# Fast Processes in Large Scale Models: Their Parameterization and Evaluation


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**EMC/NCEP**

# Appetizer

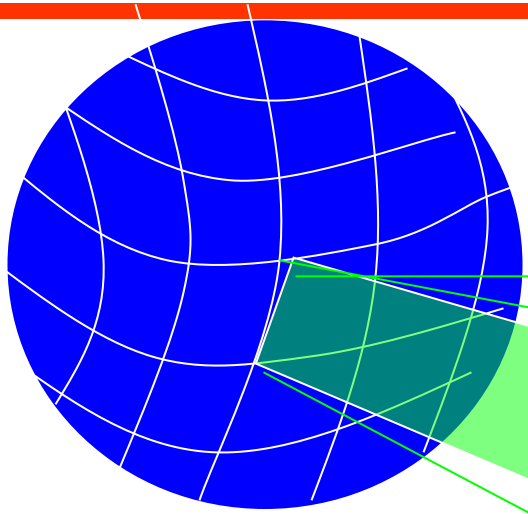
**What is Life?**
with *Mind and Matter*
and *Autobiographical Sketches*

ERWIN SCHRÖDINGER

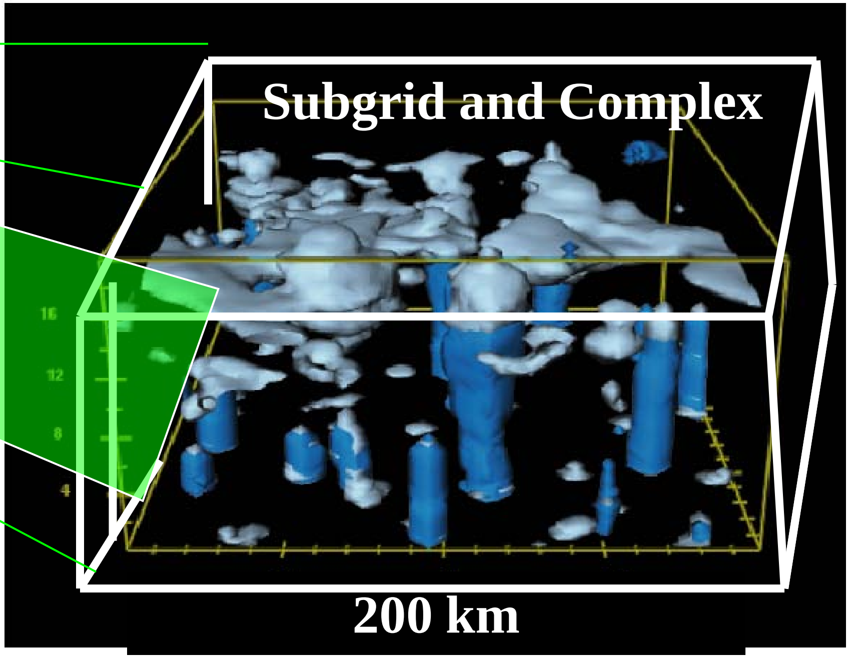
**"I can see no other escape from this dilemma than that some of us should venture to embark on a synthesis of facts and theories, albeit with second-hand and incomplete knowledge of some of them – *at the risk of making fools of ourselves*."**

**I venture to take the risk of making fools of myself …**

# Climate Model, Fast Physics and Parameterization



$$\frac{dX}{dt} = \underset{\text{(Resolved)}}{\text{Dynamics}} + \underset{\text{(Unresolved)}}{\text{Fast Physics}}$$




