Multi-Scale Modeling System with Unified Physics

W.-K. Tao

- **What is the Multi-Scale Modeling System with Unified Physics?**
- **Current status of each component of the multi-scale modeling system (including recent improvements in microphysics)**
- **Current & Future Improvements**

Team Work

- Jiundar Churn: MMF
- Steve Lang: GCE Bulk-Microphysics & TRMM Latent Heating
- Xiaowen Li: Bin-Microphysics, Aerosol-precipitation
- Toshi Matsui: Aerosol, Radiation & Satellite Simulators
- Bo-Wen Shen: Global Mesoscale & MMF
- Roger Shi: WRF & Cloud library
- S. Thomson (NPP): WRF
- Xiping Zeng: GCE & Precipitation Processes
- T. Iguchi: WRF and Bin-Microphysics

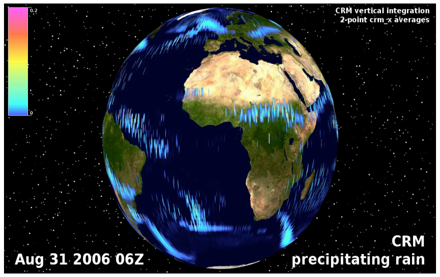
Collaborators/Co-Is (Proposals)

W. Lau, A. Hou, M. Chin, C. Peters-Lidard, K. Pickering, GMAO (Rienecker, M.-I., Lee, M. Suarze, Schubert), NCAR (J. Bacmeiste, A. Heymsfield), R. Atlas (NOAA), C. Zhang (U. of Miami), JPL (D. Waliser, S. Tanelli), CSU (D. Rnadall, G. Stephen), C. Henze (Ames), R. Houze (U. of Washington), X. Huang (U. of Michigan)

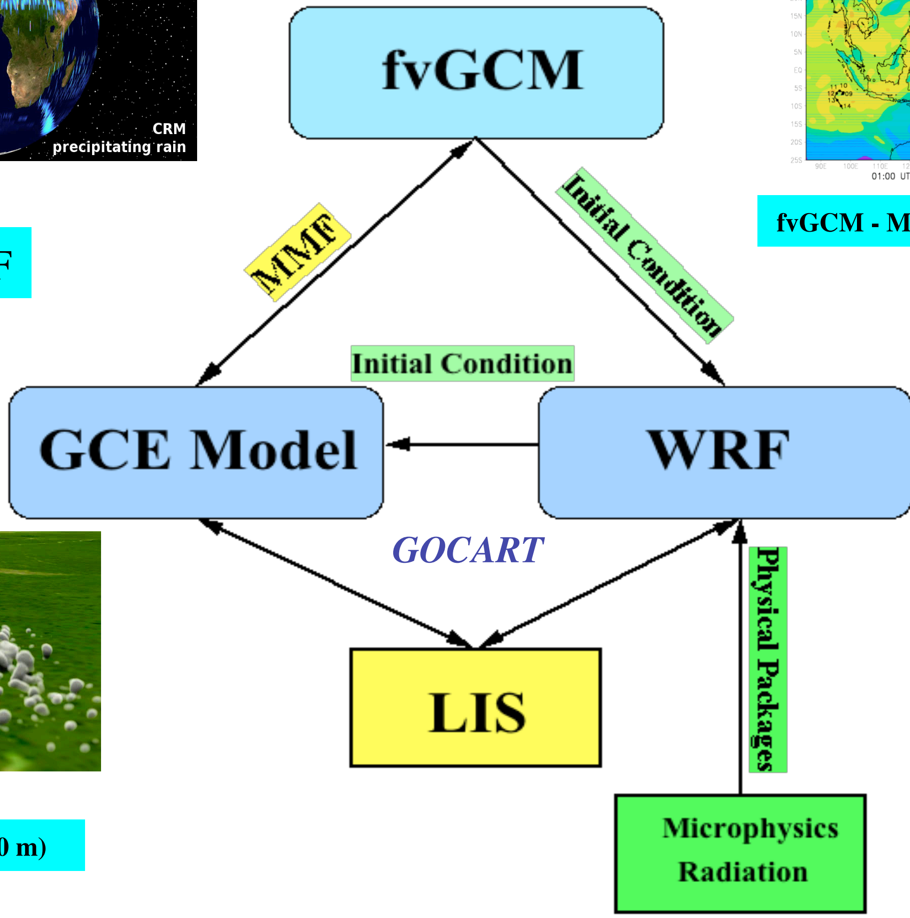
Website for mesoscale modeling group and cloud library

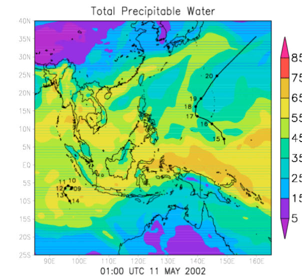
http://portal.nccs.nasa.gov/cloudlibrary/index2.html

Multi-Scale Modeling System with Unified Physics



MMF

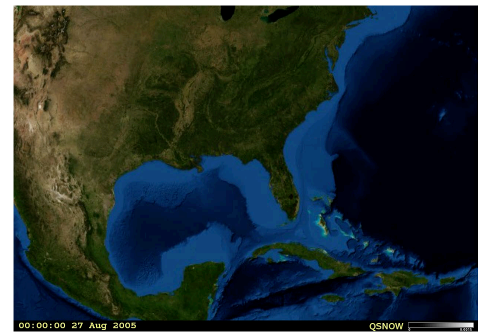




fvGCM - MJO (0.25° x 0.25°)

Observation

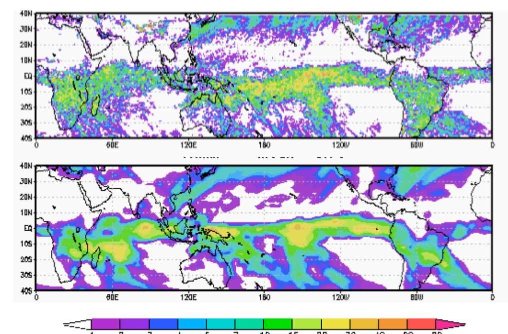
Satellite Data
Field Campaigns
Re-analyses



WRF- *Hurricane Katrina* (1.67 km)

GCE - LBA (250 m)

TRMM Jan/99



MMF

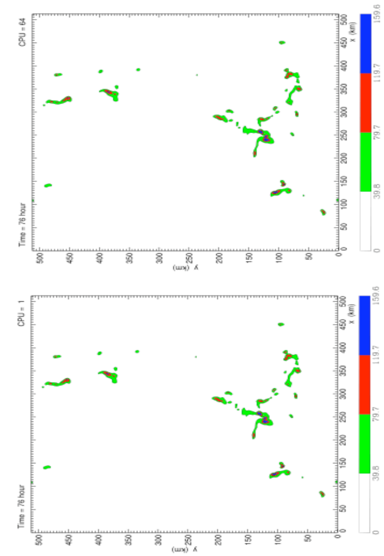
MMF: Multi-Scale Modeling Framework
LIS: Land Information System
GCE: Goddard Cumulus Ensemble Model
WRF: Weather Research Forecast

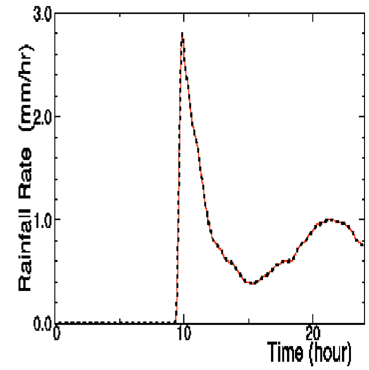
**Microphysical Package (5 options)
& Long/Shortwave Radiative Transfer
(including cloud-radiation interaction)**

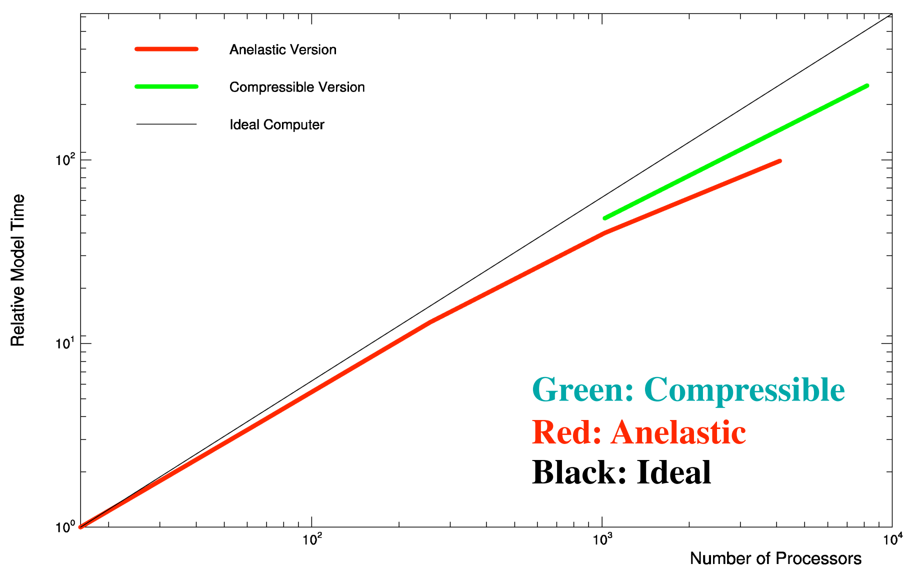
Tao, W.-K., D. Anderson, J. Chern, J. Estin, A. Hou, P. Houser, R. Kakar, S. Lang, W. Lau, C. Peters-Lidard, X. Li, T. Matsui, M. Rienecker, M. R. Schoeberl B.-W. Shen, J.-J. Shi, and X. Zeng, 2009: Goddard Multi-Scale Modeling Systems with Unified Physics, *Annales Geophysics*, **27**, 3055-3064.

