The 20-22 January 2007 Snow Events over Canada: Microphysical Properties

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Submitted to Proceeding of the International Precipitation Workshop Group
(Electronic publication)

ABSTRACT

One of the grand challenges of the Global Precipitation Measurement (GPM) mission is to improve precipitation measurements in mid- and high-latitudes during cold seasons through the use of high-frequency passive microwave radiometry. Toward this end, the Weather Research and Forecasting (WRF) model with the Goddard microphysics scheme is coupled with a Satellite Data Simulation Unit (WRF-SDSU) that has been developed to facilitate over-land snowfall retrieval algorithms by providing a virtual cloud library and microwave brightness temperature (Tb) measurements consistent with the GPM Microwave Imager (GMI). This study tested the Goddard cloud microphysics scheme in WRF for snowstorm events (January 20-22, 2007) that took place over the Canadian CloudSAT/CALIPSO Validation Project (C3VP) ground site (Centre for Atmospheric Research Experiments – CARE) in Ontario, Canada.

In this paper, the performance of the Goddard cloud microphysics scheme both with 2ice (ice and snow) and 3ice (ice, snow and graupel) as well as other WRF microphysics schemes will be presented. The results are compared with data from the Environment Canada (EC) King Radar, an operational C-band radar located near the CARE site. In addition, the WRF model output is used to drive the Goddard SDSU to calculate radiances and backscattering signals consistent with direct satellite observations for evaluating the model results.

1. Introduction

The NASA Global Precipitation Measurement (GPM) mission is a multi-national, multi-satellite mission designed to provide a uniformly calibrated precipitation measurement around the world. GPM consists of two components: a core satellite and a constellation of satellites. The core satellite carries a dual-frequency precipitation radar (DPR) and a microwave radiometric imager (GMI) with high-frequency capabilities. The constellation satellites consist of one NASA provided satellite, USA satellite assets from NOAA and DMSP, and international satellites with passive microwave instruments.

One of the major objectives of the GPM mission is to measure precipitation in mid- and high-latitudes over land during cold seasons through the use of GMI high frequency radiometry calibrated by DPR measurements, and to further our understanding of precipitation processes at high latitudes. In 2007, a Canadian CloudSAT/CALIPSO Validation Project (C3VP) field campaign took place in south central Ontario, Canada. C3VP was a multi-national, multi-agency field experiment hosted by Environment Canada in and around the Centre for Atmospheric Research Experiments (CARE) about 80 km north of Toronto, Ontario. GPM's participation in C3VP was aimed at improving space-based snowfall detection and estimation algorithms. For this paper, the Weather Research and Forecasting (WRF) model with the Goddard cloud microphysics scheme was utilized. WRF has also been coupled with the Goddard Satellite Data Simulation Unit (SDSU), which was developed to facilitate the development of over-land snowfall retrieval algorithms by providing a virtual cloud library and microwave brightness temperature (Tb) measurements consistent with the GMI.

In this study, results from high-resolution WRF simulations are compared with observations, including the operational King polarimetric radar near the CARE site and CloudSAT-observed reflectivities. The Goddard cloud microphysics scheme in WRF is tested for two distinct snowstorm events observed over the C3VP site in Ontario between 00 UTC 20 and 00 UTC 23 January 2007. In addition, this bulk microphysical parameterization was compared with WRF’s three other bulk microphysical schemes.

2. Model and Model set ups

2.1 WRF

WRF is a next-generation mesoscale forecast model and assimilation system that can be used to advance the understanding and prediction of convective-precipitation systems. It consists of four primary subsystems: the (1) WRF Pre-processing System (WPS), (2) WRF Variational Data assimilation system (WRF-Var), (3) Advanced Research WRF (ARW) and Nonhydrostatic Mesoscale Model (NMM) dynamic solvers, and (4) numerous physics packages contributed by the research community. WRF can 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. For large domain applications such as regional weather and climate processes, WRF is typically run within a domain covering several thousand kilometers using interactive nesting technique.