**Nonlinear PDE System:**

$$\overline{x_1 x_2} = \overline{x_1}\,\overline{x_2} + \overline{x_1' x_2'}$$

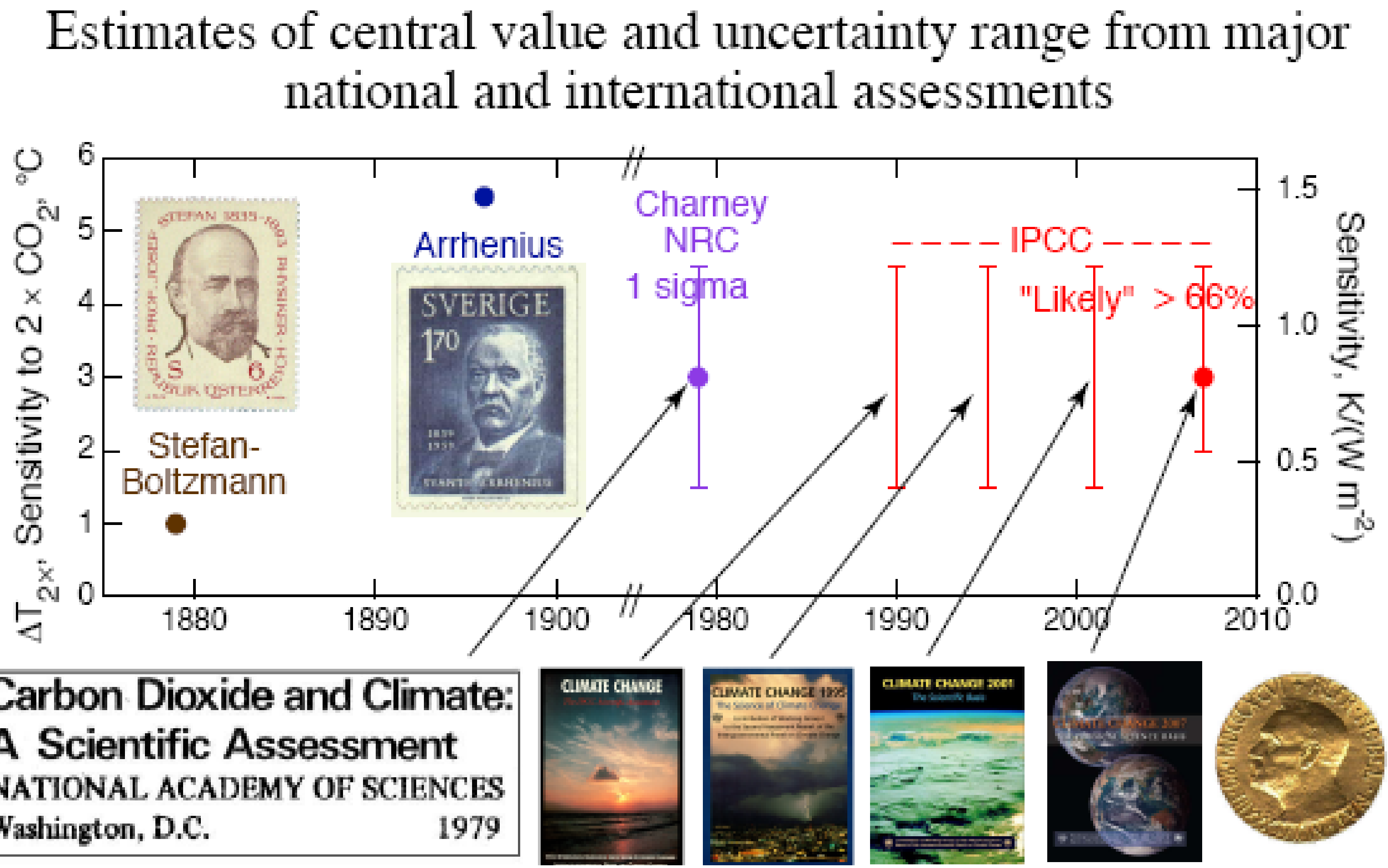
$$\text{Dynamics} \equiv \overline{x_1}\,\overline{x_2}$$

$$\text{F Physics} \equiv \overline{x_1' x_2'}$$

$$\text{Parameterization} \equiv \overline{x_1' x_2'} \approx f\left(\overline{x_1}, \overline{x_2}\right)$$

**Parameterization is responsible for model uncertainty and significant resource consumption.**

# Virtually Unchanged Large Uncertainty of Model Climate Sensitivity through Ages




**The wide spread of model climate sensitivity has been attributed to parameterization of cloud-related fast processes.**

# The pace of progress has been frustratingly slow.

*"...The modeling of clouds is one of the weakest links in the general circulation modeling efforts."*

*--Charney et al., National Academy Report, 1979*


Deficiencies in the representation of cloud processes in climate models drive much of the uncertainty surrounding predictions of climate change.

This was true 30 years ago, it's true now, and at the rate we are going it will still be true 30 years from now. (D. Randall, 2008)

