Sensitivity of Microphysics and Model Configuration on Precipitation Processes

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Motivation and Objective

Tools ***(Goddard Cumulus Ensemble Model - Data Sets)***

Results

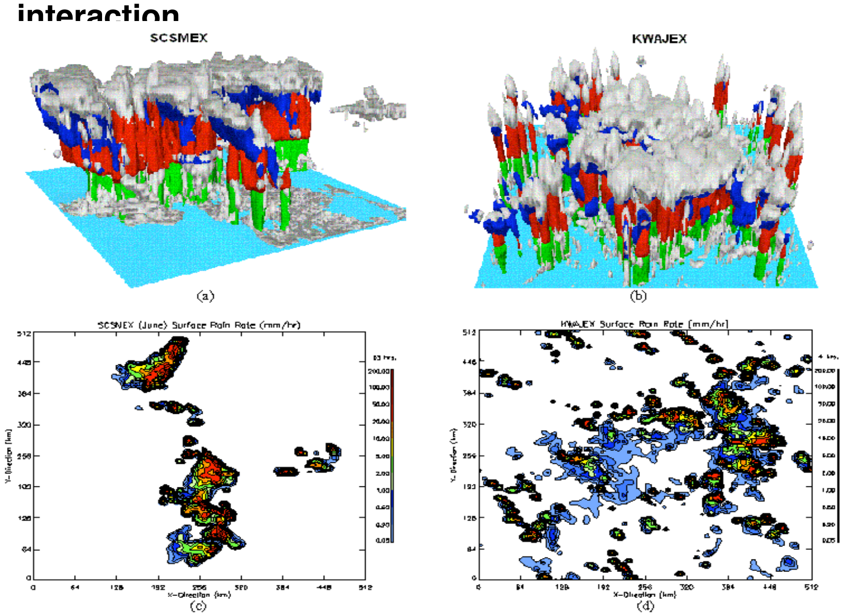
Conclusions and Future Works (Issues)

Global model - cloud-resolving model coupling: 4D cloud datasets

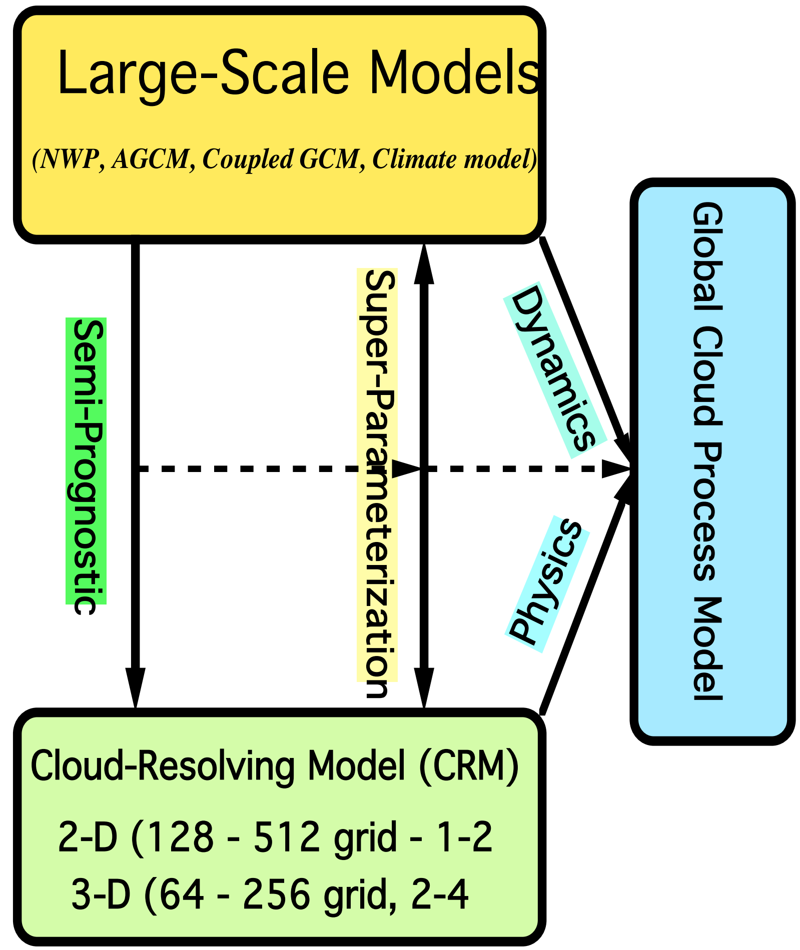
R. Atlas, SJ Lin, Tao and others

Goals

- **To improve our understanding of cloud-precipitation processes and their interaction with radiation, surface (land and ocean) processes and the large-scale circulation**
- **To improve the understanding and representation of cloud processes in large-scale models**
- **To provide detailed cloud structures for satellite retrieval**
- **To explicitly quantify the processes associated with local, regional and the global-scale water cycle**
- **To quantify chemistry transport and cloud-aerosol interaction**



3D GCE model simulation - 2-km grid (512 km x 512 km)
Top:5 types of hydrometeor, Bottom: Rainfall at surface



CRM: Microphysics (aerosol), Radiation, Surface Processes, Turbulence

Significance

- NASA Satellite Programs (TRMM, GPM, Terra, CloudSat and others)
- NASA ESE (climate variation, hydrological cycles ….)
- International programs (IPCC, GEWEX…)
- National Programs (USWRP, Climate Initiative….)

Unique – NASA

- Better usage of high temporal and spatial resolution data for validation and initialization of operational and research models through assimilation
- Better and more realistic 4D cloud datasets for improving satellite retrieval algorithms

Computational Requirements for a Global circulation model (FvGCM) with embedded 2D cloud process model (GCE model - radiation/surface processes)

Super-parameterization

Case		I	II
Grid size Global model		2.5 x 2.5 degrees	4x4 degrees
Gridpoints Global model		144x72x40	90x45x40
Gridpoints 2D CRM		128x40	256x40
Total memory		50 GB	35 GB
Disk space		2.5 TB	2 TB
No. of CPUs	Model Time	Wall-clock -time	Wall-clock -time
10	1 month/year	200/2400 days	141/1684 days
100	1 month/year	20/240 days	14.2/170 days
1,000	1 month/year	2/24 days	1.5/17.5 days

Objectives

The super-parameterization requires a cloud-resolving model to represent the moist processes and their interactions with radiation and surface processes

This implies that reliable cloud-resolving models are needed (through testing QC-observation)

To examine the sensitivity of microphysics used in cloud resolving models on the precipitation processes/rainfall and atmospheric energy and water budgets

To examine and compare the similarities and differences between 2D, semi-2D (W-E, S-N) and 3D cloud model simulations

To examine the sensitivity of grid mesh (250-4000m), vertical layers (24-40) and horizontal domain size (128-2048 km) used in the cloud resolving model

Goddard Cumulus Ensemble (GCE) Model

The Goddard Cumulus Ensemble (GCE) Model is a cloud-resolving model (also called a cloud-system model or cloud-process model) and has been developed and improved at NASA Goddard Space Flight Center over the past two decades.

