Evaluations and Improvements of Goddard Multi-scale Modeling Framework using High-Resolution NASA Satellites

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Outlines

- Development of Multi-scale Modeling Frameworks (MMF) in climate modeling

  - Motivations
  - MMF developing history
  - Brief description of the NASA Goddard MMF
  - The MMF experiments and results

- Confront model results with NASA high-resolution satellites

  - NASA state-of-the-art satellite measurements
  - Satellite simulators
  - Evaluate the MMF results with Aura/MLS and CloudSat

Motivations

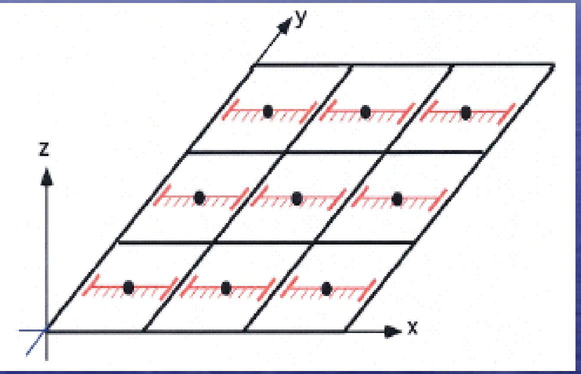
- The cumulus parameterization is a longstanding problem and major bias in climate models.

- Closure assumptions (Kou, CAPE, relaxation time scale, CAPE in free atmosphere (Zhang 2003, 2004))
- Trigger assumptions (threshold, moisture convergence, RH)
- Saturated/unsaturated convective downdraft
- Mesoscale updraft/downdraft
- Convective momentum transport
- Representation of sub-grid cloud: ensemble of entraining plumes, buoyancy sorting parcels, undiluted/diluted member, 1D/2D cloud model.
- Shallow convection and transition from shallow to deep convection

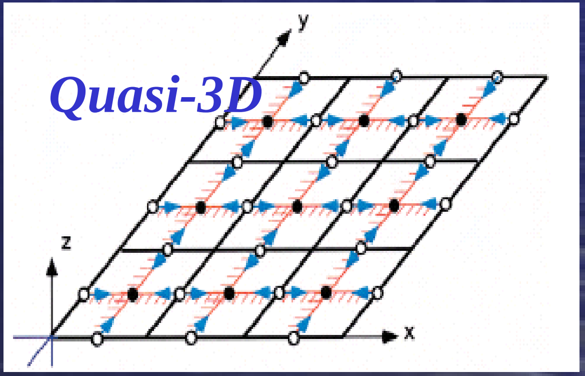
- The GEWEX Cloud System Study (GCSS) has demonstrated that CRMs are superior to SCMs in the prediction of temperature and moisture tendencies using the same large-scale forcing derived from field campaigns.

MMF Developing History

- Grabowski and Smolarkiewicz (1999) and Grabowski (2001) : Replace the convectional convective parameterizations with a CRM in each grid column of a GCM (called Cloud Resolving Convective Parameterization (CRCP)).
- 2D CRM with E-W orientation and periodic boundary condition



- Khairoutdinov and Randall (2001), Randall et al. (2003), and Khairoutdinov et al. (2005)
- Super-parameterization: unified all physical processes in one framework (i.e. deep/shallow convection, radiation, PBL turbulence, surface processes interact with each other in CRM temporal and spatial scale.)



- Arakawa (2004):
- Multi-scale Modeling Framework: Embedded high-resolution explicit model inside a coarse host model.
- Quasi-3D MMF

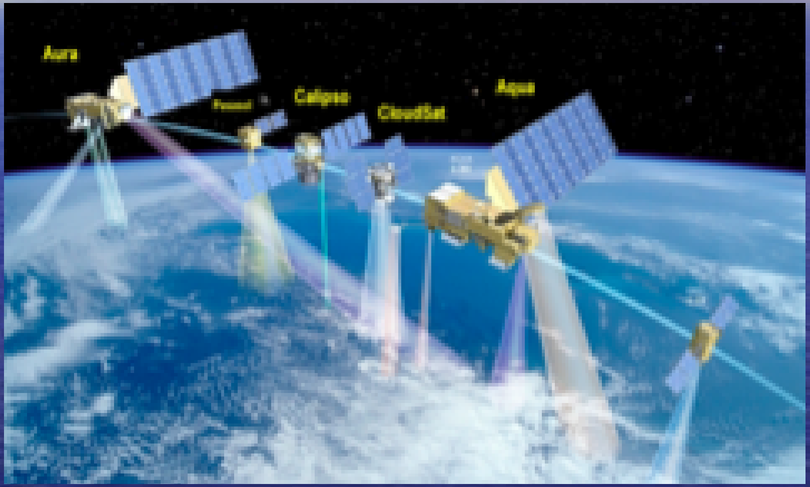
Differences in modeling approach

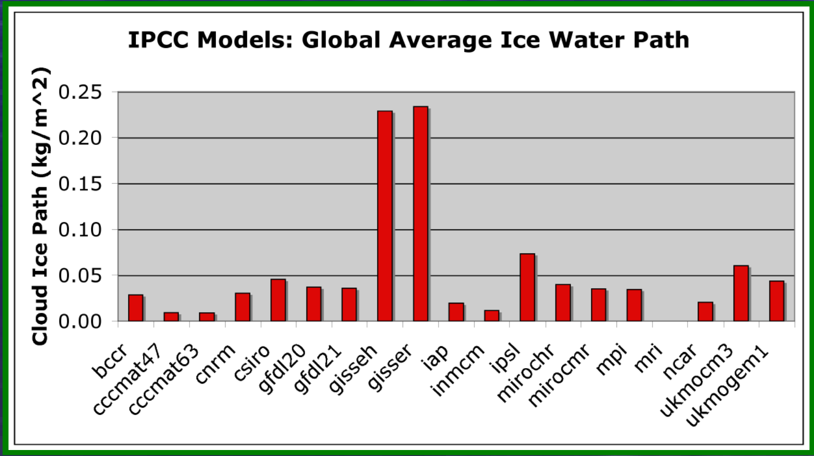
	Global Coverage	Sub-grid Clouds	Two-way interaction	Computing Resource
GCM	Yes	Yes	Yes	1
CRM	No	No	No	10-100
Nested MM	No	Yes	Yes	10-100
MMF	Yes	Yes	Yes	100-1000
Global CRM	Yes	No	Yes	1000-100,000

- The MMF run one month per day with 364 processors on Columbia supercomputer

Goddard MMF Research Objectives

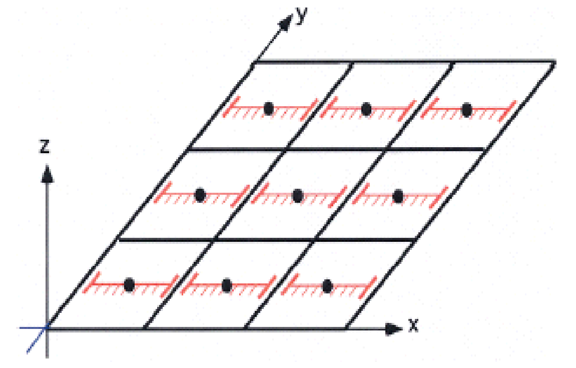
- Develop a MMF based on the Goddard Cloud Ensemble Model (GCE) and the finite-volume General Circulation Model (fvGCM)
- Better use of NASA high resolution satellite measurements (i.e.TRMM/GPM, the EOS A-Train)
  - The MMF provides a link between high resolution observations and the coarse resolution of a GCM's grid box
  - The NASA satellite measurements provide data for improving physical parameterizations in GCE.
- Intercomparison of results from different MMFs to explore the capabilities and limitations of MMFs and study the effects of different GCMs and CRMs.
- The MMF provides global cloud data for improving the convectional parameterization schemes in GCMs.





The Goddard MMF

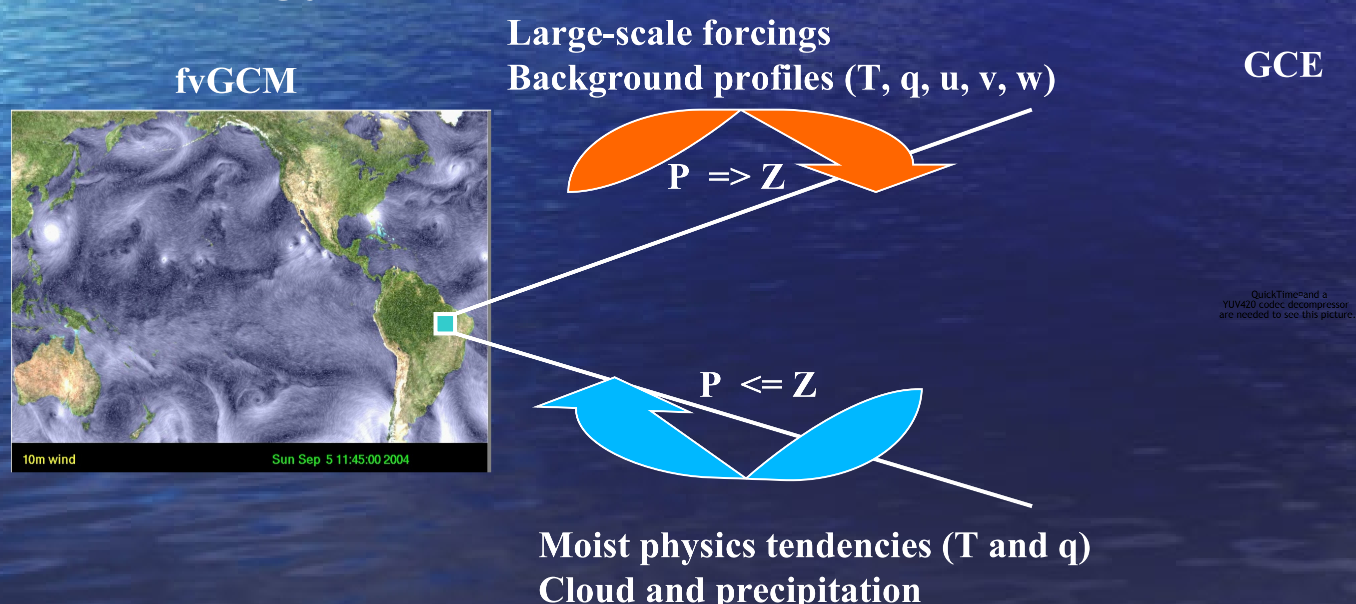
- Based on the coupling system of fvGCM and 2D GCE model.
- fvGCM has been constructed with the finite-volume dynamic core (Lin, 2004), NCAR CCM3 physics package with an upgraded gravity wave scheme (NCAR WACCM), and the Community Land Model (CLM).
- 2D GCE is embedded in each grid point of the fvGCM based on the simple MMF framework.



- fvGCM at 2.0^{o} X 2.5^{o} latitude-longitude grids with 32 vertical levels from surface to 0.4 Pa (there are 8 layers below 850 hPa)
- Globally there are 13,104 copies of 2D GCE running at the same time.