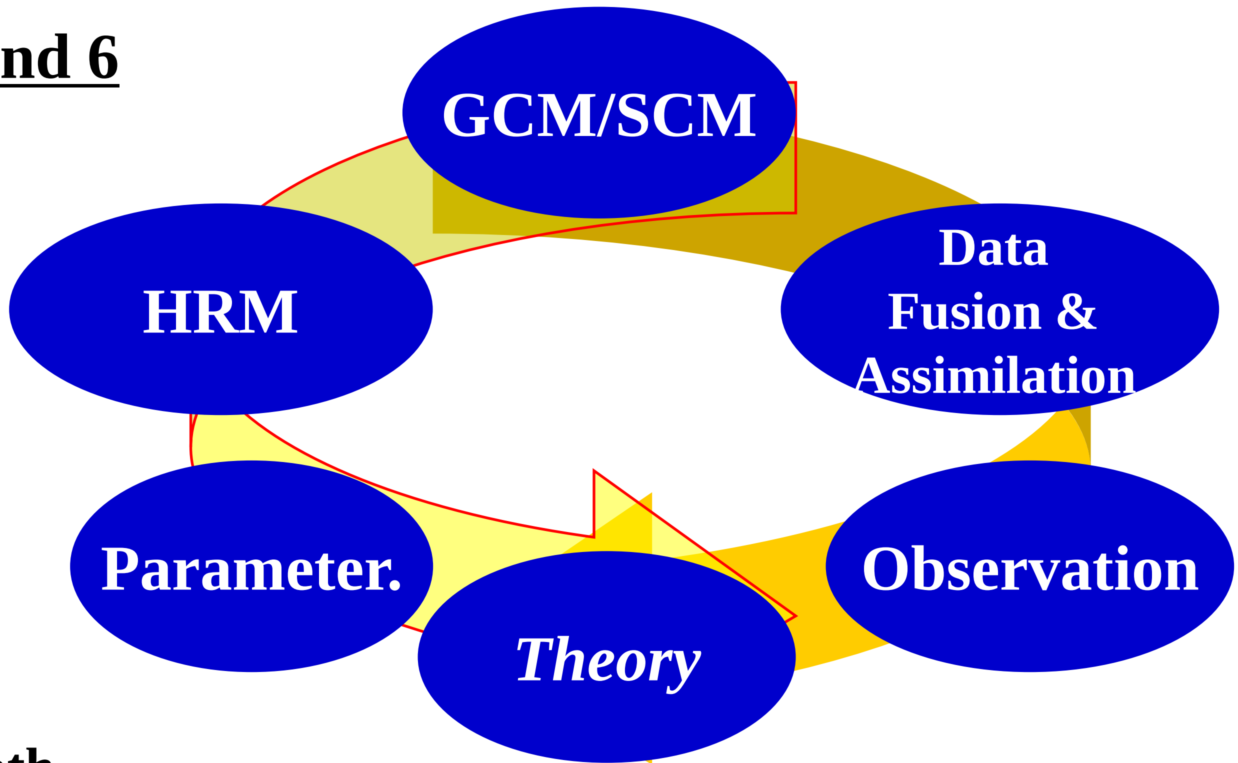
**Why is progress so slow ?**
**How can we accelerate it ?**

# 4M-1E Complexity and Components Involved

**"4M-1E" Complexity and 6 Components:**

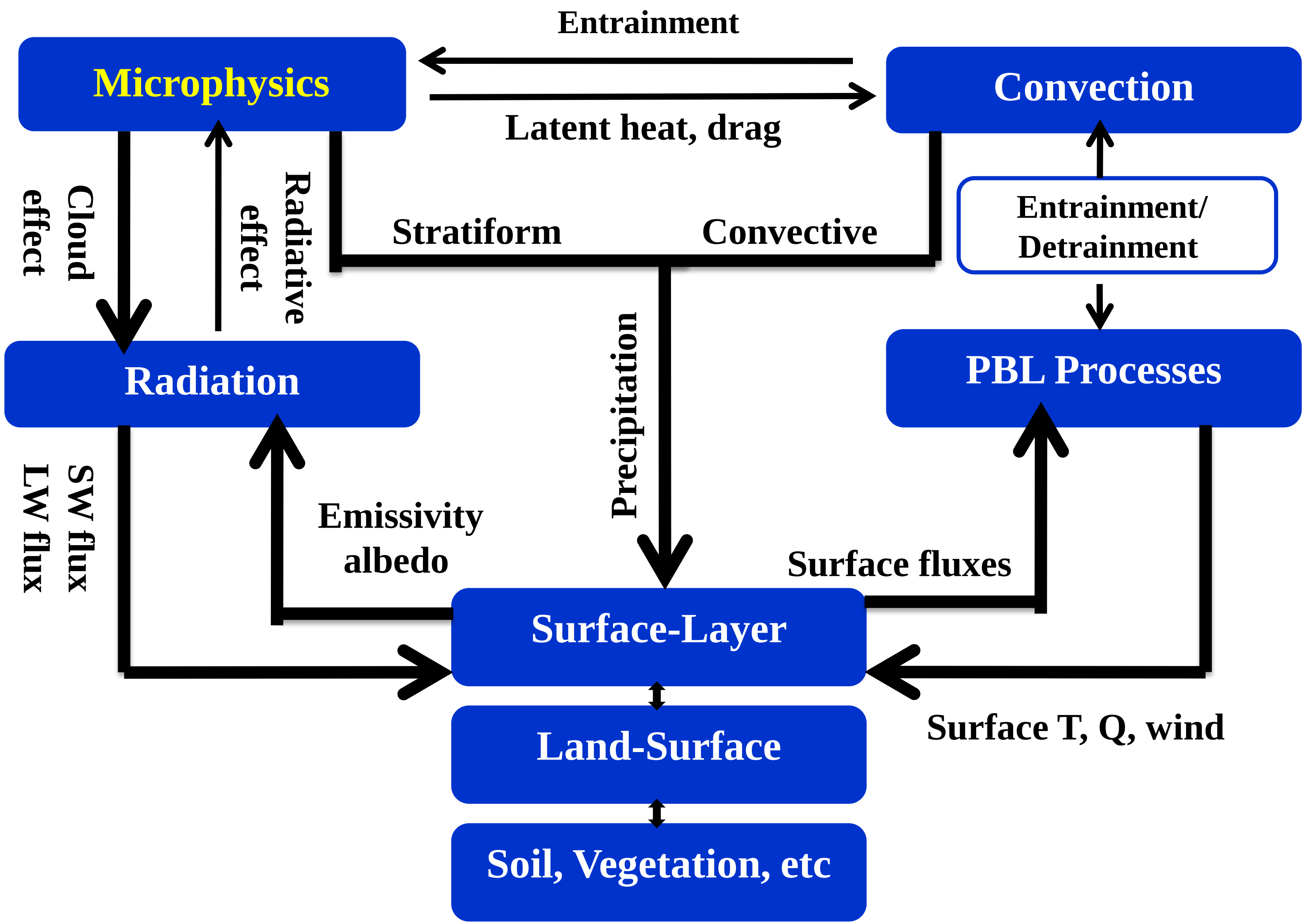
- **4M scientific**
  - -- Multibody
  - -- Multiscale
  - -- Multitype
  - -- Multi-dimension