For this study, multiple nested domains were constructed with grid resolutions of 9, 3 and 1 km, with corresponding numbers of grid points 301 x 241 x 31, 430 x 412 x 31, and 457 x 457 x 31, respectively (Fig. 1). Time steps of 30, 10 and 3.333 seconds were used in these nested grids, respectively. The coarse domain covers almost two thirds of the entire contiguous US. The finest domain covers the entire C3VP region and the immediate vicinity. The model was initialized from NOAA/NCEP global analyses (1.0^{o} by 1.0^{o}). Time-varying lateral boundary conditions were provided at 6-h intervals. The model was integrated from 00 UTC 20 January to 00 UTC 23 January 2007.

The Grell-Devenyi (2002) cumulus parameterization scheme was used for the outer grid (9 km) only. In the 3- and 1-km grid domains, it was turned off. The WRF atmospheric radiation model includes longwave and shortwave parameterizations that interact with the atmosphere. The longwave scheme is based on Mlawer *et al.* (1997) and is a spectral-band scheme using the correlated-k method. The shortwave scheme uses a Goddard radiation scheme with a k-distribution for gaseous absorption with eight bands, and four-stream discrete-ordinate scattering. The planetary boundary layer parameterization employed the Mellor-Yamada-Janjic (Mellor and Yamada 1982 coded/modified by Dr. Janjic for the NCEP Eta model) Level-2 turbulence closure model through the full range of atmospheric turbulent regimes. The surface heat and moisture fluxes (from both ocean and land) were computed from similarity theory (Monin and Obukhov 1954). The land surface model is based on Chen and Dudhia (2001). It is a 4-layer soil temperature and moisture model with canopy moisture and snow cover prediction. It provides sensible and latent heat fluxes to the boundary layer scheme.

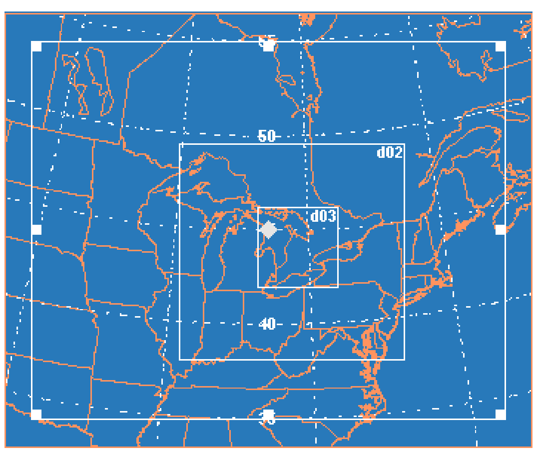

Fig. 1 Nesting configuration used for the C3VP simulations. Horizontal resolutions for domains 1, 2, and 3, are 9, 3 and 1 km, respectively.

2.2 Goddard Satellite Data Simulation Unit (SDSU)

The Goddard SDSU is an end-to-end multi-satellite simulator unit. It has six simulators at present: passive microwave, radar, visible-infrared spectrum, lidar, ISCCP type, and broadband. The SDSU can compute satellite-consistent radiances or backscattering signals from simulated atmospheric profiles and condensate fields consistent with the unified microphysics within the multi-scale modeling system (Fig. 2). For example, it can generate estimates from modeled-retrieved microphysical quantities that can be directly compared with high-resolution satellite (e.g., TRMM, CloudSAT) products. These simulated radiances and backscattering 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.* 2008). Once the cloud 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 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 allow us to better understand cloud processes in the Tropics middle and high latitudes as well as to improve precipitation retrievals from current and future NASA satellite missions (i.e., TRMM, the A- Train, and GPM).