The Goddard MMF (continue)

- 2D GCE has 64 x 28 (x-z) grid points with 4 km horizontal resolution
- The time step for GCE is 10 second.
- fvGCM and 2D GCE coupling time is one hour
- Interpolation between hybrid P (fvGCM) and Z (GCE) coordinate: using finite-volume Piecewise Parabolic Mapping (PPM) to conserve mass, momentum and moist static energy.



The MMF experiments and results

- 4+ yearly (1998,1999, 2005, 2006, and 2007) control runs were carried out on NASA Columbia supercomputer.

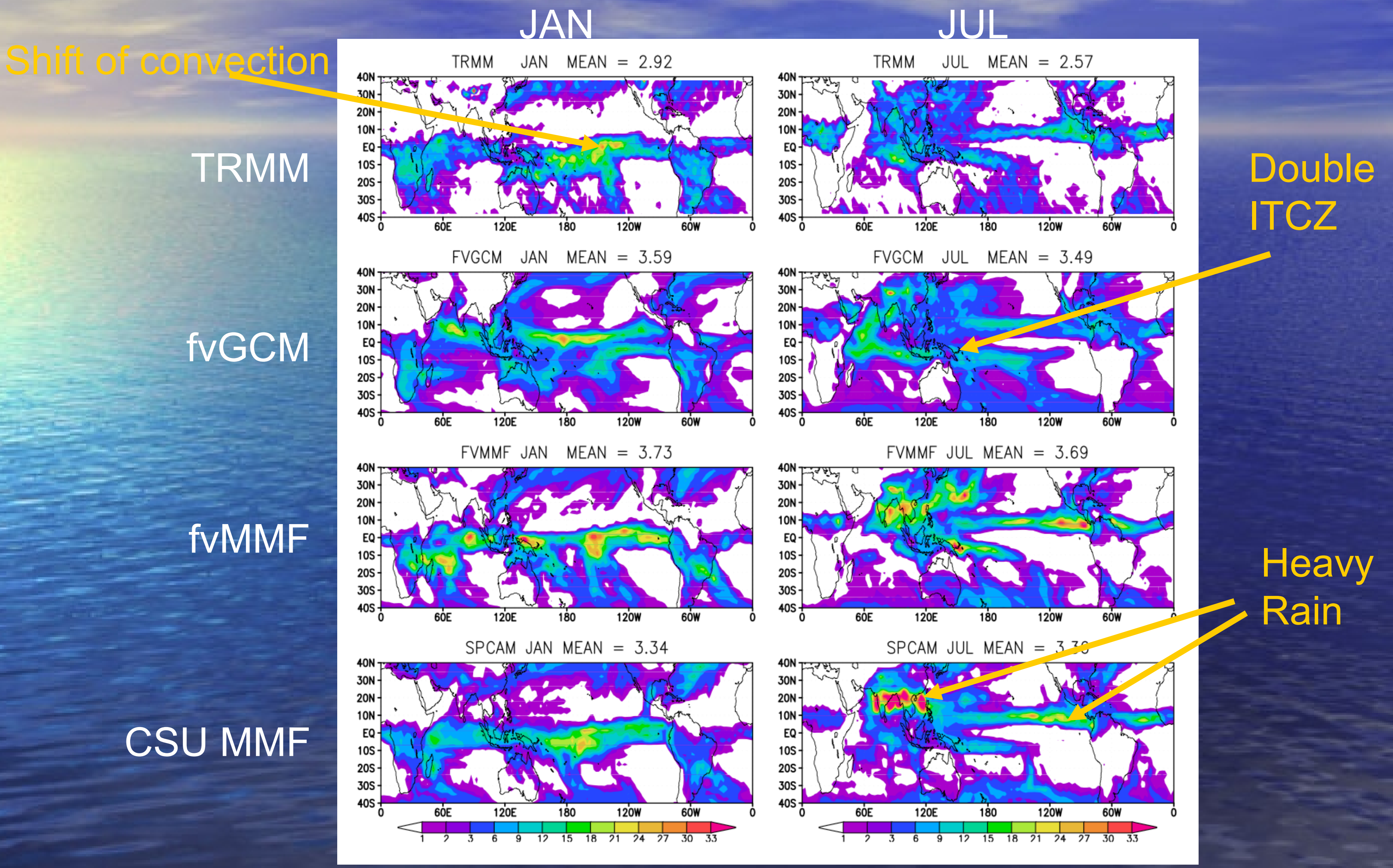
- More than 20 monthly sensitivity experiments (July, 2006) have been performed.

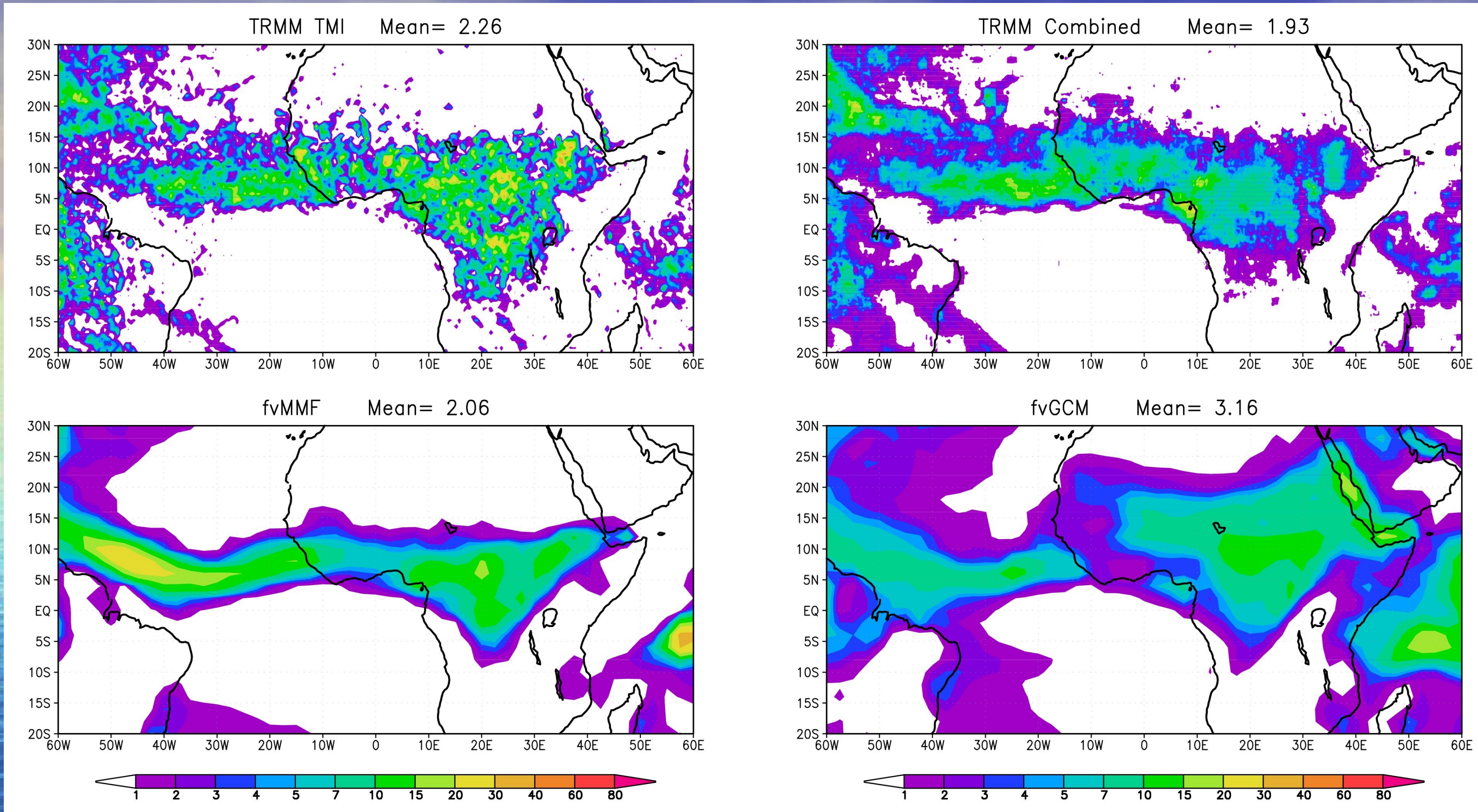
- Initial conditions were interpolated from GEOS 4 CERES analysis (1^{o} x 1.25^{o} with 55 vertical levels)

- Observed SST (NOAA weekly OI SST) was used.

- Feedback from GCE: tendencies of T and qv.

Monthly Mean Precipitation Rate 1998





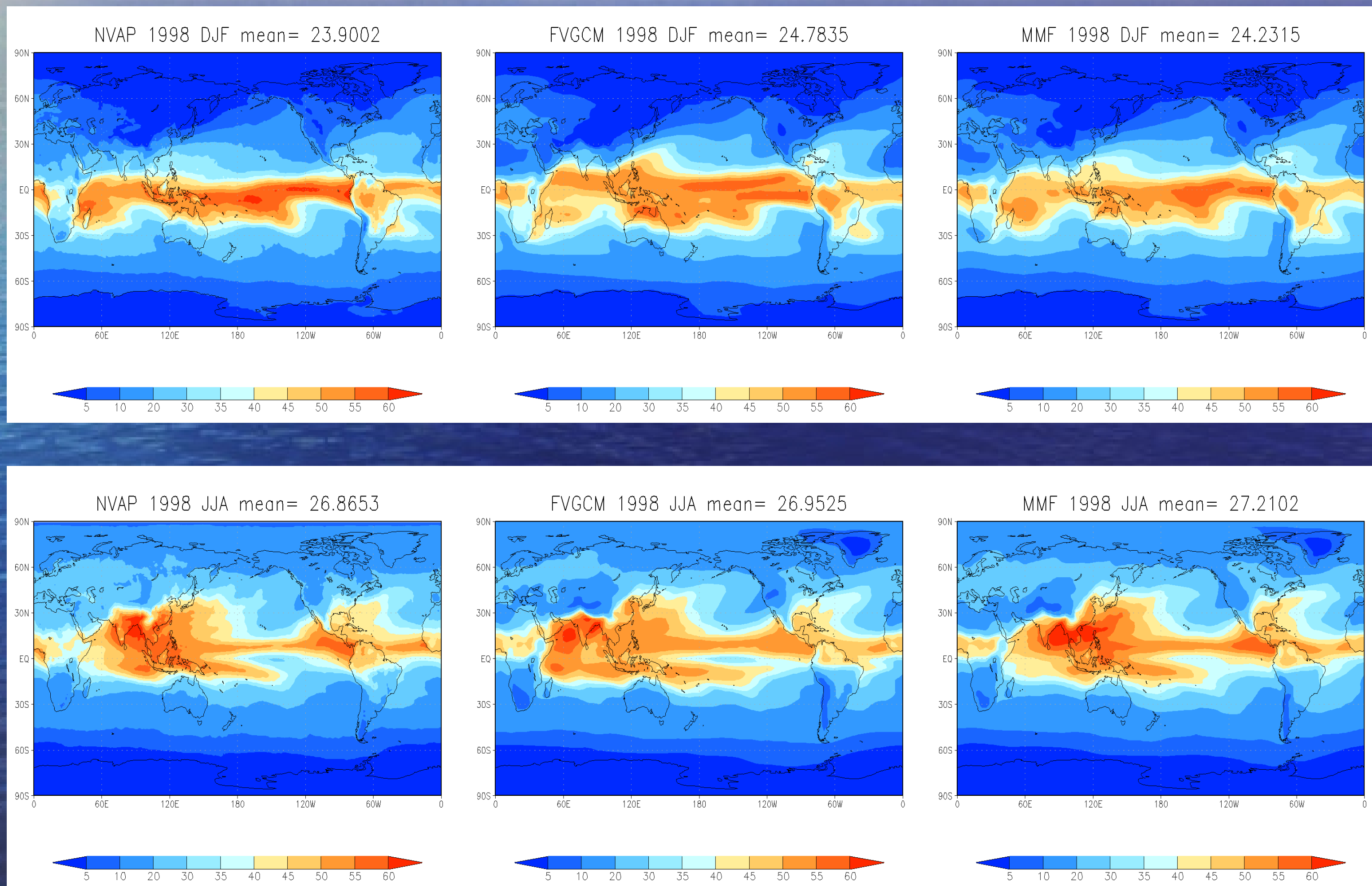
Monthly precipitation rates (mm/day) over West Africa for September 1999 from TRMM observations (TMI, top-left, and Combined, top-right) and simulations from the Goddard MMF (lower-left panel) and the fvGCM (lower-right panel).