- **1E engineering**
  - -- coordination among both investigators and components

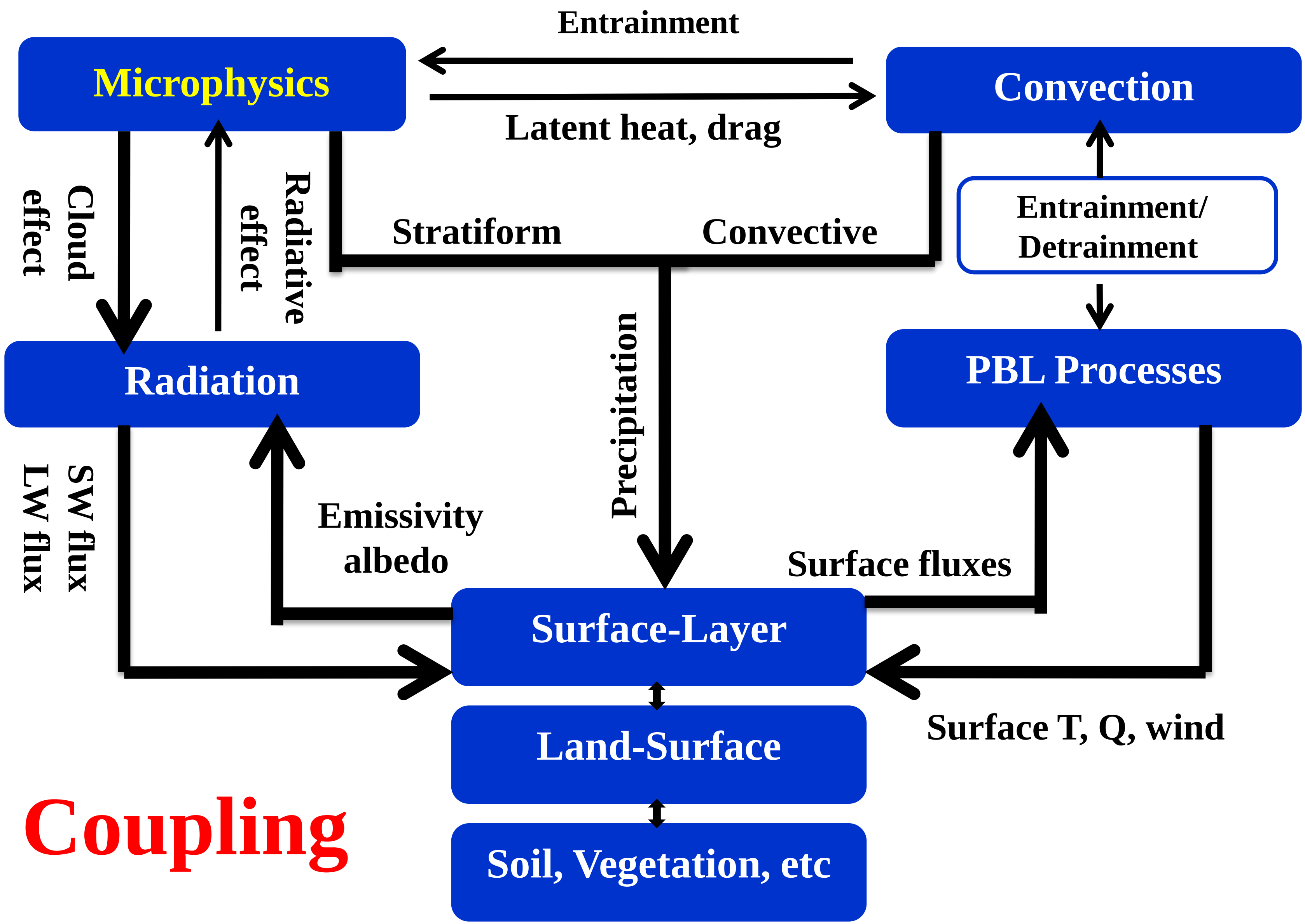



**Aerosol** **Droplet** **Turbulent Eddies** **Convection** **Clusters** **Global**

# Major Parameterized Fast Processes in Climate Models

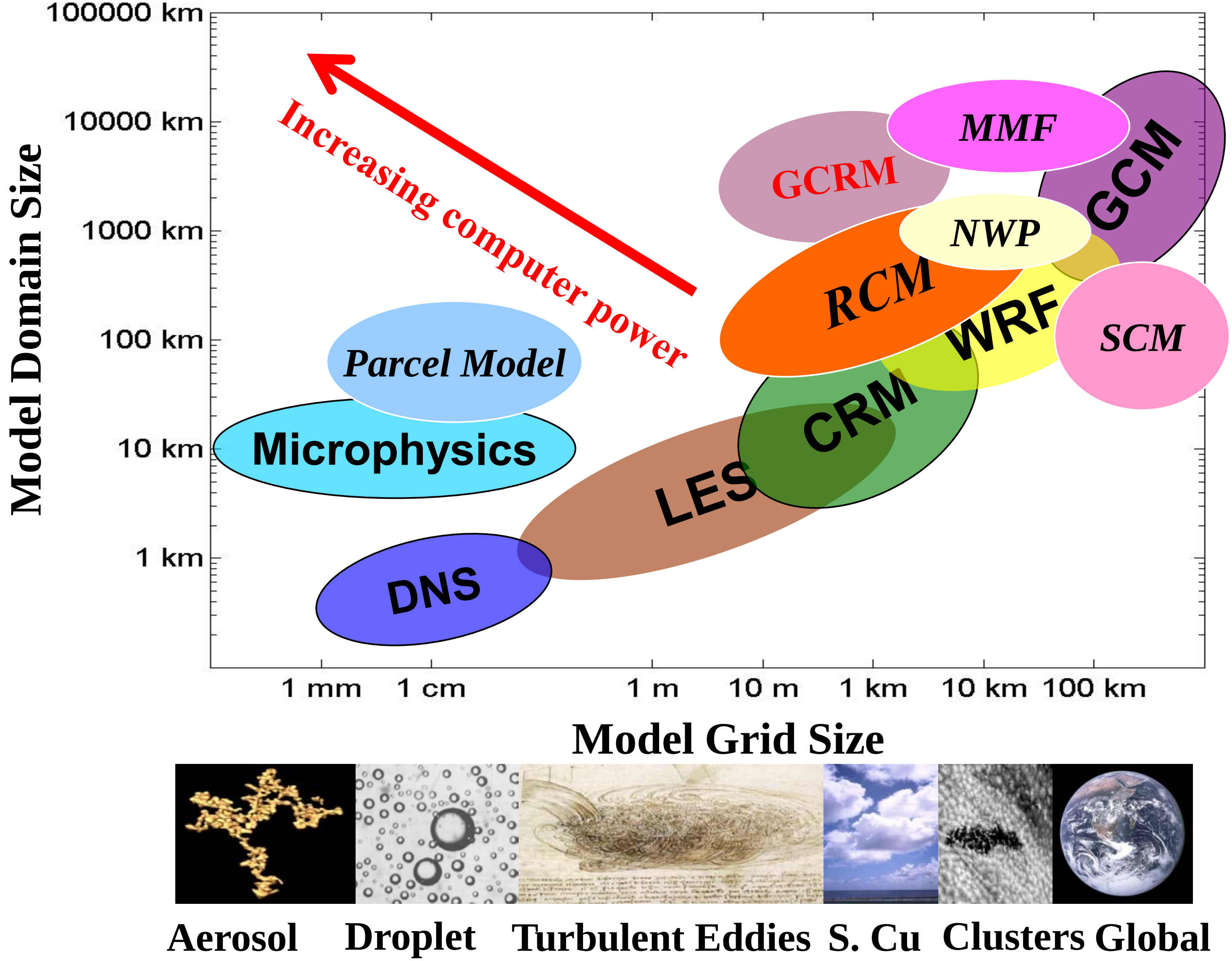


# Major Parameterized Fast Processes in Climate Models




Coupling

# Model/Data Multiscale Hierarchy




*DNS = Direct Numerical Simulation*

