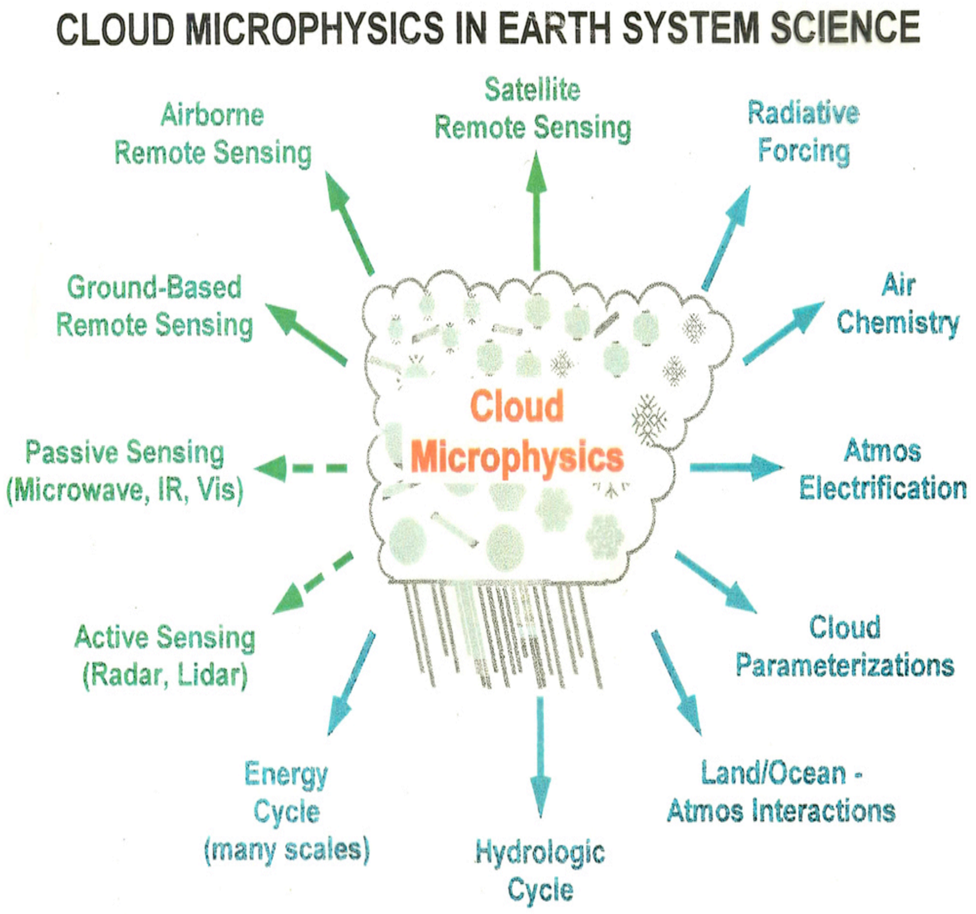
Climate Change Science Program (CCSP)
Cumulus Parameterization



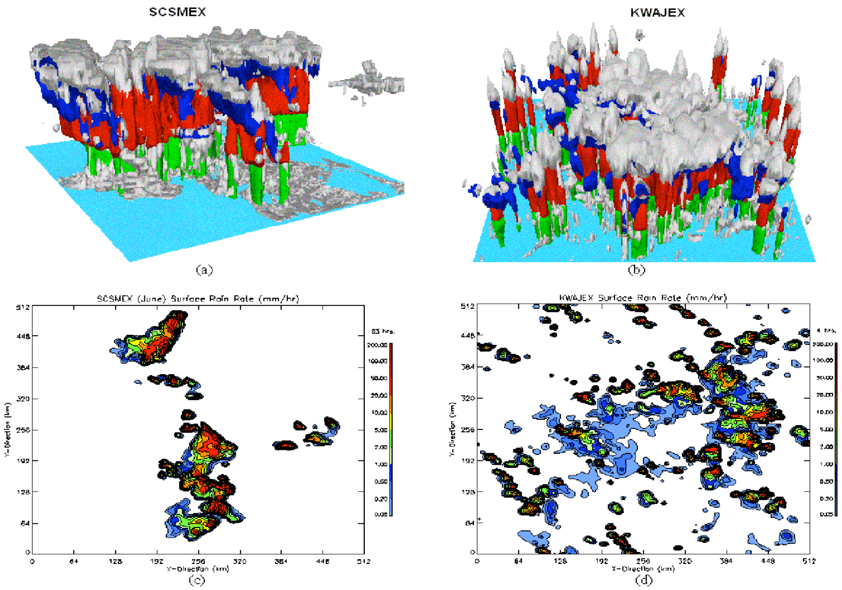
- *Traditional* (1-D Cloud Model) - **Hou, Chou, Sud, Lau, … Tao(GFDL/NCAR)**
- *Statistical* (Multi- and High-Moments)
- *Super-Parameterization* (2-D cloud model and multi-scale) **- R. Atlas, SJ Lin, Lau, …….Tao(CSU)**

Tao, W.-K., D. Starr, A. Hou, P. Newman, and Y. Sud, 2003 A cumulus parameterization workshop, BAMS, 1055-1062. :

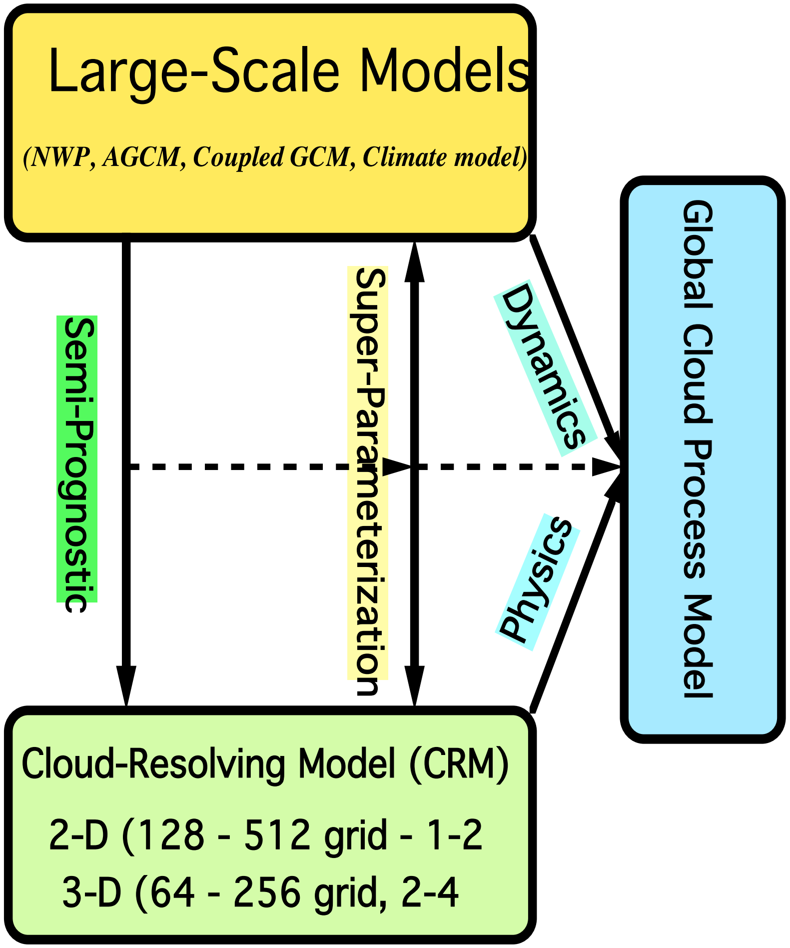
Global - cloud-resolving model coupling: 4D cloud datasets

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/energy 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



Large-Scale Models

(NWP, AGCM, Coupled GCM, Climate model)

Semi-Prognostic

Super-Parameterization

Dynamics

Physics

Global Cloud Process Model

Cloud-Resolving Model (CRM)

2-D (128 - 512 grid - 1-2

3-D (64 - 256 grid, 2-4

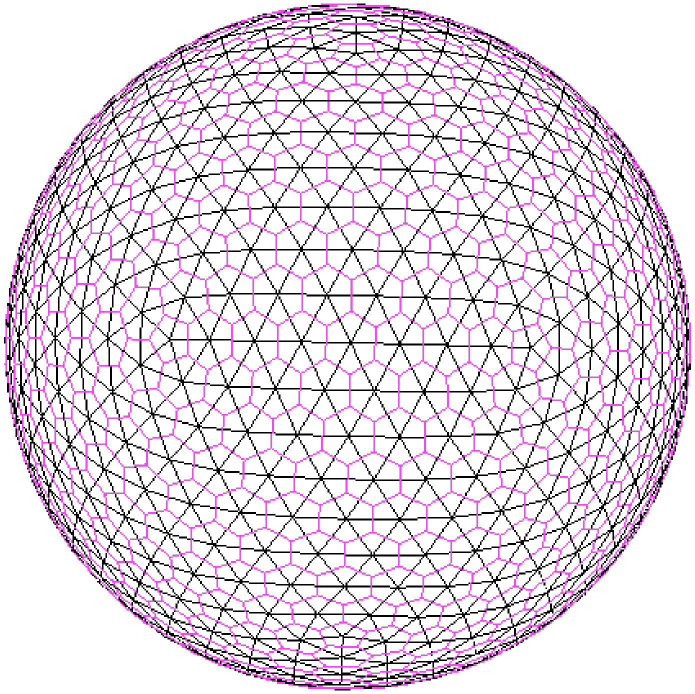
CRM: Microphysics (aerosol), Radiation, Surface Processes, Turbulence

Model Needs in Support of ESE

S.J. Lin/R. Atlas

- Cumulus parameterization-free "***cloud microphysics***"
- High-order finite-volume (fv) non-hydrostatic dynamics
- ***Gravity-wave*** & ***cloud resolving resolution*** (5 km or finer)
- Model top at/above the mesopause (80 km)
- Scalable to over 40,000 CPUs
- Coupled to an eddy resolving ocean model
- Coupled to a dynamic sea ice model
- Coupled to a ***ultra-high-resolution land model***
- Coupled to a full chemistry with 50 plus species
- Enabling the assimilation of **NASA** and **NOAA** high-resolution satellite data

Geodesic Grid



Cloud Superparameterization

- Superparameterization provides a common reality for global models to assimilate CRM-retrieved satellite observations (precipitation, latent heating, etc.)
- Superparameterization has the potential to substantially reduce systematic errors in forecast models to improve long-range forecasts and climate prediction capabilities.
- Development of cloud super-parameterization in *partnership with university and NOAA investigators* (Randall et al.)

Significance

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

Unique – NASA

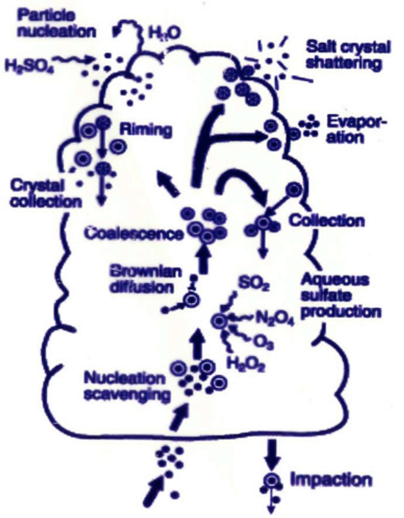
- **Better usage of high temporal and spatial resolution data for validation and initialization of operational and research models through assimilation**
- **Better and more realistic 4D cloud datasets for improving satellite retrieval algorithms**

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

Super-parameterization

Case		I
Grid size - Global model		2.5 x 2.5 degrees
Gridpoints - Global model		144x72x40
Gridpoints - 2D CRM		128x40
Total memory		50 GB
Disk space		2.5 TB
No. of CPUs	Model Time	Wall-clock -time
10	1 month/year	200/2400 days
100	1 month/year	20/240 days
1,000	1 month/year	2/24 days

Complicated Interactions between Cloud, aerosol and Chemistry



(from: D.A. Hegg, IGACtivity No. 23)