Total Precipitable Water (mm)

NVAP fvGCM MMF

1998 DJF

1998 JJA

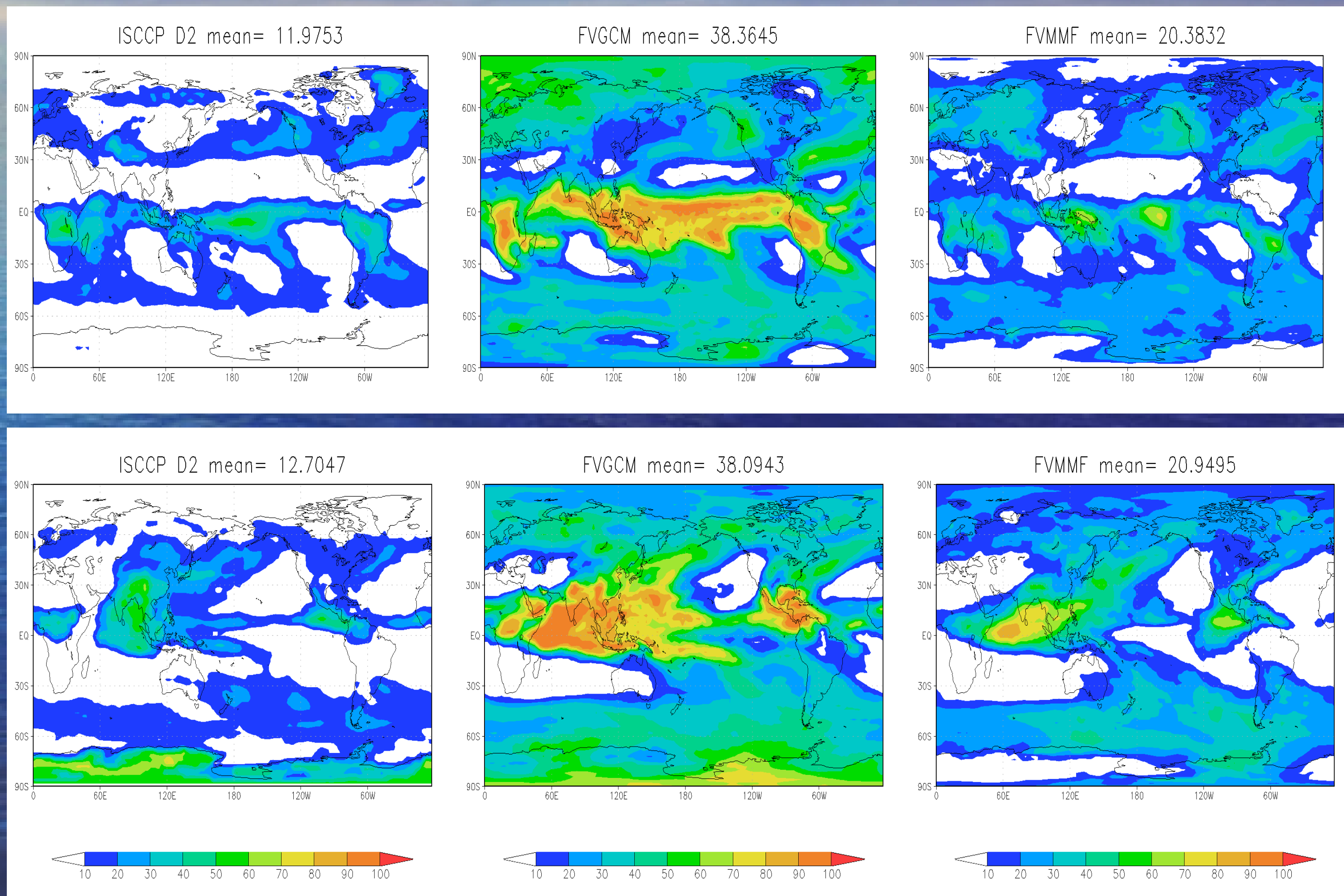


Seasonal Mean High Cloud Amount

ISCCP D2 | fvGCM | MMF

1999 DJF

1999 JJA



Summer Excessive Precipitation Problem

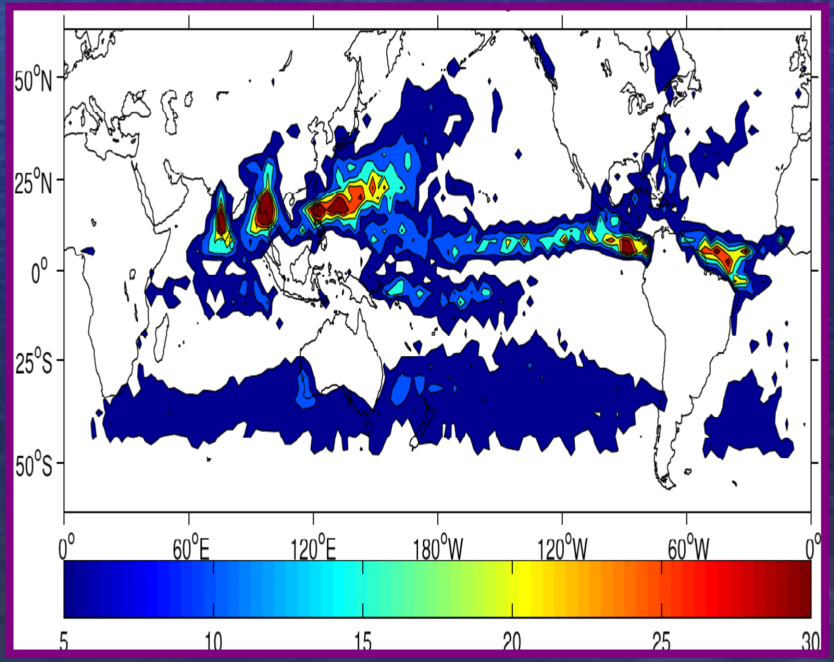
- Both Goddard and CSU MMFs exhibit similar bias despite using different GCMs and CRMs

- Possible causes
- Due to nonlinear coupling, the physical causes are very difficult to isolate and identify
- The use of cyclic lateral boundary condition in CRM
- Dimensionality (2D CRM vs 3D CRM)
- Convective momentum transport
- Excessive local convective-wind-evaporation feedback (Luo and Stephens 2006)
- Sensitive to the orientation of the CRM major axis. N-S axis produces better result.
- Sensitive to the dynamics of the CRM. Elastic system reduce precipitation.
- Sensitive to the microphysical scheme of the CRM.

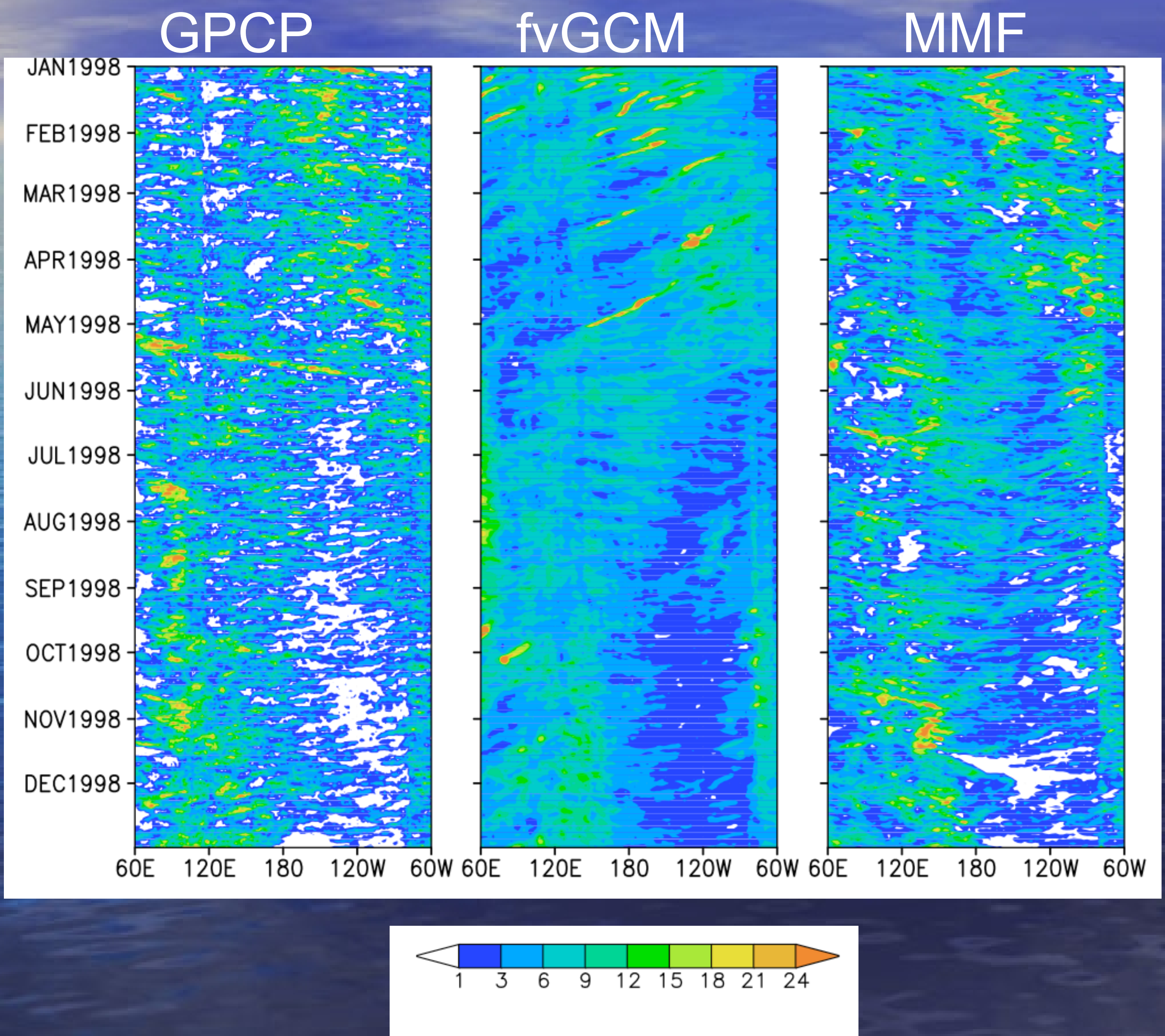
Summer Excessive Precipitation Problem (cont.