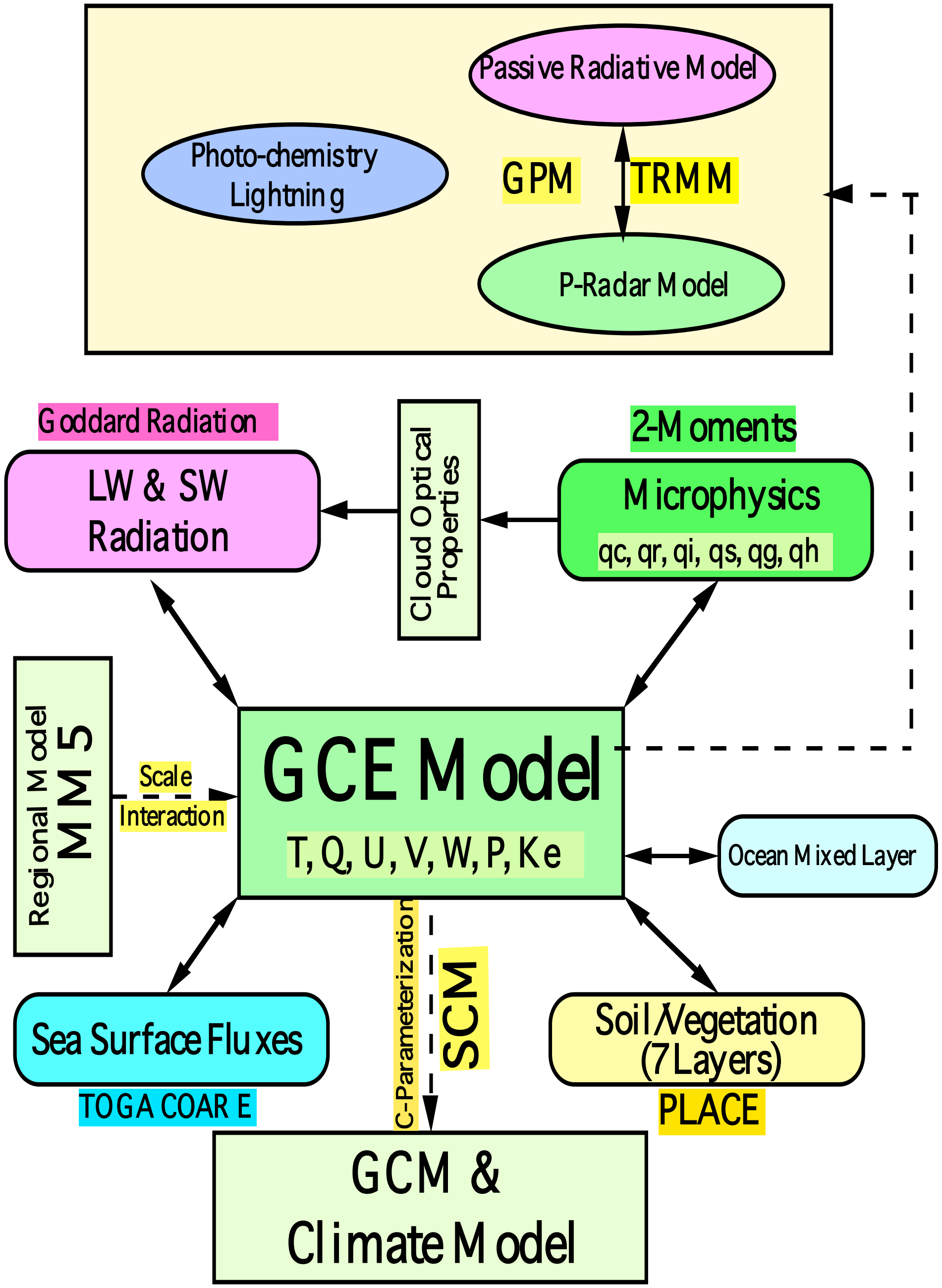
- very **fine grid spacing** (50-1000m) in the horizontal,
- sophisticated and realistic representation of cloud **microphysical** processes, and
- explicit interaction between **clouds** and **radiation** [out-going longwave (cooling) and in-coming solar (heating)] and the **surface** (ocean and land).

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.

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



3D Version

- *Cyclic Lateral Boundary Conditions (Anelastic System)*
- *Open or Cyclic Lateral Boundary Conditions (Compressible System)*

2D Version

- *Cyclic Lateral Boundary Conditions (Anelastic System)*
- *Open Lateral Boundary Conditions - Slab-symmetric (Anelastic System)*
- *Axis-symmetric (Anelastic System)*
- *Open Lateral Boundary Conditions - Slab-sysmetric (Compressible System)*

1D Version

- *Cumulus Parameterization (Convective)*
- *Explicit Microphysics (Stratiform - minor modification)*
- *Radiation*
- *Cloud-Radiation (Need modification - cloudiness and overlap)*
- *Land and Ocean Surface Processes*
- *Boundary Processes (TKE)*
- *Ocean Mixed Layer Model (Minor modification)*
- *BM and KF Parameterization schemes*
- *Dynamics (w, thea, qv and others)*
- *Stratocumulus Convection*

Clouds and cloud systems from different geographic locations

CAPE stands for Convective Available Potential Energy

	CAPE $m^2 s^{-2}$	Precipitable W ($g\ cm^{-2}$)	
SCSMEX (May18-26 1998)	825	62.53	S. China Se
SCSMEX (June 2–11 1998)	1324	62.34	S. China Se
TOGA COARE (December 19-27	898	54.64	W. Pacific
TOGA COARE (December 10-17	1238	56.48	W. Pacific
GATE (December 1-8 1974)	736	47.61	E. Atlantic
ARM (June 26-30 1997)	1954	37.76	USA
ARM (July 7-12 1997)	1761	37.56	USA
ARM (July 12-17 1997)	2806	36.80	USA
KWAJEX (August 7-12 1999)	2111	53.50	C. Pacific
KWAJEX (August 17-21 1999)	2082	54.39	C. Pacific
KWAJEX (August 29-September	2025	55.69	C. Pacific