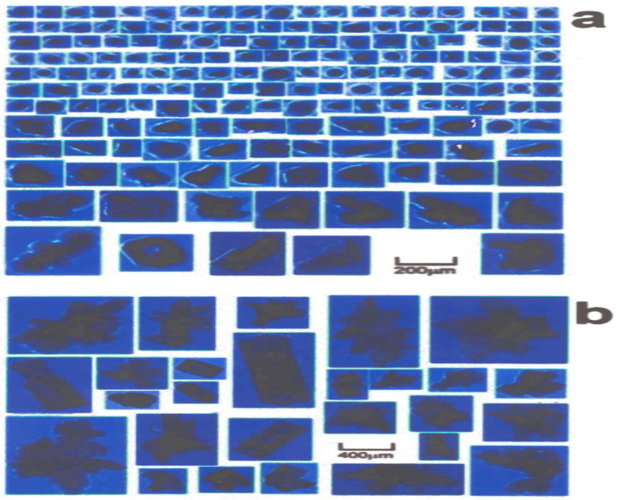
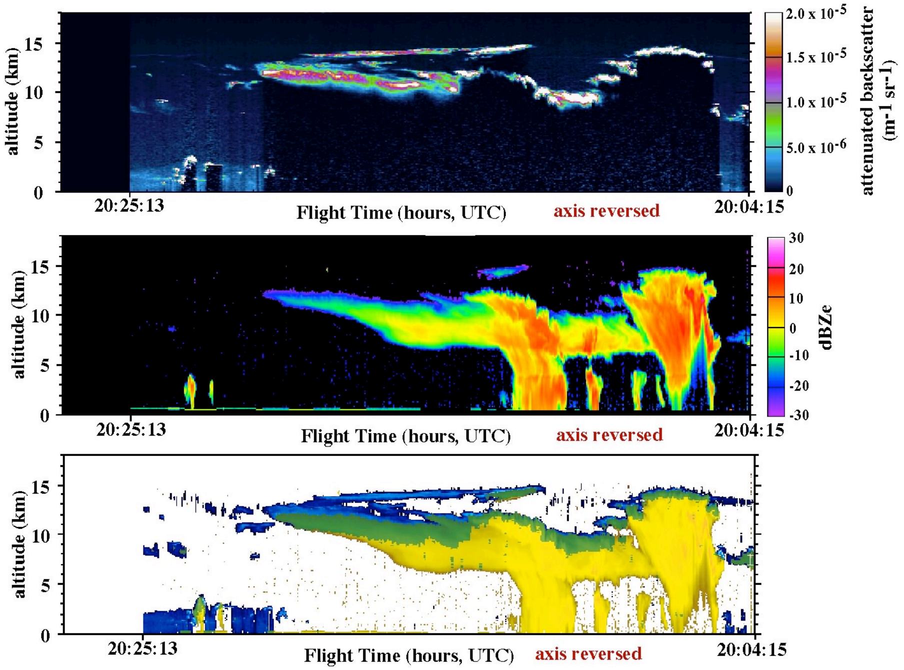


Figure 5. Images of cloud particles measured in glaciated cloud within the time interval indicated by gray shade in Fig. 4. Small particles in (a) have a lot of circular images.

Cloud Radar - Lidar Detectabilities

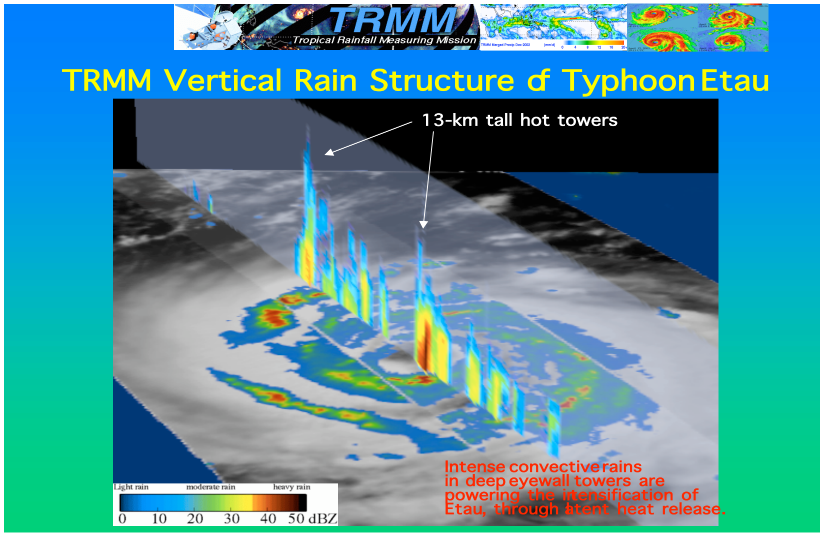
CRL (lidar)

CPS (94 GHz)



Blue-lidar
Green-overlap
Yellow-radar

¬Radar and lidar are very complementary in terms of sensitivity, but there is less overlap than expected.



TRMM Vertical Rain Structure of Typhoon Etau

13-km tall hot towers

Intense convective rains in deep eyewall towers are powering the intensification of Etau, through latent heat release.

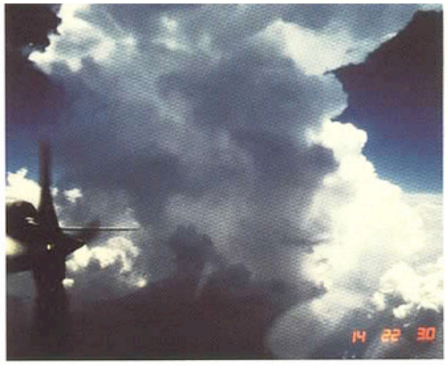
Cloud 140646 CDT

140934

141246

141539

Cloud 142014 CDT



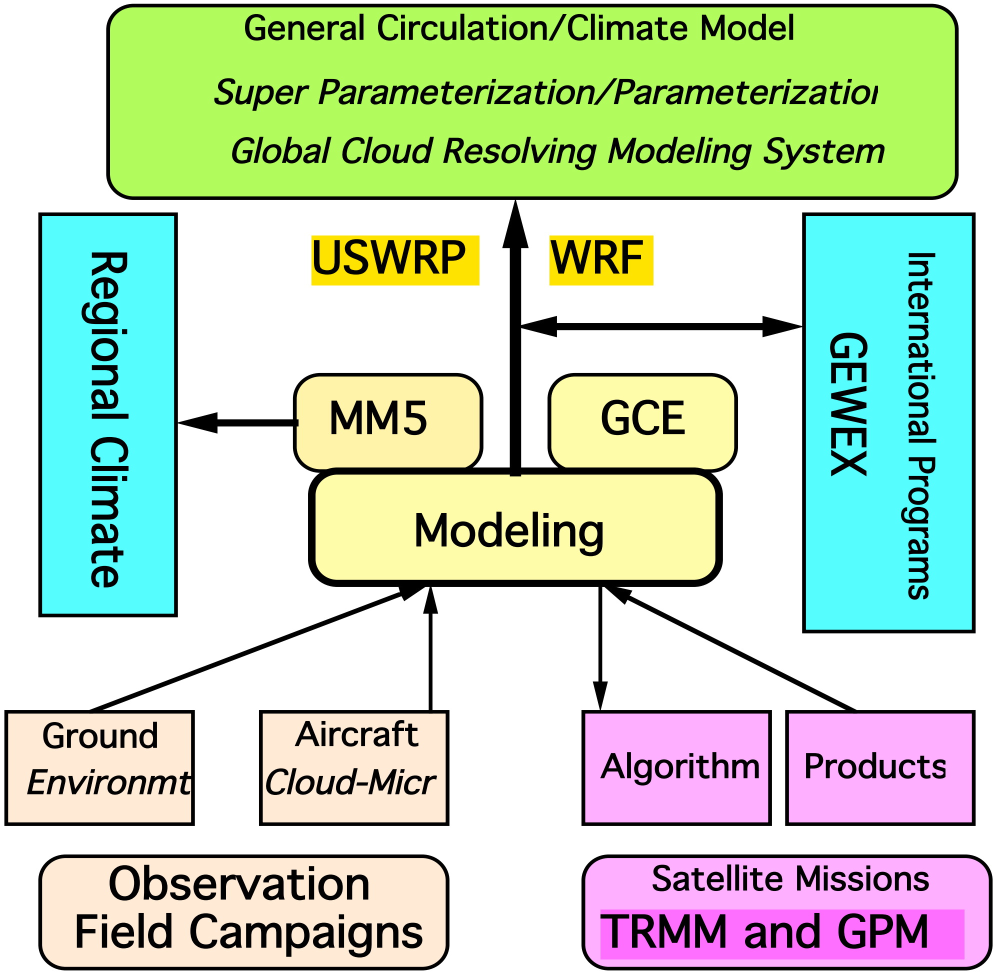
142230

142533

142620

Goddard Mesoscale Modeling Activities

- **Improve *Microphysics* using observational data**
- **Develop a second generation GCE model - *Earth Science Modeling Frame (ESMF)***
- **Provide four-dimensional cloud datasets to *satellite retrieval algorithm and large-scale parameterization developers***
- **Implement the Goddard Physical Packages into the WRF**
- **Implement the GCE model into the Goddard GCM (FvGCM) *(super parameterization)***
- **Provide needed physical packages to global cloud process modeling systems - *Global Cloud Simulator* (GCS)**



General Circulation/Climate Model

Super Parameterization/Parameterizatio

Global Cloud Resolving Modeling System

Regional Climate

USWRP

WRF

GEWEX

International Programs

MM5

GCE

Modeling

Ground *Environmt*

Aircraft *Cloud-Micr*

Algorithm

Products

Observation Field Campaigns

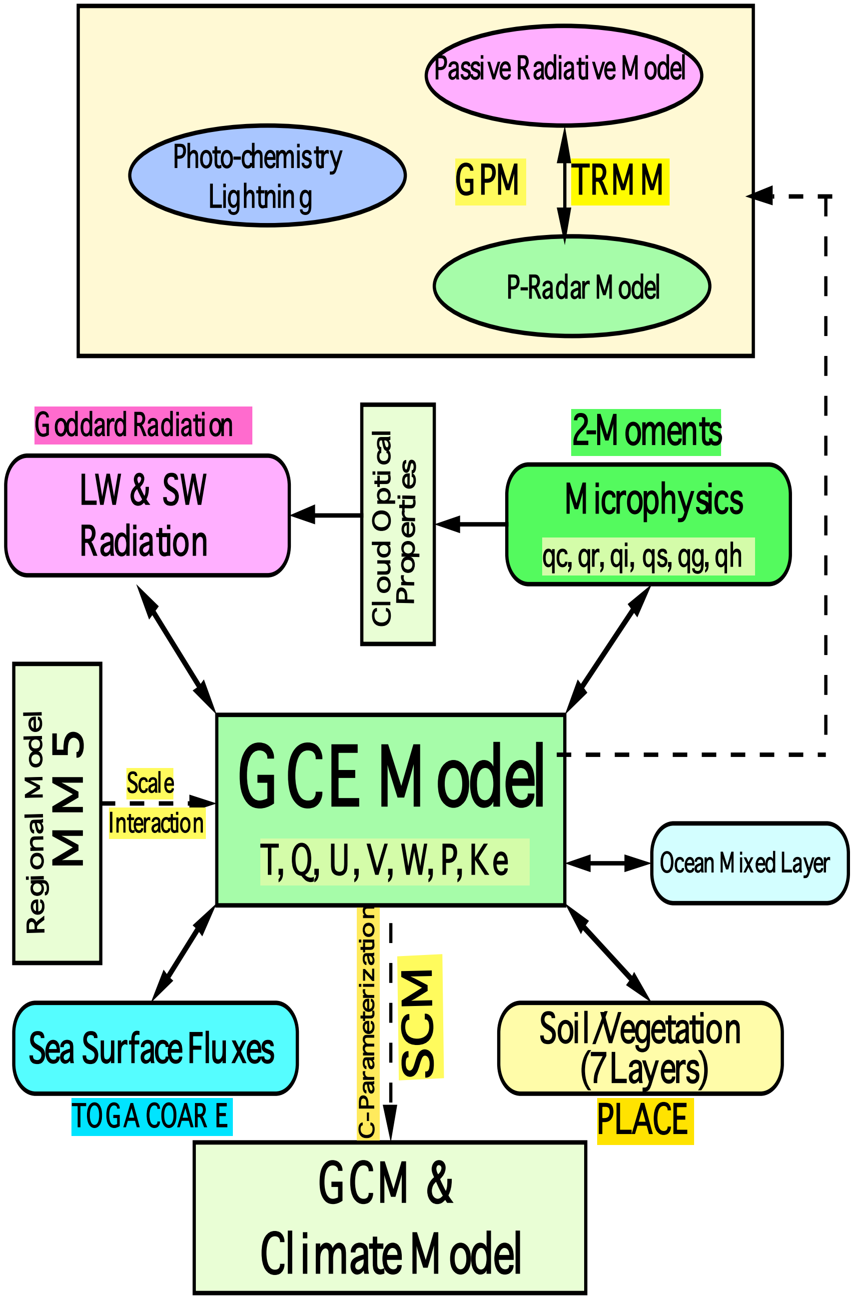
Satellite Missions

TRMM and GPM

Precipitation Processes -Hydrological Cycl

Goddard Cumulus Ensemble (GCE) Model

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 Processes	Ocean Mixed Layer 7-Layer Soil Model (PLACE) CLM-LIS TOGA COARE Flux Module
Parallelization	OPEN-MP and MPI