*LES = Large Eddy Simulation*

*CRM = Cloud-Resolving Model*

*WRF = Weather Research and Forecast Model*

*GCM = Global Climate Model*

*RCM = Regional Climate Model*

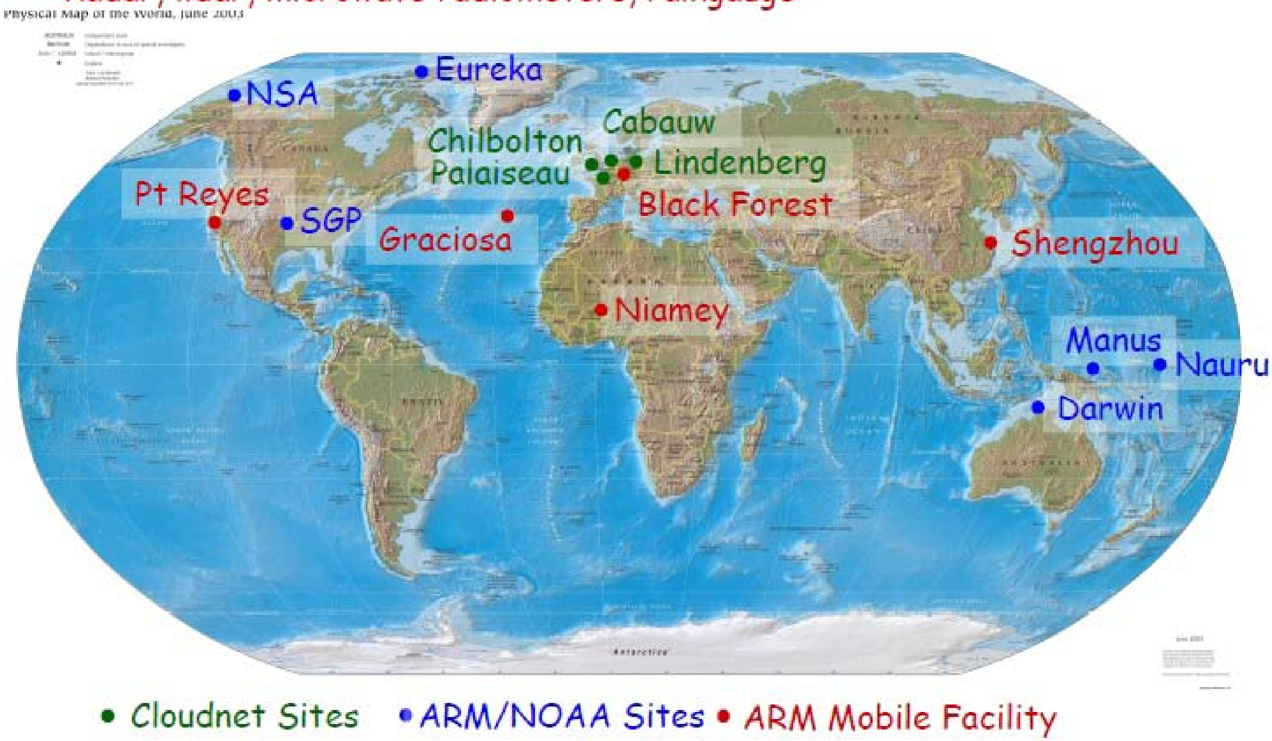
*GCRM = Global CRM*

*NWP = Numerical Weather Forecasting*

*SCM = Single Column Model*

# Lack of adequate observations is another reason for the slow progress.

- Core instrumentation at each site
  - Radar, lidar, microwave radiometers, raingauge




**Surface-Based Cloud-Profiling Measurements Complementary to Satellites and In-Situ**

# Critical Experiment and Evaluation

• **Critical experiments test competitive theories/models and help determine the correct one.**

• **Complexity and nature of GCM fast physics calls for critical evaluation.**

• **Critical evaluation calls for FASTER project to *focus and constantly* deal with multiscale modeling, observations, and process hierarchies, with 6M strategy.**