GCE Model's characteristics and computational performance

Parameters/ Processes	GCE Model
Dynamics	Non-hydrostatic: Anelastic or Compressible 2D (Slab- and Axis-symmetric) and 3D
Vertical Coordinate	Z (height)
Microphysics	2-Class Water & 3-Class Ice 2-Moment 2-Class Water & 2-Moment 5-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 Model Re-analyses (MERRA)
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) Land Information System (LIS) TOGA COARE Flux Module
Parallelization	OPEN-MP and MPI







Almost no differences in instantaneous and accumulated surface rainfall between 1 CPU and 512 CPUs

Model configuration: 2048 x 2048 x 41
1 km grid spacing and 6 s time step

8192 CPUs: 12 h integration, 4 h wall clock

	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	*33 bins for 6 types 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)

CSU RAMs' 2-Moments: Cloud-Aerosol/ Precipitation Interactions

Three-Moments: Milbrandt and Yau (2005)

Unified GCE V. 1 (FY09)

Document will be available soon

GCE Model's papers – Improvement of Microphysics

Lang, S., W.-K. Tao, R. Cifelli, W. Olson, J. Halverson, S. Rutledge, and J. Simpson, 2007: Improving simulations of convective system from TRMM LBA: Easterly and Westerly regimes. *J. Atmos. Sci.*, **64**, 1141-1164.

Zeng, X., W.-K. Tao, S. Lang, A. Hou, M. Zhang, and J. Simpson, 2008: On the sensitivity of Atmospheric ensemble to cloud microphysics in long-term cloud-resolving model simulations. *J. Meteor. Soc. Japan*, *Special Issue on high-resolution cloud models*, **86**, No. 6, 839-856.

Li, X., W.-K. Tao, A. Khain, J. Simpson and D. Johnson, 2008: Sensitivity of a cloud-resolving model to bulk and explicit-bin microphysics schemes: Part I: Comparisons. *J. Atmos. Sci.*, **66**, 3-21.

Li, X., W.-K. Tao, A. Khain, J. Simpson and D. Johnson, 2008: Sensitivity of a cloud-resolving model to bulk and explicit-bin microphysics schemes:: Part II: Cloud microphysics and storm dynamics interactions. *J. Atmos. Sci.*, **66**, 22-40.

Zeng, X., 2008: The influence of radiation on ice crystal spectrum in the upper troposphere. *Quart. J. Roy. Meteor. Soc.* **134**, 609-620.

Zeng, X., W.-K. Tao and J. Simpson, 2008: A choice of prognostic variables for long-term cloud-resolving modeling. *J. Meteor. Soc. Japan*, **86**, 839-856.

Matsui, T., X. Zeng, W.-K. Tao, H. Masunaga, W. S. Olson, and S. Lang, 2009: Evaluation of long-term cloud-resolving model simulations using satellite radiance observations and multi-frequency satellite simulators. *J. Atmos. Oce. Tech., 26*, 1261-1274.

Zeng, X., W.-K. Tao, M.-H. Zhang, A. Y. Hou, S. Xie, S. Lang, X. Li, D. O'C Starr and X. Li, 2009:A contribution by ice nuclei to global warming. *Quart. J. Roy. Meteor. Soc.* (**in press**).

Li, X., W.-K. Tao, T. Matsui, C. Liu and H. Masunaga, 2009: Improving spectral bin microphysical scheme using TRMM satellite observations. *Quart. J. Roy. Meteor. Soc.* (in revision).

Goddard Microphysics (> 10 Different Schemes)

No Scheme is perfect yet

2 liquid, 3 ice bulk

	Cloud Water (QC)	Rain (QR)	Cloud Ice (QI)	Snow (QS)	Graupel/Hail (QH)
Condensation	CND				
Evaporation	*DD*	*ERN*			
Auto-conversion	*-PRAUT*	+PRAUT			
Accretion	*-PRACW*	+PRAC W			
Deposition			PIDEP	PSDEP	
DEPOSITION OF QS			PINT		
DEPOSITION OF QG			DEP		
Sublimation			*-DD1*	*-PSSUB*	
Melting	PIMLT	PSMLT	-PIMLT	*-PSMLT*	*-PGMLT*
		PGMLT			
AUTOCONVERSION OF QI TO QS			*-PSAUT*	PSAUT	
ACCRETION OF QI TO QS			*-PSACI*	PSAC I	
ACCRETION OF QC BY QS (RIMING)	*-PSACW*	QSAC W		PSACW	
(QSACW FOR PSMLT)	*-QSACW*				
ACCRETION OF QI BY QR			*-PRACI*	del3*	(1-del3)*
				PRAC I	PRAC I
ACCRETION OF QR OR QH BY QI		*-PIACR*		del3*	(1-del3)*
				PIAC R	PIAC R
BERGERON PROCESSES FOR QS	*-PSFW*			PSF W	
BERGERON PROCESSES FOR QS			*-PSFI*	PSF I	
ACCRETION OF QS BY QH				*-PGACS*	PGACS
(DGACS,WGACS: DRY AND WET)				*-DGACS*	DGACS
				-WGACS	WGAC S
ACCRETION OF QC BY QH (QGACW	*-DGACW*				DGACW
FOR PGMLT)	*-QGACW*				QGAC W
ACCRETION OF QI BY QH (WGACI			*-DGACI*		DGACI
FOR WET GROWTH)			*-WGACI*		WGAC I
ACCRETION OF QR TO QH (QGACR		*-DGACR*			DGACR
FOR PGMLT)		*-(1-del)**			WGAC R
		WGACR			
		*-del**			
		WGACR			
WET GROWTH OF QH					
				WGACR=	
				PGWET-	
SHED PROCESS		QGACW		DGACW-	QGACW
				WGACI-	
				WGAC S	
AUTOCONVERSION OF QS TO QH				*-PGAUT*	PGAUT
FREEZING		*-PGFR*			PGFR
ACCRETION OF QS BY QR				*-PRACS*	PRACS
ACCRETION OF QR BY QS (QSACR		*-PSACR*		del2*	(1-del2)*
FOR PSMLT)				PSACR	PSACR
HOMOGENEOUS FREEZING OF QC	*-PIHOM*		PIHOM		
TO QI (T < T00)					
DEPOSITION GROWTH OF QC TO QI	*-PIDW*		PIDW		

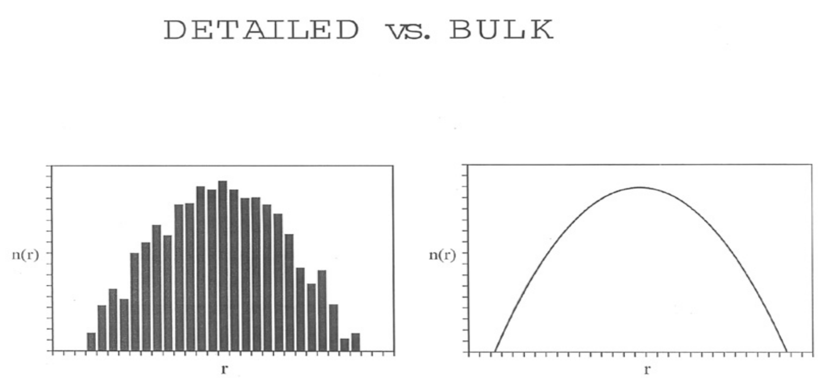
Spectral Bin Microphysics

Water droplets (cloud droplets and raindrops)

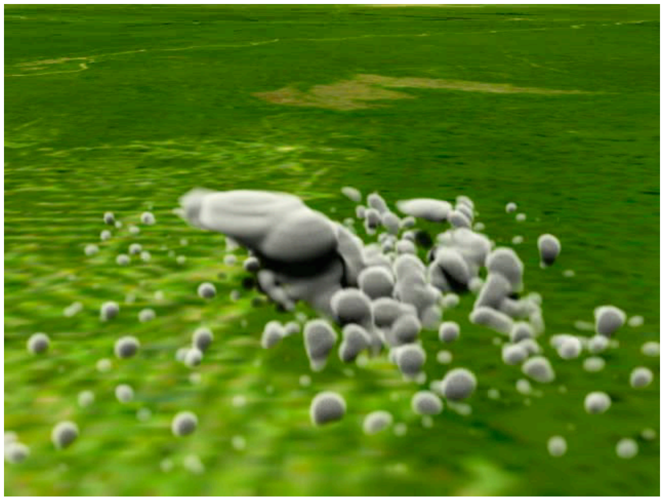
Six types of ice particles*: *pristine ice crystals (columnar and plate-like), snow (dendrites and aggregates), graupel and frozen drops/hail.

33-43 bin for each species including aerosol

- ***Nucleation of droplets and ice particles***
- ***Immersion freezing***
- ***Ice multiplication***
- ***Detailed melting procedure***
- ***Condensation/evaporation of liquid drops***
- ***Deposition/sublimation of ice particles***
- ***Drop/drop, drop/ice, and ice/ice collision/coalescence***
- ***Turbulence effects on liquid drop collisions***
- ***Collisional breakup***



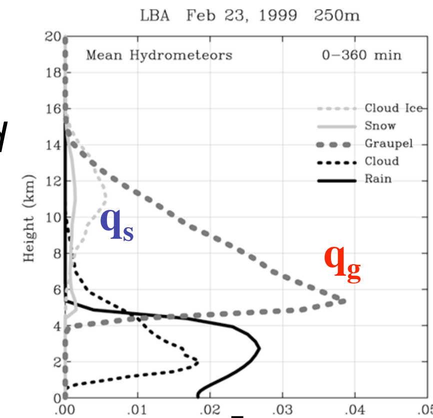
Improving the Simulation of Convective Cloud Systems: higher resolution and improved ice physics



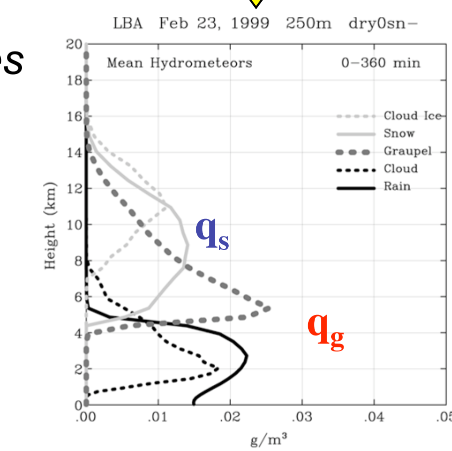
High resolution simulation of 23 Feb 1999 TRMM LBA case

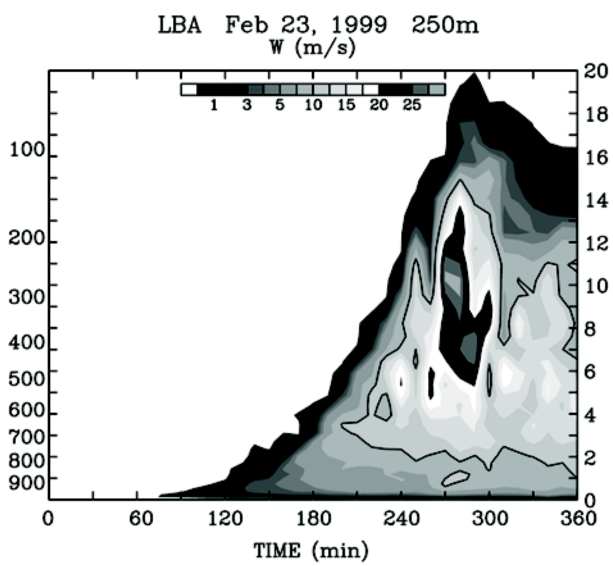
Image by J. Williams (Scientific Visualization Studio)

The Goddard Cumulus Ensemble (GCE) model is a cloud-resolving model developed at NASA Goddard by the Mesoscale and Dynamics Group to simulate convective cloud systems.