ARM cases are GCSS Case 3

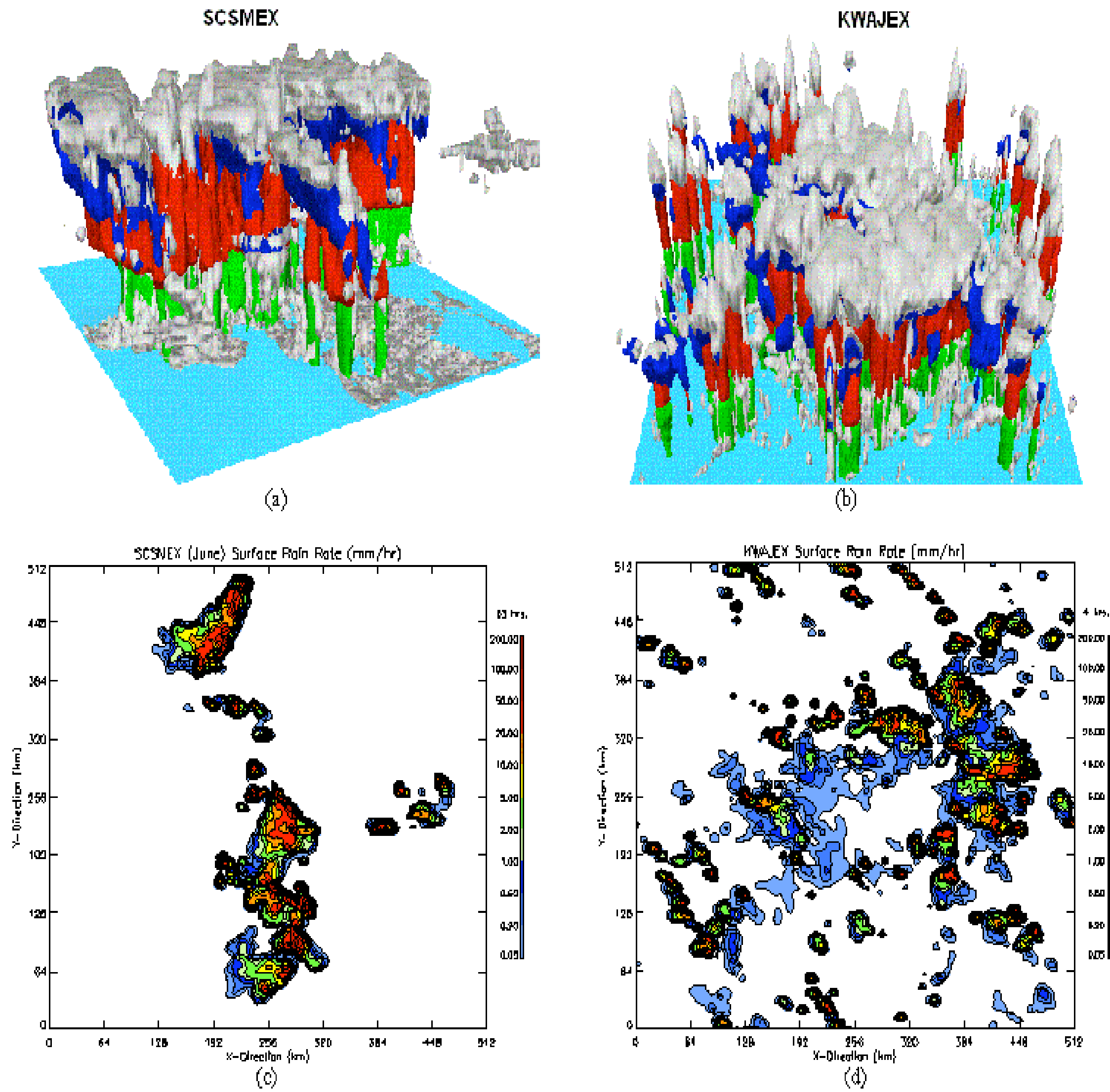
TOGA COARE December 19-27 is GCSS Case 2

SCSMEX and KWAJEX are TRMM priority cases

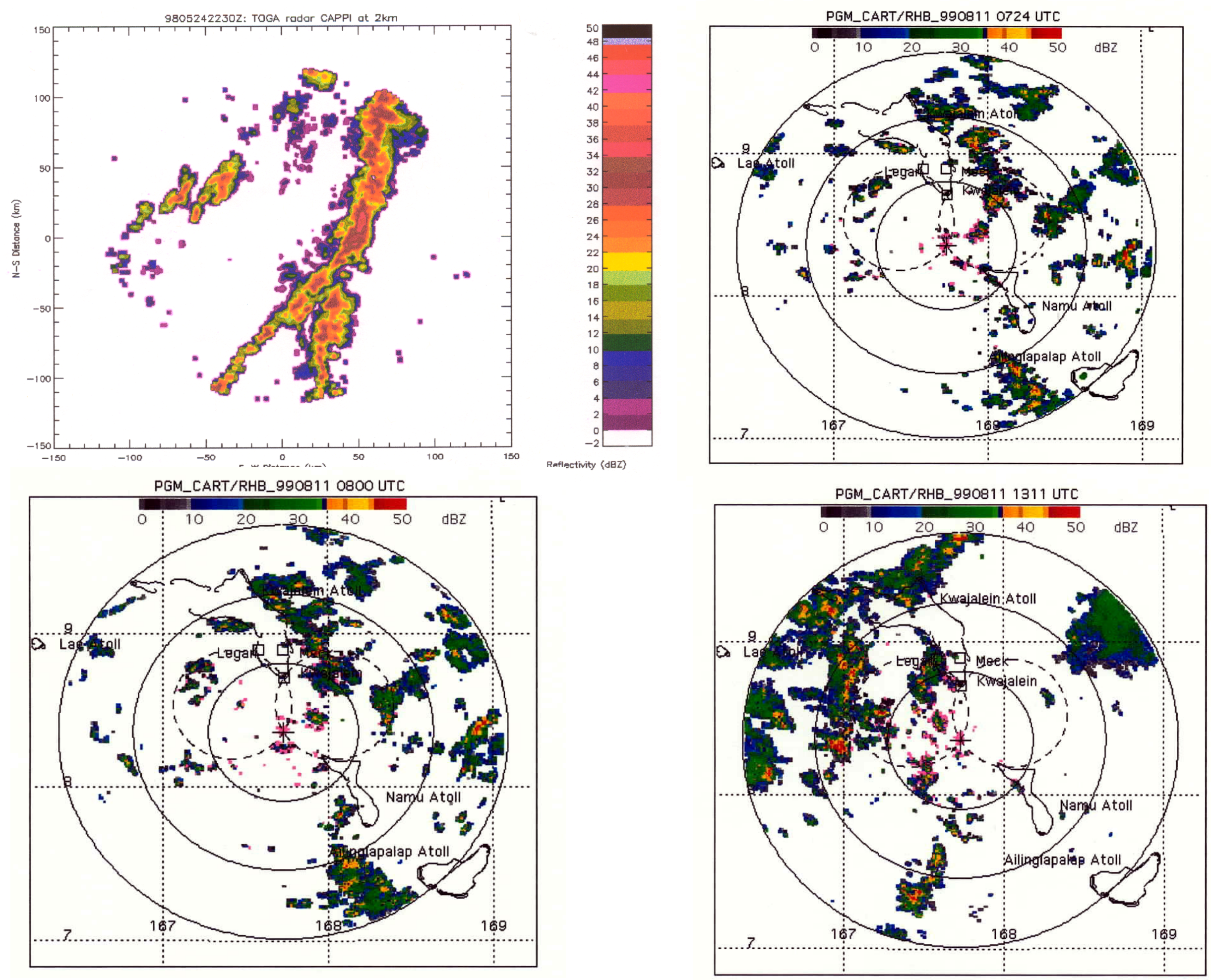
Convective systems - LBA and TOGACOARE (6-10 h)

