Sensitivity of precipitation processes to microphysics and resolution in a cloud-resolving model

Wei-Kuo Tao[1]
Laboratory for Atmospheres
NASA/Goddard Space Flight Center
Greenbelt, MD 20771
U.S.A.

1. Introduction

A basic characteristic of cloud-resolving models (CRMs) is that their governing equations are non-hydrostatic since the vertical and horizontal scales of convection are similar. Such models are also necessary in order to allow gravity waves, such as those triggered by clouds, to be resolved explicitly. CRMs use sophisticated and physically realistic parameterizations of cloud microphysical processes with very fine spatial and temporal resolution. Another major characteristic of CRMs is their explicit interaction between clouds and radiation. It is for this reason that GEWEX (Global Energy and Water Cycle Experiment) has formed the GCSS (GEWEX Cloud System Study) expressly for the purpose of studying these types of problems using CRMs. Observations can be used to verify model results and improve the initial and boundary conditions. The major advantages of using CRMs are their ability to quantify the effects of each physical process upon convective events by means of sensitivity tests (eliminating a specific process such as evaporative cooling, terrain, PBL), and their detailed dynamic and thermodynamic budget calculations.

In this paper, the sensitivity of precipitation processes to microphysics and resolution in a CRM, the Goddard Cumulus Ensemble (GCE) model, will be conducted and examined.

2. 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 decades. Improvements and testing were presented in Tao and Soong (1986), Tao *et al.* (1989), Tao and Simpson (1993), Ferrier (1994), Tao *et al.* (1996), Wang *et al.* (1996a), Lynn *et al.* (1998), Baker *et al.* (2001) and Tao *et al.* (2003). The GCE model can resolve the structure and life cycles of individual clouds and larger cloud systems (ranging from 2 to 200 km in size), and calculate cloud properties (e.g., transport processes and diabatic heating associated with phase changes of water). More than 90 refereed papers using the GCE model have been published in the last two decades. Also, more than 10 national and international universities are currently using the GCE model for research and teaching. A review on the application of the GCE model to the understanding of precipitation processes can be found in Simpson and Tao (1993) and Tao (2003). Table 1 shows the major characteristics of the GCE model.

Parameters/ Processes	GCE Model
Dynamics	Anelastic or Compressible 2D (Slab- and Axis-symmetric) and 3D
Vertical Coordinate	z
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) CLM - LIS TOGA COARE Flux Module
Parallelization	OPEN-MP and MPI

Table 1 Characteristics of the Goddard Cumulus Ensemble Model.

Recently, the GCE model has been re-coded to allow it to use the massively parallel processor machines at the NASA Ames and NASA Goddard super computing centers. For example, NASA Ames has applied a computer tool (CAPO, CAPTools-based Automatic Parallelizer using OpenMP) to the 3D version of the GCE model. However, the current version of the GCE model has limited scalability beyond 64 CPUs partly due to the outer-loop parallelization strategy used in the code. Therefore, a MPI (message passing interface) version of the GCE model is being developed. The GCE model's MPI version is very readable for the model developer (this allows the developer to modify the code easily). It is flexible enough to run with any number of PEs (process elements) in 2D decomposition with 1D as an option, to use even only a single CPU, and to reproduce binary results.

---

[1] Email: tao@agnes.gsfc.nasa.gov

One of the most unique characteristics of the GCE model is its microphysical processes (Table 2). The cloud microphysics include a parameterized Kessler-type two-category liquid water scheme (cloud water and rain), and a three-category ice-phase scheme (cloud ice, snow and hail/graupel) mainly based on Lin *et al.* (1983) and Rutledge and Hobbs (1984). The following major improvements have been made to the model during the past several years: **(i)** the addition of a two-moment four-class ice scheme (Ferrier 1994; Ferrier *et al.* 1995), and **(ii)** the addition of two detailed, spectral-bin models (Khain *et al.* 1999, 2000; Chen and Lamb 1999). These new microphysics require the multi-dimensional Positive Definite Advection Transport Algorithm (MPDATA, Smolarkiewicz and Grabowski 1990) to avoid "decoupling" between mass and number concentration[2].