	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), Scott et al (2000)
3Ice - 5	Saturation Technique	Tao et al (1989), Tao et al (2000)
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** types of ice, liquid water and cloud condensation nuclei	Khain and Sednev (1996) and 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 Aqueous-phase chemistry (**NH_3, H_2SO_4, HNO_3, SO_2, O_3, H_2O_2, CO_2**)	Chen and Lamb (1994, 1999)

GCE MPI Performance - Halem

No. of CP used	Wall-Clock Time	CPU Time for Effective Computation	System Time for Data Communicatio	Efficiency of Parallel Computatio	Equivalen No. of CPU
1	41016 s	41016 s	0	100%	1
4	13059 s	10254 s	2805 s	78.5%	3.1
16	3594 s	2563 s	1030 s	71.3%	11.4
32	1614 s	1281 s	332 s	79.4%	25.4
64	860 s	641 s	219 s	75.5%	47.7
128	419 s	256 s	162 s	61.2%	97.9
256	324 s	128 s	196 s	40.0%	126.6
512	297 s (200 s)	64 s	233 s (136 s)	21.6% (40.1%)	138.1 (205.1)

CPU Time for Effective Computation is defined as
The ratio of the CPU time for the single processor to
CPU number

(): No in-line statistics

Structure of GCE

Gridpoints : 256-1024 x 256-1024 x 32
Domain Size : 512-1048 x 512-2048 x 22 km3
Horizontal grid Size : 2 km
Vertical grid Size : variable with the minimum 5-30 m

No. of CPU used	Grid Points	Wall-Clock Time	Efficiency of Parallel Computatio
128	256x256x32	419 s	61.2%
128	512x512x32	1644 s	62.4%
128	1024x1024x32	6938 s	59.1%

Readable to users
Easy to modify the existing physical modules
Easy to add new physical processes (i.e., spectral bin microphysics, CLM, Chemistry)
Able to better simulate cirrus, stratocumulus, hurricanes, convective clouds -fine grid size

Computer System	Test Run	Number of CPU	Model Integration Time	Wall-Clock Time (sec)	Wall-Clock Time (hr)
Halem (Control Run)	**256x 256x 34**	**4(2x2)**	**1 hr**	**3,380**	**0.94**
Halem	256x 256x 34	32(4col,8row)	1 hr	476	0.13
Halem	256x 256x 34	64(8x8)	1 hr	236	0.066
Hopper	**256x 256x 34**	**4(2x2)**	**1 hr**	**99,970**	**27.77**
Hopper(-O3)	256x 256x 34	4(2x2)	1 hr	15,079	4.19
Lomax	**256x 256x 34**	**4(2x2)**	**1 hr**	**36,725**	**10.20**
Lomax	256x 256x 34	32(4col,8row)	1 hr	4,466	1.24
Lomax	256x 256x 34	64(8x8)	1 hr	2,262	0.63
Lomax (-O3)	**256x 256x 34**	**4(2x2)**	**1 hr**	**8,440**	**2.34**
Lomax (-O3)	256x 256x 34	32(4col,8row)	1 hr	831	0.23
Lomax (-O3)	256x 256x 34	64(8x8)	1 hr	423	0.12
Chapman	**256x 256x 34**	**4(2x2)**	**1 hr**	**25,335**	**7.04**
Chapman	256x 256x 34	32(4col,8row)	1 hr	3,066	0.85
Chapman	256x 256x 34	64(8x8)	1 hr	1,548	0.43
Chapman(-O3)	**256x 256x 34**	**4(2x2)**	**1 hr**	**6,848** (6840,6844,6860)	**1.90** (1.90,1.90,1.91)
Chapman(-O3)	256x 256x 34	32(4col,8row)	1 hr	650	0.18
Chapman(-O3)	256x 256x 34	64(8x8)	1 hr	339 (334,339,340,342)	.094 (.093,.094,.094,.095)

Computer System	Test Run	Number of CPU	Model Integration Time	Wall-Clock Time (sec)	Wall-Clock Time (hr)
Halem (Control Run)	**256x 256x 34**	**4(2x2)**	**1 hr**	**3,380**	**0.94**
Halem	256x 256x 34	32(4col,8row)	1 hr	476	0.13
Halem	256x 256x 34	64(8x8)	1 hr	236	0.066
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Lomax (-O3)	256x 256x 34	32(4col,8row)	1 hr	831	0.23
Lomax (-O3)	256x 256x 34	64(8x8)	1 hr	423	0.12
Chapman(-O3)	*256x 256x 34*	*64(1col,64row)*	*1 hr*	*479*	*0.133*
Chapman(-O3)	256x 256x 34	64(64col,1row)	1 hr	641	0.178
Chapman(-O3)	*256x 256x 34*	*64(2col,32row)*	*1 hr*	*347*	*0.096*
Chapman(-O3)	256x 256x 34	64(32col,2row)	1 hr	431	0.120
Chapman(-O3)	*256x 256x 34*	*64(4col,16row)*	*1 hr*	*321*	*0.089*
Chapman(-O3)	256x 256x 34	64(16col,4row)	1 hr	344	0.095
Chapman(-O3)	256x 256x 34	64(8x8)	1 hr	339 (334,339,340,342)	0.094 (.093,.094,.094,.095)

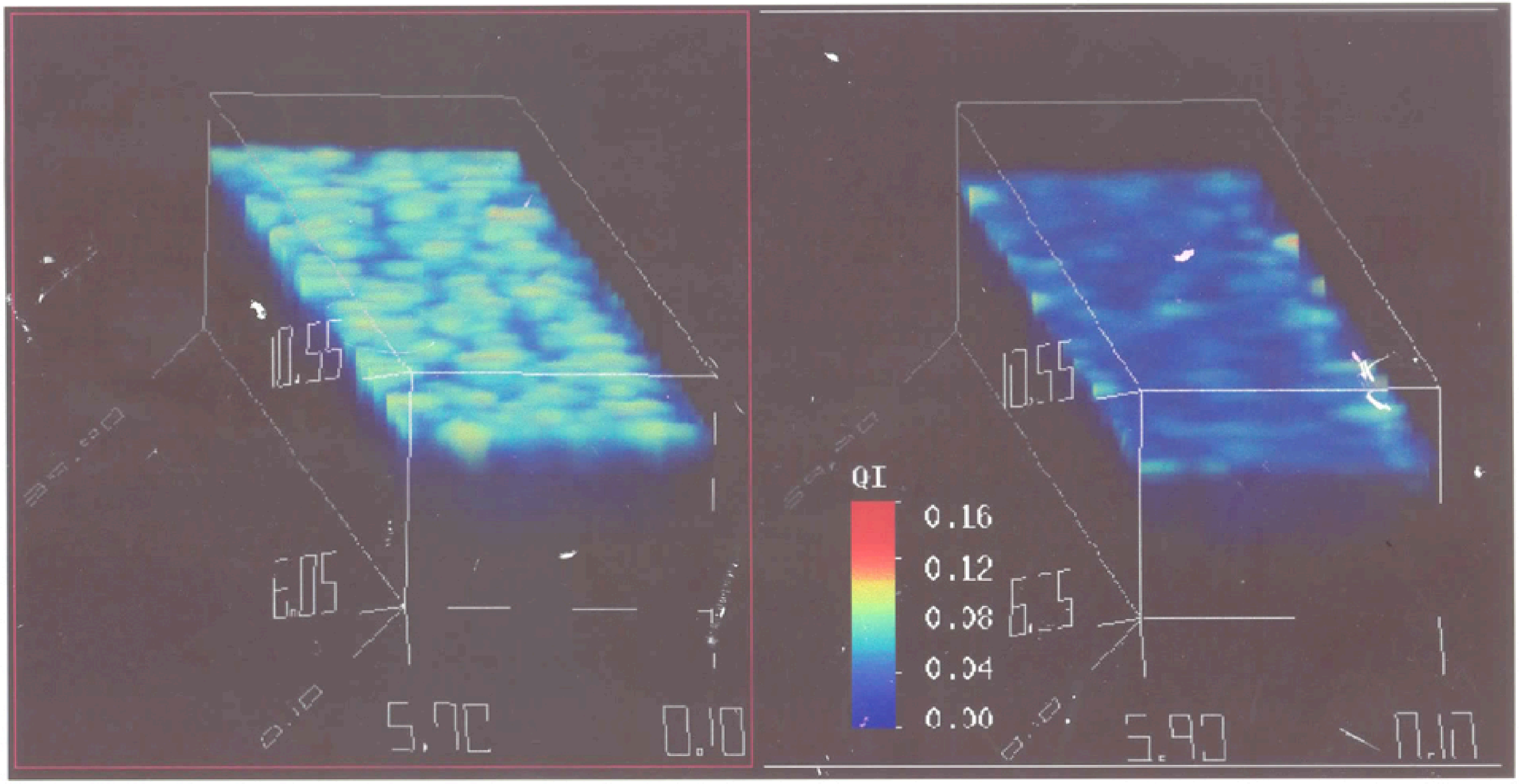
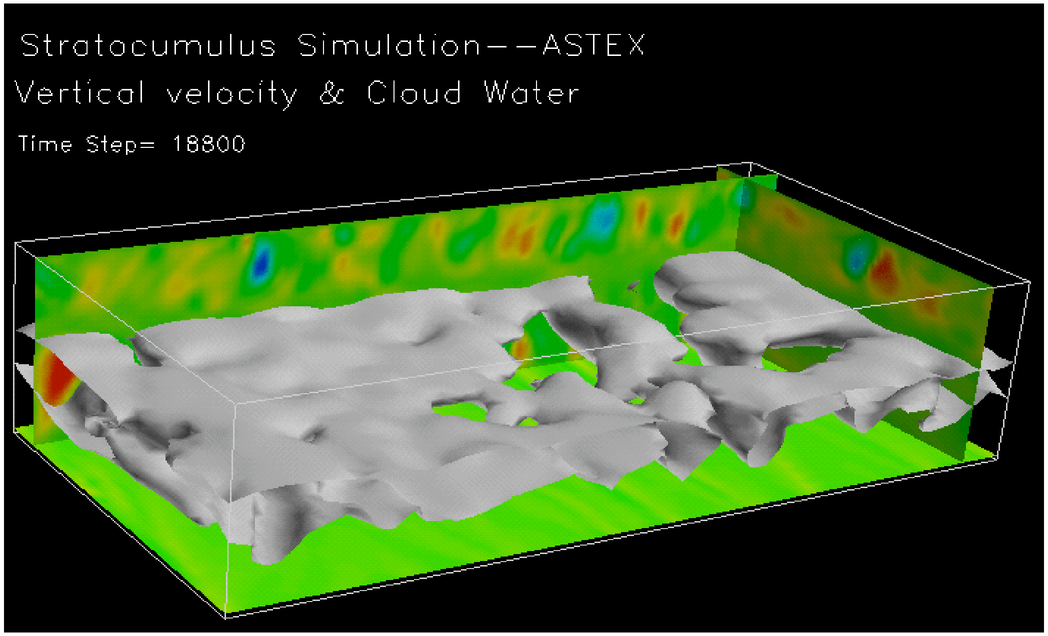
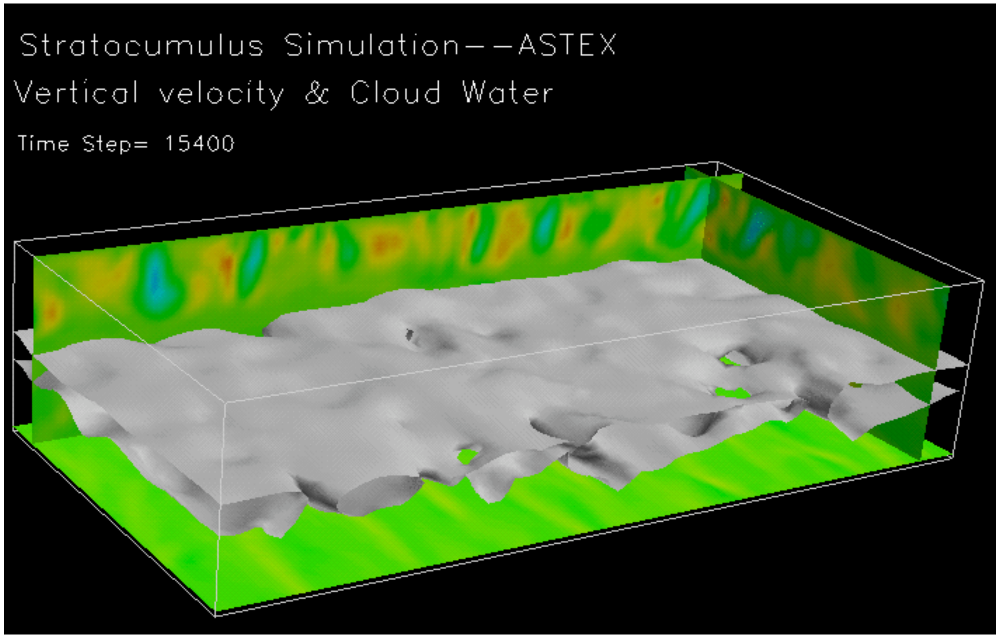


Fig. 3.2.1 3–D GCE model simulation of cirrus clouds. The domain size is 40 x 6 x 4.5 km, with grid sizes of 200 and 100 m in the horizontal and vertical respectively. The left panel shows the cloud ice content (g/kg) when interactive longwave radiative processes are included, while the right panel does not include the longwave radiative processes.