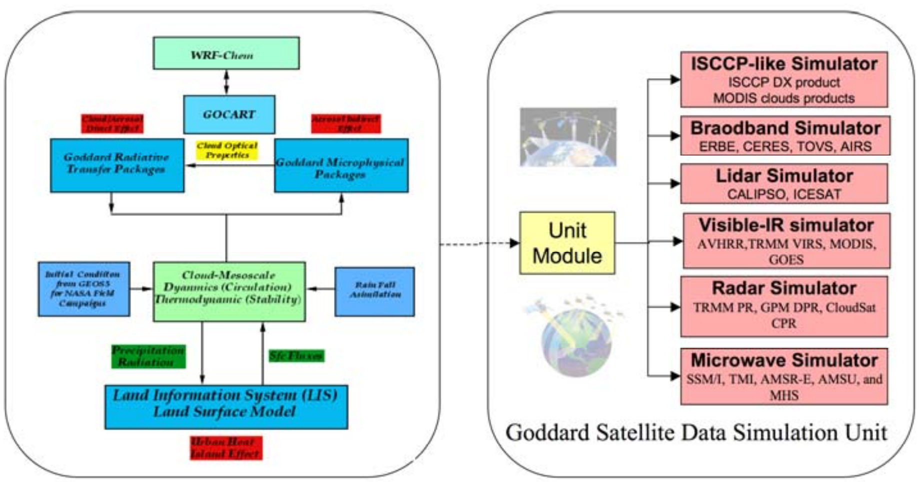

Fig. 2 Schematic diagram of the Goddard Multi-scale Modeling System with unified physics coupled with the Goddard Satellite Data Simulation Unit (SDSU). LIS is the Land Information System developed in the Goddard Hydrological Sciences Branch. LIS has been coupled interactively with WRF. Additionally, 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.

3. Results

There were two significant snow events during the 72-h period from 00 UTC 20 January to 00 UTC 23 January in 2007. On 20 January 2007, a cold front passed the Toronto area from the north in association with an upper level trough centered over eastern Canada. The passage of the cold front produced northwesterly flow near the surface, allowing for the development of isolated snow bands oriented in the NW-SE direction in the lee of the Georgian Bay of Lake Hurson. This first event was mainly driven by cold air passing over the relatively warm lake surface (lake-effect). In contrast to the first snow event on 20 January, the second snow event on 22 January was the result of broader uplift associated with a synoptic-scale cold frontal passage across southern Ontario. The 22 January event developed in response to the passage of a 500 hPa shortwave trough and an associated surface low across the C3VP domain (synoptic event). This synoptic scale system was associated with widespread light to moderate snowfall.

3.1 Comparison between model-simulated radar reflectivity and King radar observations

For the lake-effect event (Fig. 3), the cloud streak simulated by the model is in good agreement with the observed in terms of the timing (near 03 UTC 20 Jan 2007) and location; however, the observed cloud streak seems to be oriented more north-south and the model-predicted reflectivities are about 10-dbz stronger than the observed. Observed echo tops reach to around 3.5 km while those in the model only reach to 2.5 km. CloudSAT-observed reflectivities also confirm the 3.5 km echo tops. On the other hand, Fig. 4 shows that the model-simulated radar reflectivity for the synoptic event is in good agreement with the observed system in terms of the strength and vertical structure. However, the model-simulated reflectivity shows a larger area of reflectivities above 20 dBz compared to the observations. Both the model and observed reflectivity cross-sections show radar echoes extending to around 4 km except for a few spikes that go above 4 km in the observed reflectivity cross-section. The latter may be artifacts of the interpolation of the radar data to Cartesian coordinates.