- Diabatic Acceleration and Rescaling (DARE), consists of accelerating all diabatic processes, reducing the planetary radius and increasing its rotation (Kaung et al. 2005).
- DARE Experiment with WRF (75S-75N) at ~ 4 km resolution also show similar precipitation bias as the MMFs.

Summer season mean precip

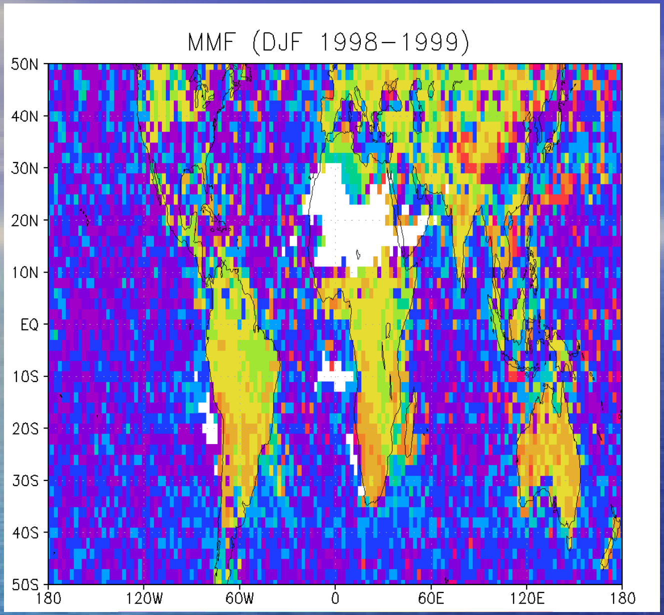


Hovmoller diagrams of Tropical Precipitation



Local Time of Maximum Precip. Frequency

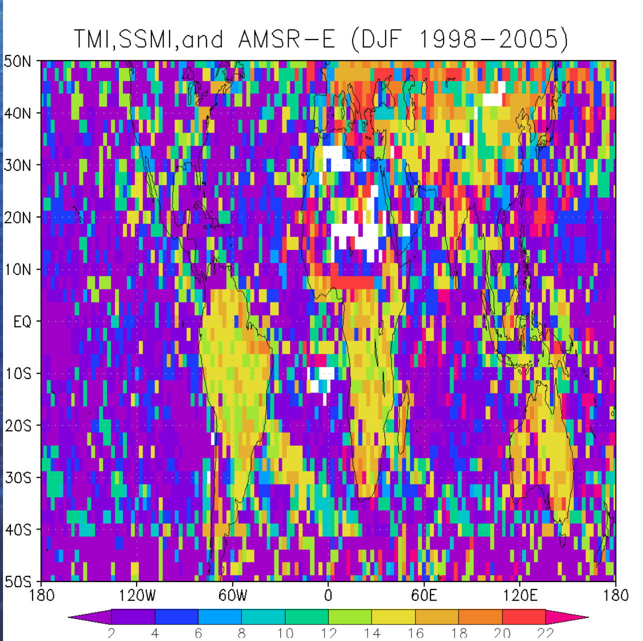
MMF
DJF
1998-1999

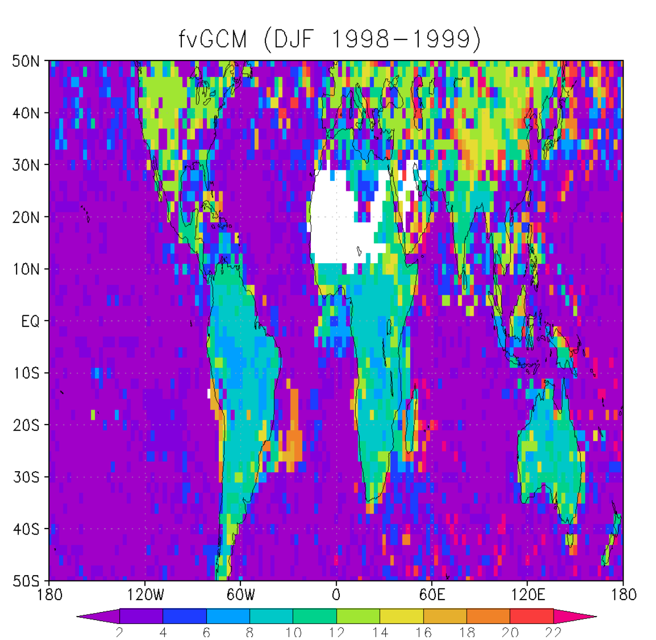


Observation:

Merged microwave only hourly precipitation (X. Lin): TRMM/TMI, DMSP/F13, F14,F15, AMSR-E/Aqua (1998-2005) at 2.5º x 2.5º resolution

Merged MW
DJF
1998-2005

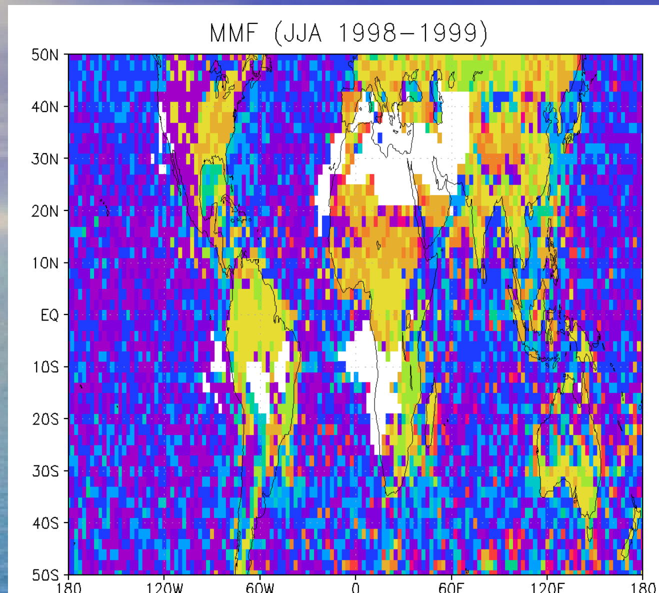




fvGCM
DJF
1998-1999

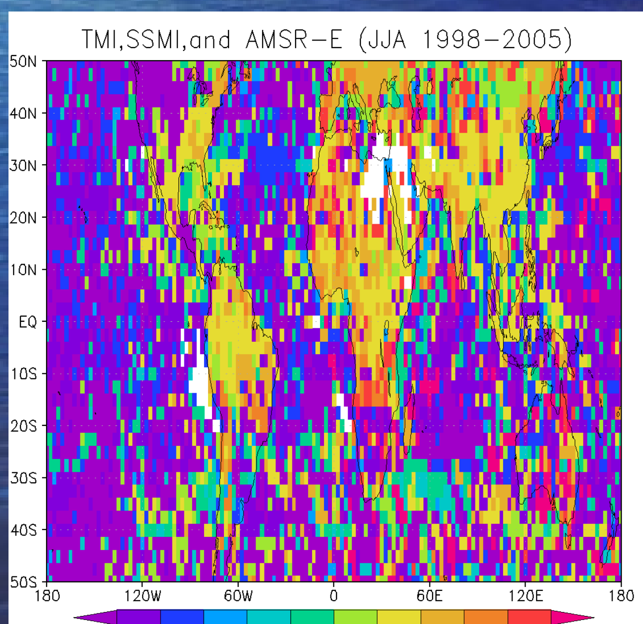
Local Time of Maximum precip. frequency

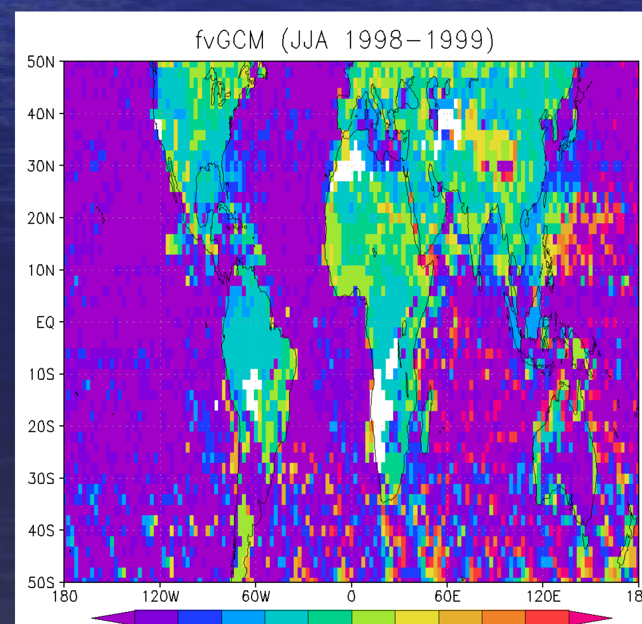
MMF
JJA
1998-1999



	Land	Ocean
MW	1600-1800	0200-0600
MMF	1600-1800	0200-0600
GCM	0800-1000	0000-0400

