Precipitation Processes During ARM (1997), TOGA COARE (1992), GATE (1974), SCSMEX (1998), and KWAJEX (1999): Consistent 2D and 3D Cloud Resolving Model Simulations

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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 Global Energy and Water Cycle Experiment (GEWEX) has formed the GEWEX Cloud System Study (GCSS) 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, planetary boundary layer [PBL]), and their detailed dynamic and thermodynamic budget calculations.

Real clouds and cloud systems are three-dimensional (3D). Few 3D CRMs (e.g., Tao and Soong 1986; Tao et al. 1987; Lipps and Hemler 1986) have been used to study the response of clouds to large-scale forcing. The 3D Goddard Cumulus Ensemble (GCE) modeling results, however, are in better agreement with the aircraft measured updrafts and downdrafts (Zipser and LeMone 1980) in the middle troposphere. In these 3D simulations, the model domain was small and integration time was 6 hours. Only recently, 3D experiments were performed for multi-day periods for tropical cloud systems with large horizontal domains (Grabowski et al. 1998; Petch and Gray 2001; and Tao 2003). Table 1 lists the model set-ups, integration time, and cases for the previous 3D cloud ensemble modeling studies.

Recently, an improved 3D GCE model was used to simulate periods during Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE), Global Atmospheric Research Program Atlantic Tropical Experiment (GATE), Atmospheric Radiation Measurement (ARM), SCSMEX and KWAJEX using a 512 by 512 km domain (with 2 km resolution). In this paper, the main improved GCE model features will be discussed. Sensitivity tests of the model configuration will be conducted and compared.

Table 1. Previous 3D cloud ensemble modeling studies.

	Model Set-ups & Time Integration	**Case**
Tao and Soong (1986) Tao, Simpson, and Soong (1987)	32 x 32 km^2 (dx = dy = 1 km) - 6h 128 km (dx = 1 km) - 6 & 12h No Ice, Prescribed Radiation	GATE Slow-Moving Squall Line
Lipps and Helmer (1986)	24 x 16 km^2 (dx = dy = 0.5 km) - 4h 64 & 32 km (dx = 0.5 km) - 4h No Ice, Prescribed Radiation	As Tao and Soong, 1986
Grabowski et al. (1998)	400 x 400 km^2 (dx = dy = 2 km) – 7 day 2ICE Prescribed Radiation	GATE September 1 - 7, 1974
Petch and Gray (2002)	256 x 256 km^2 (dx = dy = 2 km) - 6 day 3ICE	TOGA COARE December 20-26 1992
Tao (2003)	512 x 512 km^2 (dx = dy = 2 km) - 7 day 3ICE	TOGA COARE December 19-26, 1992; and GATE September 1-7, 1974

Goddard Cumulus Ensemble 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), as well as 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).

Recently, the GCE model has been re-coded to allow it to use the massively parallel processor machines at the National Aeronautics and Space Administration (NASA) Ames and 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. In addition, a message passing interface (MPI) version of the GCE model is being developed. The GCE model’s MPI version is very readable for the model developer and users (this allows the users to modify the code easily). It is flexible enough to run with any number of CPUs.

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: (1) the addition of a two-moment four-class ice scheme (Ferrier 1994; Ferrier et al. 1995), and (2) 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.(a)

Table 2. The microphysical schemes in the GCE model.

	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 et 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)

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

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(a) 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 atmospheric phenomenon related to clouds. In addition, the spectral bin microphysics can be used to improve the simpler bulk (3ICE and 4ICE) parameterizations.

Results and Discussions

Figure 1 shows the GCE model-simulated cloud hydrometeor mixing ratios for an ARM case (June 12 to June 17, 1997). The 3D version of the GCE model has 256 x 256 horizontal grid points using 2 km resolution and 39 vertical layers. The Lin et al. (1983) microphysics scheme is used for this ARM case. Model results indicated that most (but not all) of the surface rainfall is being produced by the melting of snow and hail. This indicates the importance of ice for this particular ARM case.

Table 3 shows the GCE model simulated domain-averaged surface rainfall amounts (in mm day^{-1}) for the ARM, SCSMEX, TOGA COARE, GATE, and KWAJEX cases. Similar rainfall amounts were simulated by the two-dimensional (2D) and 3D GCE model for all cases. Grabowski et al. (1998) also found a similar conclusion for their GATE and TOGA COARE multi-day 2D and 3D simulations. Petch and Gray (2001) also showed that the surface rainfall between their 2D and 3D TOGA COARE simulations is within a few percent. Larger differences in rainfall amount were found in other CRMs for ARM cases.