Improvements to the cloud microphysics results in less high-density ice and more realistic hydrometeor profiles for use in satellite retrievals





Higher horizontal model resolution leads to a more realistic, gradual transition from shallow to deep convection

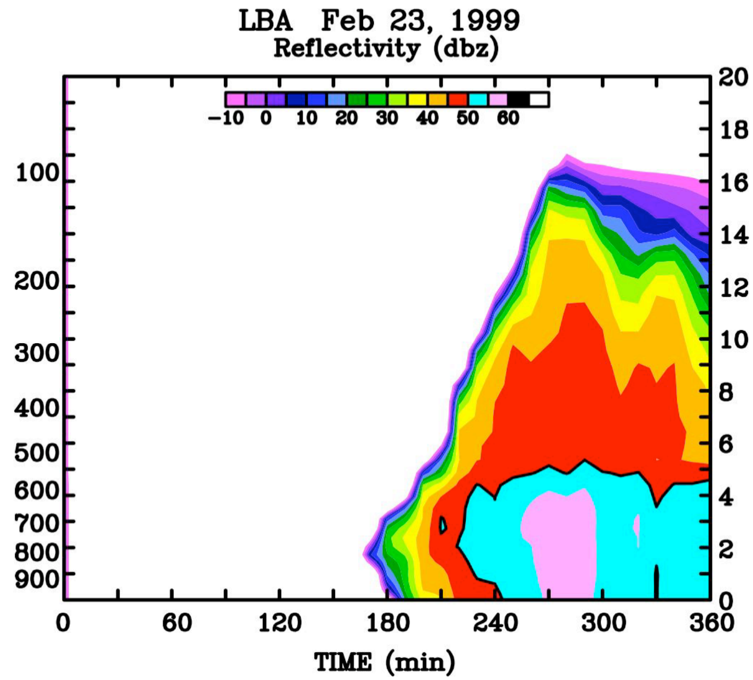
Need to continue improving the microphysics

Lang, S., W.-K. Tao, R. Cifelli, W. Olson, J. Halverson, S. Rutledge, and J. Simpson, 2007: Improving simulations of convective systems from TRMM LBA: Easterly and westerly regimes. *J. Atmos. Sci.*, **64**, 1141-1164.

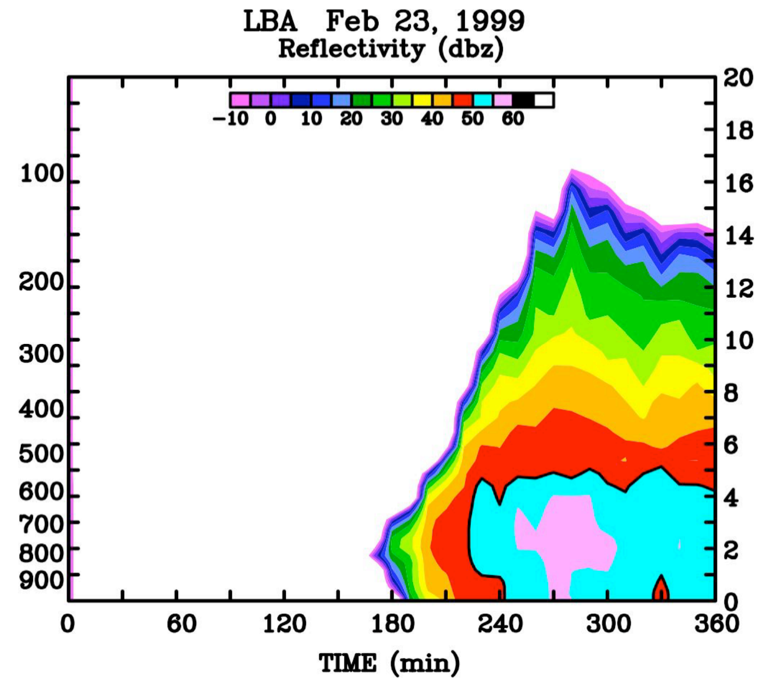
Reduce 40dBZ at high altitude

(3ICE Bulk Scheme)

Lang *et al.* (2007)



Lang *et al.* (2009)

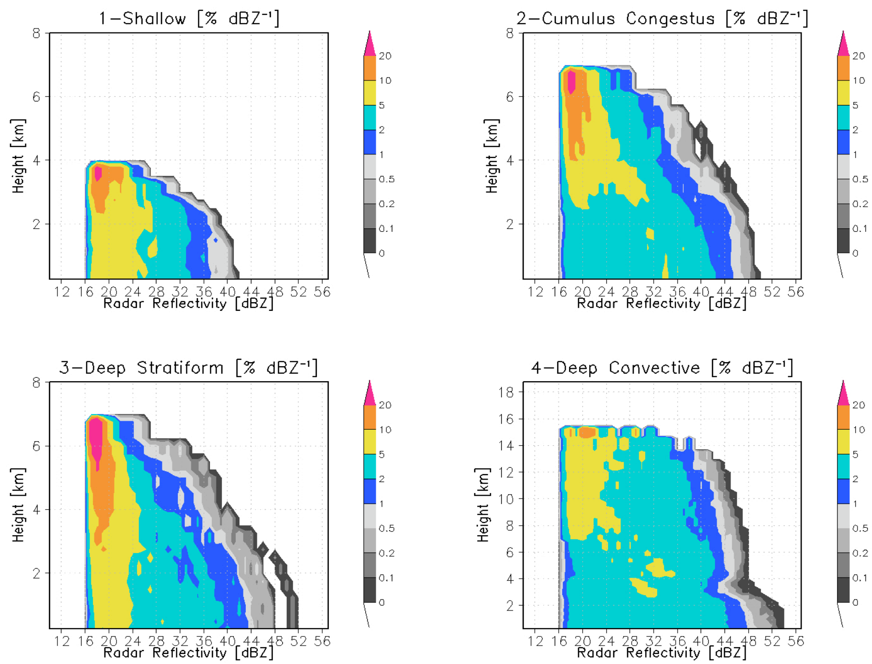


Climatologically, 40-dBZ penetrations above 10 km are rare even over land (Zipser et al. 2006; Liu et al. 2008).

Recently, Utah U. CRM simulation for KWAJEX case, model simulated dbz is higher than radar observation above 5 km level up to 10 dbz (Li et al. 2008)

SCSMEX (1km - multi-week)

G
C
E



T
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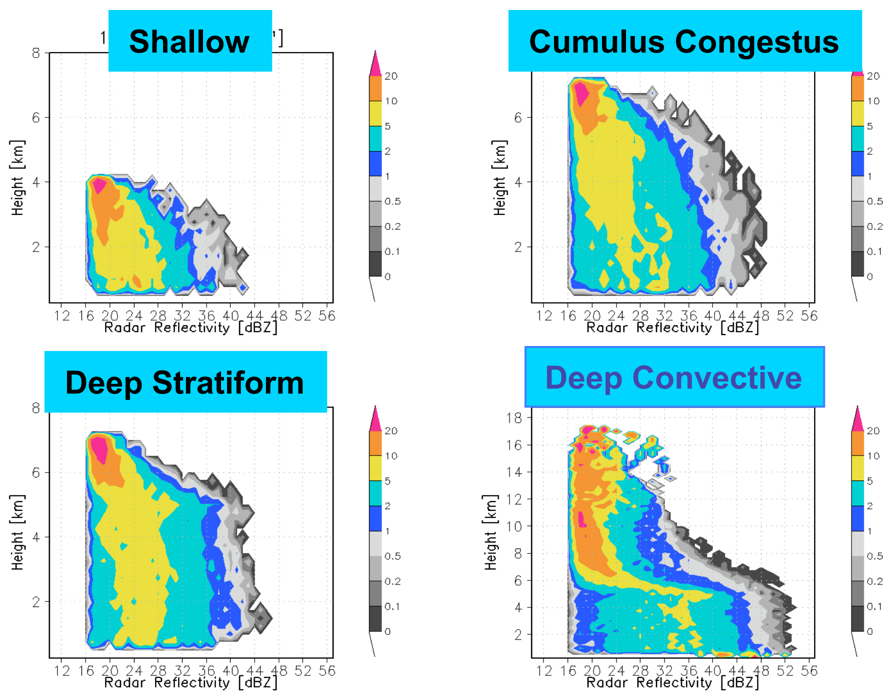
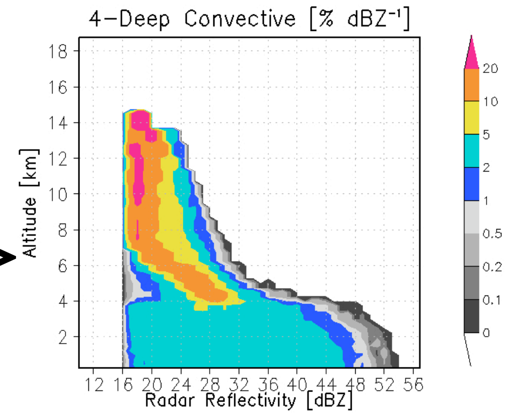