Dynamic model -
Engineering Applications
Ghosal et al. JFM, 1995

Cloud break-up is more common with the dynamic model



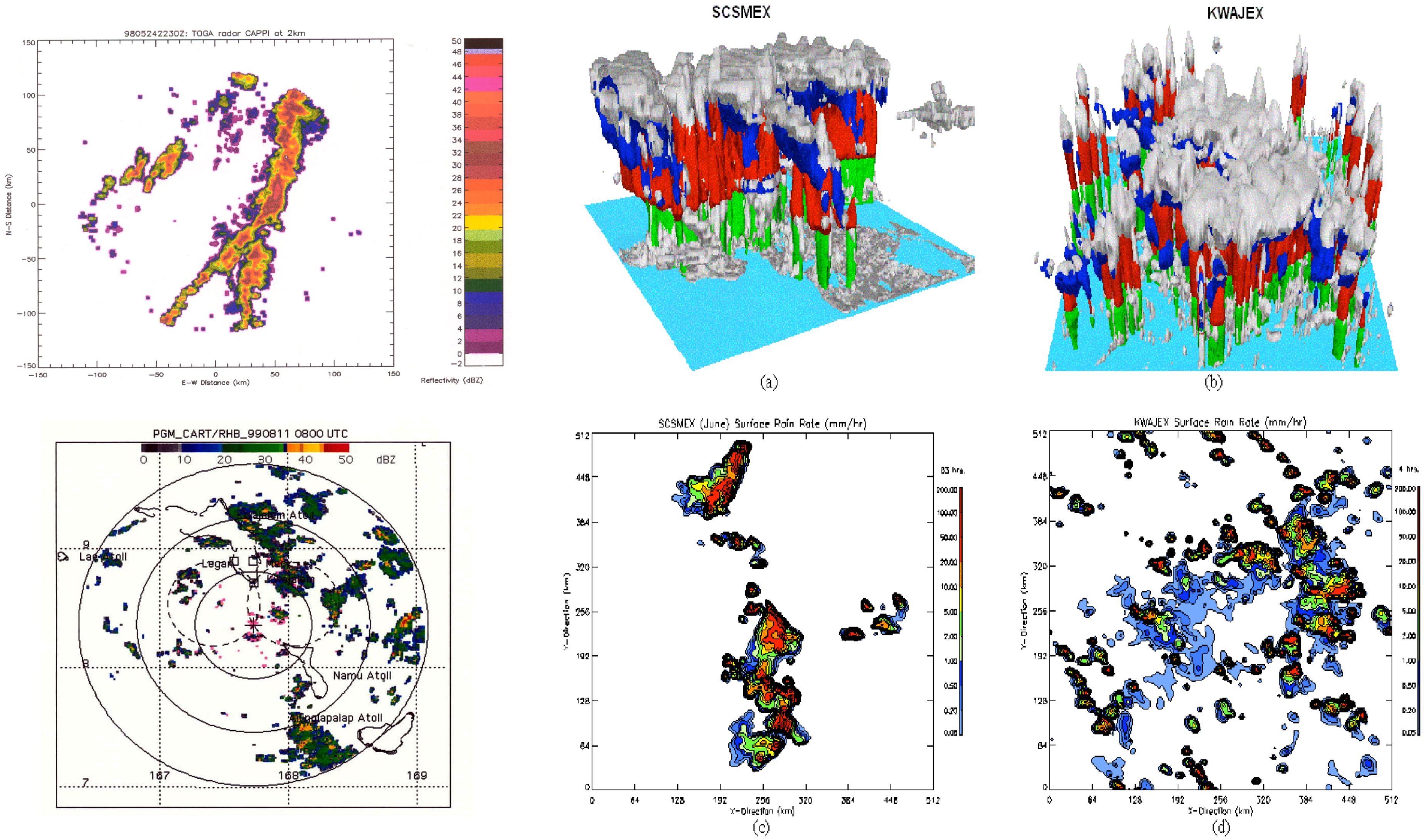


TKE model

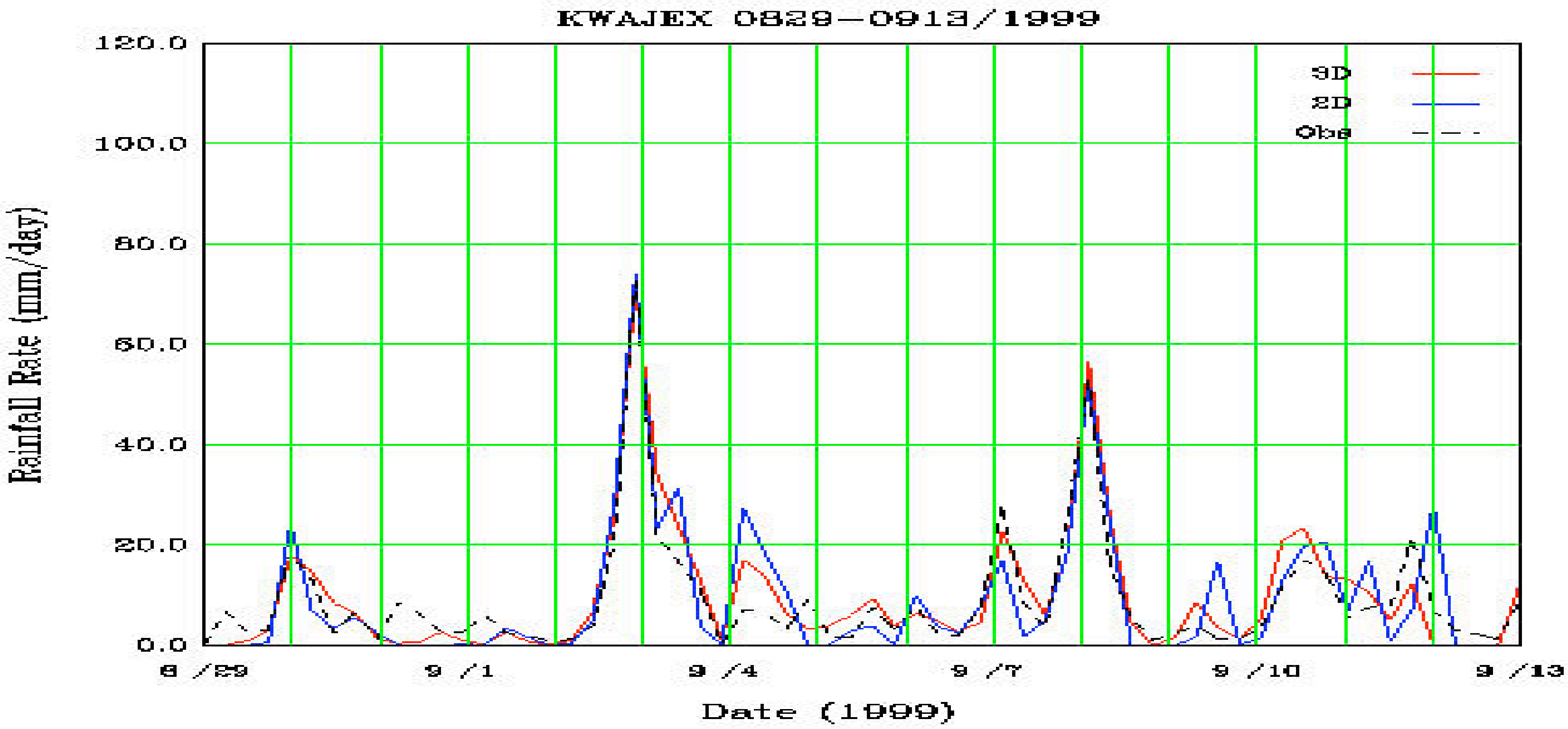
N. N. Mansour - NASA/Ames

$dx=dy=50\ m,\ dz=25\ m,\ dt=1\ s$

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



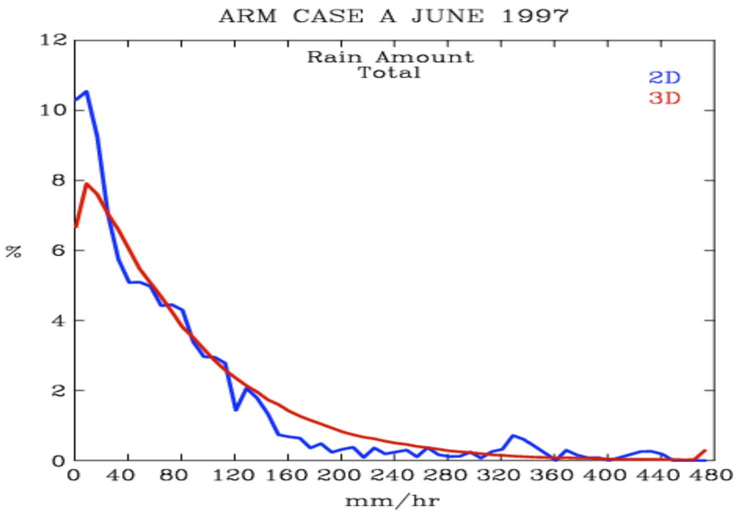
Radar Observations (dBZ) from SCSMEX (upper left panel)and KWAJEX (lower left panels). Linear cloud systems typically propagated from west to east in SCSMEX. Less organized and short-lived clouds/cloud systems dominated in KWAJEX



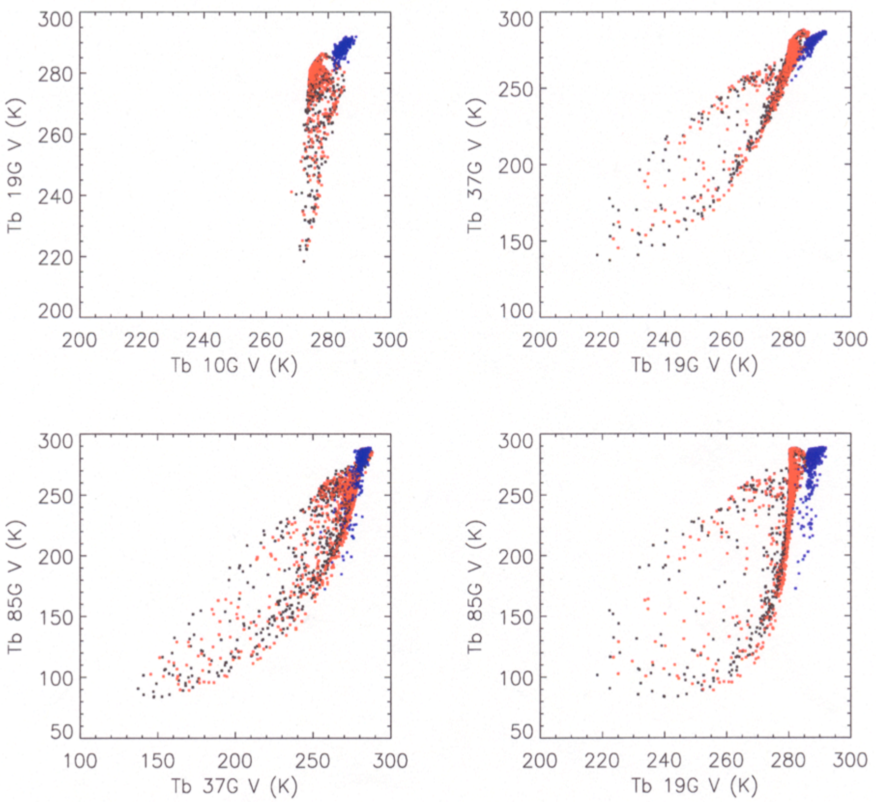
2D and 3D GCE model simulated ***rainfall*** amounts and evolution are in good agreement with observations (sounding network ground-based radar and TRMM PR estimated) -- **KWAJEX**