The reason for the strong similarity between the 2D and 3D CRM simulations is that the same observed large-scale advective tendencies of temperature and water vapor mixing ratio were used as the main forcing in both the 2D and 3D models (Tao et al. 1987). Similar rainfall amounts between the 2D and 3D model results suggested that net condensation (condensation minus evaporation) is similar for 2D and 3D model results. Mean and time-dependent Q1 Q2 budgets, as well as mean and integrated rain water and hail mass (for the ARM case) are also almost identical for 2D and 3D results. The cloud structures simulated in both 2D and 3D are similar and are caused by the fact that cloud structure is significantly influenced by the imposed large-scale horizontal winds.

However, there are some major differences between the 2D and 3D model results. For example, less stratiform rainfall was simulated in 3D compared to 2D for all cases. Stronger cloud updrafts/mass fluxes are simulated in 3D. Stronger convection-induced subsidence in 3D produces less cloudiness. Also, stronger cloud downdrafts are simulated in 3D than in 2D. However, downward mass fluxes below the melting level in the stratiform region are stronger in 2D. Both 2D and 3D produced a cold or warm bias in the troposphere compared with observations. However, the temperature error was reduced in the upper troposphere in 3D. This is caused by less cloudiness simulated in 3D. In addition, the 3D GCE modeled water vapor (Q2) budget is usually in better agreement with observations in the lower troposphere than its 2D counterpart.

A weaker convective updraft velocity and a stronger convective downdraft were simulated in a 2D CRM than those from a 3D CRM (Tao and Soong 1996). Lipps and Helme (1986) and Wu and Moncrieff (1996), however, found that stronger updraft and downdraft mass fluxes were simulated in their 2D simulations. Less cloud water in the 2D model (Lipps and Helme) was caused by stronger downdraft and more evaporation. However, more cloud water was simulated in Wu and Moncrieff (1996). The results also indicated that the 3D modeled cloud draft properties are in better agreement with aircraft observation (e.g., Tao et al. 1987).