Using Spectral Bin Microphysics to improve bulk scheme - TeDD



Matsui, T., X. Zeng, W.-K. Tao, H. Masunaga, W. S. Olson, and S. Lang, 200(
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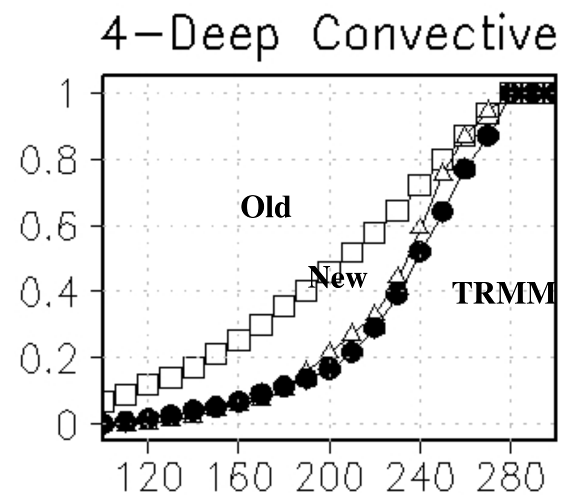
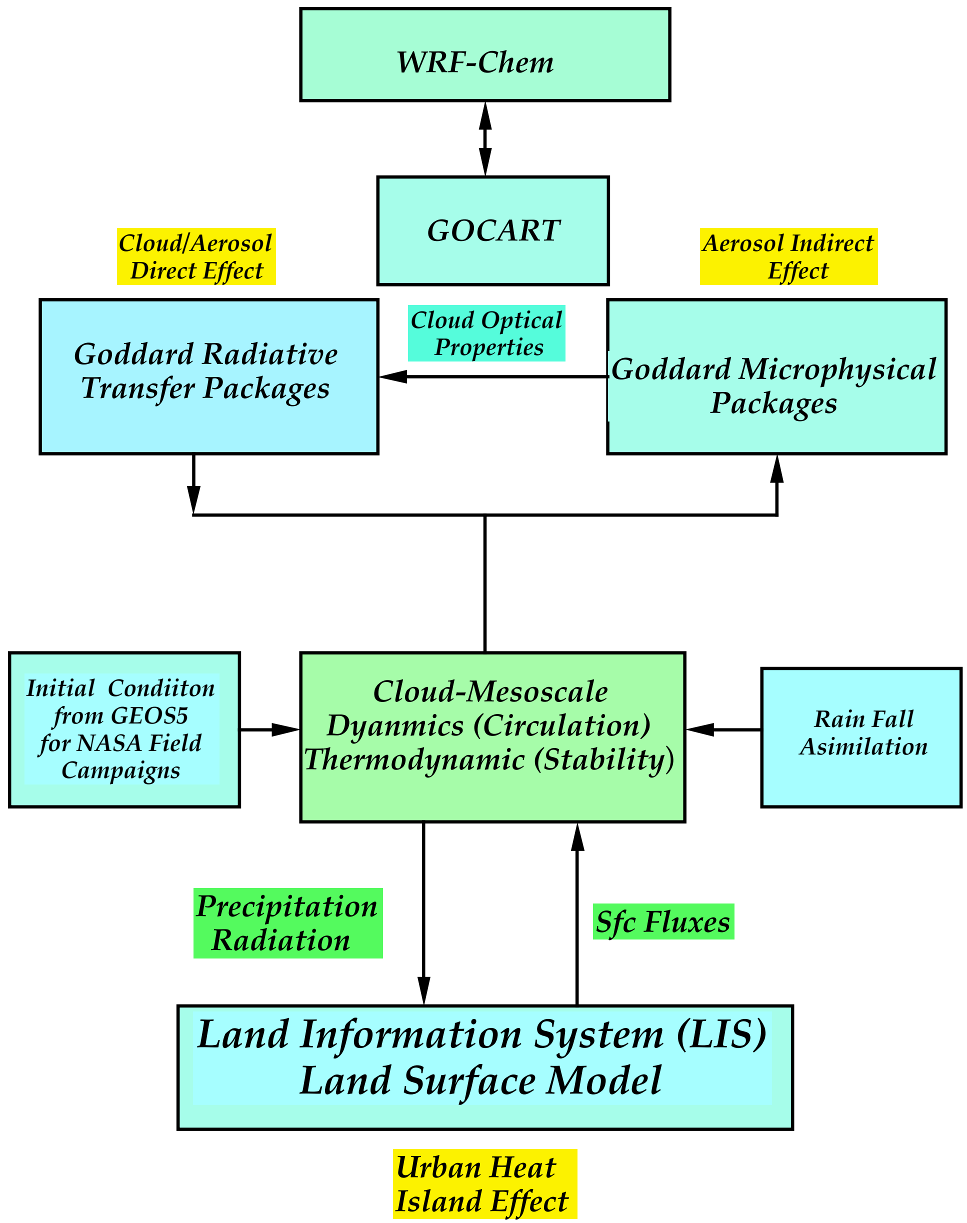


PDF

Tb (85GHz)

NASA Unified WRF (Physics)

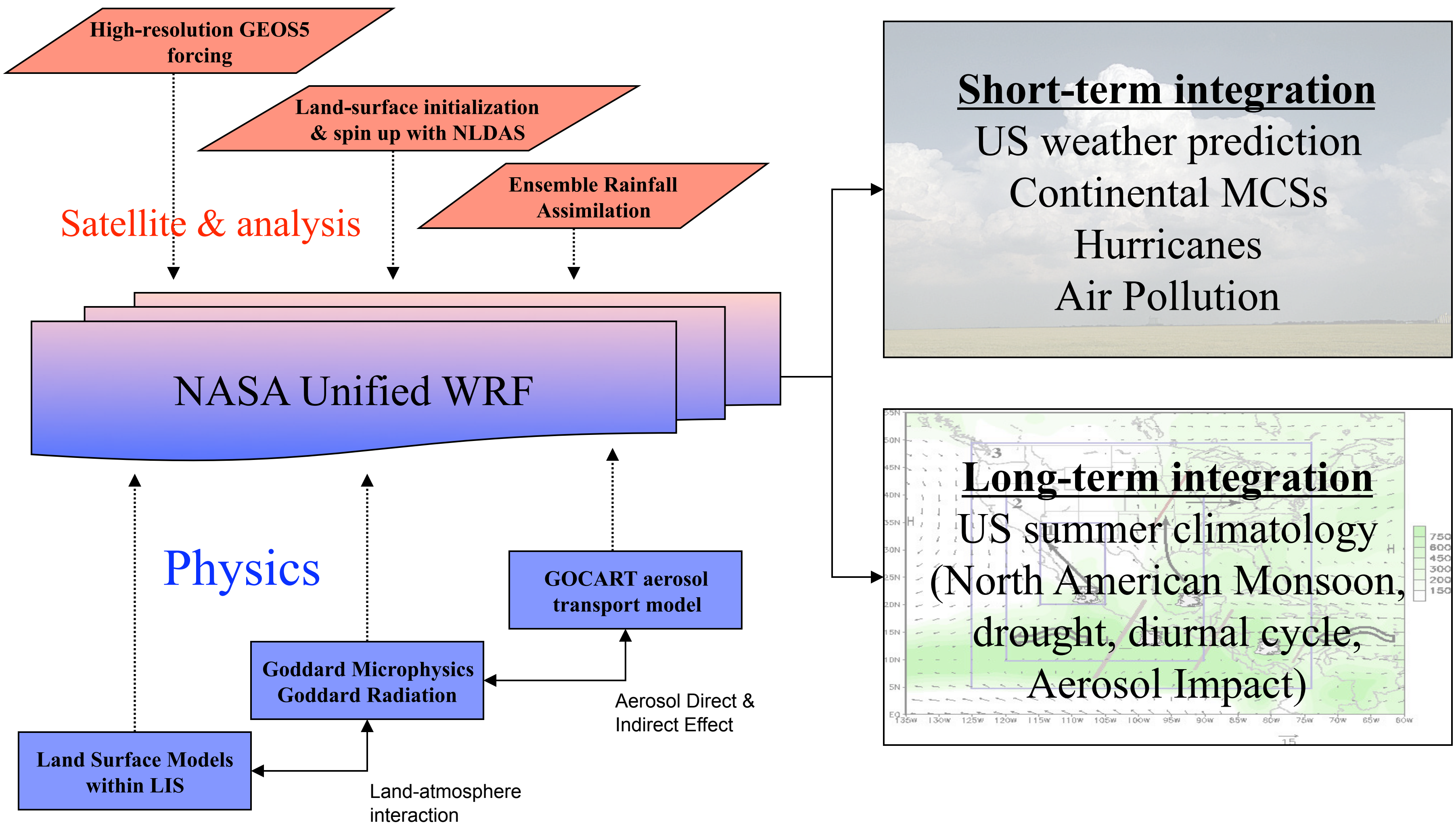


Blue Boxes:
NASA Physical Packages

Integrated Modeling of Aerosol, Cloud, Precipitation and Land Processes at Satellite-Resolved Scales

Co-PIs: Christa Peters-Lidard, Wei-Kuo Tao, and Mian Chin

Co-Is: Scott Braun, Jonathan Case, Arthur Hou, Sujay Kumar, William Lau, Toshihisa Matsui, Tim Miller, Joseph Santanello, Jr., Jainn Shi, David Starr, Qian Tan, Benjamin Zaitchik, Jing Zeng, Sara Zhang