	Characteristics	References
Warm Rain	qc, qr	Kessler (1969), Soong and Ogura (1973)
2 Ice	qc, qr, qi, qg	Cotton *et al.* (1982), Chen (1983), McCumber *et al.* (1991)
3Ice - 1	qc, qr, qi, qs, qh	Lin *et al.* (1983), Tao and Simpson (1989, 1993)
3Ice - 2	qc, qr, qi, qs, qg	Rutledge and Hobbs (1984), Tao and Simpson (1989, 1993)
3Ice - 3	qc, qr, qi, qs, qh	Lin *et al.* (1983), Rutledge and Hobbs (1984), Ferrier *at al.* (1995)
3Ice - 4	qc, qr, qi, qs, qg or qh	Lin *et al* (1983)
3Ice - 5	Saturation Technique	Tao *et al.* (1989), Tao *et al.* (2002a)
4Ice - 1	qc, qr, qi, qs, qg, qh Ni, Ns, Ng, Nh	Ferrier (1994) Ferrier *et al.* (1995)
4Ice - 2	qc, qr, qi, qs, qg, qh Ni, Ns, Ng, Nh	Tao *et al.* (2002a)
One-Moment Spectral - Bin	**43** bins for **6** types of ice, liquid water and cloud condensation nuclei	Khain and Sednev (1996), Khain *et al.* (1998)
Multi-component Spectral - Bin	Liquid: **46 bins for water mass, 25 for solute mass** Ice: water mass, solute mass, aspect ratio	Chen and Lamb (1994, 1999)

Table 2 The microphysical schemes in the GCE Model.

The formulation of the explicit spectral bin-microphysical processes is based on solving stochastic kinetic equations for the size distribution functions of warm and ice clouds. The explicit spectral bin microphysics can be used to study cloud-aerosol interactions and nucleation scavenging of aerosols, as well as the impact of different concentrations and size distributions of aerosol particles upon cloud formation. The spectral bin microphysics is expected to lead to a better understanding of the mechanisms that determine the intensity and the formation of precipitation for a wide spectrum of atmospheric phenomenon related to clouds. In addition, the spectral bin microphysics can be used to improve the simpler bulk (3ICE and 4ICE) parameterizations.

3. Results

3.1 Microphysics

In the sensitivity tests of different microphysical schemes, 3-D simulations were made for two well-documented tropical squall lines, the 12 September 1974 GATE and the 22 February 1993 TOGA COARE cases. The results indicated that the use of different ice schemes does not have any significant impact on the organization of cloud systems. For example, an arc shape and the presence of vortices along the edges for the TOGA COARE and GATE squall system are both simulated by the 3ICE and 4ICE scheme. The propagation speed of two tropical squall systems is quite similar between 3ICE and 4ICE runs. The total stratiform percentage (over 8 h) is also quite similar between the 3ICE and 4ICE runs. However, the temporal evolution of stratiform rain during the life cycle of the squall systems in runs using 4ICE and 3ICE schemes is different. The 3ICE scheme produced more stratiform rain in the first 5 h of simulation time but less later in the simulation. This is because the various ice schemes lead to different vertical hydrometeors profiles. Small ice particles (cloud ice and snow) with slow fall speeds (1 - 3 m s^{-1}) are more dominant in the 4ICE scheme. The 3ICE scheme produces more and larger graupel (with 2 - 5 m s^{-1} fall speeds) in the convective towers and which is transported into the trailing portion of the squall system (i.e., stratiform region). These larger ice particles can melt and reach the surface in the stratform region. The smaller (but abundant) ice particles simulated in the 4ICE scheme require longer time to reach the surface. That is why the stratiform rain percentage increases in the runs using the 4ICE scheme. In addition, the different ice microphysical parameterizations can effect the surface precipitation for both cases. There is (about 30%) less surface precipitation with the 4ICE scheme than the 3ICE scheme (Table 3).

	TOGACOARE		GATE	
	3ICE	4ICE	3ICE	4ICE
Rainfall (mm)	13.38	10.06	4.70	3.04
Stratiform (%)	35%	35%	24%	21%

Table 3 Surface rainfall amounts (mm) accumulated over 9 hours for GCE simulated TOGA COARE and GATE squall systems using the 3ICE and 4ICE schemes. The percentage of rainfall that was stratiform is also given.

The GCE model recently simulated convective events associated with the onset of the monsoon over the South China Sea (SCSMEX), convective clouds and cloud systems over the central Pacific (KWAJEX) and South America (LBA). The results indicate that the runs with the 3ICE scheme simulate more precipitation than the 4ICE scheme. Also, a modified 3ICE scheme

---

[2] Decoupling means that a grid point has mass without number concentration or has number concentration without mass. The decoupling is caused by large phase errors associated with the spatially centered (second- or fourth-order) advection scheme.

that produced more snow and less graupel simulated less precipitation than the un-modified 3ICE scheme for both the SCSMEX and KWAJEX convective systems.