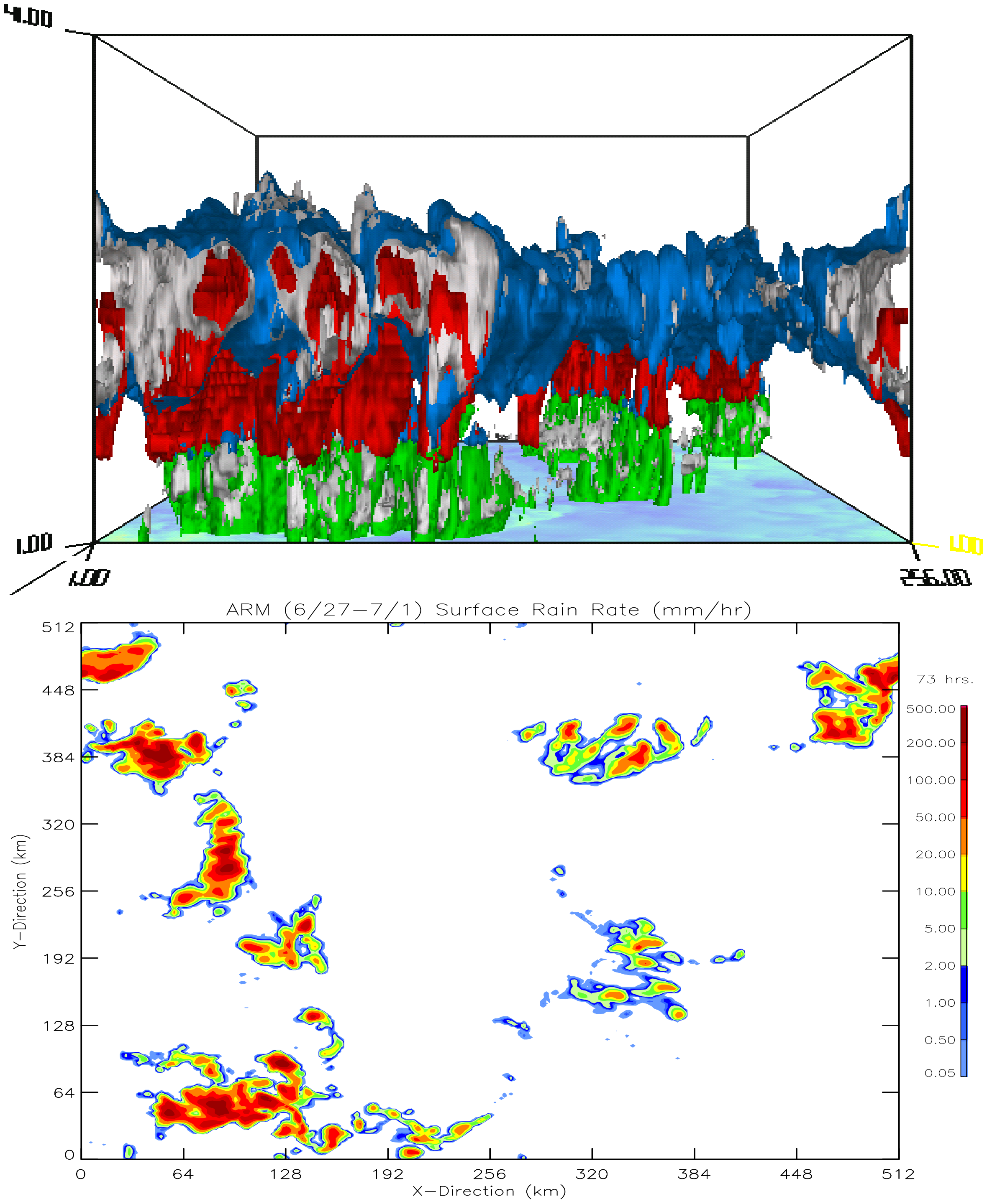

Figure 1. 3D GCE model-simulated cloud hydrometeor mixing ratios for an ARM case. The white isosurfaces show the cloud water and cloud ice, blue the snow, green the rain water, and red the hail. Also shown are the GCE-simulated surface rainfall rate (mm/hr) corresponding to the same the cloud fields.

Table 3. Both 2D and 3D GCE model-simulated rainfall amounts for ARM, TOGA COARE, SCSMEX, GATE, and KWAJEX cases.

	2D Rainfall/Stratiform (%)	**3D Rainfall/Stratifom (%)**
TOGA COARE December 19-27, 1992	20.2 mm/day 45	20.7 mm/day 37
SCSMEX May 18-26, 1998	11.14 mm/day 49	11.65 mm/day 40
SCSMEX June 2 – June 11, 1998	16.5 mm/day 38	17.0 mm/day 31.4
ARM June 26-31, 1997	7.73 mm/day 17.9	7.48 mm/day 8.0
ARM July 12-17, 1997	5.85 mm/day 20.2	5.97 mm/day 11.3
GATE September 1-7, 1974	14.4 mm/day 38	13.9 mm/day 31
KWAJEX August 7-13, 1999	13.19 mm/day 43.5	13.65 mm/day 32.4
KWAJEX August 18-21, 1999	12.94 mm/day 43.3	12.85 mm/day 31.3
KWAJEX August 29-September 13, 1999	9.24 mm/day 47.3	9.89 mm/day 36.2

The 3D GCE model-simulated multi-dimensional (space, time, multivariate, and multiple cloud/cloud system types) cloud database representing different geographic locations will be produced and archived. This cloud database will be provided to the large-scale modeling community for improving the representation of moist processes in GCMs and climate models. The standard model output includes pressure, temperature, water vapor mixing ratio, five species of hydrometeors (cloud water, rain, cloud ice, snow, and graupel, or hail), latent heat (through the phase change of water), vertical and horizontal eddy heat transport by clouds/cloud systems, moistening/drying, vertical and horizontal moisture eddy transport by cloud/cloud systems, long-wave cooling and short-wave heating (in clear and cloudy regions), cloudiness and cloud mass fluxes associated with cloud updrafts and downdrafts and the three-dimensional wind. Cloud water and ice path are also included. This cloud database is generated at a horizontal grid-size 1-2 km and at 40 vertical levels. In addition, this cloud database is separated into clear, convective, stratiform, and non-surface precipitation regions based on our convective-stratiform partitioning methods (Tao et al. 1993; Lang et al. 2003). This cloud database is also separated into active and inactive in the cloudy region based on the method described in Tao et al. (1987). The surface fluxes and rainfall are also produced.

This data will be available on public domain, with ftp access made available from a web site created within the Goddard Mesoscale Atmospheric Processes Branch (MAPB) or through requests by contacting the authors.

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