Merged MW
JJA
1998-2005



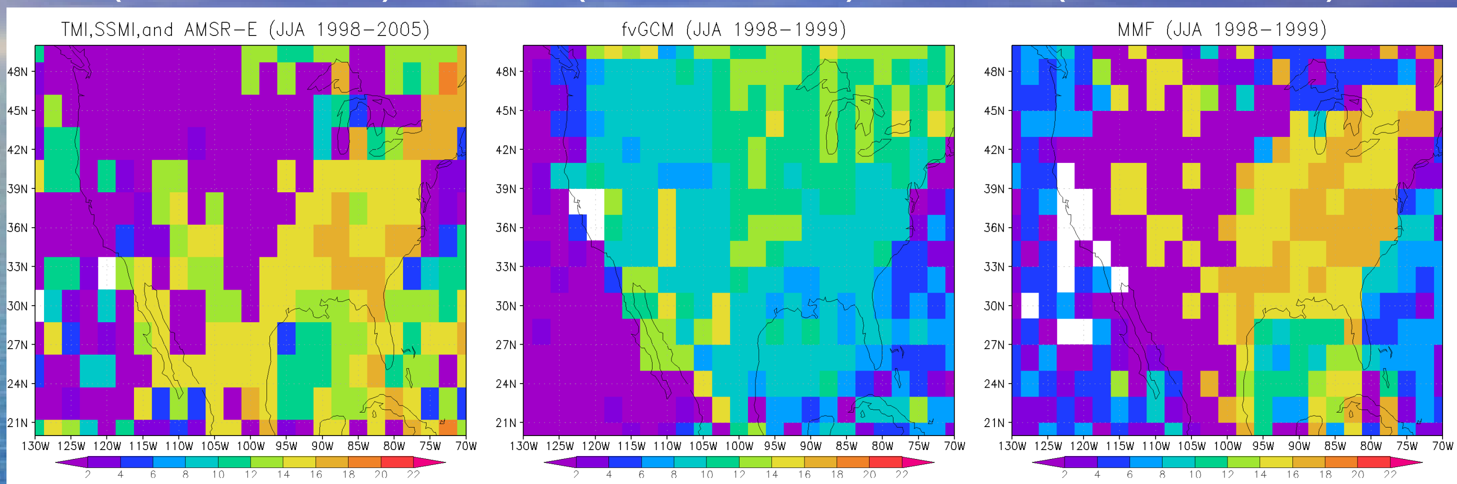


fvGCM
JJA
1998-1999

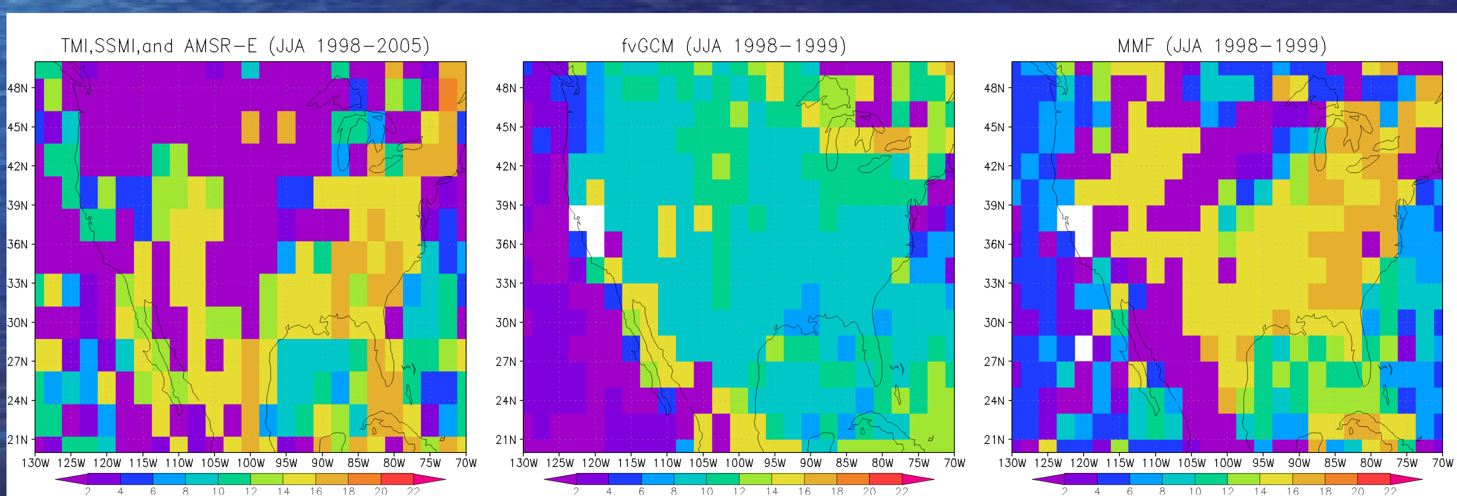
Diurnal Cycle of Summer Precip. over US

	Merge MV (1998-2005)	fvGCM (1998-1999)	MMF (1998-1999)

Frequency



Intensity

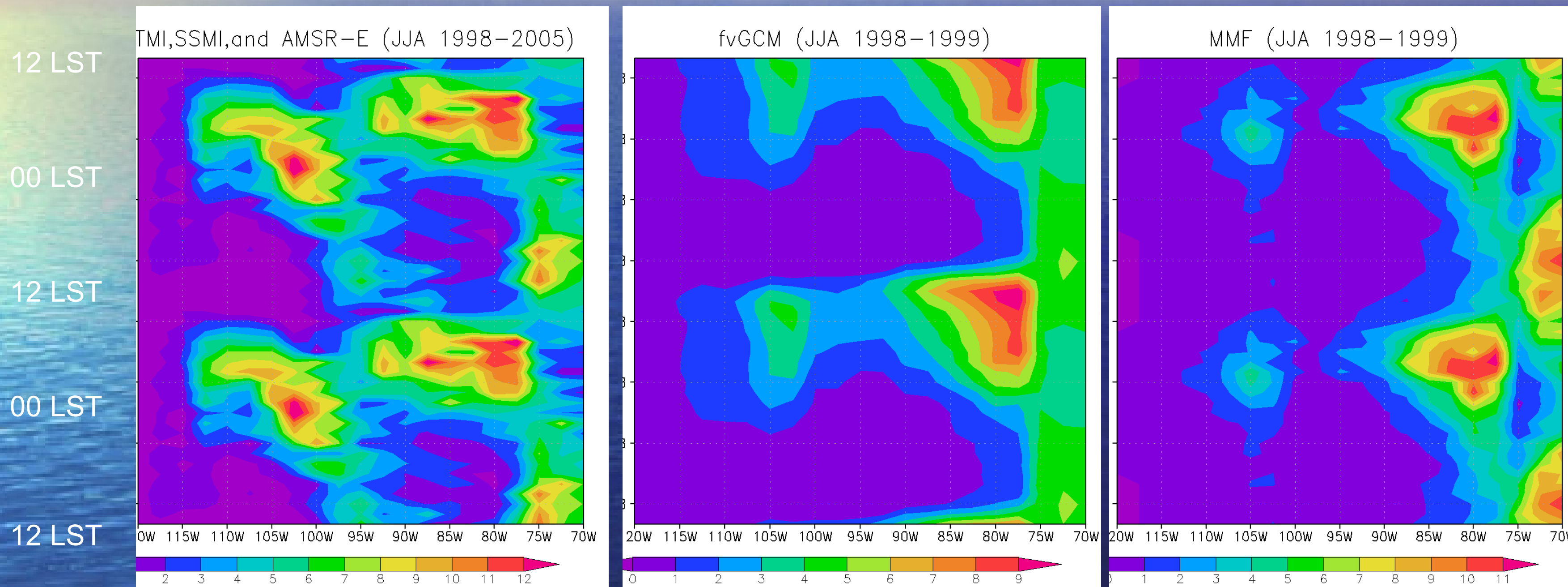


Diurnal Cycle of Summer Precip. over US along 35N

Merge MV (1998-2005)

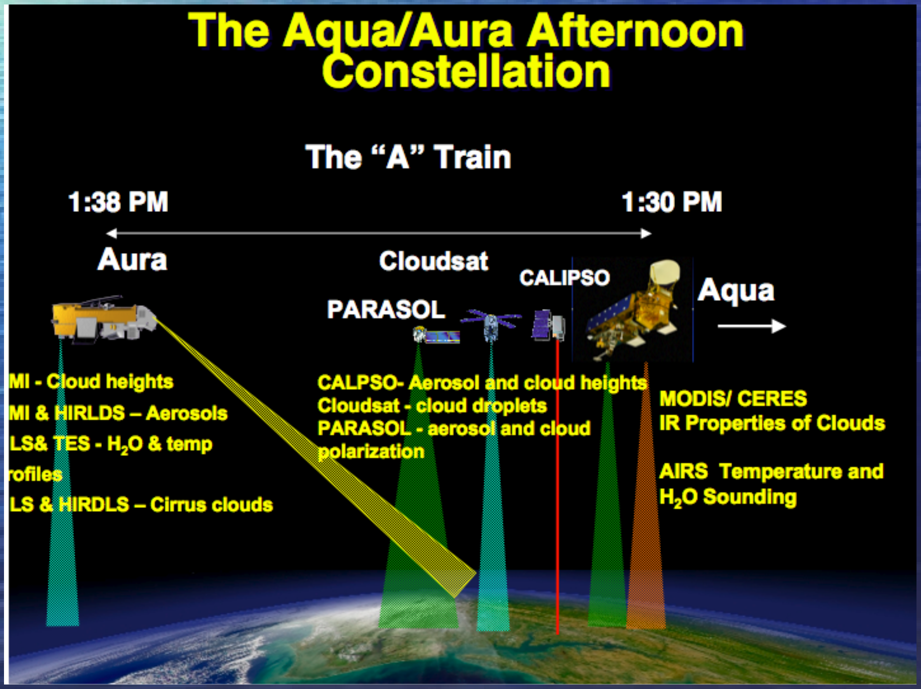
fvGCM (1998-1999)

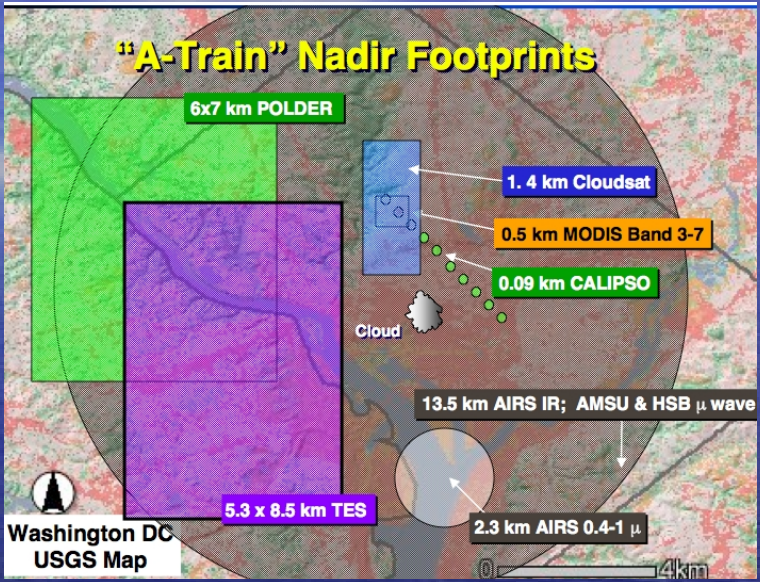
MMF (1998-1999)

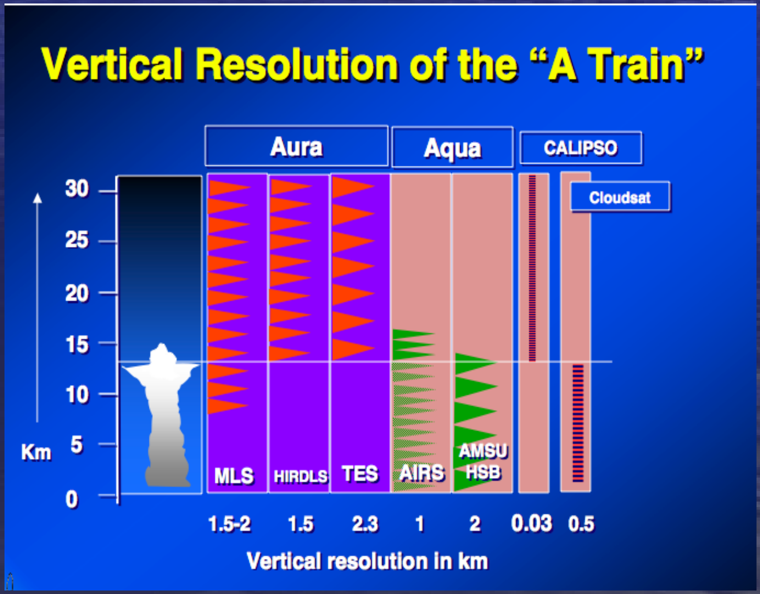


NASA state-of-the-art satellites

- Current and Future NASA satellites (EOS "A" Train and TRMM/GPM) can provide high-resolution cloud, precipitation, aerosal, water vapor, temperature, and other products for model validation and improvement.