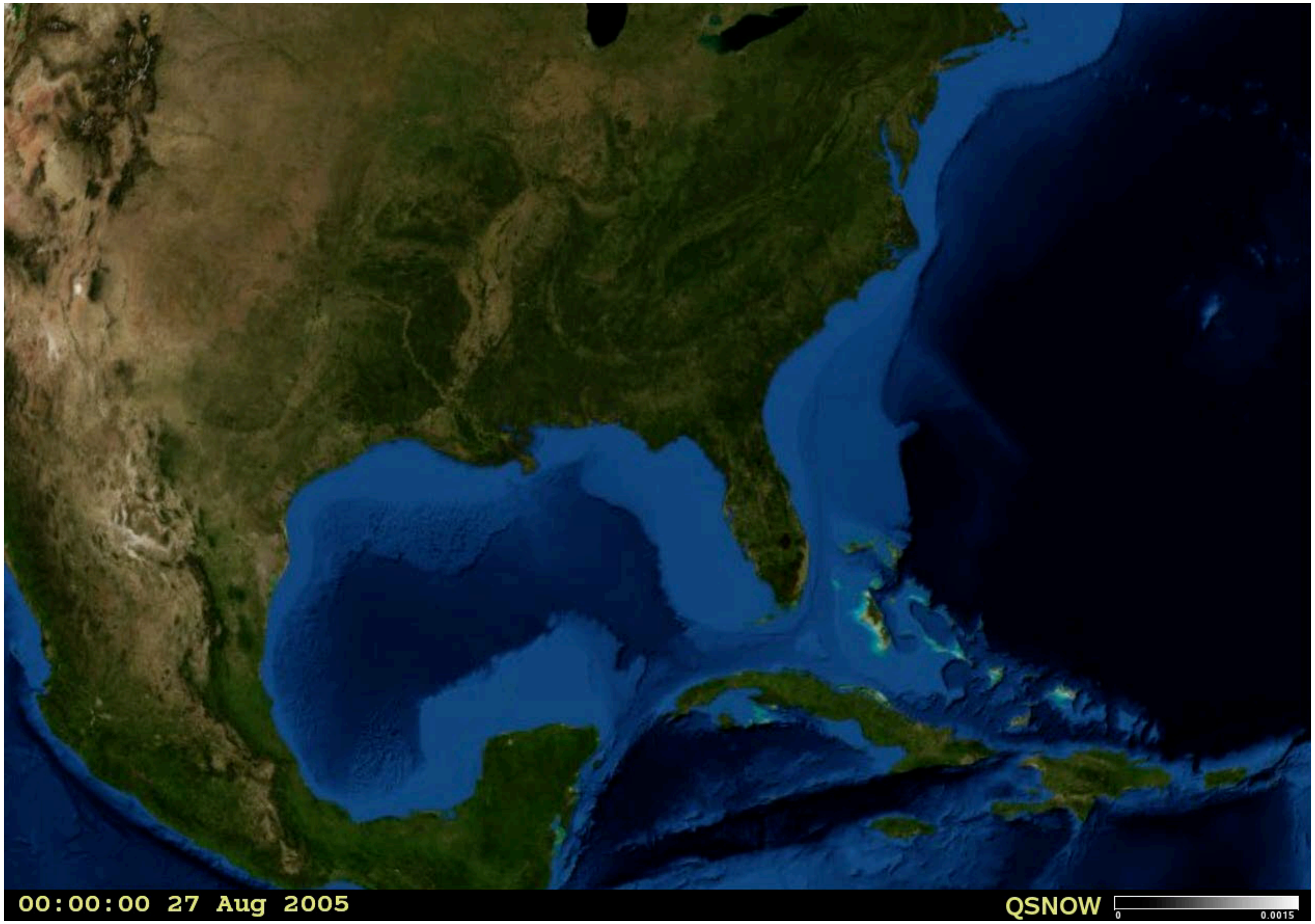
Concurrent Visualization (21 different fields)

WRF simulated snow - 1 min

Shape/size of the eye

Two more Hurricanes

Trajectory/Tracer Analyses

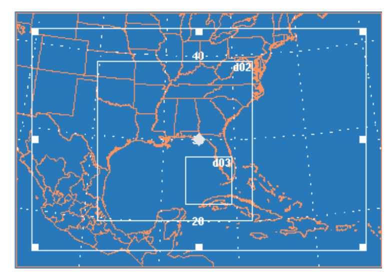


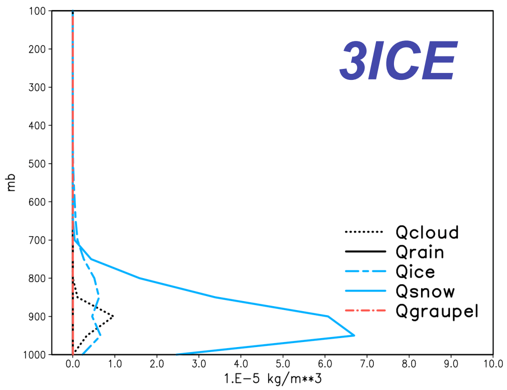
NASA Ames Visualization Group

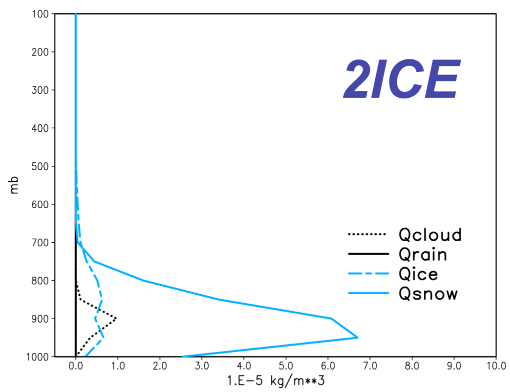
Katrina 2005

Resolutions: 15, 5 and *1.667 km*   Grid size: 300x200, , 418x427, *373x382*
Dt = 60, 20, 6.67 seconds Starting time: 00Z 8/27/2005

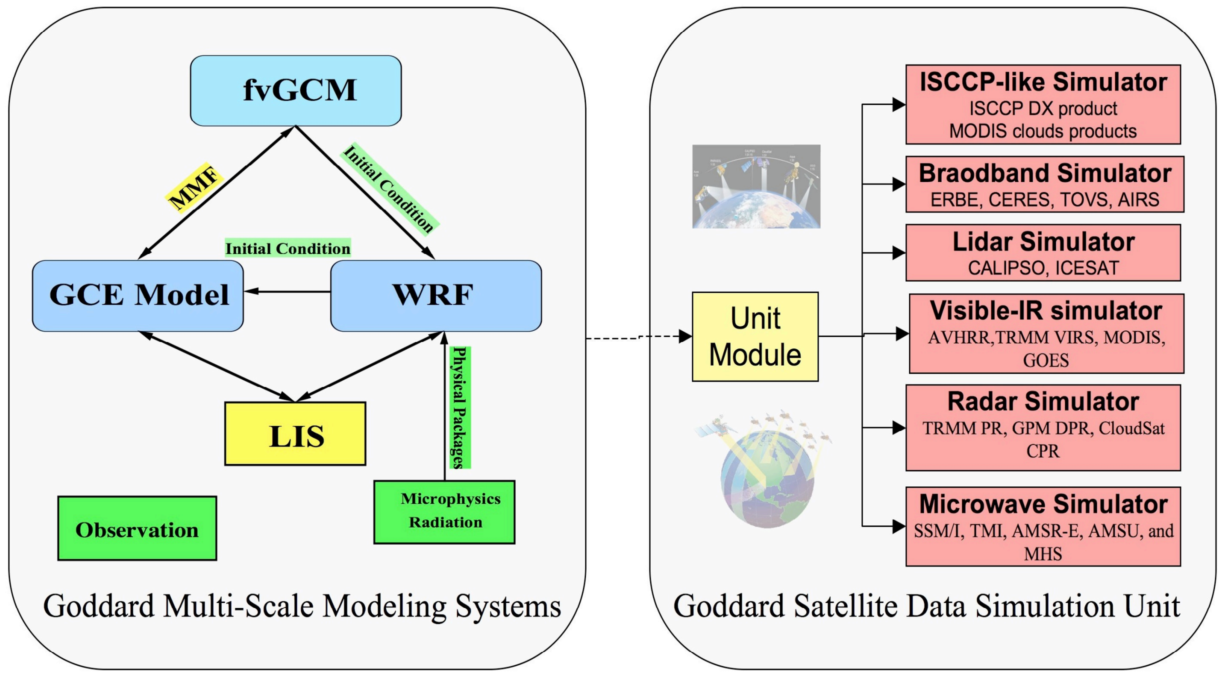
Initial and Boundary Conditions: NCEP/GFS, with bogus but no data assimilation



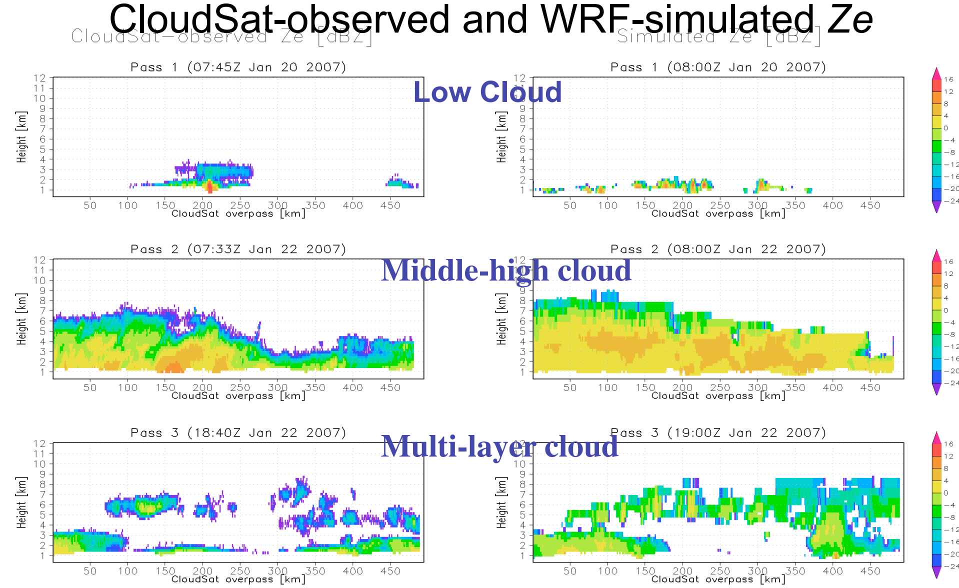




Satellite Simulator



CloudSat-observed and WRF-simulated *Ze*



Similar profiles for cloud water, cloud ice and snow for both experiments.

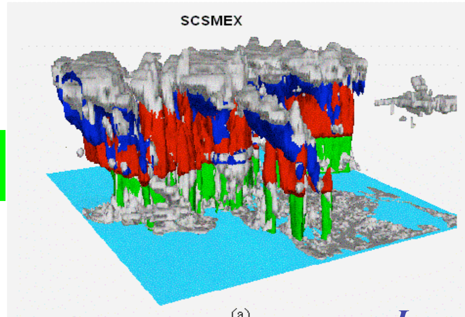
Weak vertical velocities (~50 cm/s) --> 3ICE microphysical scheme responded well to the cloud dynamics and did not produce large precipitating particles (graupel and rain).