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

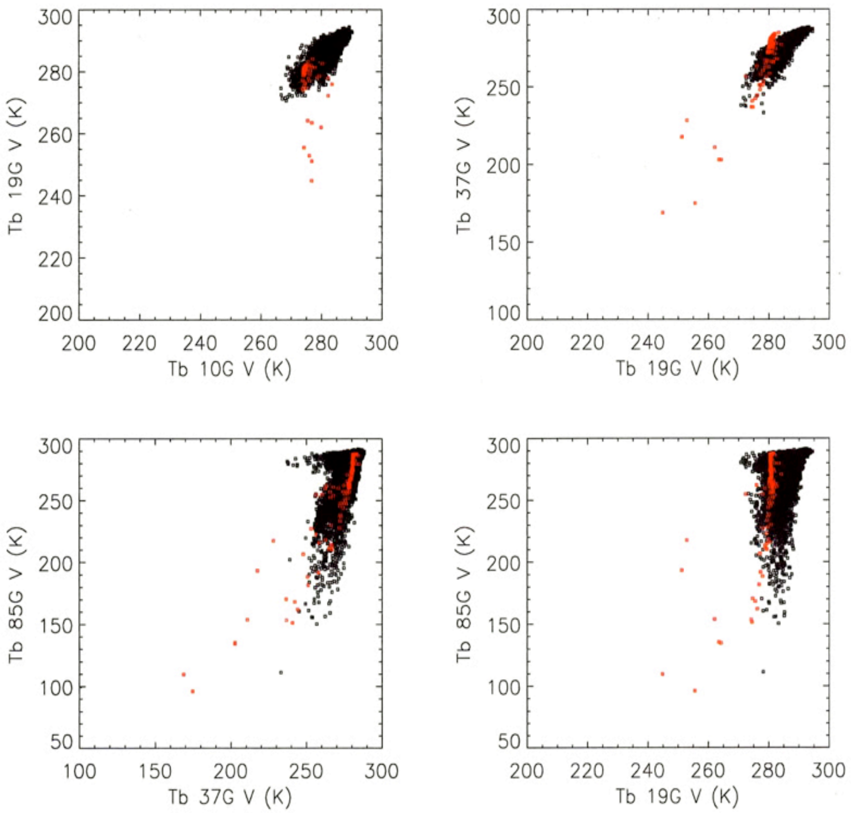
	2-D Rainfall/Stratiform %	3-D Rainfall/Stratiform %
TOGA COARE December 19-27 1992	20.2 mm/day 45%	20.7 mm/day 37%
SCSMEX May 18-26, 1998	11.14 mm/day 49%	11.65 mm/day 40%
SCSMEX June 2 – June 11, 1998	16.5 mm/day 38%	17.0 mm/day 31.4%
ARM June 26-31 1997	7.73 mm/day 17.9%	7.48 mm/day 8.0%
ARM July 12-17 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%



- 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
- Differences in rainfall amount were found in other CRMs for ARM cases



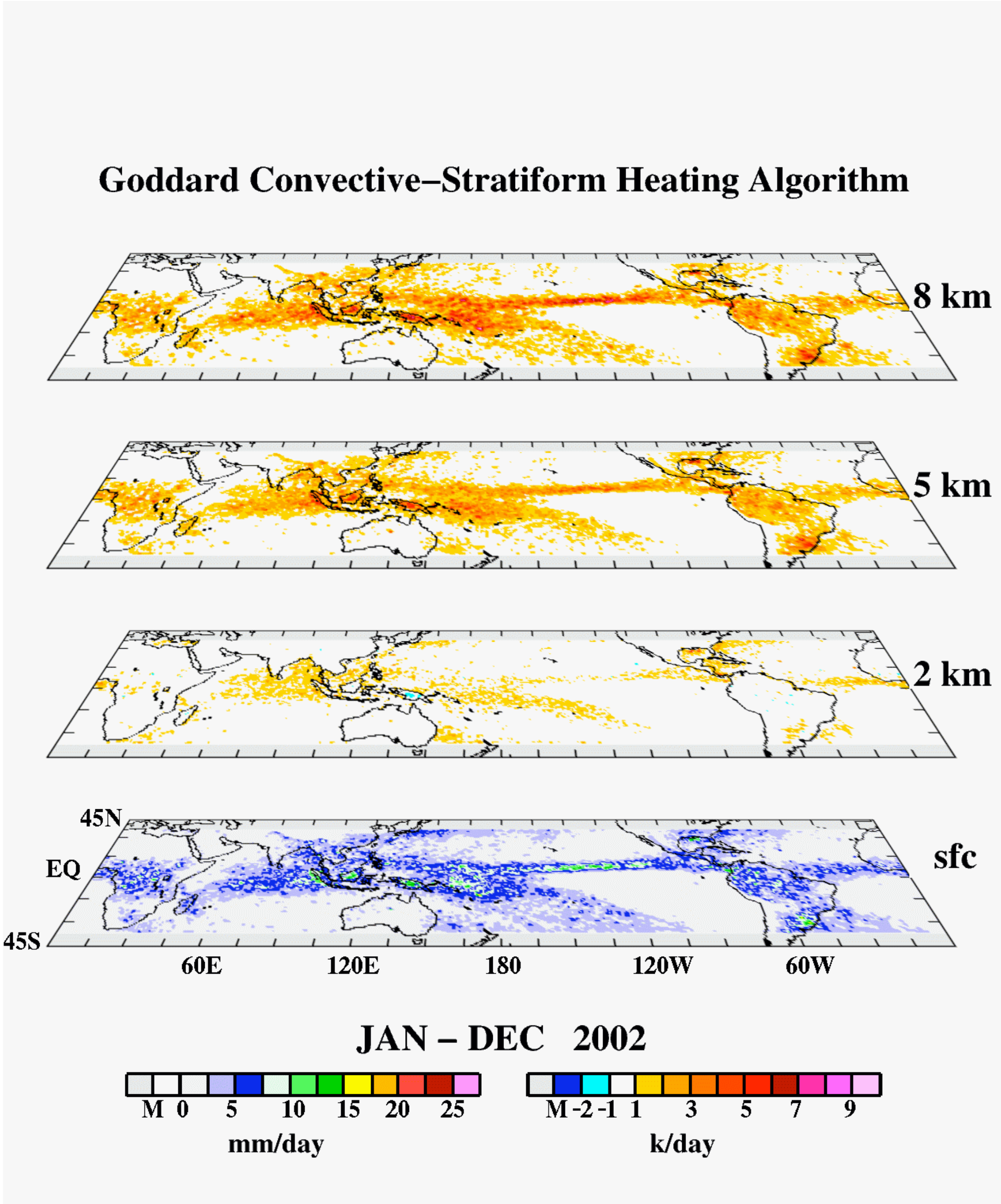
Black: Feb23; Red: Reduced graupel; Blue: Observation



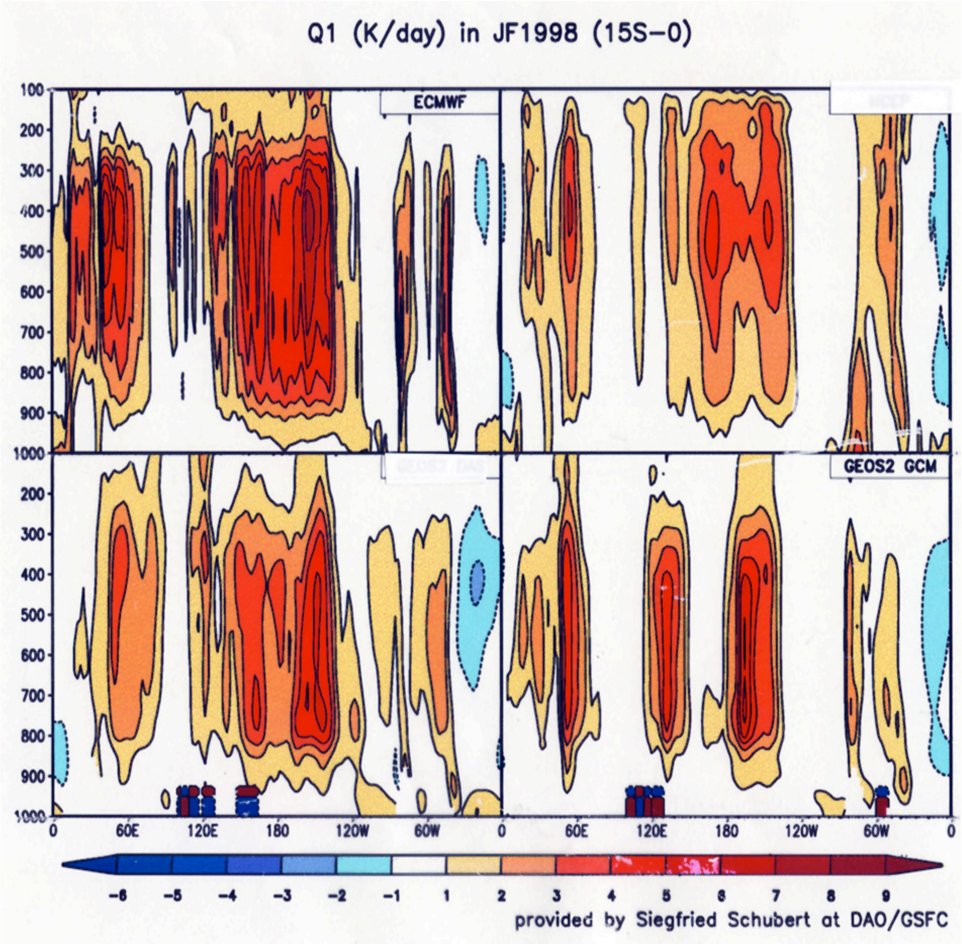
Red: GCE 4x4 run; Black: Feb23 Observation

Simulated brightness temperature scatter plots at different TMI channels using GCE model output [original (black) and modified (red) ice scheme]. TBs (blue) from TRMM are also shown for comparison. The modified scheme simulated more snow and less graupel. Its simulated TBs agree better with the observed values. However, they are still a few degrees colder than observed. These results are from a 3D GCE model simulation for a TRMM LBA case (February 23 1999).