SCSMEX (S. China Sea) and KWAJEX (W. Pacific)

3-D GCE model-simulated cloud hydrometeor mixing ratios for (a) a **SCSMEX** and (b) a **KWAJEX** case. The white isosurfaces show the cloud water and cloud ice, blue the snow, green the rain water, and red the graupel. Also shown are the GCE simulated **surface rainfall rates** (mm/hr) for (c) SCSMEX and (d) KWAJEX corresponding to the same cloud fields in (a) and (b). Most (but not all) of the surface rainfall is being produced by the melting of graupel [red surface in (a) and (b)] near 0 C. This indicates the importance of ice processes even in tropical environments.The rain patterns resemble radar observations (Johnson *et al.* 2002; S. Yuter and R. Houze, 2002, personal communication).



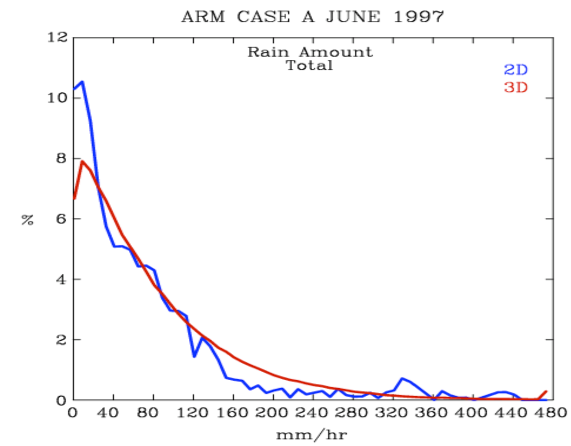
Radar observation - SCSMEX and KWAJEX



Radar Observations (dBZ) from SCSMEX (upper left panel)and KWAJEX (remaining three panels). Linear cloud systems typically propagated from west to east in SCSMEX. Less organized and short-lived clouds/cloud systems dominated in KWAJEX.

Simulated Rainfall and stratiform % from the 2D and 3D GCE model

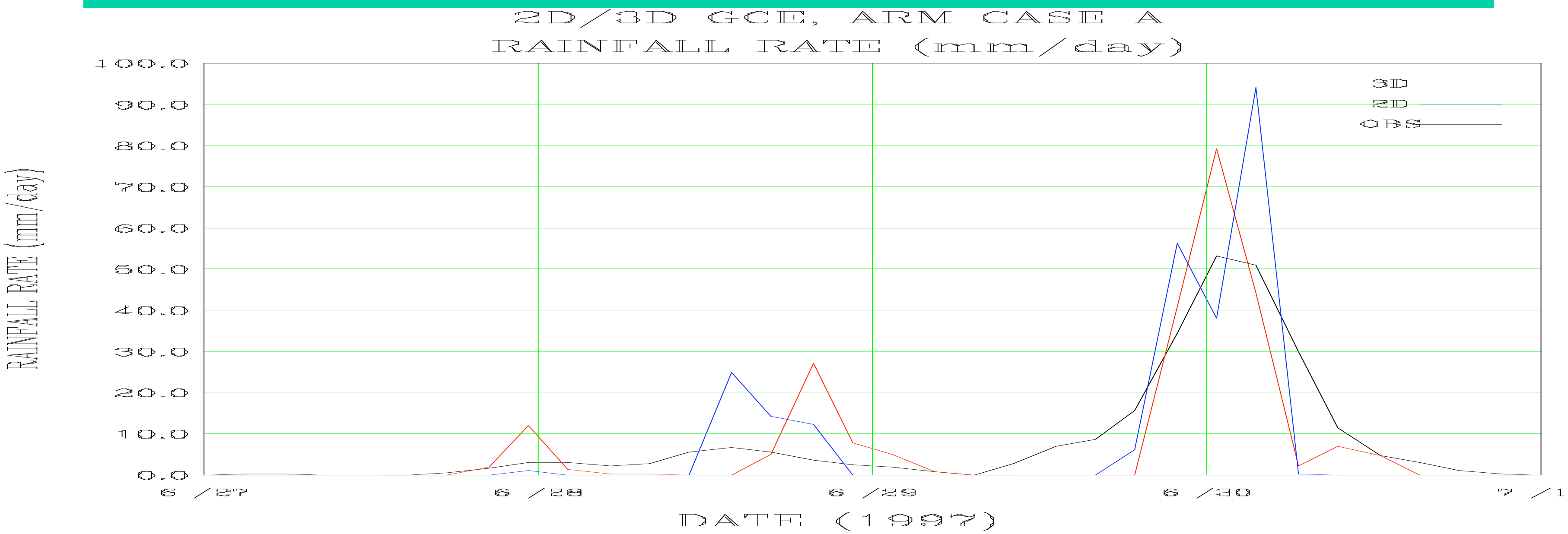
	2-D Rainfall/Stratiform %	3-D Rainfall/Stratiform %
TOGA COARE December 19-27 1992	20.2 mm/day 45%	20.7 mm/day 37%
SCSMEX May 18-26, 1998	11.14 mm/day 49%	11.65 mm/day 40%
SCSMEX June 2 – June 11, 1998	16.5 mm/day 38%	17.0 mm/day 31.4%
ARM June 26-31 1997	7.73 mm/day 17.9%	7.48 mm/day 8.0%
ARM July 7-12 1997		
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%



$$\frac{\bar{\rho}}{g}\int_{Lx}\int_{Lz}\left(\frac{\partial\bar{\theta}}{\partial t} + \vec{V}\bullet\nabla\bar{\theta} + \bar{w}\frac{\partial\bar{\theta}}{\partial z}\right)\Delta z\Delta x = LP_o + S_o + \frac{1}{g}\int_{Lx}\int_{Lz}(Q_R)\Delta z\Delta x$$

- **Similar rainfall amounts were simulated by the 2D and 3D GCE model for all cases**
- **Less stratiform rainfall was simulated in 3D compared to 2D for all cases**
- **Big differences in rainfall amount were found in other CRMs for ARM cases**

Differences and Similarities between 2D and 3D GCE Model Simulations



Similarities

- Mean and time-dependent Q1 Q2 budgets
- Total rainfall <-> Net condensation
- Mean and integrated rain and hail mass
- Latent heat fluxes (KWAJEX) for active events