**6M Strategy: multi-objectives, m-tasks, m-approaches, m-tools, m-disciplines, and m-institutions**

**Aerosol Droplet Turbulent Eddies Convection Clusters Global**

# What is FASTER?

- Represent ***FAst-physics System TEstbed and Research***

  — **Treat fast physics as a system**
  — **Combine testbed and research**
  — **Evolve with GCMs**
  — **Aim at faster "realtime" evaluation of fast physics**

- **FASTER is a DOE effort to *bridge ESM and ASR* sciences by utilizing *ARM* measurements to accelerate/improve evaluation and parameterization of cloud-related fast processes in climate models.**


**Related DOE Programs**

# FASTER Project Pyramid

**Better climate model** — Ultimate goal

**Evaluation and parameterization** — 1 project goal

**Testbed and Research** — 2 components

**Testbed, HRM Suite, Model Evaluation, Metric, Theory/Para, GCM assessment** — 6 objectives

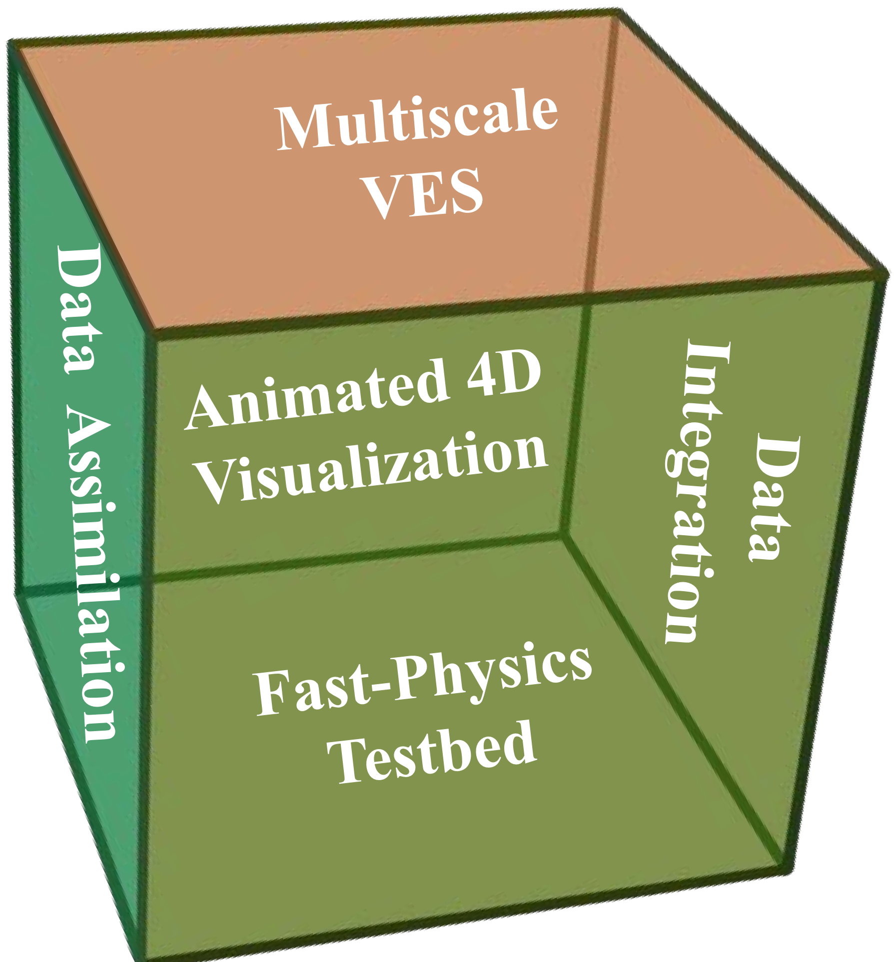
**Testbed, HRM Suite, Model Evaluation, Evaluation Metric, Theory/Parameterization, GCM assessment, Data Assimilation, Data Integration** — 8 tasks