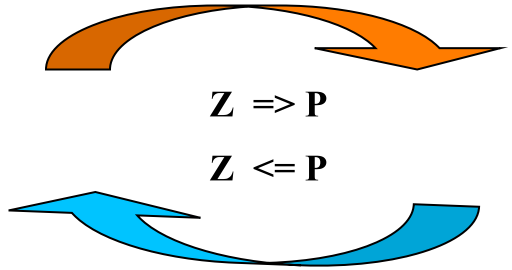
Other schemes simulated graupel at surface, or simulated no ice at all

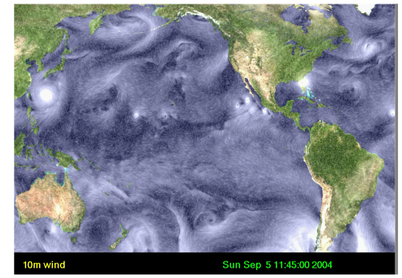
NASA Goddard MMF

Moist physics tendencies (T and q) Cloud and precipitation

GCE







fvGCM

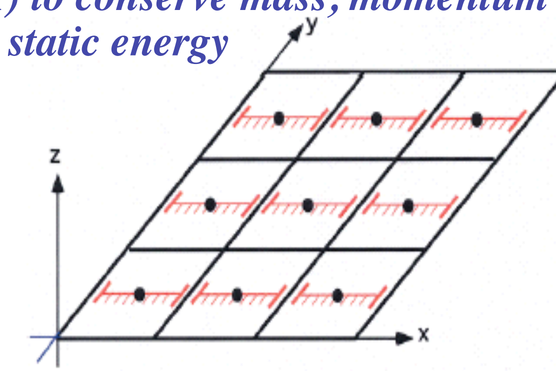
Large-scale forcing, Background profiles (T, q, u, v, w)

NASA MMF
Goddard fvGCM – GCE Model
2 x 2.5 degree (*13,104 CRMs*)
Microphysics (>40 processes)
Positive definite advection scheme
1.5 order TKE
Radiation (every 3 min)
Time step (10 s)
32 vertical layers (32 in fvGCM)
V – Component (no PGF)
Online cloud statistics (every 2 min)
278 hours/per simulated year on a 512 CPU computer

2D GCE has 64 x 32 (x-z) grid points with 4 km horizontal resolution

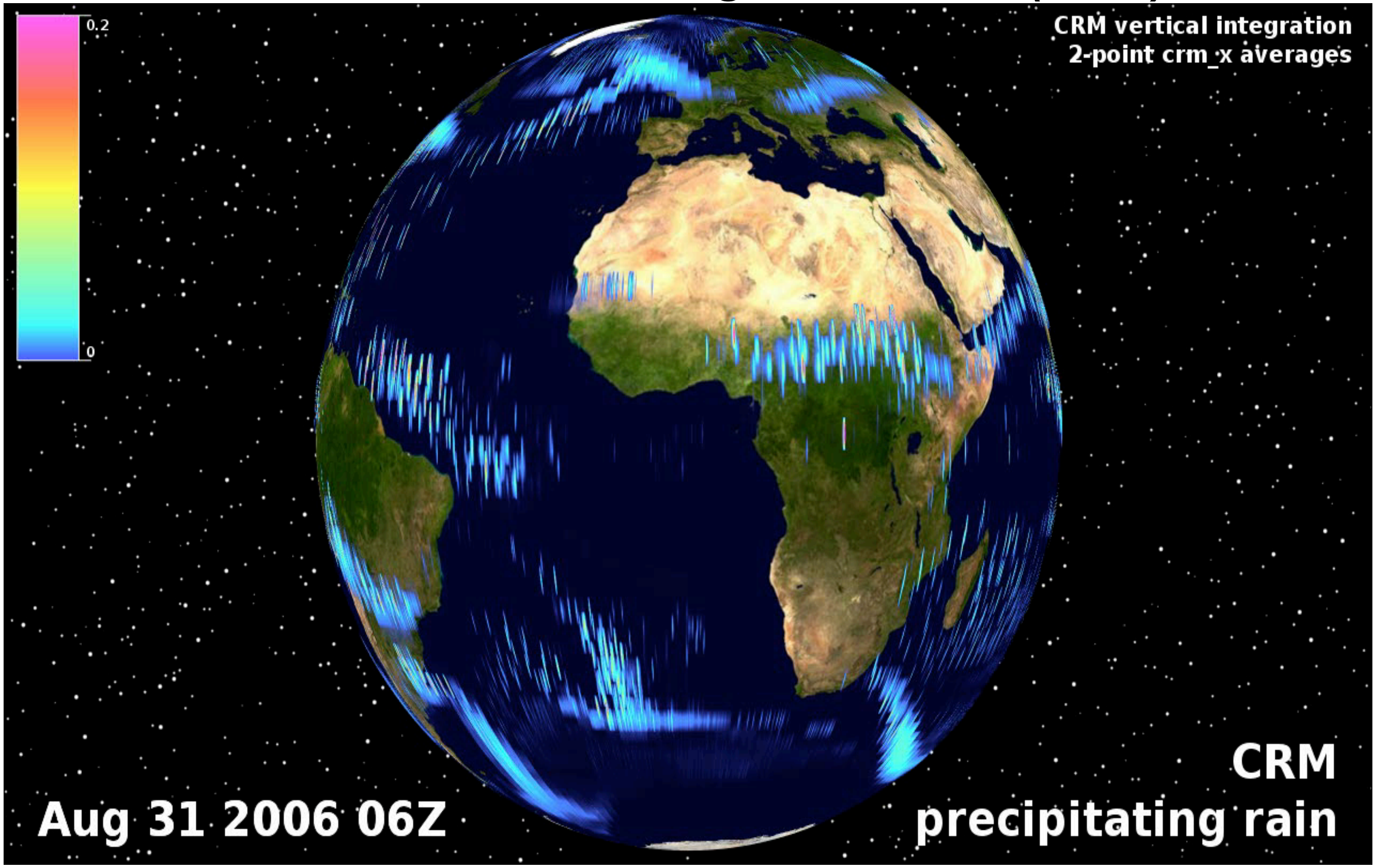
fvGCM and GCE coupling time is one hour

Interpolation between hybrid P (fvGCM) and Z (GCE) coordinate: using finite-volume Piecewise Parabolic Mapping (PPM) to conserve mass, momentum and moist static energy



Tao, W.-K., J. Chern, R. Atlas, D. Randall, X. Lin, M. Khairoutdinov, J._L. Li, D. E. Waliser, A. Hou, C. Peters-Lidard, W. Lau,J. Jiang and J. Simpson, 2009: Multi-scale modeling system: Development, applications and critical issues, *Bull. Amer. Meteor. Soc*. **90**, 515-534.

Goddard Multiscale Modeling Framework (MMF)



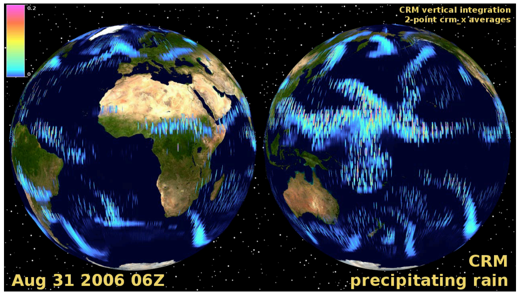
1) Tropical waves move off the coast of Africa and propagate westward. [It is known that tropical cyclogenesis can be initialized (or triggered) by these tropical waves. Therefore, accurate simulations of their interactions with small-scale convection are important for improving the simulations of TC genesis.]

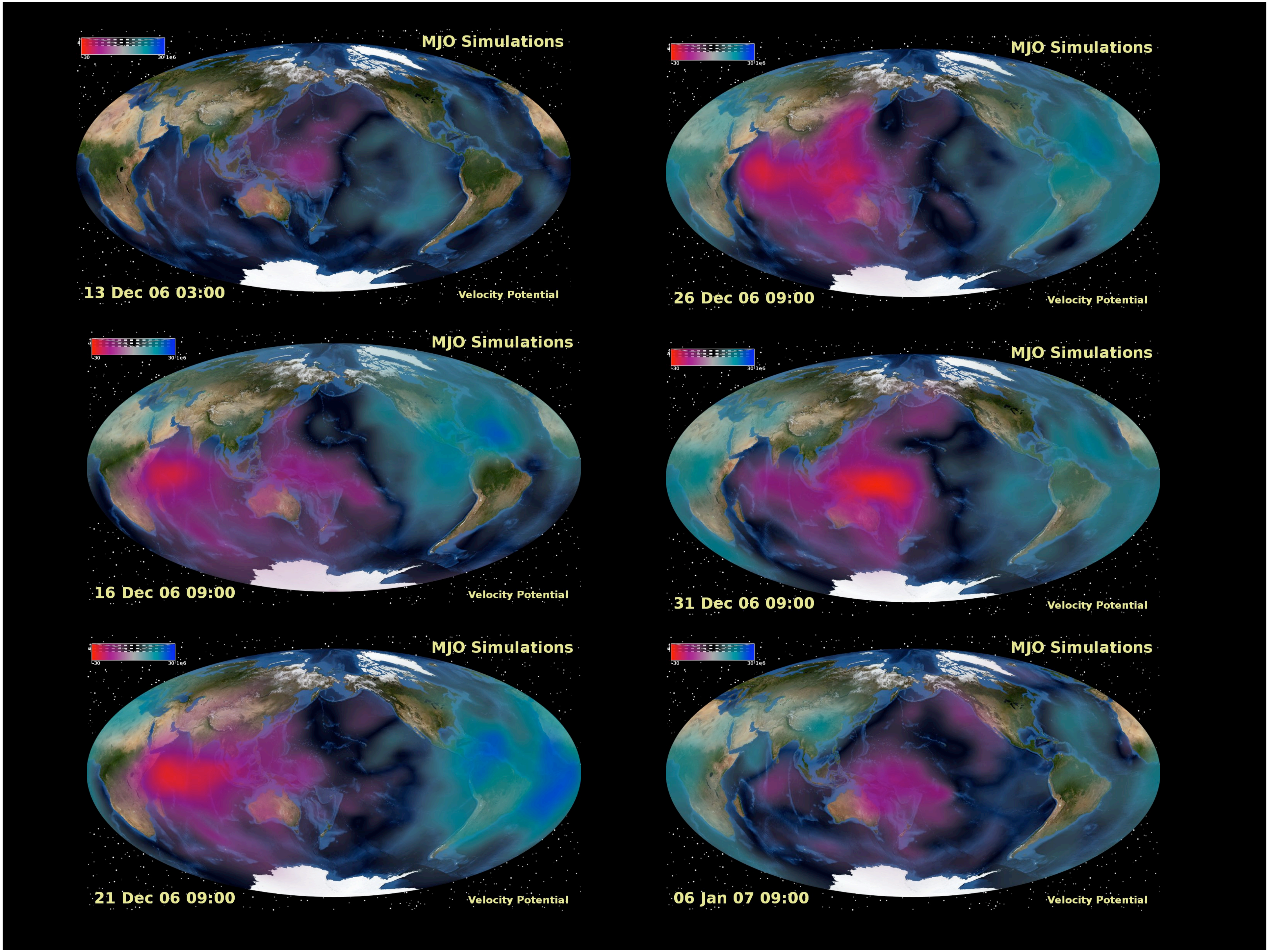
2) The eastward-traveling system in the southern hemisphere (SH) are the so-called the polar vortex, which is most powerful in the hemisphere's winter (JJAS, in the SH).