Aura Microwave Limb Sounder (MLS) Measurements of Upper-Tropospheric Cloud Ice

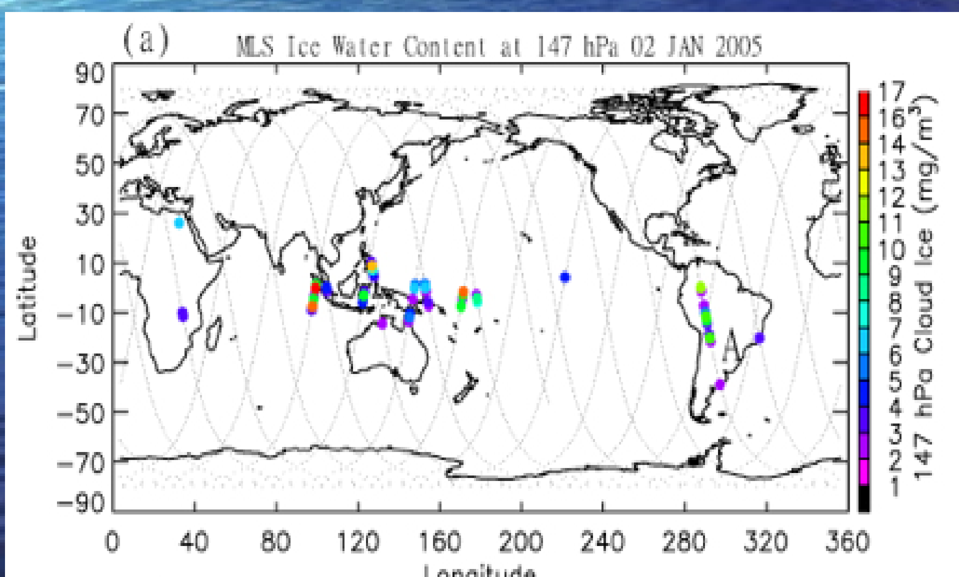
Resolutions:

~ 3.5 km vertical

~ 200 km horizontal

Range of Sensitivity:

~ 2 to 50 mg/m^3



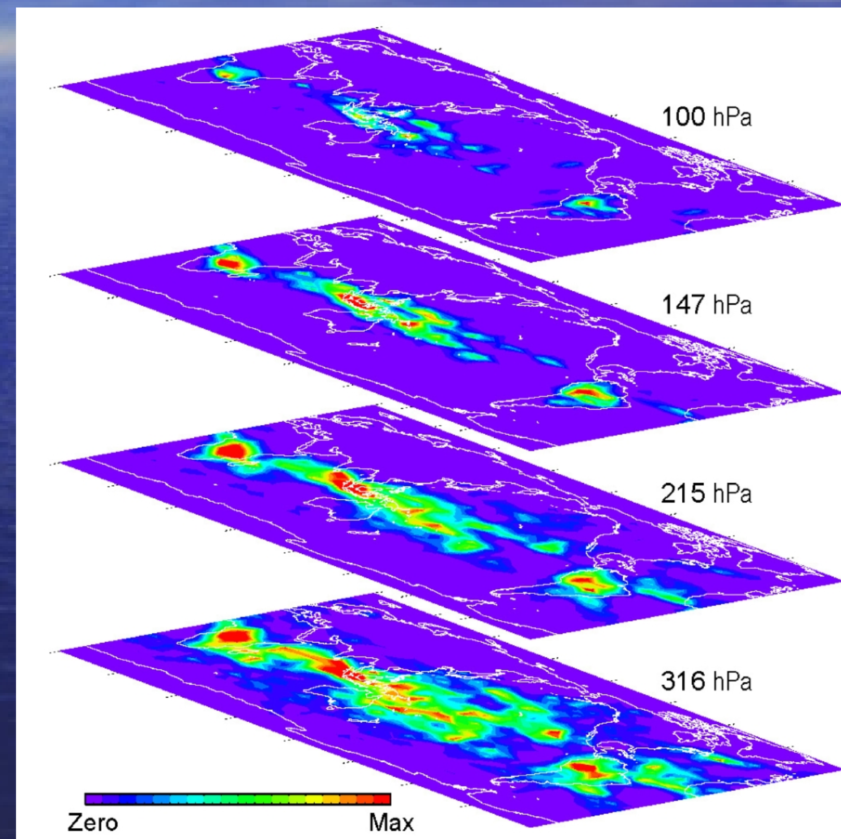
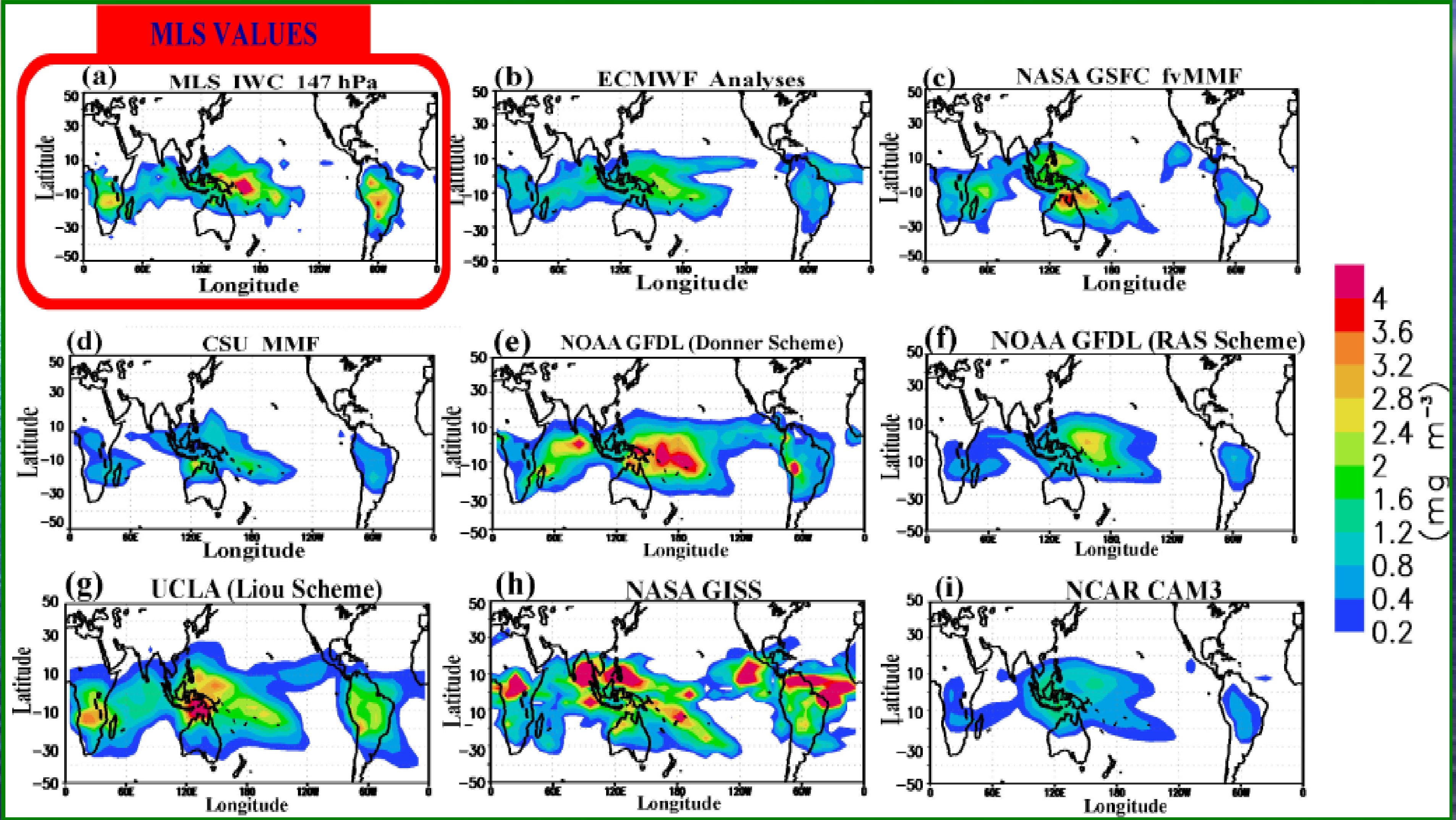


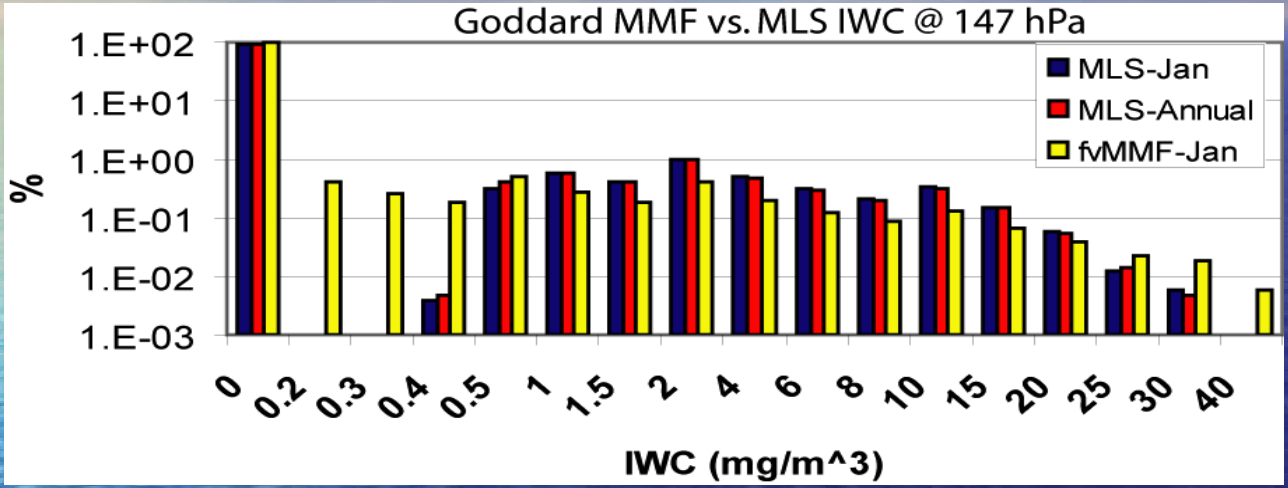
FIG 1. EOS MLS measurements of cloud ice. Maps shown here give average values for Aug 25 to Sep 6 ,2004 at four pressure levels.