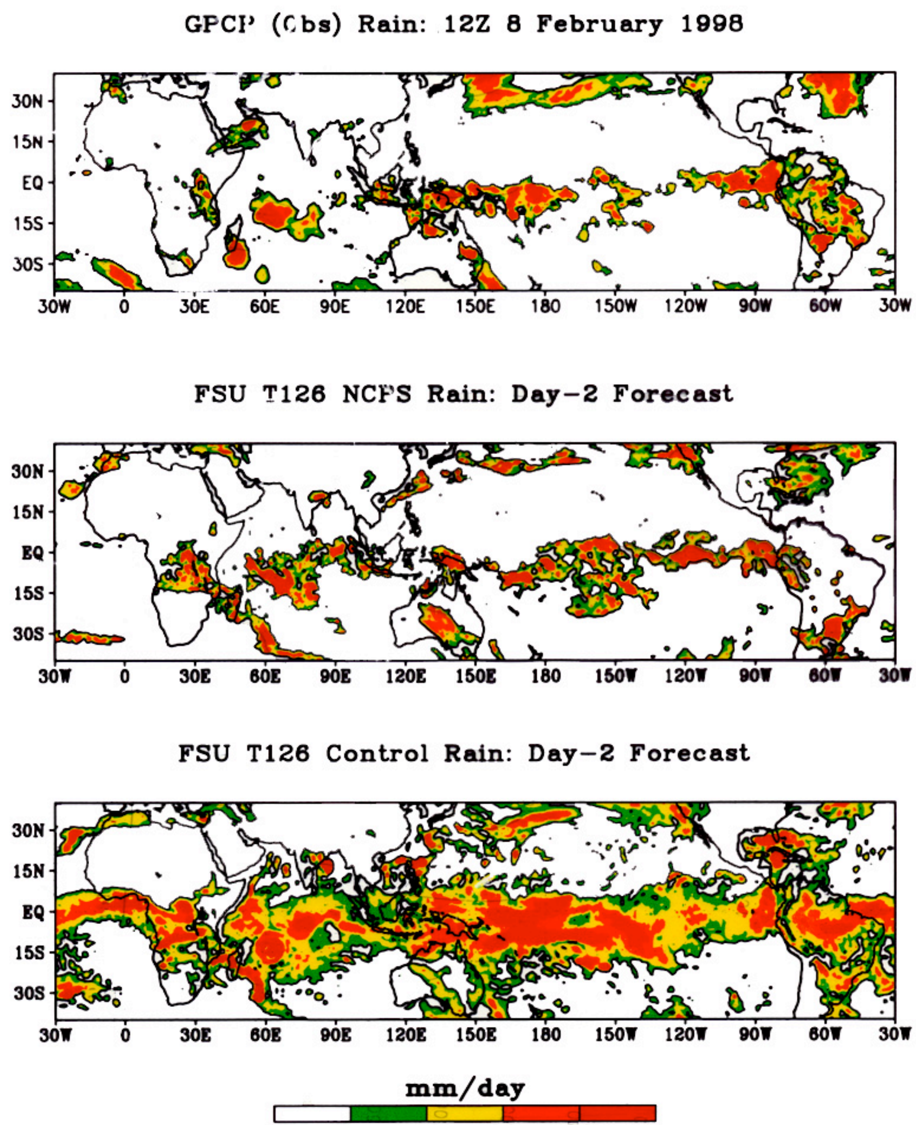
Latent Heating Retrieved from TRMM



- **Heating aloft mimics surface rainfall**
- **Averaged low-level heating is usually weak, slight warming over the maritime continent and east Atlantic**

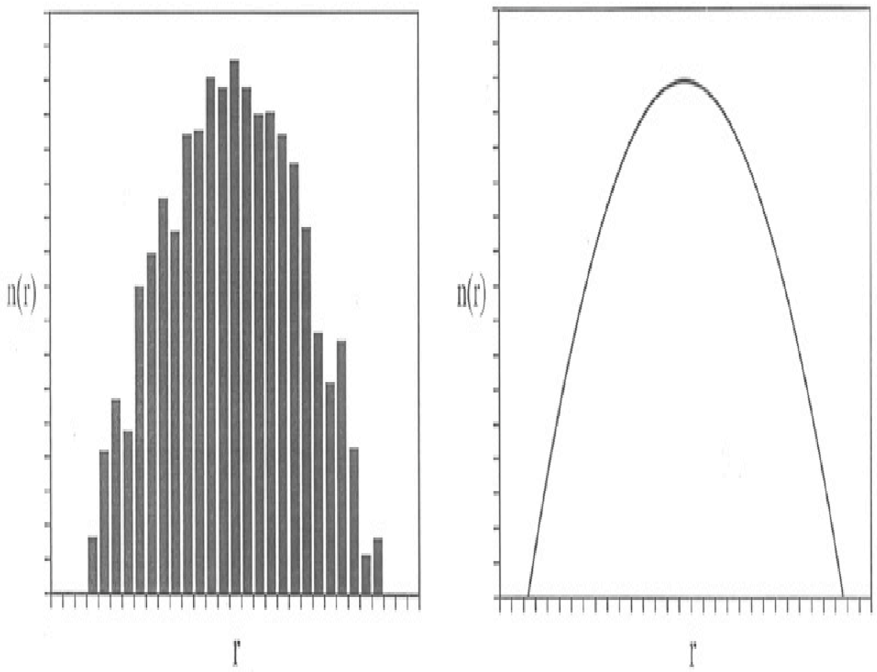


TRMM estimated heating profiles can provide validation for climate models - Different global models produced different heating structures(S Schubert/GSFC*)*



TRMM Latent heating profiles can also be assimilated into GCMs to improve weather forecasts (Krishnamurti and Rajendran/FSU)

DETAILED vs. BULK



Spectral-Bin Microphysics

Based on solving **stochastic kinetic equations** for the size distribution

(33-43 size categories for water droplets and ice particles)

Two water categories (**cloud droplets and raindrops**)

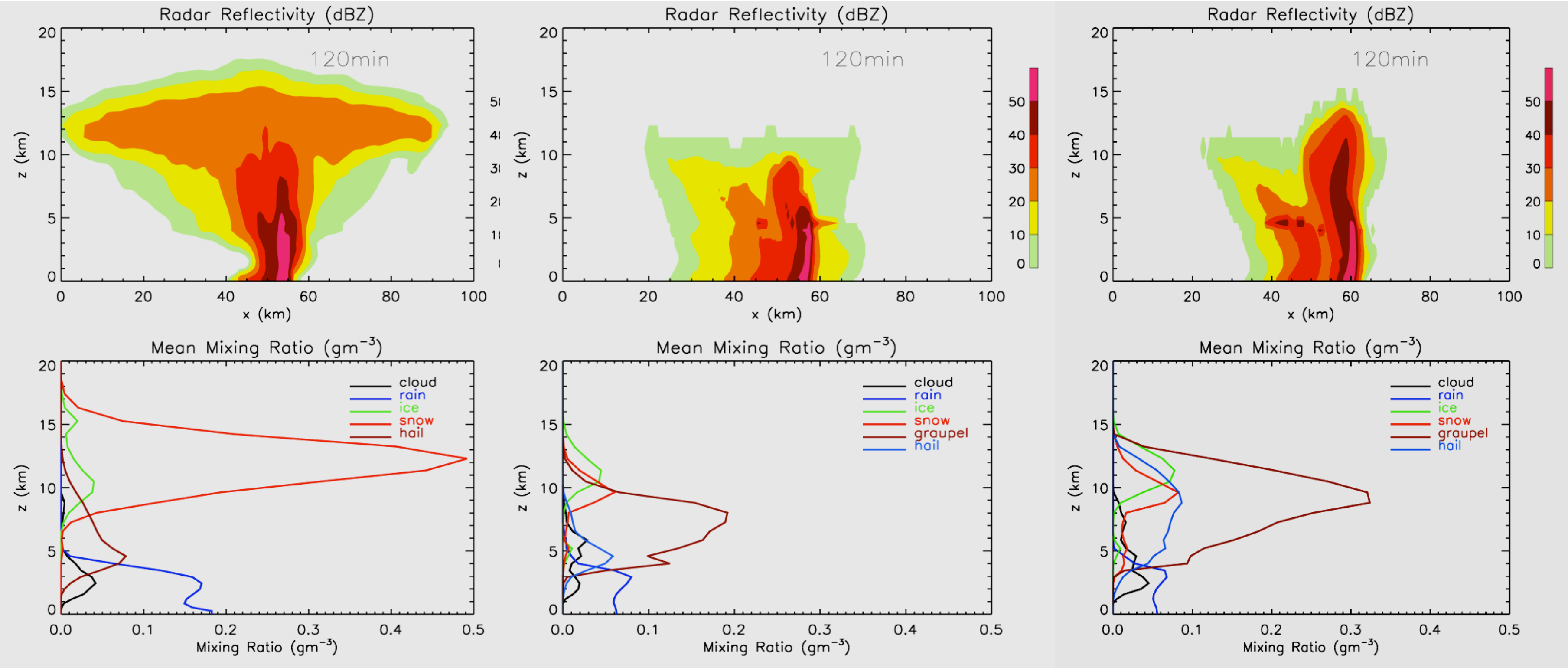
Six types of ice particles: ice crystals (**columnar, plate-like and dendrites), snowflakes, graupel and frozen drops**)

Nucleation (activation) processes are based on the size distribution function for cloud condensation nuclei **(43 size categories)**

	A. Khain	**J.P. Chen**
	One moment	**Two moment**
Cloud Condensation Nuclei (CCN)	**One-way interaction**	**Two way interaction**
Chemistry	**No**	**Sulfate**
Other minor species	**No**	**HNO_3, nitrate, NH_3, O_3, H_2O_2**

PRESTORM at 2 h model integration

Left (Bulk), Middle (Low CCN), Right (High CCN)



High radar reflectivity and up-shear tilt of strong updraft at the convective region for bulk and bin scheme

More melting processes (hail) -> Stronger evaporation cooling/gust front -> More rain for bulk scheme

Better melting band at stratiform region in bin model (especially for high CCN case) - more small and slow-falling ice particle (green) from convective region to stratiform.

Different cloud covers and hydrometeors (cloud optical property) were simulated -> cloud-radiation interaction

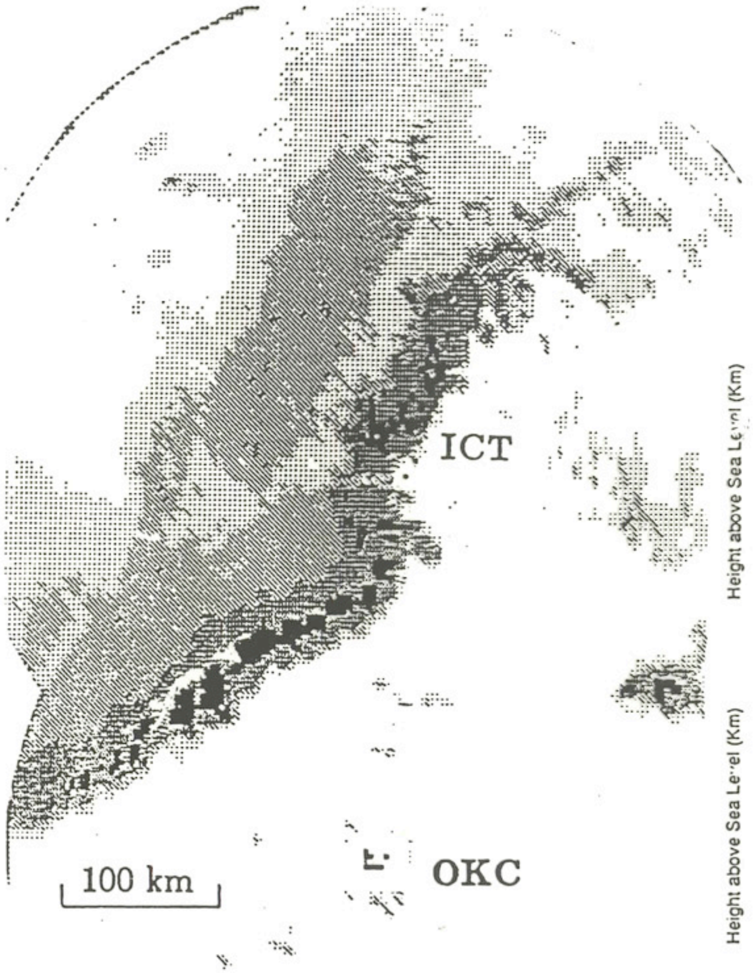
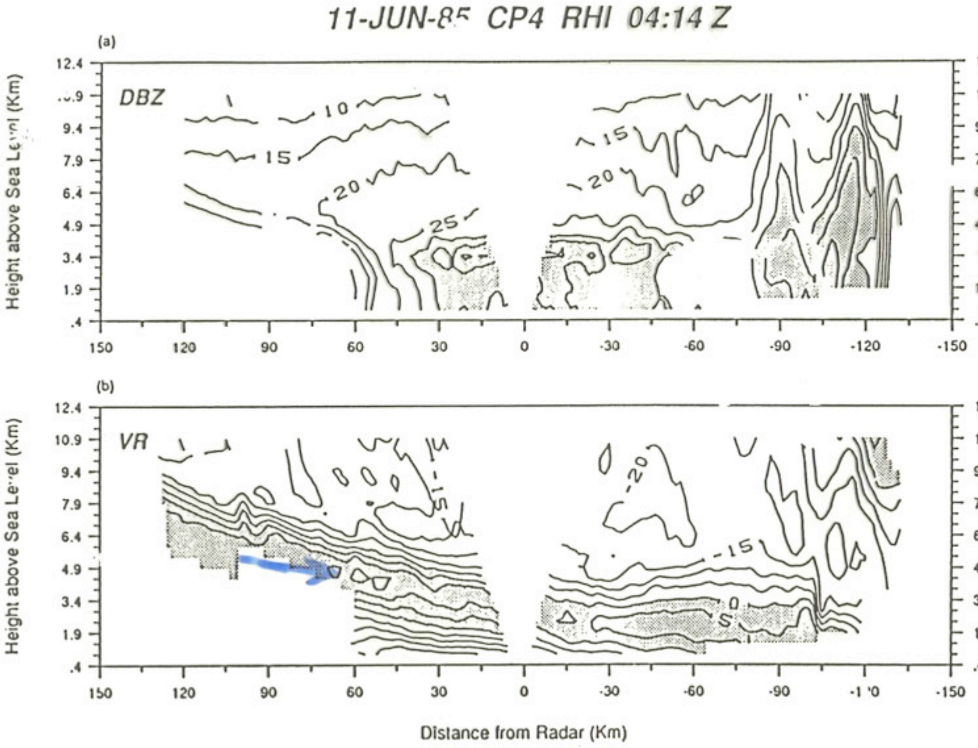
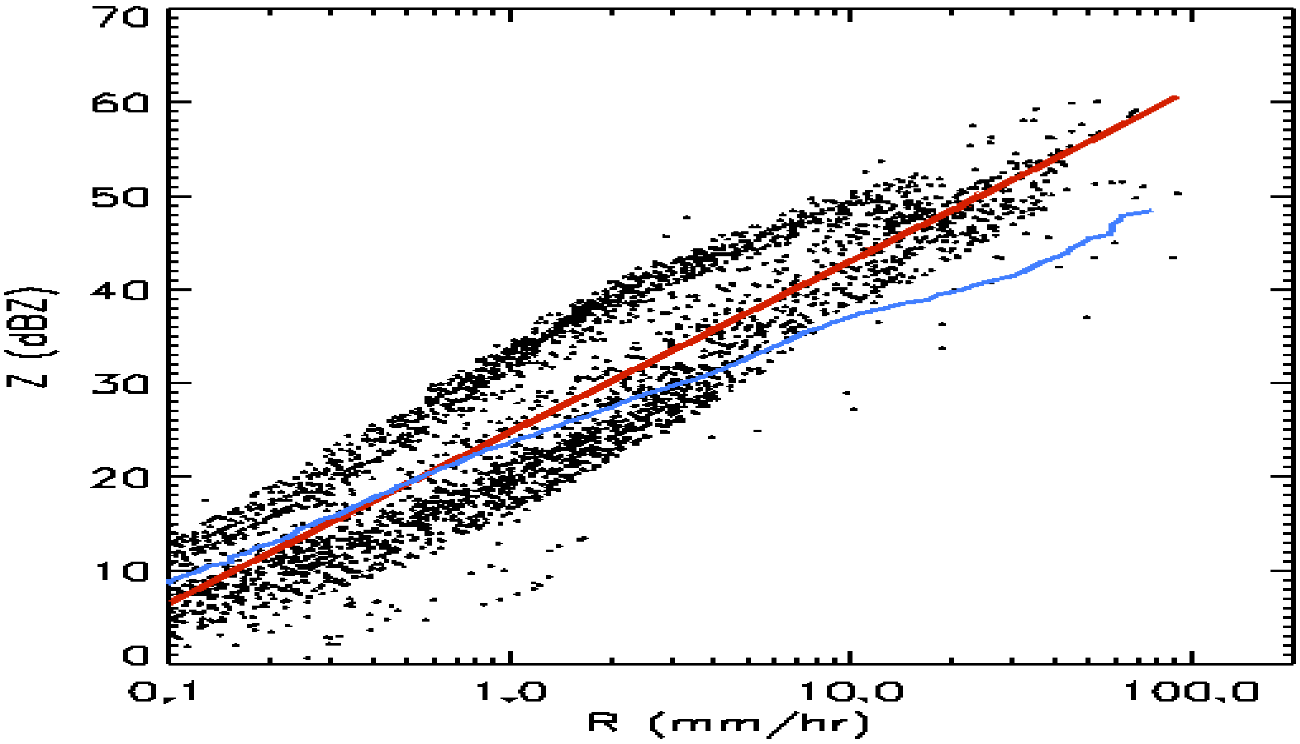