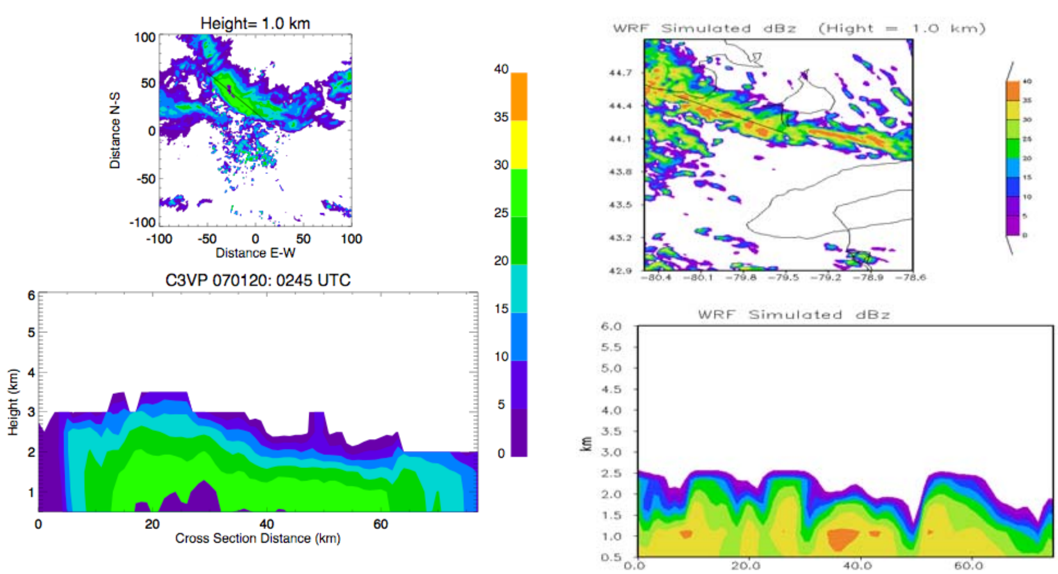

Fig. 3 *Observations from King radar (a) are compared against the WRF-simulated radar reflectivities (b) for the lake-effect event. The upper panels show radar reflectivity at a height of 1 km centered at the King radar site (79.57W, 43.96N), and the slanted lines show the locations of the radar reflectivity cross-sections (lower panels).*

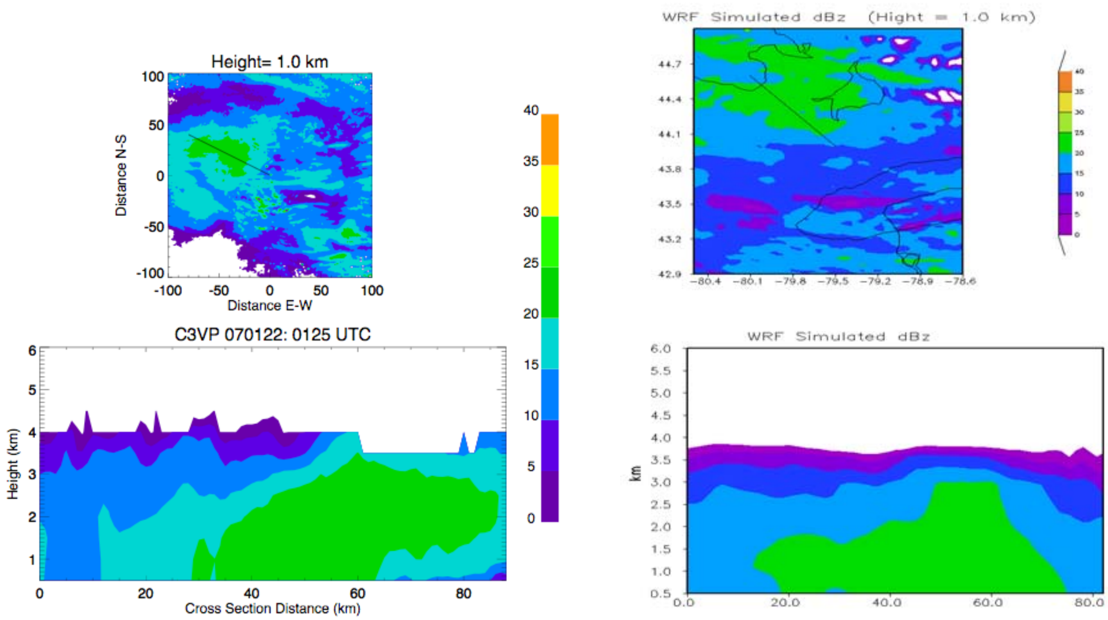

Fig. 4 *Same as Fig. 3 except for the synoptic event.*

3.2 Comparison between model-simulated radar reflectivity and CloudSAT observations

Figure 5 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 (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 one-moment bulk microphysics is now being developed based largely on the comparison between model-simulated (from cloud and precipitation properties) and satellite-observed direct radiances and backscattering signals. In addition, finer spatial resolutions (as opposed to the current 1-km horizontal grid spacing and 31 vertical layers) should be applied so that simulations can realistically represent the evolution of less vigorous cold cloud systems. 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.