Cloud Ice Content at 150 hpa

(Duane Waliser and Frank Li at NASA/JPL)



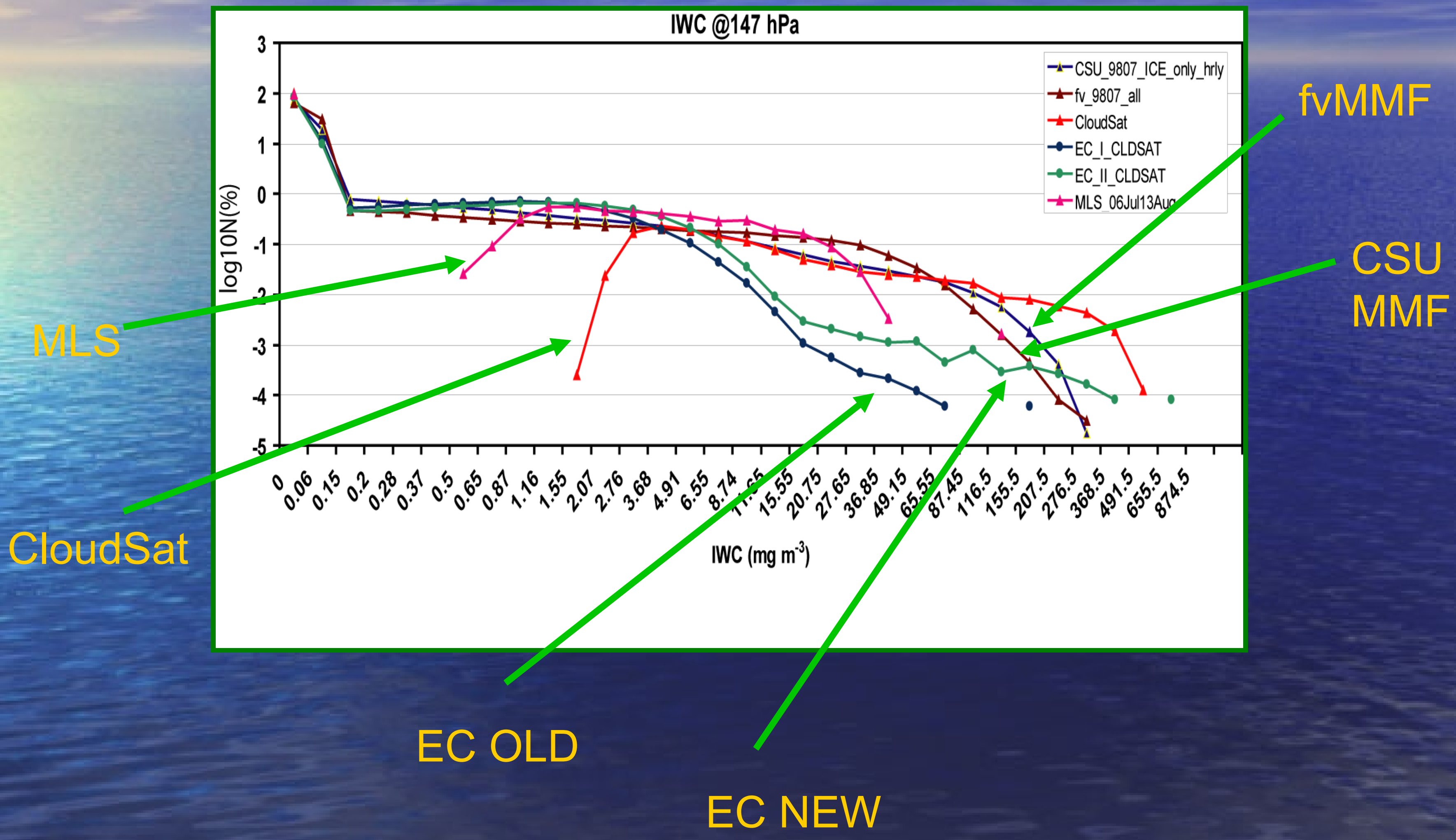
Probability distribution of MLS ice water content (mg/m3) at 147hpa



Blue: Jan 2005
Red: Aug 2004-July 2005
Yellow: fvMMF Jan 1998

It is expected the ice microphysical processes in the model, instrument sensitivity, and uncertainties in retrieval algorithms cause the difference.

Probability distribution of MLS ice water content (mg/m^3) at 147hpa



Earth Satellite Simulator (ESS)

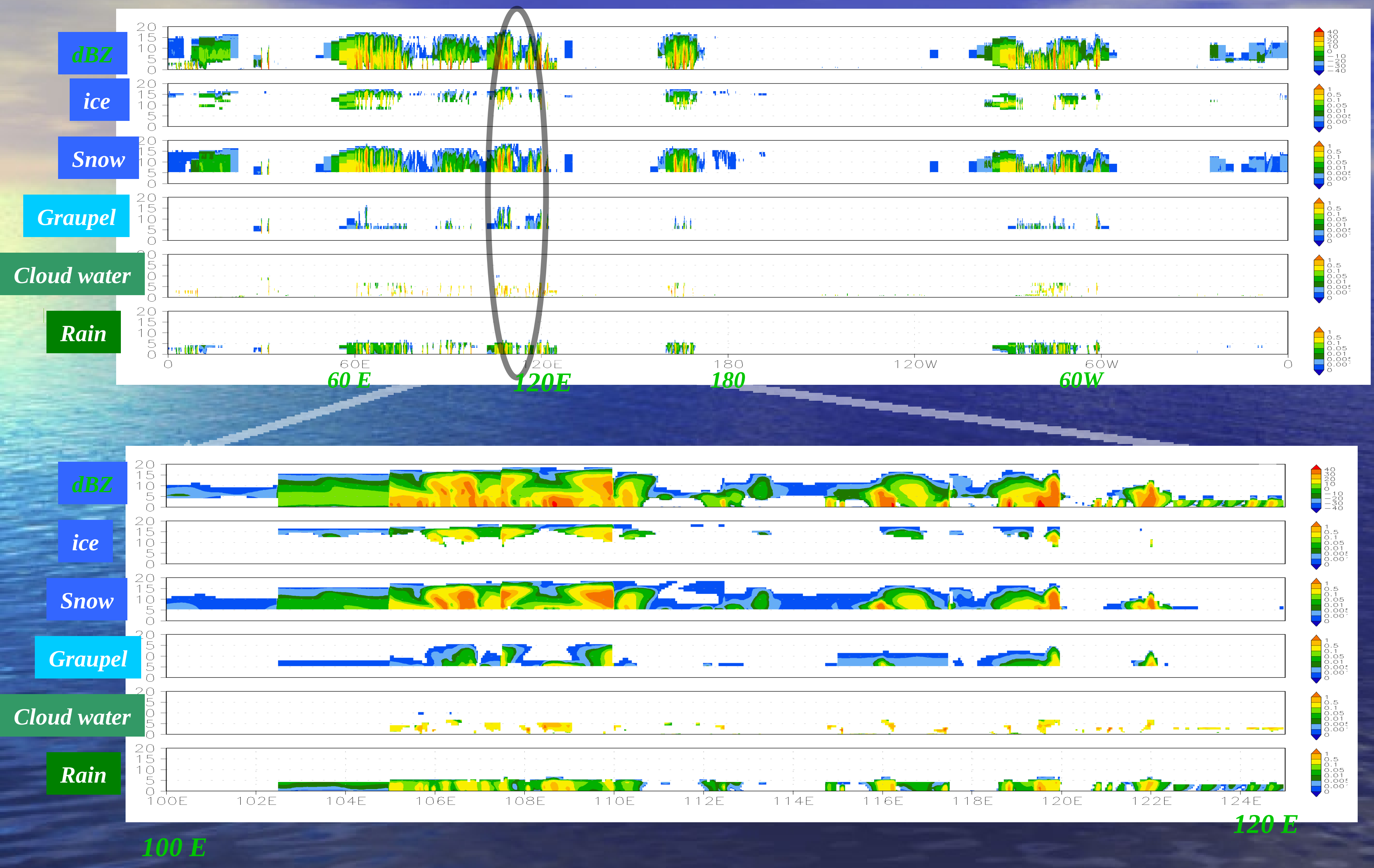
- The Earth Satellite Simulator (ESS)
  - whole-spectrum (visible, infrared, and microwave) cloud/aerosol optical properties
  - active/passive radiative transfer solver

- ESS can compute satellite-consistent
  - visible-IR radiance
  - Lidar attenuating backscattering coefficient
  - microwave brightness temperature (Tb)
  - Rain Radar Reflectivity
  - Cloud Radar Reflectivity

QuickBeam Radar Simulator (CSU)

- Developed by John Haynes at CSU
- Simulate vertical radar reflectivity profile at any common microwave frequency (TRMM, ClouSat)
- From either the top-down or the bottom-up
- Input: the state of the atmosphere, water/ice species, and the size distribution of species
- Output: profiles of effective radar reflectivity factor that emulate what a physical radar system would observe.

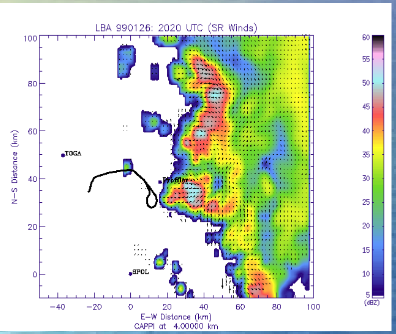
Goddard MMF Simulated Cloud Species (at Equator, 0000UTC December 2004)



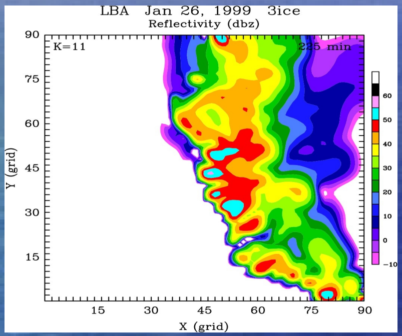
Using Radar Reflectivity to improve Microphysics in GCE (Lang et al. 2007)

Radar Reflectivity

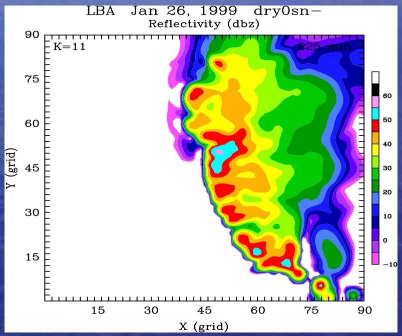
obs



RH84

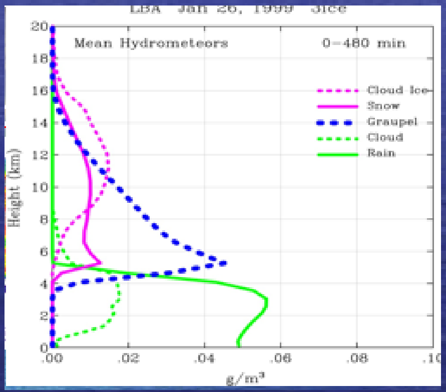


new



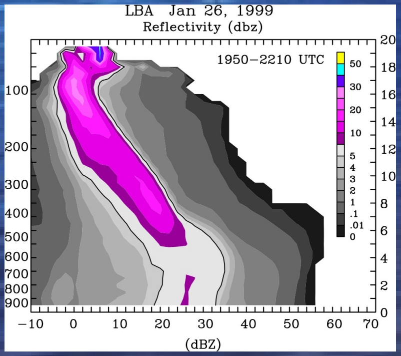
GCE Simulated hydrometeors

control

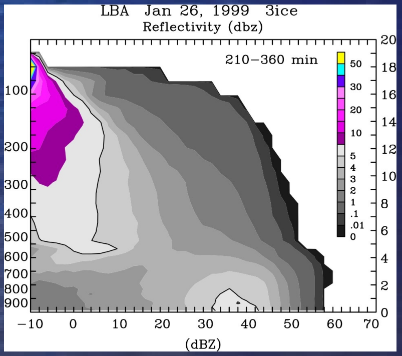


CFAD (Contour Frequency by Altitude Diagrams)