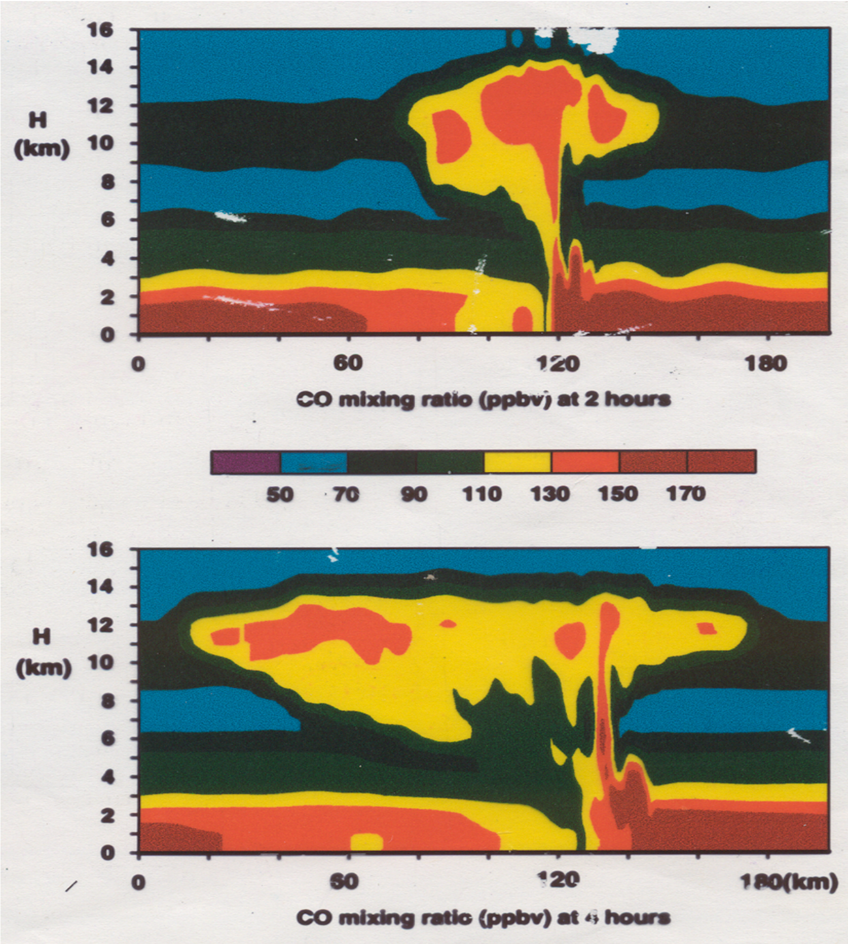
Fig. 1. Merged NWS WSR-57 base scans from Wichita (IC), Kansas, and Oklahoma City (OKC) at 0300 UTC, 11 June 1985. Reflectivity thresholds are 15, 25, 35 and 50 dBz.

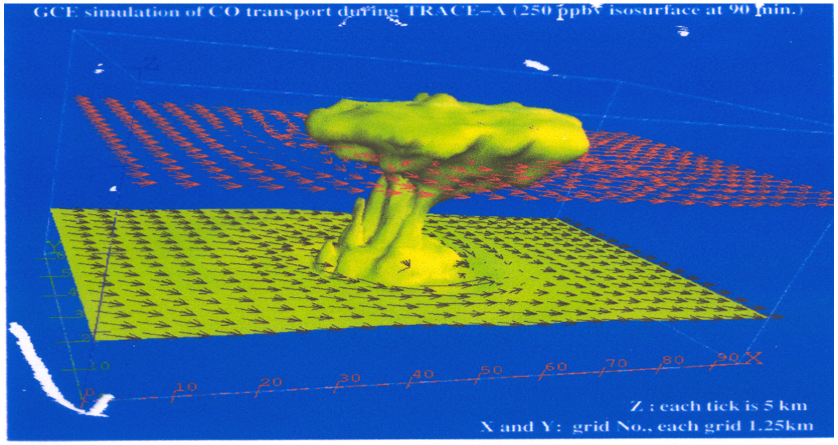

11-JUN-85 CP4 RHI 04:14 Z

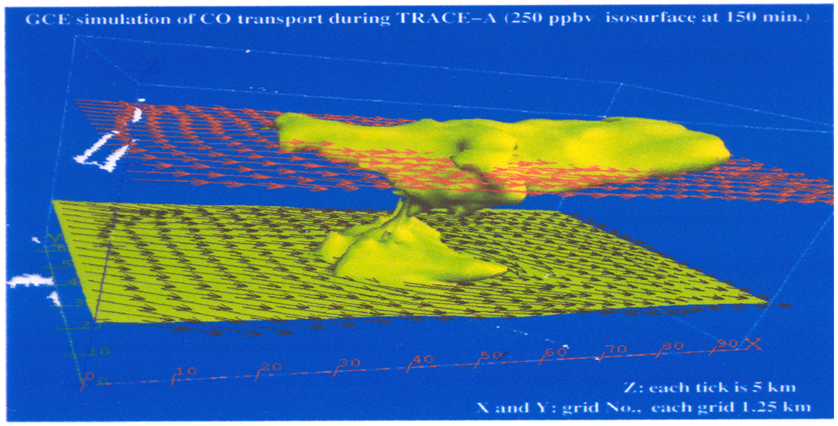
The Impact of Cloud-Aerosol Interactions on Precipitation and Z-R relationship (TRMM and GPM)



The red line (the best fit) separates the warm rain (lower) and ice dominated (upper) periods. *The Z-R relationship for the warm rain is close to those obtained from radar* (**blue**).
Less rainfall is produced in the high CCN case than in the low CCN case.
Note that the GCE modeling case is a well organized convective system, and the observations are not.




GCE simulation of CO transport during TRACE–A (250 ppbv isosurface at 90 min.)


GCE simulation of CO transport during TRACE–A (250 ppbv isosurface at 150 min.)

Tracer calculation

The GCE model-generated wind fields were used to redistribute the concentrations of CO, O_3 and NOx, which were assumed to act as conserved tracers during the period of convective mixing. Rapid (upward and downward) vertical transport of air from urban plumes through deep convective clouds occurs quite often. (K. Pickering/A. Thompson)

Cloud-Aerosol Interaction

Quantify Processes

Cloud Process Model (Goddard Cumulus Ensemble Model)

Model Physics (Spectral-Bin Microphysics Model)

Allow the interaction between cloud and polluted air (CCN – clean or dirty)

Allow explicit cloud-aerosol-chemistry interactions (JP Chen's model)

Need to use satellite and field campaign data (AERONET, ARM, CRYSTAL)

Regional Scale Model (Goddard version of improved MM5 and WRF)

Estimate the transport and dynamic processes (cloud and large-scale) associated with aerosols/dust

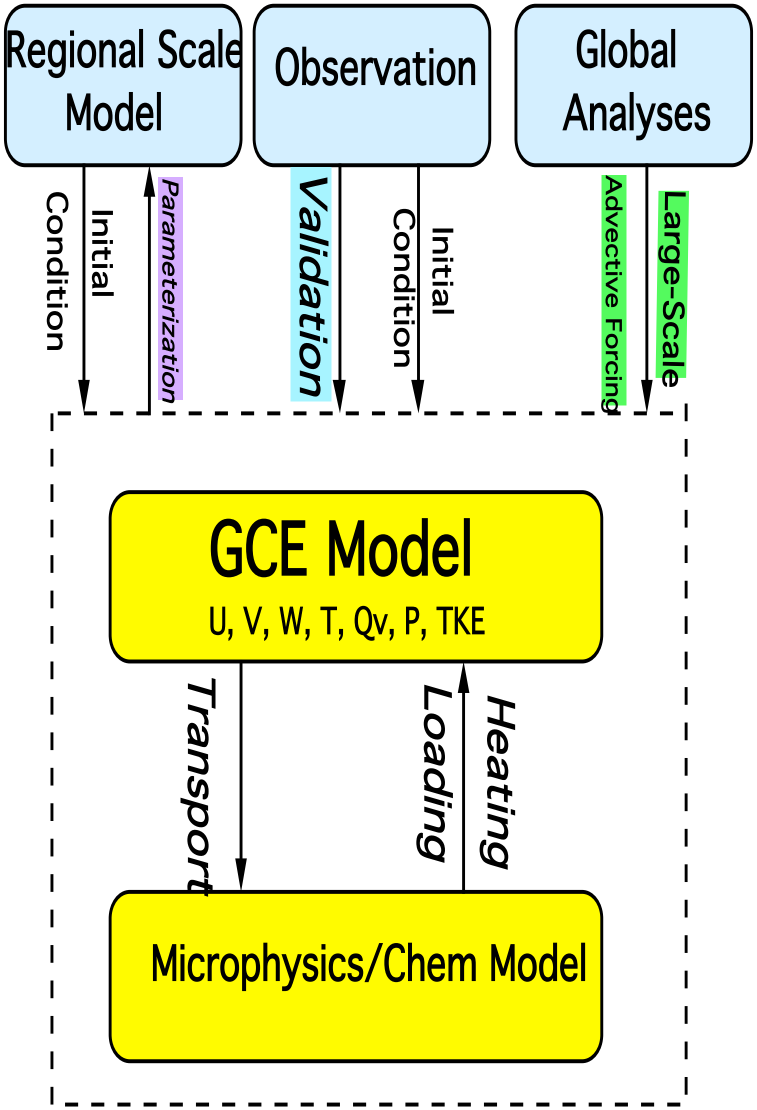
Use regional and cloud process models to study cloud-aerosol interaction associated with typhoons and other regional scale weather phenomena