3) The equatorial Amazon has abundant rain between November and May. During the Brazilian spring season (October/November/December), most of the countries get wetter, except for the Brazilian northeast.

4) In comparison, during this period (winter in the northern hemisphere), mid-latitude periodic frontal systems move eastward across the USA.

5) Near the end of simulations, heavy precipitations appear near the ITCZ

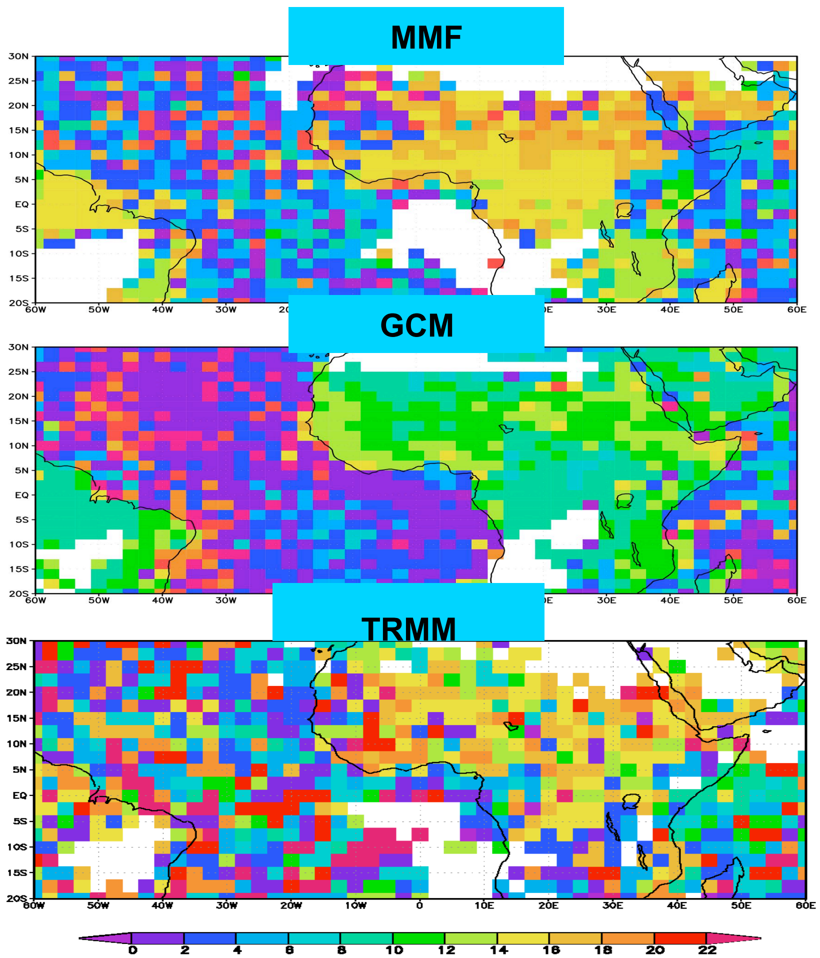



MJO Simulations
13 Dec 06 03:00
Velocity Potential
MJO Simulations
26 Dec 06 09:00
Velocity Potential
MJO Simulations
16 Dec 06 09:00
Velocity Potential
MJO Simulations
31 Dec 06 09:00
Velocity Potential
MJO Simulations
21 Dec 06 09:00
Velocity Potential
MJO Simulations
06 Jan 07 09:00
Velocity Potential

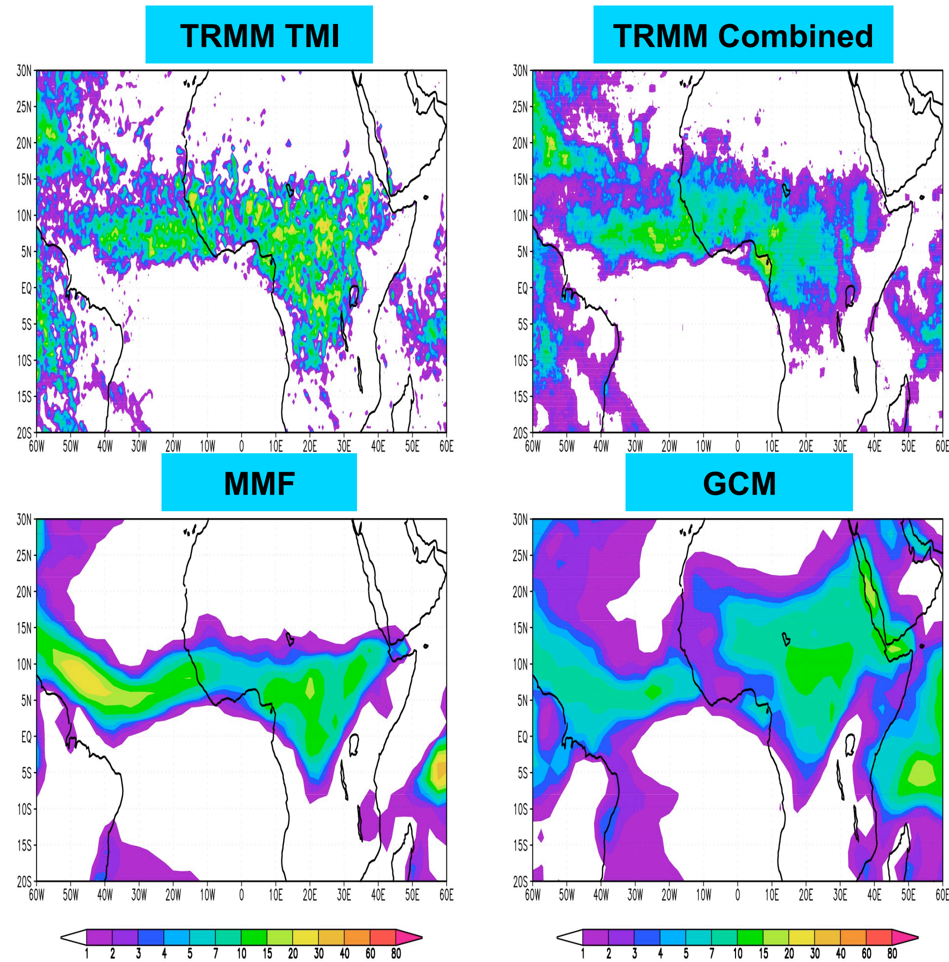
Monthly precipitation and local time of precipitation frequency maximum over West Africa

MMF captured satellite observed surface precipitation and its diurnal variation.

The results imply that the MMF could be used to study local and regional surface water/energy cycle



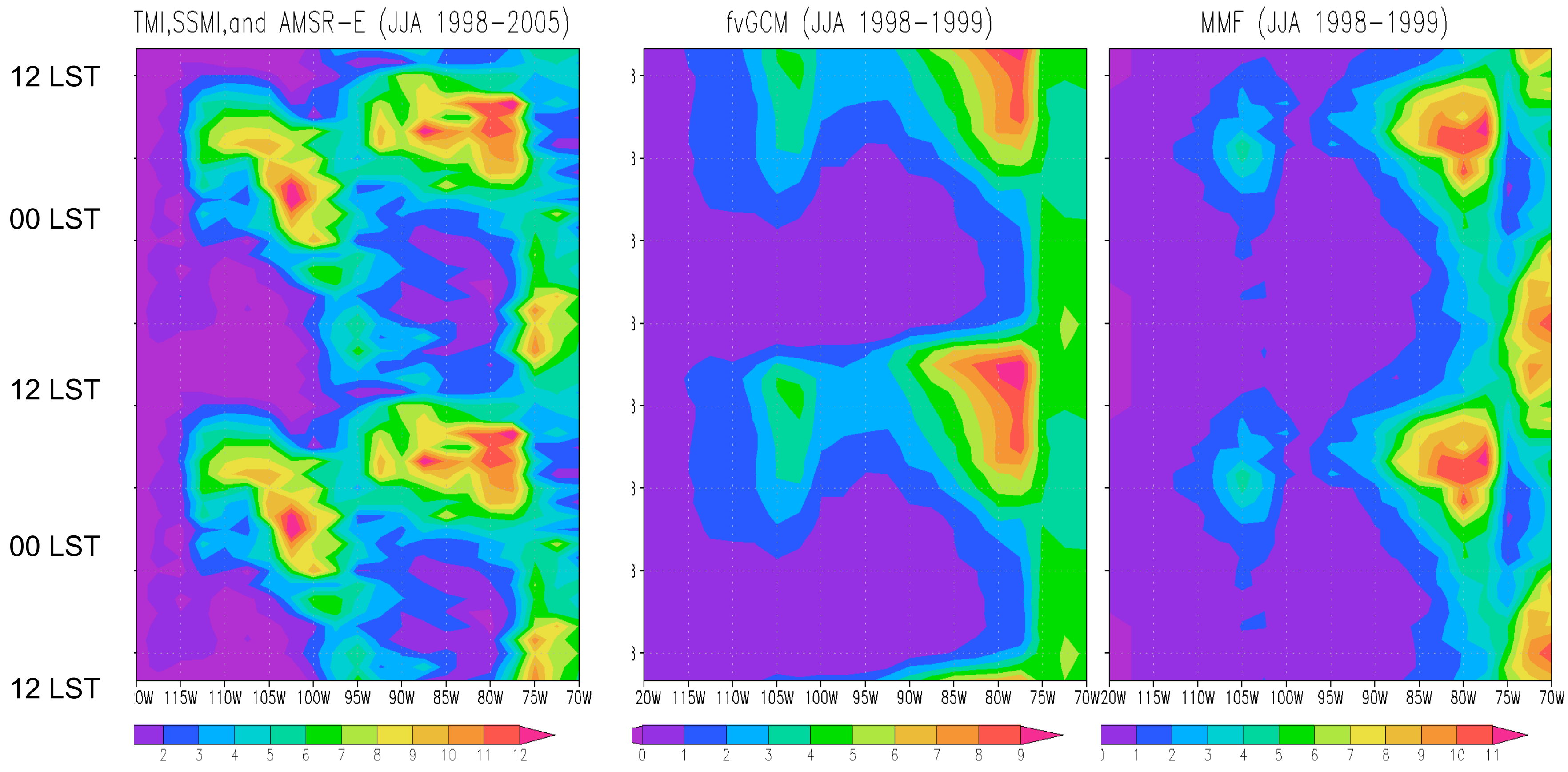
Geographical distribution of the local solar time (LST) of non-drizzle precipitation frequency maximum over West Africa in summer 1999 as simulated with the Goddard MMF (upper panel) and the GCM (middle panel) and as observed by the TRMM TMI (bottom panel). Blank regions indicate no precipitation.