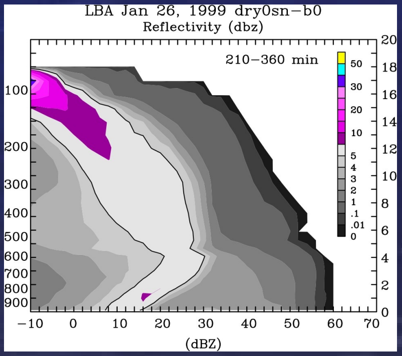
obs



RH84



new



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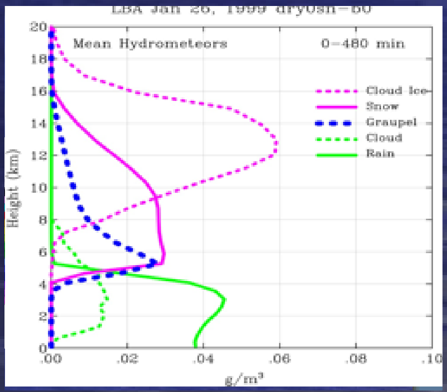
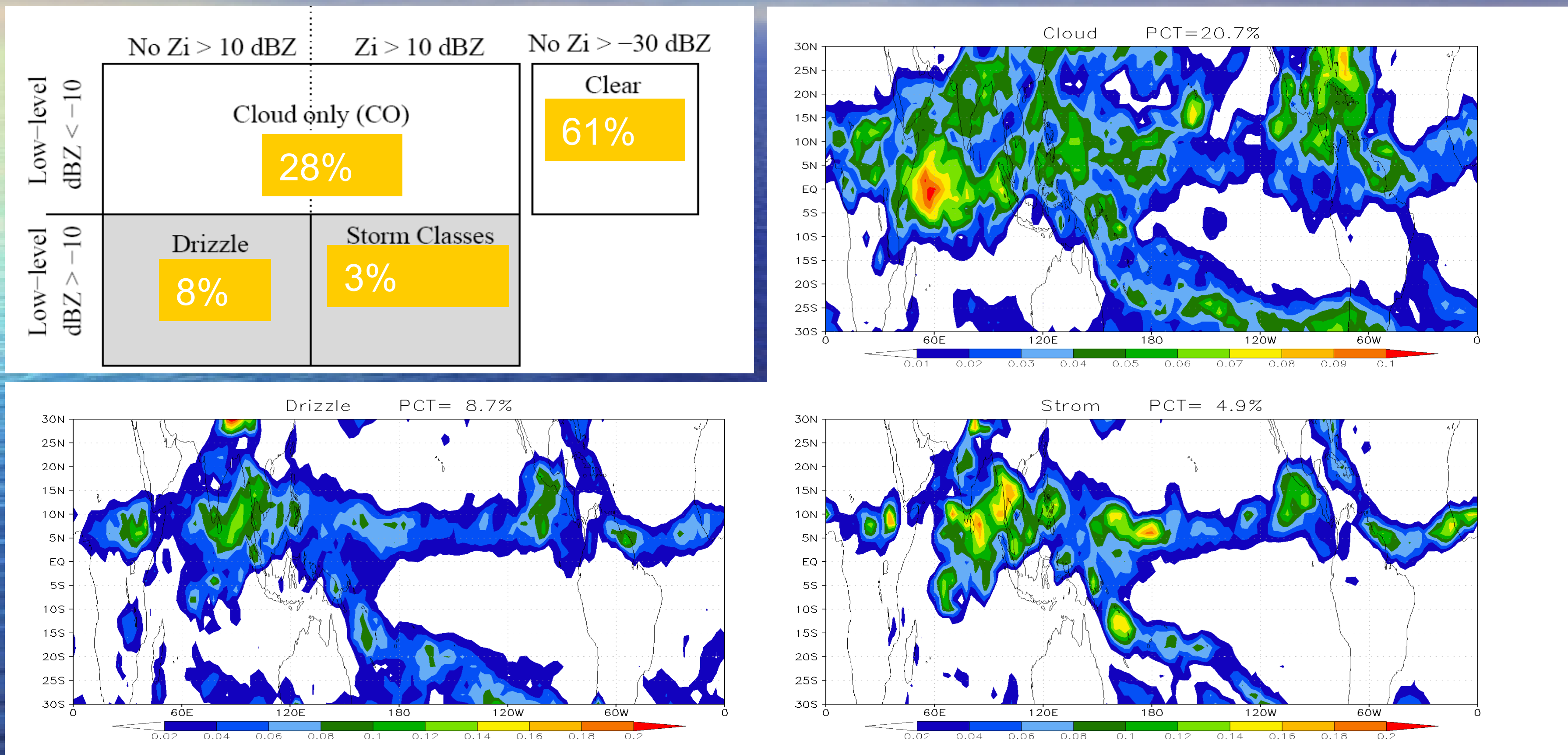
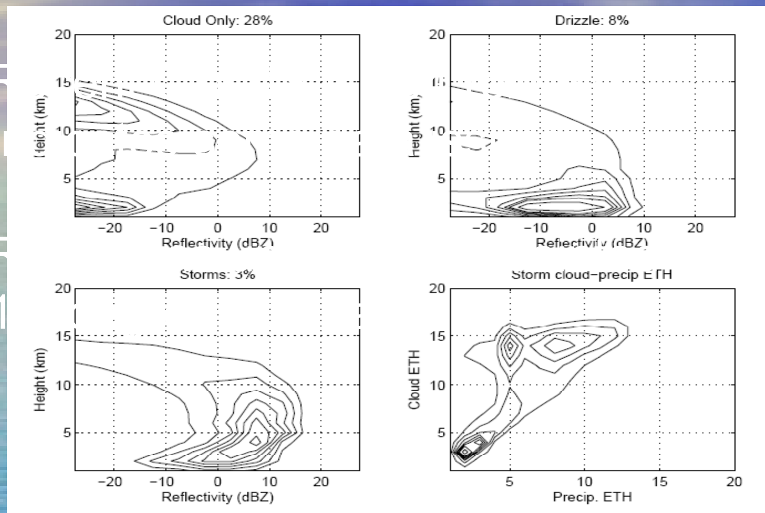


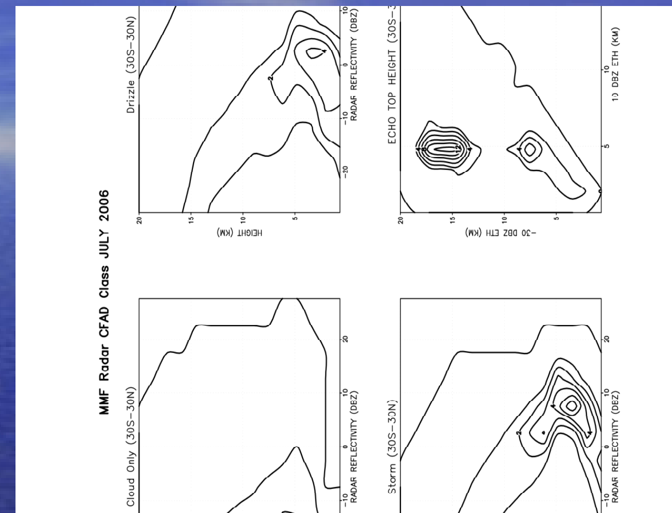
Radar Profile Classification (Stephens and Wood 2006)



Preliminary CFAD and ETH Results

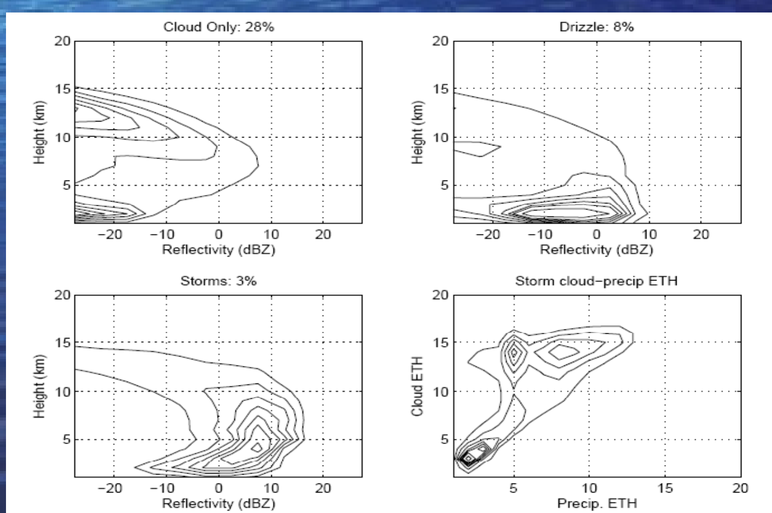
Control (JUL 2006)

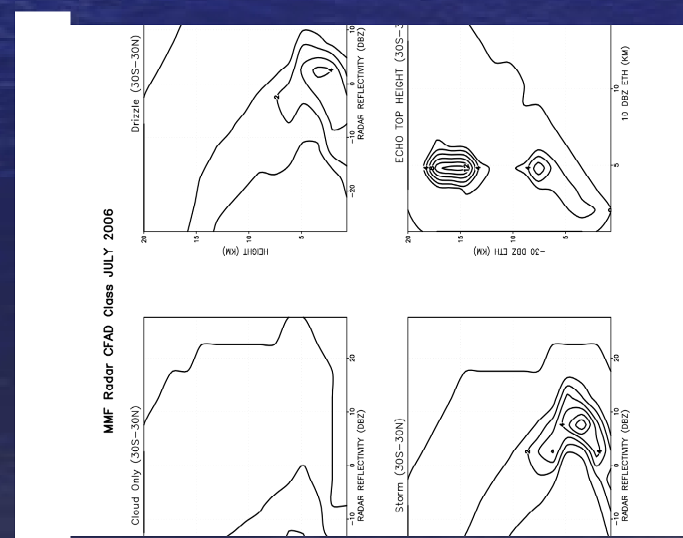




CloudSat (Jul-Aug 2006)

New scheme





Summary

- The MMF improves many common biases found in GCMs such as the precipitation pattern, high cloud amount, double ITCZ, MJO signal, and diurnal variation.

- The MMF precipitation in the western Pacific, Bay of Bengal, western India Ocean, and eastern tropical Pacific is too active during summer.

- The MMF does not produce the nocturnal precipitation maxima over the Great Plain in US. This might indicate the limitation of the embedded 2D CRM with cyclic BC to simulate the propagating MCSs.

- Preliminary results show the usefulness of cloudsat simulator and reflectivity CFAD statistical analyses to understand and improve the cloud microphysical processes in the model.