However, the different ice microphysical parameterizations do not effect the surface precipitation for two LBA convective systems that developed under different environmental regimes (Table 4). For the January 26, 1999 case, low-level easterly flow results in moderate to high CAPE and a drier environment. Convection is more intense like that seen over continents. But for the February 23, 1999 case, low-level westerly flow results in low CAPE and a moist environment. Convection is weaker and more widespread characteristic of oceanic or monsoon-like systems. The 3D GCE model results showed that ice processes are more important in the easterly regime, consistent with the observed electrical activity. The 3ICE scheme with hail process produced less rain than either the 3ICE scheme with graupel or the 4ICE scheme for the intense easterly regime convective event. Also note that the initial conditions have more of an impact on microphysics for the weaker convective event (westerly regime).

January 26 1999	Rainfall (120 min)	Rainfall (180 min)	Stratiform Amount (%)
3ICE - Hail	0.46	0.97	22%
3ICE - Graupel	0.68	1.33	27%
4ICE	0.64	1.30	27%
February 23 1999 Cool Pool	Rainfall (90 min)	Rainfall (150 min)	Stratiform Amount (%)
3ICE - Graupel Unmodified Sounding	0.59	1.72	38%
3ICE - Graupel Modified Sounding	0.14	0.32	40%
4ICE Modified Sounding	0.15	0.30	41%

Table 4 Surface rainfall amounts (mm) accumulated for two GCE-simulated LBA convective systems using the 3ICE and 4ICE schemes. The percentage of stratiform rainfall is also given.

A spectral-bin microphysical model is tested by studying the evolution of deep tropical oceanic and midlatitude continental clouds using identical thermodynamic conditions but with different concentrations of CCN: a low "clean"concentration and a high "dirty" concentration. The results indicate that the low CCN (clean) concentration case produces rainfall at the surface sooner than the high CCN (dirty) case, but has less cloud water mass aloft. This is due to the fact that the low CCN case produces fewer droplets and larger sizes that develop faster due to greater condensational and collectional growth, leading to a broader size spectrum in comparison to the high CCN case.

3.2 Resolution

Recent significant increases in computer power allow NWP to be run at fine grid sizes. NWP, then, can include better microphysical processes that were developed for CRMs in the past few decades. Consequently, NWP could improve its QPF. However, ECMWF recently reported that its re-analyses (combined model and observation) does not produce realistic diurnal variation of precipitation over South America. The 3D GCE model has been used to conduct sensitivity tests of various horizontal resolutions (1000, 500 and 250 m) on precipitation processes associated with an LBA case (February 23,1999). The results showed that the gradual growth of the planetary boundary layer (PBL) was only simulated by the run with a 250-m grid. The results from the other two coarse resolution runs showed that the simulated PBL height graw very fast without a transition period at a later time compared to the run with a fine grid. The results also showed that more light precipitation was simulated in the run with 250-m. Consequently, a realistic gamma distribution of rainfall was simulated in this run.

A fine-resolution vertical grid is also needed to properly represent the structure of the melting layer in stratiform precipitation since the transition from pure ice to pure liquid hydrometeors may occur over a depth of 0.5 km or less if melting snow is involved. Furthermore, the variation of hydrometeor electromagnetic properties within the melting layer is strong, and so a model vertical resolution of at least 50 m is required to capture this variation for proper simulations of microwave attenuation or radar reflectivity. Preliminary results show that the amount of melted particles increased by more than 25% when a 200 m grid size was used near the melting region compared to the previous 400 m grid size used in the GCE model and others. Snow amounts also increased with the finer vertical grid. In addition, the fine-resolution vertical grid (50-100 m) may be needed for simulating cirrus/anvil and the interactions with radiation.

4. Conclusions

The GCE model has been used to examine the sensitivity of microphysics and resolution on precipitation processes associated with cloud systems that developed in different geographic locations. The major results are as follows:

Microphysics can effect surface precipitation, the vertical distribution of hydrometeors and the temporal evolution of stratiform rain, but they do no have a major impact on system organization.

Microphysics that produced fast-falling hydrometeors could simulate more surface rainfall than those generating slow-falling hydrometeors.

Cloud systems that develop over ocean are more sensitive to the microphysics than those over land.

A fine grid size is needed to realistically simulate planetary boundary layer development, diurnal variation of rainfall and rainfall characteristics.