Differences

- 3-D stronger updrafts and downdrafts
- 3-D greater rainfall % from convective regions
- 3-D more mean rainfall and graupel mass in stratiform regions
- 2-D more mean cloud water and ice mass -> less net radiation cooling

Moist Static Energy Budget

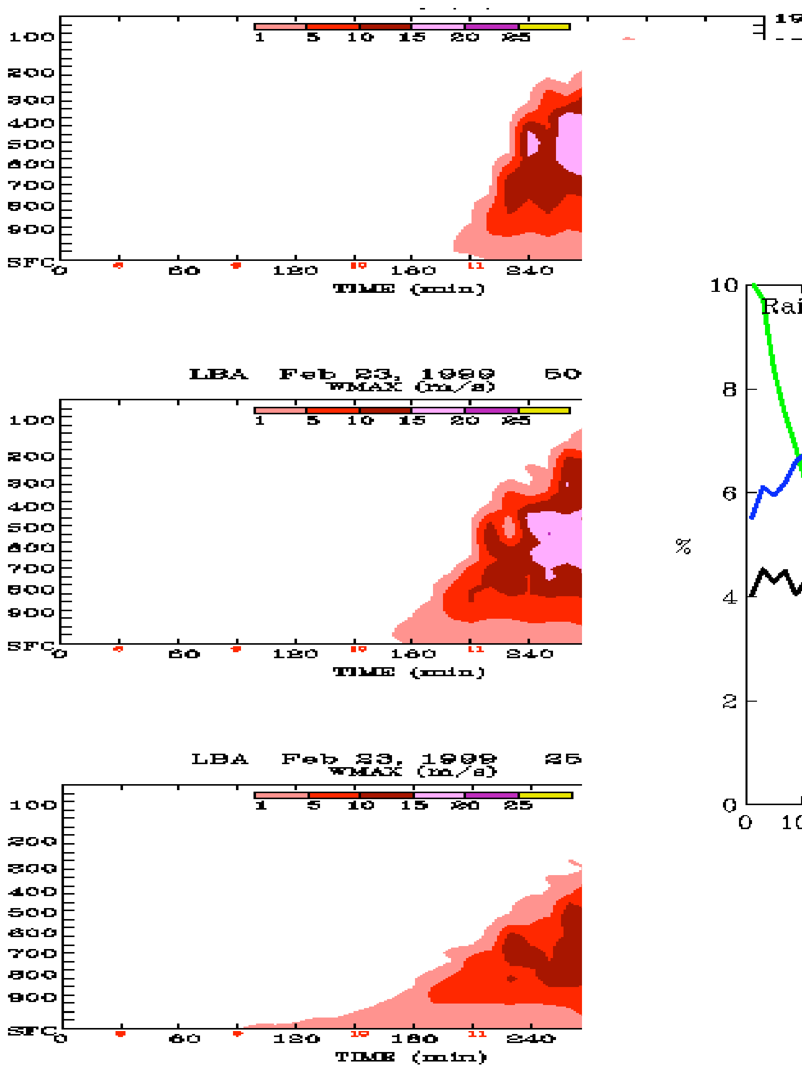
SCSMEX May 18-26 1998	D(CpT+LvQv)	Net Condensatio	Large-scale Forcing	Net QR	Sensible Heat Fluxes	Latent He Fluxes
Control Run	-18.0	2.84	48.8	-110.7	4.2	36.85
4 km – 1024 k	-9.7	4.85	48.8	-102.9	4.1	35.54
4 km – 2048 k	-14.7	4.76	48.8	-111.5	4.4	38.89
8 km –2048 km	-14.4	4.93	48.8	-111.6	4.2	39.40
4 km – 256 km	-14.2	3.00	48.8	-103.3	3.9	33.44
2 km – 128 km	-14.2	2.92	48.8	-102.5	3.9	32.62
1 km – 64 km	-2.3	3.21	48.8	-88.6	3.9	30.42
NX=512, NZ=	-19.7	3.05	54.5	-109.5	4.0	28.27
MX=64, Nz=	-2.3	3.21	48.8	-88.6	3.9	30.42
NX=64, Nz=	-12.4	3.44	54.5	-97.8	3.4	24.08
Control Run	-18.0	2.84	48.8	-110.7	4.2	36.85
Y-Z	-16.2	2.67	48.8	-110.5	4.5	38.38
1/4 Forcing	-63.8	1.23	12.2	-117.	3.8	36.80
1/4 Forcing Y-Z	-61.0	1.13	12.2	-117.	4.1	38.78

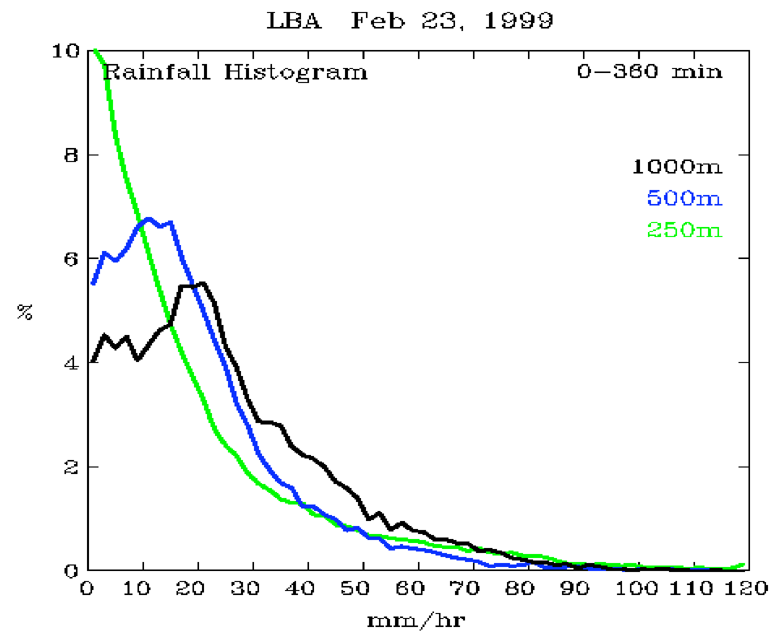
$$< \frac{\partial \bar{h}}{\partial t} >= L_f < (\bar{f} \square \bar{m}) + (\bar{d} \square \bar{s}) > \square(C_p < \frac{\partial \bar{\square}}{\partial t} >_{L.S} + L_v < \frac{\partial \bar{q}_v}{\partial t} >_{L.S}) + \bar{Q}_R$$