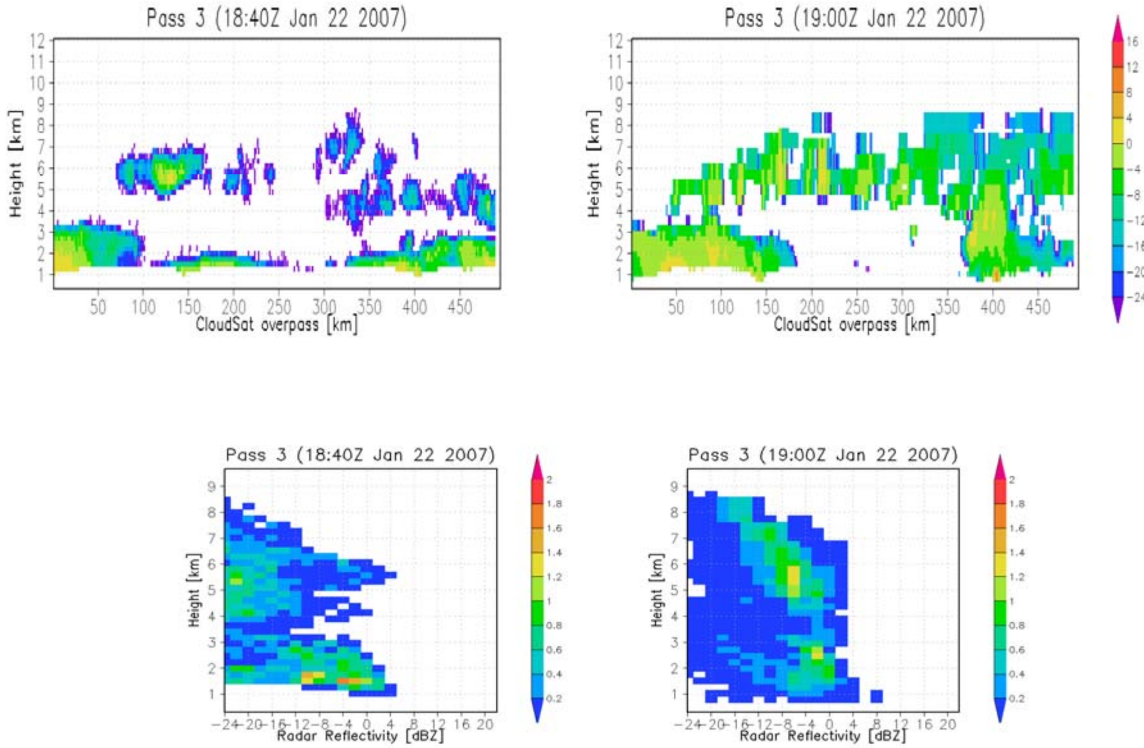

Fig. 5 Instantaneous cross-sections (upper panels) and contoured frequency with altitude diagrams (CFADs) (lower panels) of CloudSAT-observed and WRF-SDSU-simulated Cloud Profiling Radar (CPR, 94 GHz) reflectivity. Left two panels show the CloudSAT observations and the right two panels the WRF-simulated.

3.3 Comparison between model simulated brightness temperatures and AMSU observations

Figure 6 shows the direct satellite and model comparison at the GMI high frequency for snow retrieval. AMSU-B Tbs (within the 30-degree sensor-viewing angle) and corresponding Tbs simulated from the WRF simulation were sampled consistently in time (± 30min) and space (IFOV=16.4km at nadir). A total of 10 AMSU-B swaths were matched containing 1738 and 2958 Tb samples over water and land, respectively. These were then used to evaluate the simulated cold cloud systems for various Tbs. Tbs of 150 GHz have the largest discrepancy (RMSE=10.2 over water and RMSE=9.93 over land) between the observations and simulation due to uncertainties in the simulated surface properties (e.g., skin temperature and surface emissivity), which were not well parameterized in the passive microwave simulator for this initial experiment. Tbs of 183.31±1GHz and 183.31±3GHz have stronger water absorption channels; hence simulated Tbs are essentially unaffected from surface properties. As a result, Tbs between the observations and the simulation have less discrepancies. Tbs of 183.31±7GHz have the highest correlation (0.84) among the different channels. It is interesting to note that the simulation tends to overestimate Tbs of 150 GHz and 183.31±7GHz (where the atmosphere is more transparent), while it tends to underestimate Tbs of other channels (where the atmosphere is less transparent). This suggests that there might be discrepancies between the simulated and actual temperature and humidity profiles. Additional model simulations with higher resolution and improved microphysics as well as better representation of surface characteristics will be conducted in the near future.

