizzle precipitation frequency maximum in winter (left panels) and summer (right panels) as observed by satellite from 1998-2005 (upper panels) and as simulated for two years (1998-1999) with the Goddard fvGCM (middle-upper panels), 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. The MMF-simulated diurnal variation of precipitation shows good agreement with merged microwave observations. For example, the MMF-simulated frequency maximum was in the late afternoon (1400-1800 LST) over land and in the early morning (0500-0700 LST) over the oceans. The fvGCM-simulated frequency maximum was too early for both oceans and land.*

Various Goddard physical packages (i.e., CRM-based microphysics, radiation and land surface process) have recently been implemented into WRF (Tao *et al.* 2008b). The CRM-based packages have enabled 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)]. WRF has also been modified so that it can be initialized with the high-resolution fvGCM. The 3ICE scheme with a cloud ice-snow-hail configuration agreed better with observations in terms of convective line width and rainfall intensity for both the IHOP and Taiwan events as high density hail particles, which are associated with strong vertical velocities, fall quickly (over 10 m s^{-1}). For the Atlantic hurricane case, varying the microphysical schemes had no significant impact on the track forecast but did affect the intensity. For the snow events, the vertical and horizontal cloud species distributions (or radar reflectivity) were the same for the 3ice and 2ice schemes due to the weak vertical velocities (less than 0.5 m s^{-1}) involved.

The GCE has been developed and improved at Goddard over the last two and a half decades. More than 100 refereed journal papers on applications of the GCE to improve our understanding of precipitation processes were published (Tao 2003). The improved GCE has also been coupled with a NASA TRMM microwave radiative transfer model and precipitation radar model to simulate satellite-observed brightness temperatures at different frequencies (Simpson *et al.* 1996). The new, coupled GCE allows us to better understand cloud processes in the Tropics as well as to improve precipitation retrievals from NASA satellites. The GCE 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). Any new physical packages are first tested in the GCE and then implemented into WRF and the MMF, allowing the multi-scale modeling system to have unified physics.

Many recent and future earth-observing missions (including many NASA satellite programs) can provide measurements of clouds, radiation, precipitation, aerosols, land characteristics and other data at very fine spatial and temporal scales. Since the multi-scale modeling system can explicitly simulate cloud processes at the natural space and time scales of cloud-dynamical processes, cloud statistics, including radiances and radar reflectivities/attenuation, can be directly extracted from the CRM-based physics and compared against measurements. This multi-scale modeling system could be a new pathway for using these satellite data to improve our knowledge of the physical processes responsible for the variation in global and regional climate and in hydrological systems.

A comprehensive unified simulator, the Goddard Satellite Data Simulation Unit (SDSU), has been developed at GSFC. The Goddard SDSU is an end-to-end multi-satellite simulator unit, which is designed to fully utilize the multi-scale modeling system. It has six simulators at present: a passive microwave simulator, a radar simulator, a visible-infrared spectrum simulator, a lidar simulator, an ISCCP-like simulator, and a broadband simulator. All are hardwired with an integrated module that controls input-output and flow processes (Fig. 1). The SDSU can compute satellite-consistent radiances or backscattering signals from the simulated atmosphere and condensates consistent with the unified microphysics within the multi-scale modeling system. For example, it can generate estimates of retrieved microphysical quantities that can be directly compared with high-resolution CloudSat and future GPM products (Fig. 3). These simulated radiances and backscattering can be directly compared with the satellite observations, establishing a satellite-based framework for evaluating the cloud parameterizations. This method is superior to the traditional method of comparing with satellite-based products, since models and satellite products often use different assumptions in their cloud microphysics. Once a cloud model gains satisfactory agreement with the satellite observation, simulated clouds, precipitation, atmosphere states, and satellite-consistent radiances or backscattering will be provided to the science team 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 utilize and support NASA's ongoing and future Earth Observing System (EOS) missions, such as the Tropical Rainfall Measuring Mission (TRMM), A-Train project and Global Precipitation Measurement (GPM) Mission. The SDSU is being developed at NASA GSFC in collaboration with university institutions, including HyARC Nagoya University (where the original SDSU was developed) and Colorado State University.

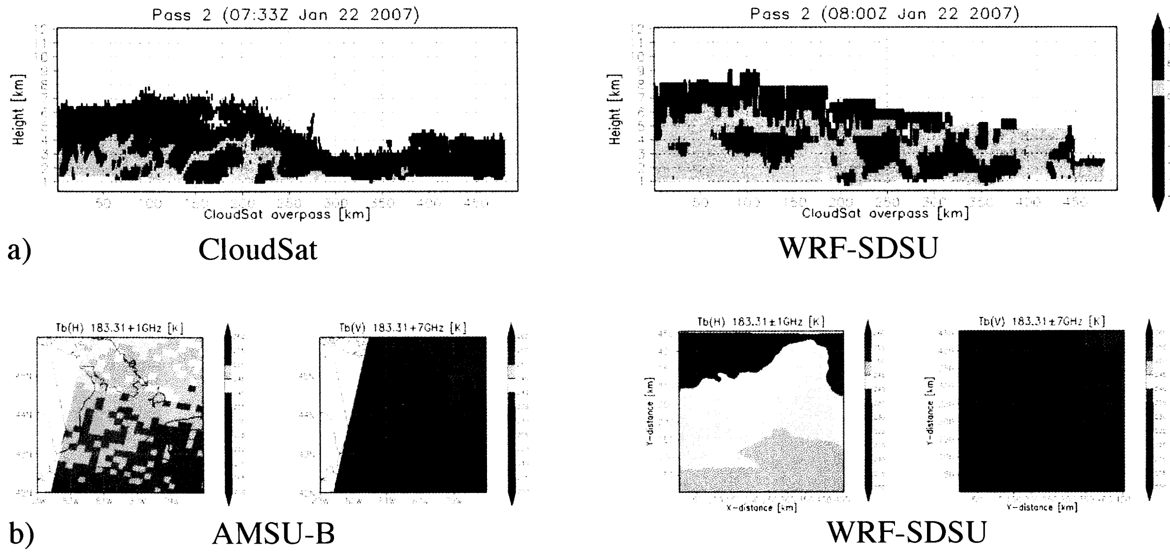

Fig. 3 *Direct satellite and model comparison over the GPM Ground Validation domain. Goddard SDSU radar reflectivity and brightness temperature are computed from WRF simulations. a) CloudSat observed CPR (94.15GHz) radar reflectivity (left) and WRF-SDSD-simulated 94.15GHz (right). b) AMSU-B observed brightness temperature at 183.31 ±1GHz and 183.31 ±7GHz (left) with corresponding brightness temperatures simulated from the WRF-SDSU (right).*

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