Radiation and Latent Heat Fluxes

Impact of Horizontal Grid Size

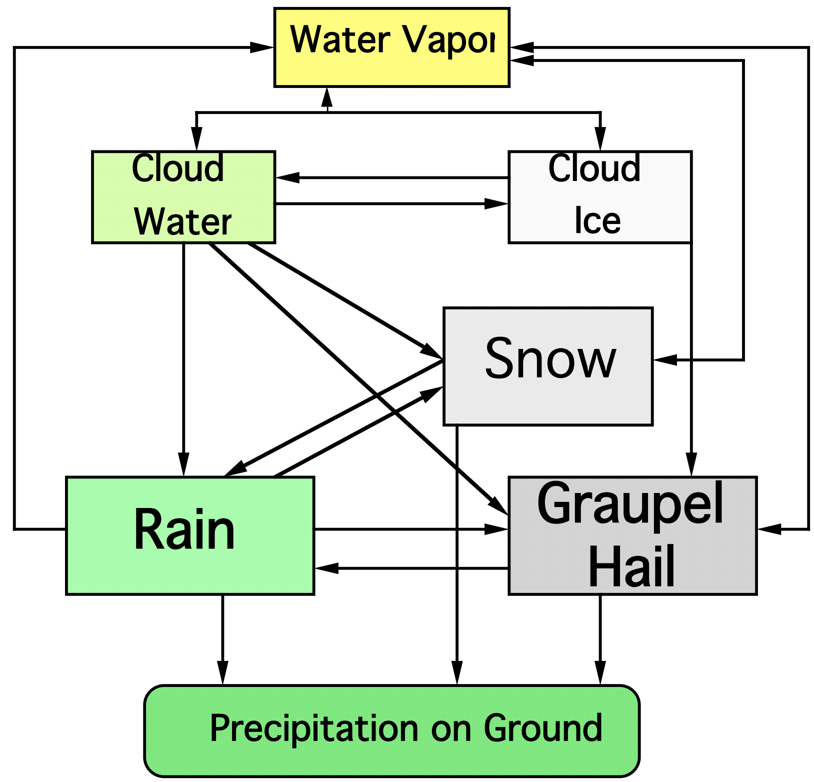
Boundary Layer Development and the diurnal variation of precipitation





Goddard Microphysics

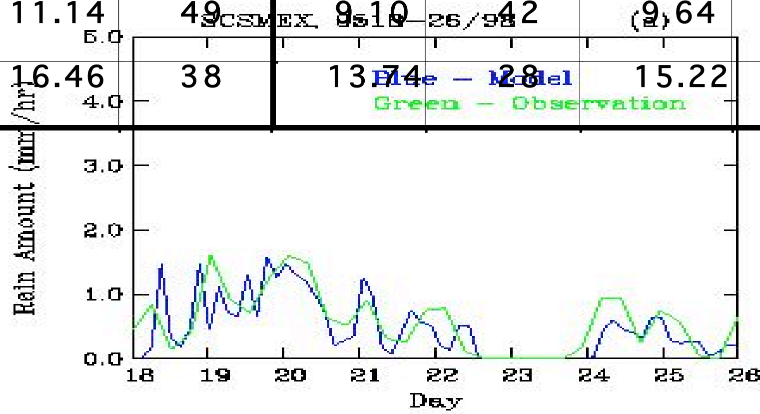
	Characteristics	References
Warm Rain	qc, qr	Kessler (1969), Soong and Ogura (19
2 Ice	qc, qr, qi, qg	Cotton et al (1982), Chen (1 McCumber et al (1991)
3Ice - 1	qc, qr, qi, qs, qh	Lin et al (1983), Tao and Simps 1993)
3Ice - 2	qc, qr, qi, qs, qg	Rutledge and Hobbs (1984), Ta Simpson (1989, 1993)
3Ice - 3	qc, qr, qi, qs, qh	Lin et al (1983), Rutledge and Hobb (1984), Ferrier at al (1995)
3Ice - 4	qc, qr, qi, qs, qg or qh	Lin et al (1983), Scott et al
3Ice - 5	Saturation Technique	Tao et al (1989), Tao et al (
4Ice - 1	qc, qr, qi, qs, qg, qh Ni, Ns, Ng, Nh	Ferrier (1994)
4Ice - 2	qc, qr, qi, qs, qg, qh Ni, Ns, Ng, Nh	Tao, Ferrier et al (2000)
One-Moment Spectral - Bin	43 bins for 6 ice types, liquid water and cloud condensation nuclei	Khain and Sednev (1996) Khain *et a* (1998)
Multi-component Spectral - Bin	Liquid: 46 bins for water mass, 25 for solute mass Ice: water mass, solute mass, aspect ratio Aqueous-phase chemistry (NH_3, H_2SO_4, HNO_3, SO_2, O_3, H_2O_2, CO_2)	Chen and Lamb (1994, 199

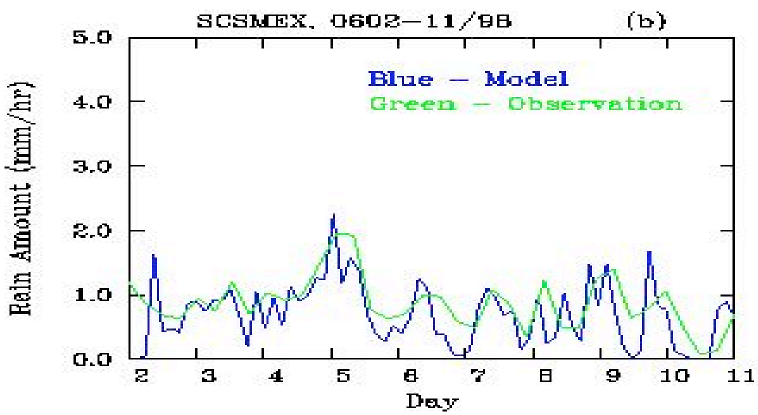


One of the most unique characteristics of the GCE model is its microphysical processes. The cloud microphysics include a parameterized two-category liquid water scheme (cloud water and rain), and a three-category ice-phase scheme (cloud ice, snow and hail/graupel). The following major improvements have been made to the model during the past several years: (i) the addition of a two-moment four-class ice scheme, and (ii) the addition of two detailed, spectral-bin models. See Tao *et al.* (2003) for a detailed description of the GCE model.