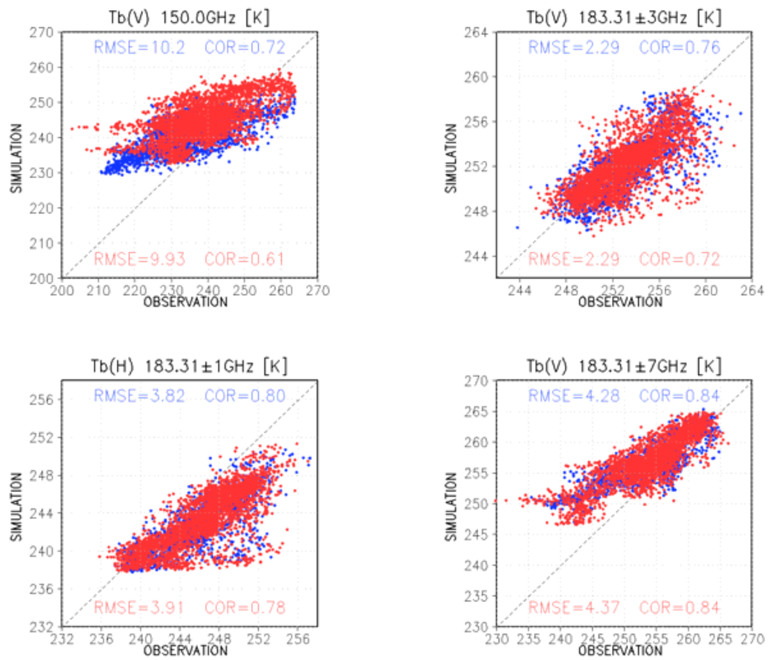

Fig. 6 Scatter plots between AMSU-B-observed and WRF-SDSU-simulated Tbs at different high-frequency channels. Red (blue) points represent over-land (water) points. Root Mean Square Error (RMSE) and correlation (COR) are also displayed.

3.4 Comparison between model-simulated cloud properties

Figures 7 shows vertical profiles of the domain- and time-averaged cloud species for the first snow event using the Goddard 3ICE-graupel and 2ICE schemes. Large precipitating particles (rain and graupel) did not form for either experiment because the simulated vertical velocities were weak (~50 cm/s). Almost identical profiles for cloud water, cloud ice and snow for both experiments were simulated. This result suggests that the Goddard 3ICE microphysical scheme responded well to the cloud dynamics by not producing graupel. Also note the presence of cloud water during this snow event. This feature has both been observed and simulated (e.g., a snow event over Japan Sea).

Cloud species simulated from WRF's other bulk microphysical schemes, the Purdue-Lin, WSM6 and Thompson schemes, are quite different compared to the Goddard scheme (Fig. 8). For example, large precipitating ice (graupel) was present and reached the surface for both the WSM6 and Purdue schemes. In addition, a smaller amount of cloud liquid water was simulated in both of those schemes compared to the Goddard and Thompson schemes. In the Thompson scheme, no cloud ice but a very large amount of cloud water was simulated. Note that model data can and often is used to infer critical cloud information/properties that are not directly observable by satellites. The linkage between the satellite and model data usually depends on simulated Tbs. As such, an accurate vertical distribution of cloud species is important for satellite retrievals. Unrealistic precipitation ice contents (i.e., snow and graupel), for example, can bias the simulated Tbs and reflectivities making it difficult to infer cloud properties from remote sensing data by linking them with synthetic values from models. Also note that cloud ice and cloud water are important cloud species for cloud-radiation interaction.

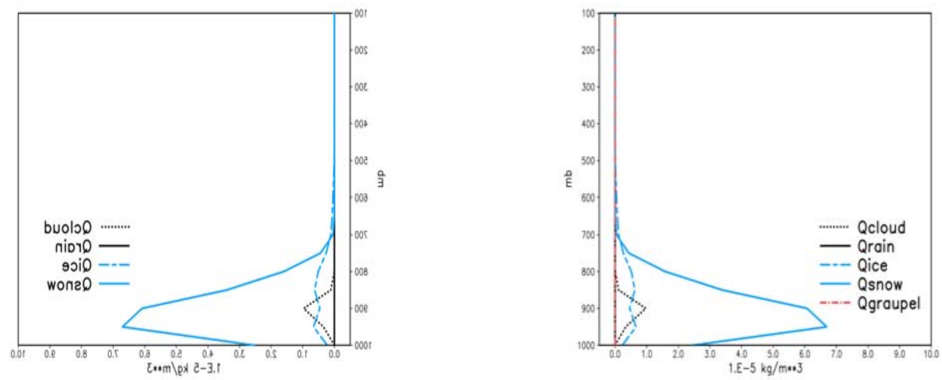

Fig. 7 Vertical profiles of domain- and 1st 24-hour time-average cloud species (i.e., cloud water, rain, cloud ice, and snow) for the 2ICE scheme (left panel) and (cloud water, rain, cloud ice, snow and graupel) for the 3ICE scheme (right panel).