Goddard Global model

Provide large-scale data to the regional scale model

Provide large-scale forcing needed for the cloud process model

Lorraine Remer, Kaufman (in-direct effect – cloud-aerosol)
Mian Chin (cloud-chemistry and in-direct effect)
Zhanqing Li (Asia – Dust storm – dynamic and transport)



Regional Scale Model

Observation

Global Analyses

Initial Condition

Parameterization

Validation

Initial Condition

Advective Forcing

Large-Scale

GCE Model

U, V, W, T, Qv, P, TKE

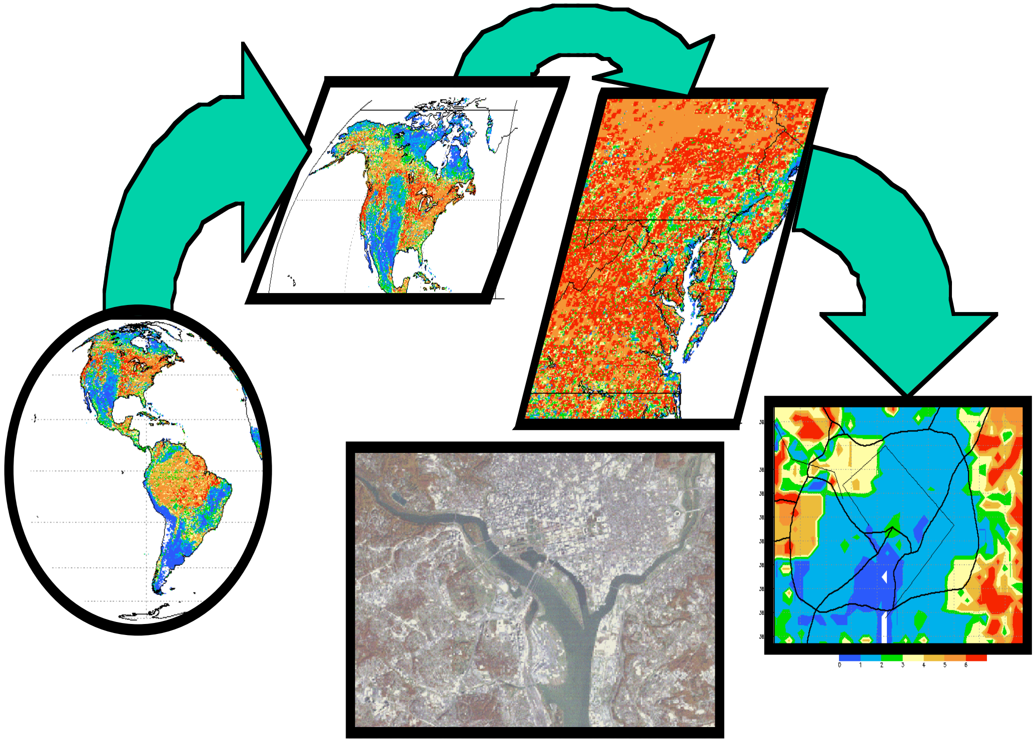
Transport

Loading

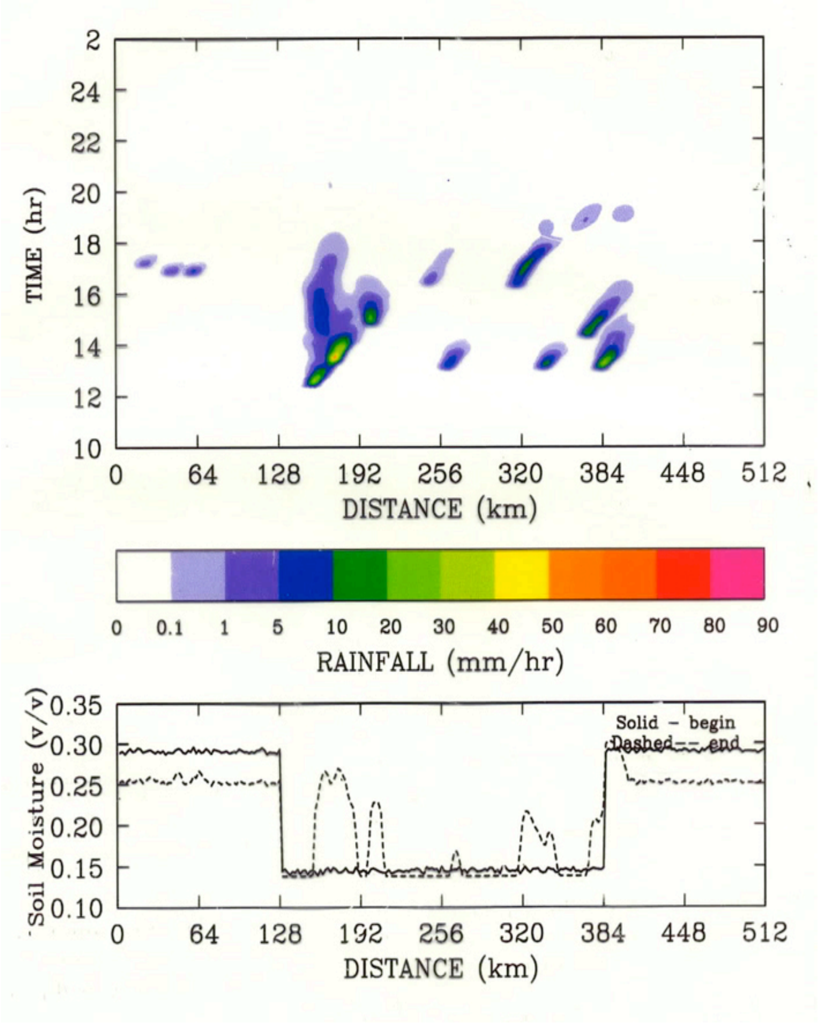
Heating

Microphysics/Chem Model

1km-resolution Modis-based LAI (Leaf Area Index) dataset from the Land Information System, shown at global, continental, regional and local (urban) scales, along with an aerial photo for Metropolitan Washington, D.C. Figure demonstrates that high resolution land cover datasets can capture urban-scale land use features anywhere on the globe



Resolution	1/4 deg	5 km	1 km
Land Grid Points	2.43E+05	5.73E+06	1.44E+08
Disk Space/Day (Gb)	1	28	694
Memory (Gb)	3	62	1561



A coupled global-, cloud-scale and land surface modeling system to study the impact of land surface processes on severe weather events

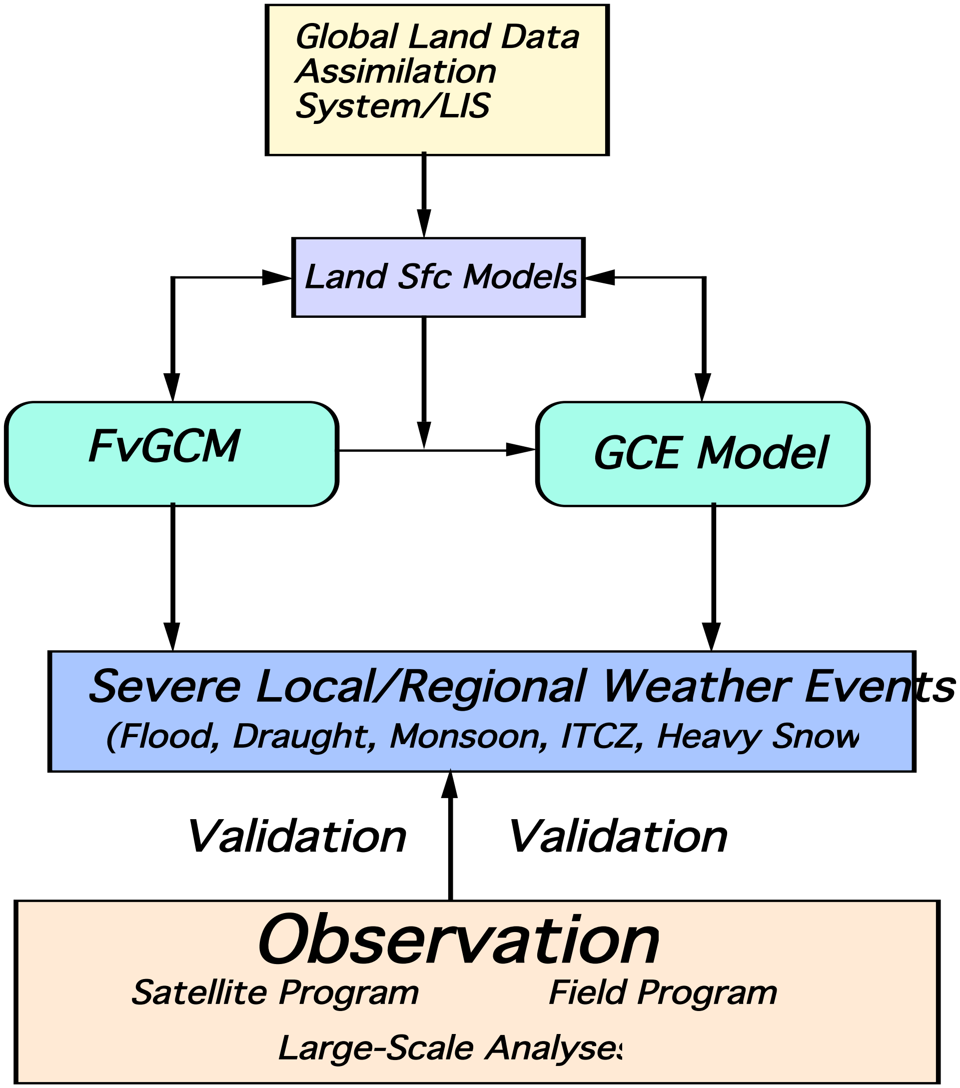
Tao, Y. Sud, R. Atlas, Lau, Bosilovich, SJ Lin, Peters-Lidard, Y. Xue (UCLA)

What is the impact of LCLUC on local and regional weather events (e.g., flooding, droughts, extreme rain or snow events, and localized convection mainly initiated by surface/land heterogeneity)?

What are the physical processes that determine the impact of land characteristics and changes (i.e., urban heating, plant/canopy growth and deforestation) on the local, regional and global hydrological cycle? Specifically, we will examine and study interactive soil-vegetation-precipitation processes, surface heterogeneity and their influence on preferential convective initiation.

What is the relationship between soil and vegetation processes and precipitation at the local and regional scale (e.g., the impact of soil-vegetation-precipitation feedback due to deforestation on the location and intensity of precipitation)?

How and at what spatial and temporal scales do land surface physics affect clouds and precipitation?



Global Land Data Assimilation System/LIS

Land Sfc Models

FvGCM

GCE Model

Severe Local/Regional Weather Events
(Flood, Draught, Monsoon, ITCZ, Heavy Snow

Validation

Validation

Observation
Satellite Program
Field Program
Large-Scale Analyse

FvGCM - GCE Coupled Modeling System
Global Cloud Simulator

- Perform seasonal forecast/simulations (1997/1998) using FvGCM-2D GCE coupling (two-way interaction)

  TRMM/GPM, Aqua/AMSR (Precipitation, IWC, LWC, Column Water vapor), CERES (TOA Flux)

- Perform target simulations over selected regions and for specific clouds/cloud systems (i.e., continental US, warm pool region) using FvGCM-3D GCE coupling (one- or two-way interaction)

  TRMM/GPM, Water and Energy Cycle

- Perform target simulations for specific clouds/cloud systems (i.e., cirrus, stratocumulus) using FvGCM-2D GCE with explicit microphysics

  CloudSat (Particle size/#CCN/Z-Profile, LWC/IWC/Drizzle), Calipso (thin clouds/cloud particle phase), Terra/MODIS (aerosol/cloud optical properties)