Warm rain, three-Ice Schemes
SCSMEX (South China Sea Monsoon Experiment 1998)

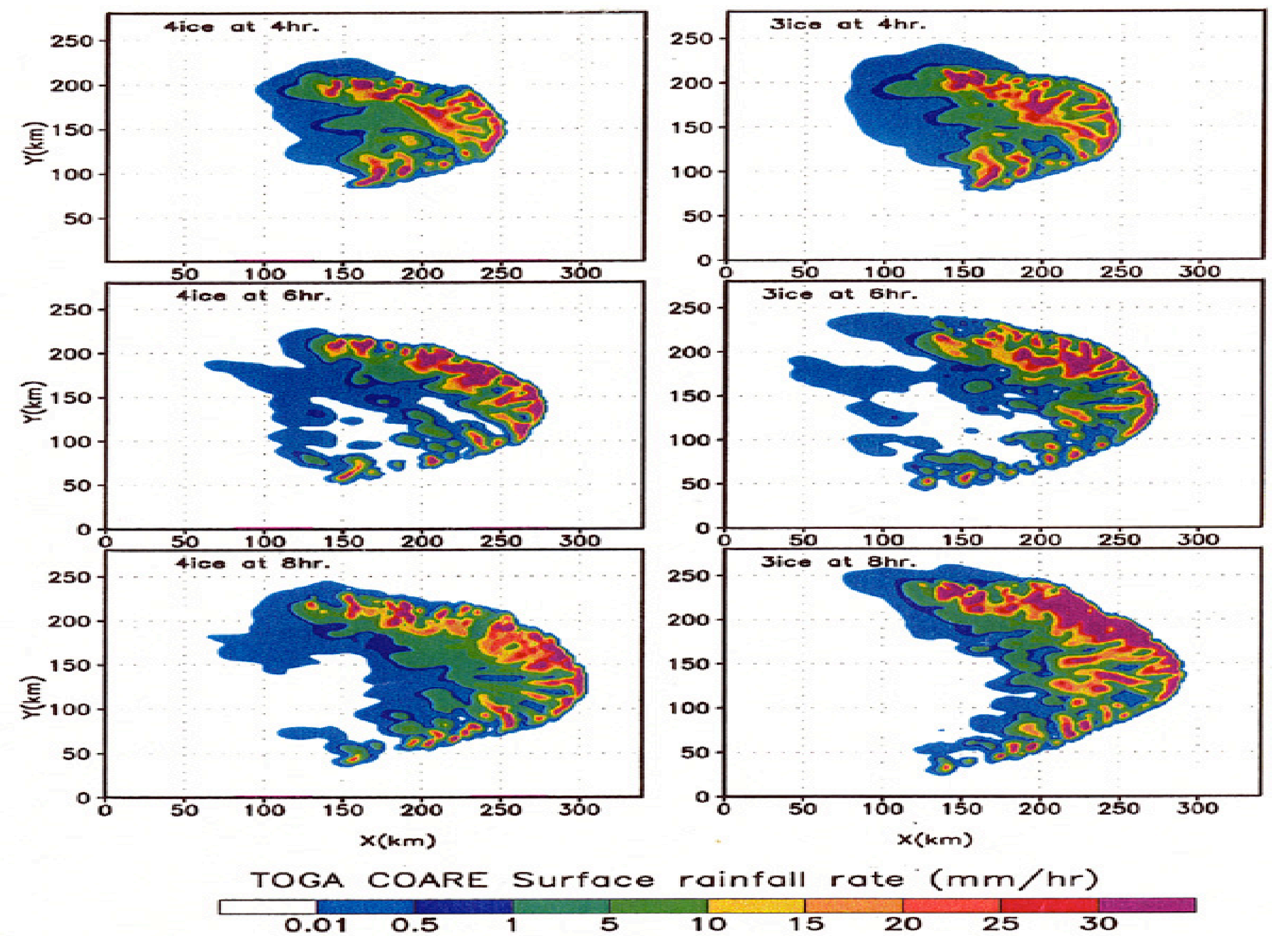
	Contr Run		Warr Rain		Modifie 3-Ice	
	Rainfall (mm/da	Stratifor (%)	Rainfall (mm/da	Stratifor (%)	Rainfall (mm/da	Stratifor (%)
May 18 – May 26	11.14	49	9.10	42	9.64	49
June 2 – June 11	16.46	38	13.74	28	15.22	36





Three-Ice and Four-Ice Schemes
TOGA COARE and GATE

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



Large-Scale Biosphere Atmosphere Experiment in Amazonia (**LBA** 1999) 3ICE and 4ICE