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 GCM (lower-right panel).

Diurnal Cycle of Summer Precipitation over USA along 35N

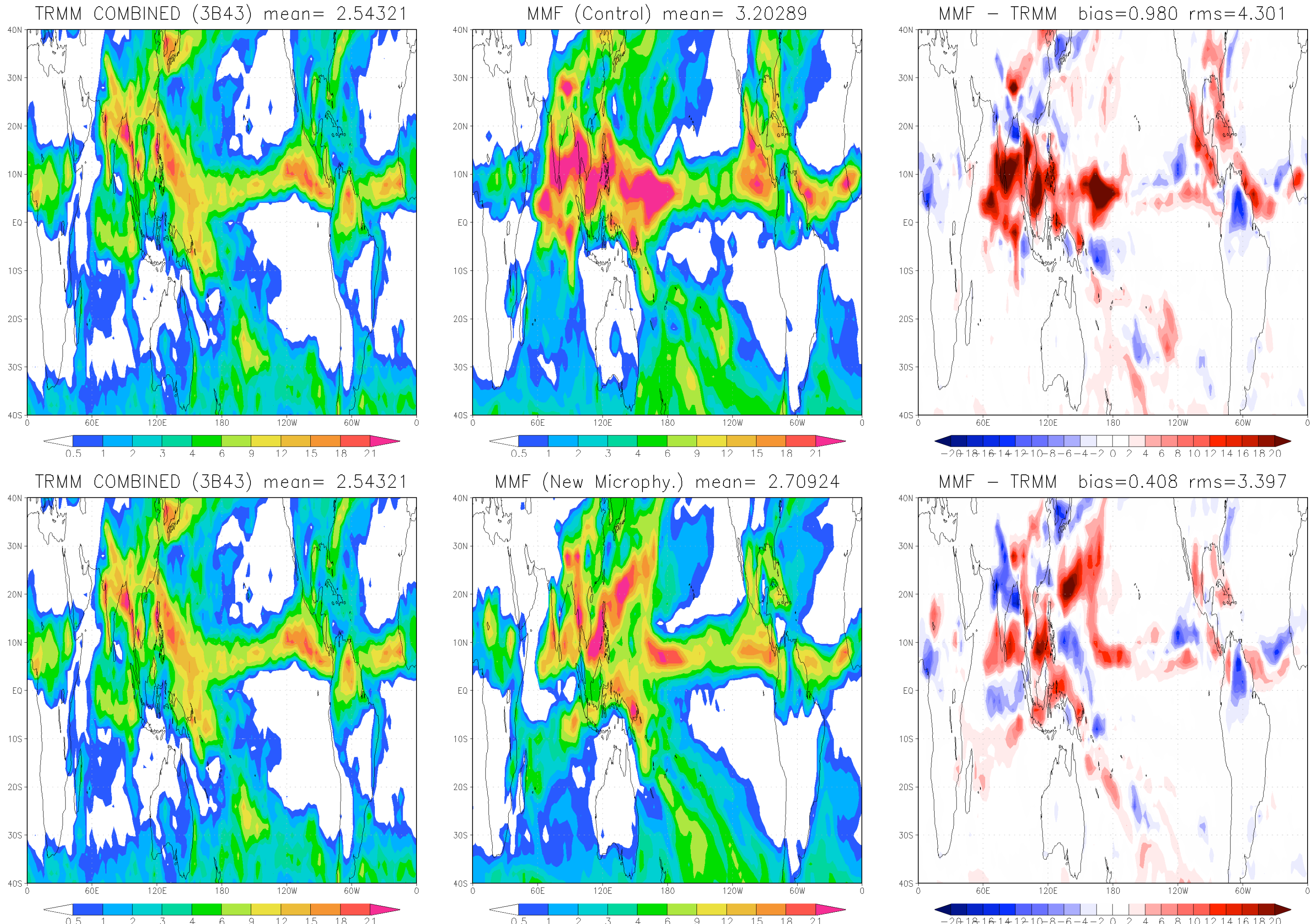
Merge MV (1998-2005) | GCM (1998-1999) | MMF (1998-1999)



Impact of GCE new microphysics on MMF simulated rainfall

Original

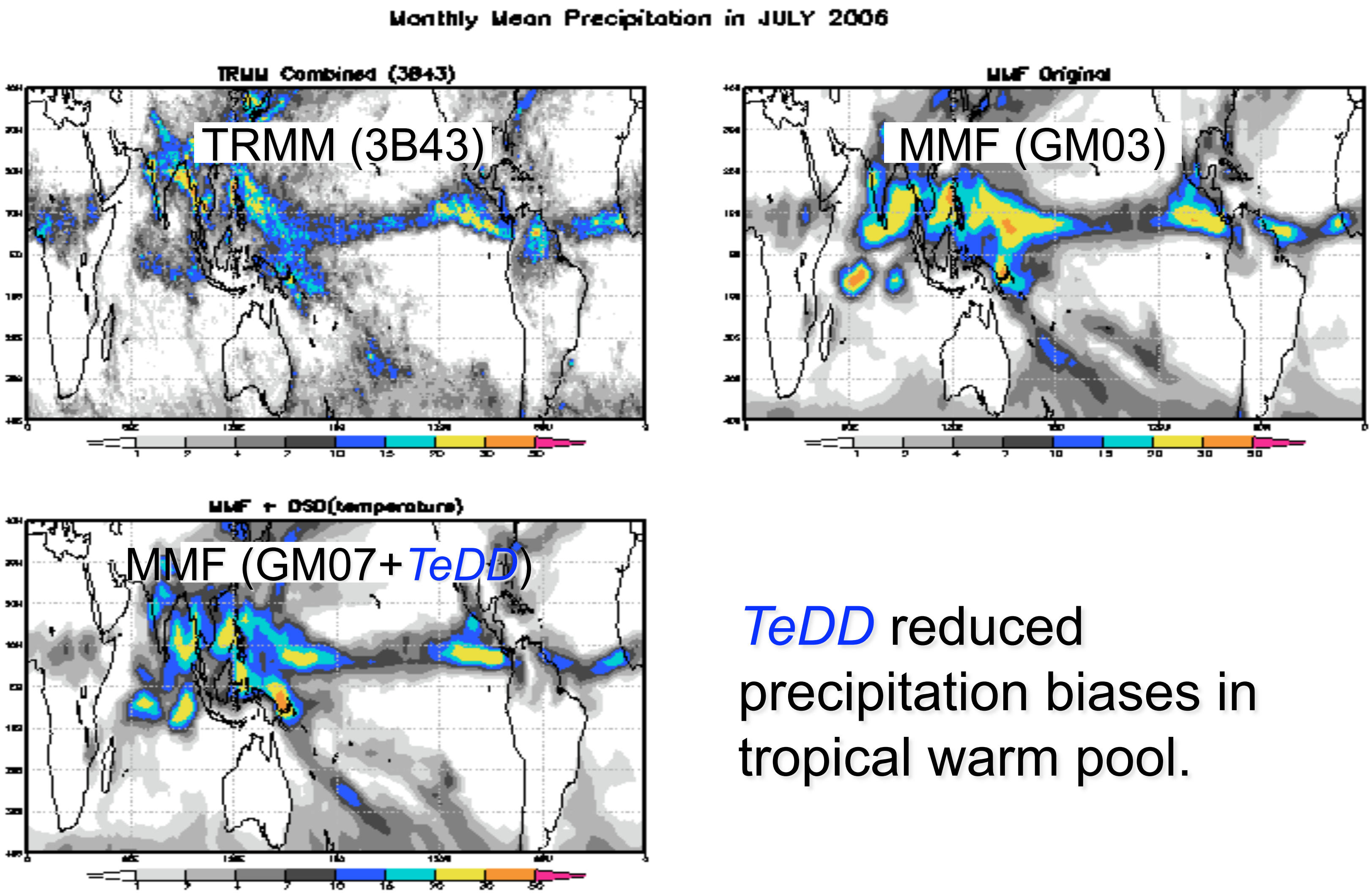
TRMM Rainfall



TRMM Rainfall

Improved (Lang et al. 2007)

Surface Precipitation



TeDD reduced precipitation biases in tropical warm pool.

Current - Future Model Improvements (with GMAO, CSU and others)

To utilize the satellite simulator to identify the strengths and weaknesses of model-simulated microphysical processes

- Model Improvements
  Complete the MMF and LIS coupling
  Test the improved microphysics in CRM that is embedded within MMF (WRF)
  Investigate the impact of terrain effect on MMF's performance
  Couple with 3D GCE MPI, GEOS5, an ocean / mixed model, and an Non-hydrostatic GCM

- Scientific Applications
  Conduct 10-year MMF integrations and examine the physical processes associated with diurnal variation of cloud/precipitation over land
  Examine the explicit cloud-aerosol-radiation interactions (GOCART)
  Investigate the flood/draught and hurricane events in USA
  Investigate the impact of surface processes on weather/climate events in local, regional scale

- MMF (1998, 1999, May 2005 to September 2007), WRF and GCE cloud data is current available through Goddard web site:

http://portal.nccs.nasa.gov/cloudlibrary/index2.html