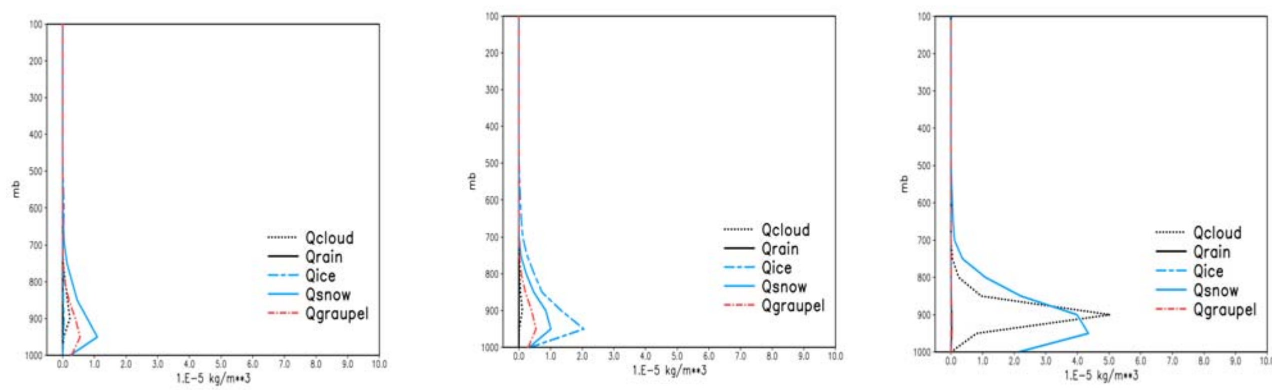

Fig. 8 Same as Fig. 7 except for the WSM6 (left panel), Purdue-Lin (Middle) and Thompson (right panel) schemes.

4. Summary

The Weather Research and Forecasting (WRF) model with the Goddard microphysics scheme coupled with the Satellite Data Simulation Unit (WRF-SDSU) was used to simulate two snowstorm events (lake effect and synoptic) observed during C3VP. The major highlights are as follows:

o Preliminary WRF simulations capture the basic cloud properties as seen by ground-based radar and satellite (i.e., CloudSAT, AMSU-B) observations. However, the model under predicts the echo top heights for the lake effect snow case.

o WRF simulations with two different Goddard microphysical schemes (3ICE and 2ICE scheme) show almost identical results (due to weak vertical velocities and therefore the absence of large precipitating liquid or ice particles) that are largely consistent with observations.

o WRF simulations using other WRF microphysical schemes (i.e., Thompson, Purdue Lin and WSM6) show a greater sensitivity in the vertical cloud profiles (important for both the radiation budget and hydrologic/energy cycles).

o The WRF-simulated cloud data set is available to the GPM science team through the Goddard Cloud library web-site (*http://portal.nccs.nasa.gov/cloudlibrary/*).

For future research, WRF simulations using higher-resolution initial conditions (NCEP Eta 32 km), more and higher vertical resolution (lower and upper troposphere), improved microphysics and sensitivity of planetary boundary layer (PBL) processes will be conducted. In addition, a WRF-Earth satellite simulator with realistic ground emissivity is required.

5. Acknowledgements

The authors thank Dr. R. Kakar at NASA headquarters for his support under the NASA Atmospheric Dynamics and Thermodynamics Program and TRMM/PMM. Acknowledgment is also made to Dr. T. Lee at NASA headquarters, the NASA Goddard Space Flight Center and the NASA Ames Research Center for computer time used in this research. . We are especially grateful to the members of the C3VP Environment Canada team led by Dr. David Hudak for their support during the C3VP field campaign.

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