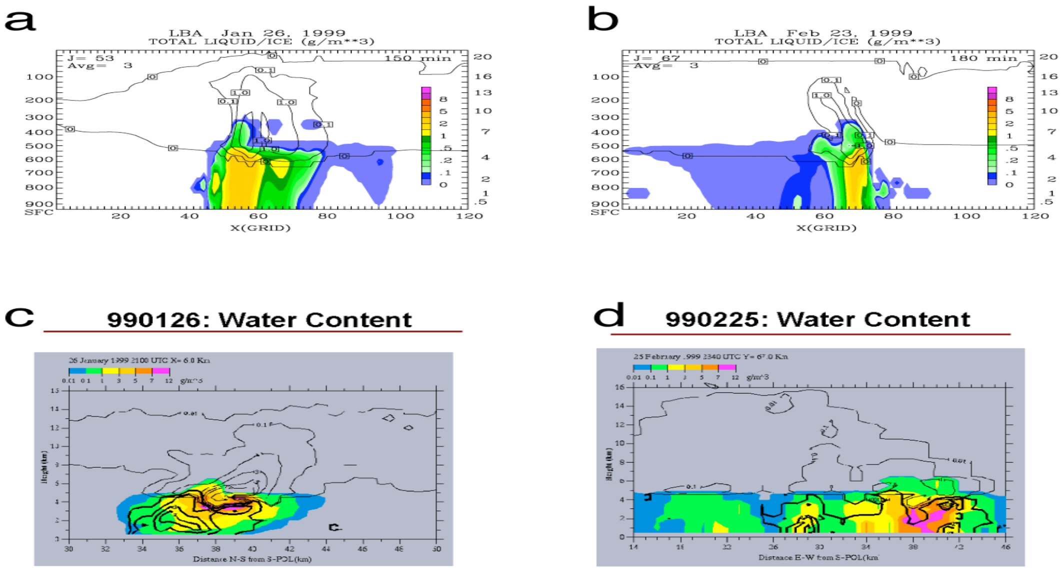
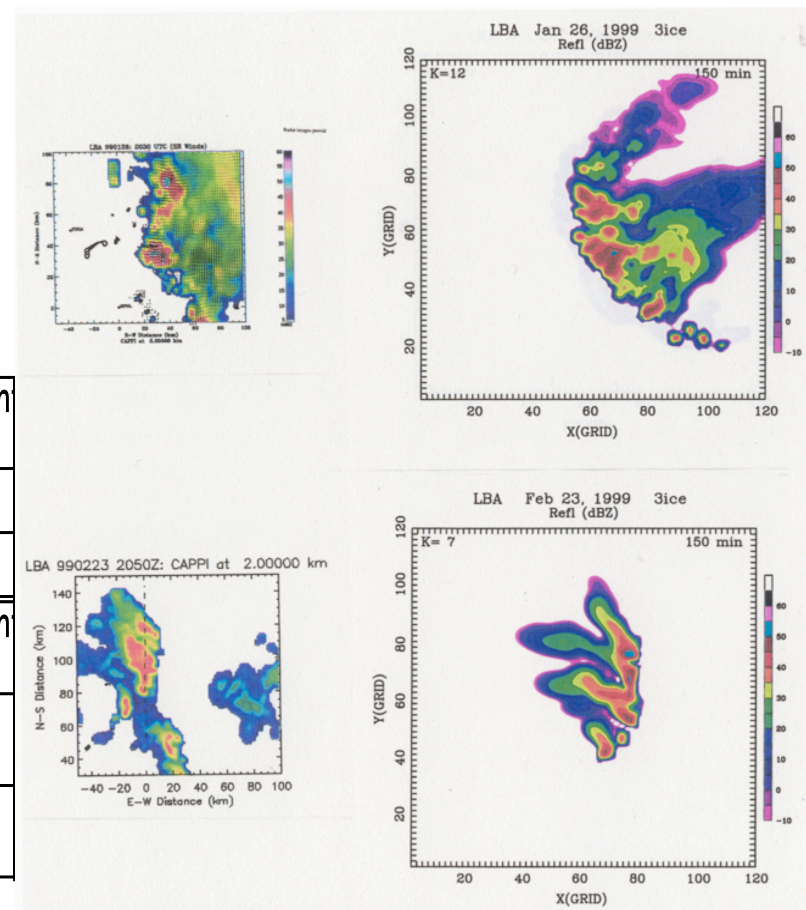
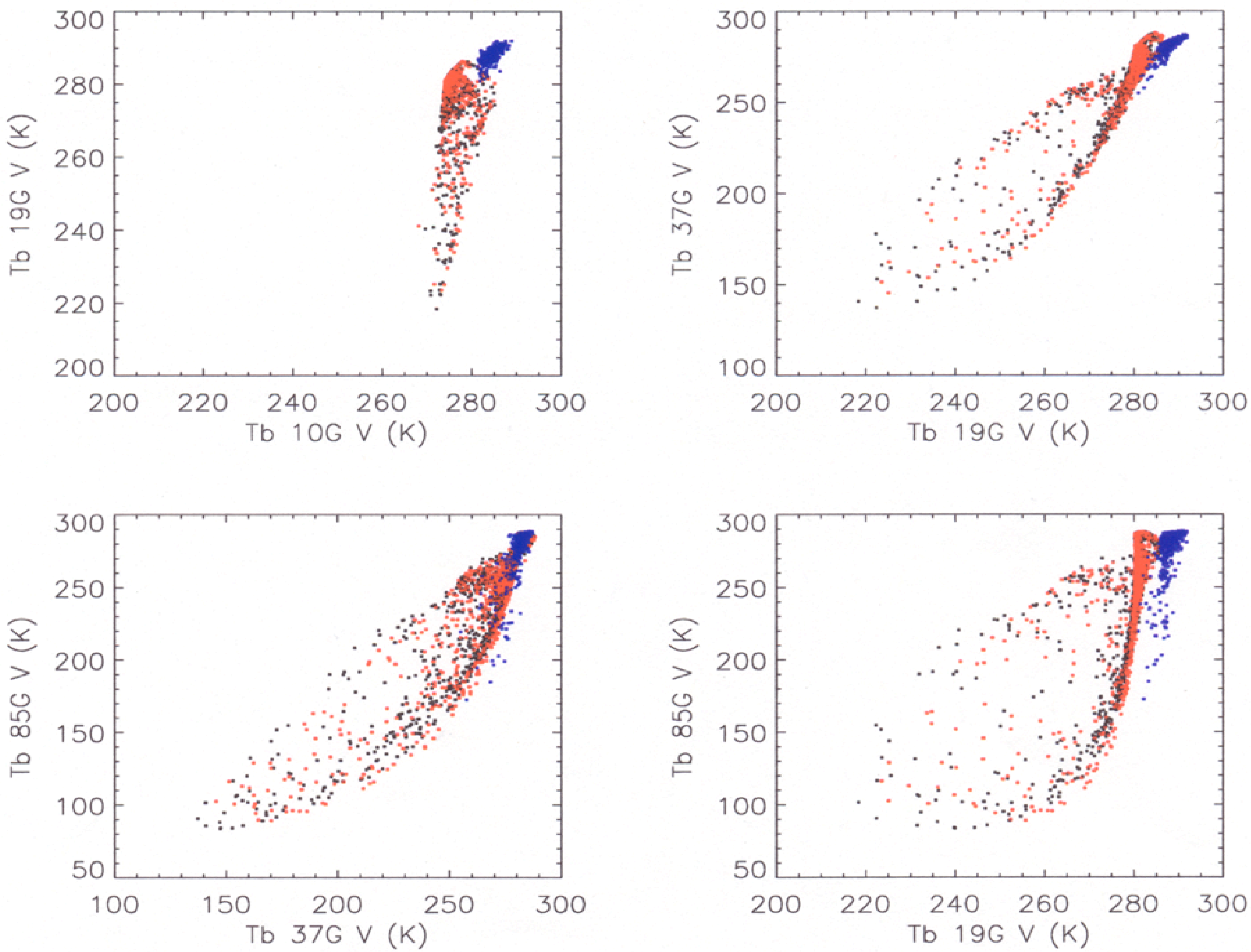


Fig. 5.6 Liquid and ice water contents in g/m**3 for two different convective systems observed during TRMM LBA. 3D GCE model simulated results for (a) the Jan 26, 1999 easterly regime case and (b) the Feb 23, 1999 westerly regime case. (c) and (d) are the same as (a) and (b) except derived from radar observations and (d) is the Feb 25, 1999 westerly regime case. (c) and (d) are courtesy of S. Rutledge and R. Cifelli (Colorado State U.)

January 26 1999 Cool Pool	Rainfall (120 min) mm/h	Rainfall (180 min) mm/h	Stratiform Amoun (%) - 180 min
3ICE -Graupel	0.68	1.33	27%
4ICE	0.64	1.30	27%
February 23 1999 Cool Pool	**Rainfall (90 min) mm/h**	**Rainfall (150 min) mm/h**	**Stratiform Amoun (%)**
3ICE -Graupel Modified Sounding	0.14	0.32	40%
4ICE Modified Sounding	0.15	0.30	41%



Black: Feb23; Red: Reduced graupel; Blue: Observation



Conclusions/Issues

- **Can we make 2D and 3D results (rainfall characteristics/cloud mass) as similar as possible?**
- **Do we need more vertical layers (interpolation - energy conservation)?**
- **Do we need finer horizontal grid mesh (2 km or finer)? If not, what physical processes do we need to include in the CRMs?**
- **What is the optimal GCM's grid mesh (2.5 - 5 degree)?**

- **Microphysics**
- **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 produce fast-falling hydrometeors will 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**
- **The aerosol distribution can have a major impact on precipitation**