Initial conditions are more important than the microphysics for some cases.

More studies are needed using observational data to improve and validate microphysical schemes.

Acknowledgement

The author is supported by the NASA Headquarters physical climate program and the NASA TRMM,. The author is grateful to Dr. R. Kakar for his support of this research. Acknowledgment is also made to NASA/Goddard Space Flight Center for computer time used in this research.

References (not complete)[3]

Chen, J-.P., and D. Lamb, 1999: Simulation of cloud microphysical and chemical processes using a multicomponent framework. Part II: Microphysical evolution of a wintertime orographic cloud. *J. Atmos. Sci.*, **56**, 2293-2312.

Ferrier, B. S., 1994: A double-moment multiple-phase four-class bulk ice scheme. Part I: Description. *J. Atmos Sc.i*, **51**, 249-280.

Khain, A. P., A. Pokrovsky, and I. Sednev, 1999: Some effects of cloud-aerosol interaction on cloud microphysics structure and precipitation formation: Numerical experiments with a spectral microphysics cloud ensemble model. *Atmos. Res.*, **52**, 195-220.

Khain, A. P., M. Ovtchinnikov, M. Pinsky, A. Pokrovsky, and H. Krugliak, 2000: Notes on the state-of-the-art numerical modeling of cloud microphysics. *Atmosph. Res.*, **55**, 159-224.

Lin, Y.-L., R. D. Farley and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Clim. Appl. Meteor.*, **22**, 1065-1092.

Lynn, B. H., W.-K. Tao and P. Wetzel, 1998: A study of landscape generated deep moist convection,", *Mon. Wea. Rev.* **126**, 928-942.

Rutledge, S. A., and P. V. Hobbs, 1984: The mesoscale and microscale structure and organization of clouds and precipitation in mid latitude clouds. Part XII: A diagnostic modeling study of precipitation development in narrow cold frontal rainbands. *J. Atmos. Sci.*, **41**, 2949-2972.

Simpson, J. and W.-K. Tao, 1993: The Goddard Cumulus Ensemble Model. Part II: Applications for studying cloud precipitating processes and for NASA TRMM. *Terrestrial, Atmospheric and Oceanic Sciences*, **Vol. 4**, 55-96.

Smolarkiewicz, P. K. and W. W. Grabowski, 1990: The multi-dimensional positive advection transport algorithm: Nonoscillatory option. *J. Comput. Phys.*, **86**, 355-375.

Soong, S.-T., and W.-K. Tao, 1980: Response of deep tropical clouds to mesoscale processes. *J. Atmos. Sci.*, **37**, 2016-2036.

Tao, W.-K., and S.-T. Soong, 1986: A study of the response of deep tropical clouds to mesoscale processes: Three-dimensional numerical experiments. *J. Atmos. Sci.*, **43**, 2653-2676.

Tao, W.-K., J. Simpson and M. McCumber, 1989: An ice-water saturation adjustment. *Mon. Wea. Rev.*, **117**, 231-235.

Tao, W.-K., and J. Simpson, 1993: The Goddard Cumulus Ensemble Model. Part I: Model description. *Terrestrial, Atmospheric and Oceanic Sciences,* Vol. **4**, 19-54.

Tao, W.-K., J. Simpson, S. Lang, C.-H. Sui, B. Ferrier, and M.-D. Chou, 1996: Mechanisms of cloud-radiation interaction in the tropics and midlatitudes. *J. Atmos. Sci* . **53**, 2624-2651.

Tao, W.-K., 2003: Goddard Cumulus Ensemble (GCE) model: Application for understanding precipitation processes, *AMS Meteorological Monographs on Cloud Systems, Hurricanes and TRMM*, 107-138.

Tao, W.-K., J. Simpson, D. Baker, S. Braun, M.-D. Chou, B. Ferrier, D. Johnson, A. Khain, B. Lynn, S. Lang, C.-L. Shie, D. Starr, C.-H. Sui, Y. Wang and P. Wetzel, 2003: Microphysics, Radiation and Surface Processes in a Non-hydrostatic Model, *Meteor. Atmos. Phys.*, **82**, 97-137.

Wang, Y., W.-K. Tao, J. Simpson, and S. Lang, 2003: The sensitivity of tropical squall lines (GATE and TOGA COARE) to surface fluxes: 3-D Cloud resolving model simulations, *Q. J. R. Met. Soc.* (in press).

---

[3] All other papers referred in the paper can be found in Tao (2003) and Tao *et al.* (2003).