12 institutions

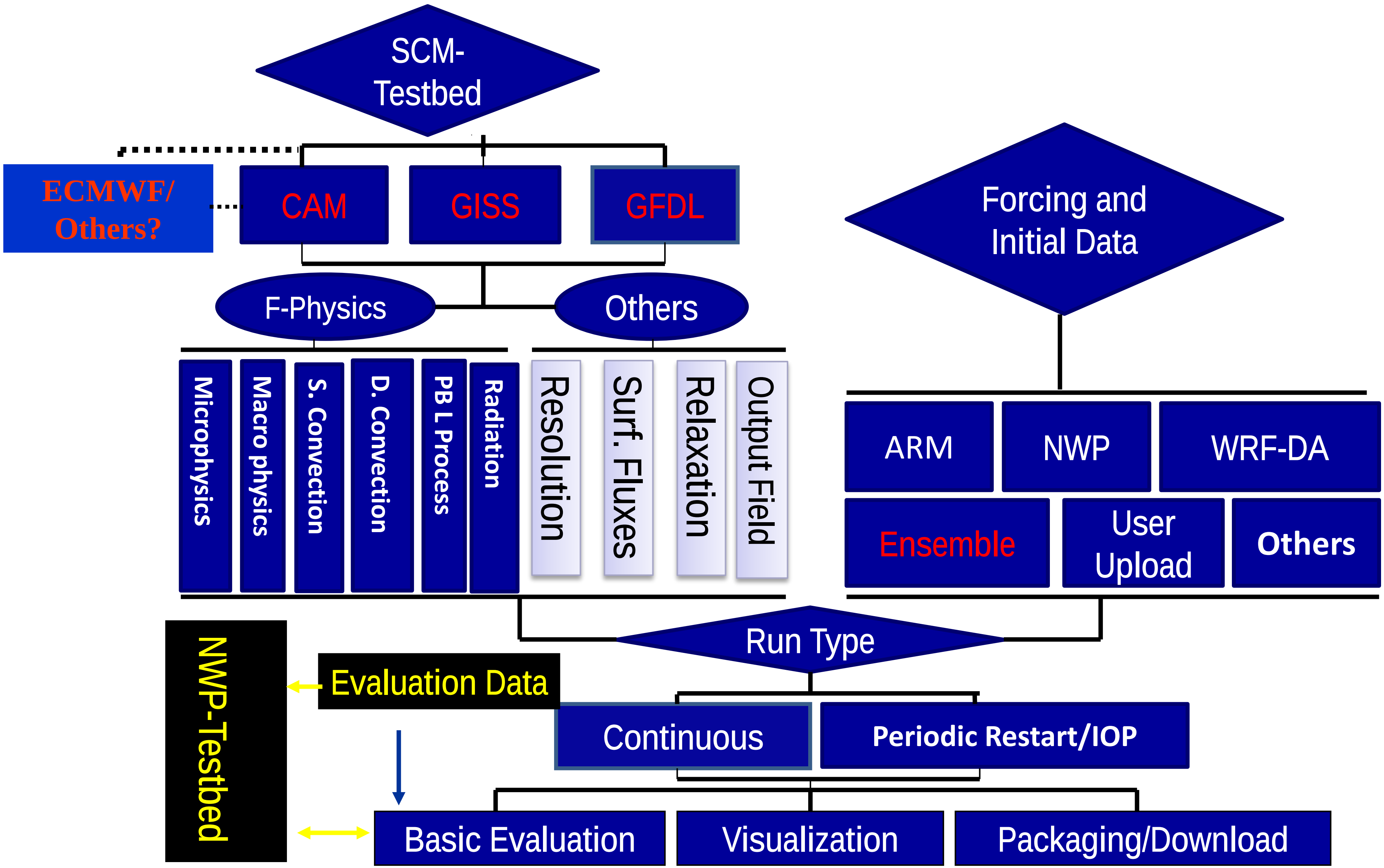
24+ investigators

*Continuous Evaluation of Fast Processes in Climate Models Using ARM Measurements*

# Facility/Model Development



# Web-Based Fast-Physics Testbed



# Web-Based FASTER Testbed

FASTER Gateway: http://www.bnl.gov/esm

Select a model    Documentation | Code Browser | Specifics

New parameterizations

○ CAM5/BAM ◉ CAM5/MAM3 ○ CESM/CAM4 ○ CAM4 ○ CAM3.1 ○ GFDL ○ GISS ☑ CAM Dev

+ Select physics schemes    User modules for CAM Dev: C:\BNL\newPhys.F9( [Browse...] [Upload&Build]

+ More model options

Regime-based

New analysis products

− Select forcing data

◉ IOP ○ Continuous Forcing ○ Ensemble Forcing ○ Regime ○ User data

| Select an IOP | Select the starting time | Select the ending time |
| --- | --- | --- |
| ARM SGP Mar. 1999 | 2000-03-01 18:00:00 | 2000-03-01 18:00:00 |
| ARM SGP Jul. 1999 | 2000-03-01 18:20:00 | 2000-03-01 18:20:00 |
| ARM SGP Mar. 2000 | 2000-03-01 18:40:00 | 2000-03-01 18:40:00 |
| ARM SGP Sep. 2000 | 2000-03-01 19:00:00 | 2000-03-01 19:00:00 |
| ARM SGP Nov. 2000 | 2000-03-01 19:20:00 | 2000-03-01 19:20:00 |
| ARM SGP Nov. 2002 | 2000-03-01 19:40:00 | 2000-03-01 19:40:00 |

**-- NWP-Testbed**

**-- DA-SCM**

**-- WRF**

**-- NCEP models ?**

+ Forcing options

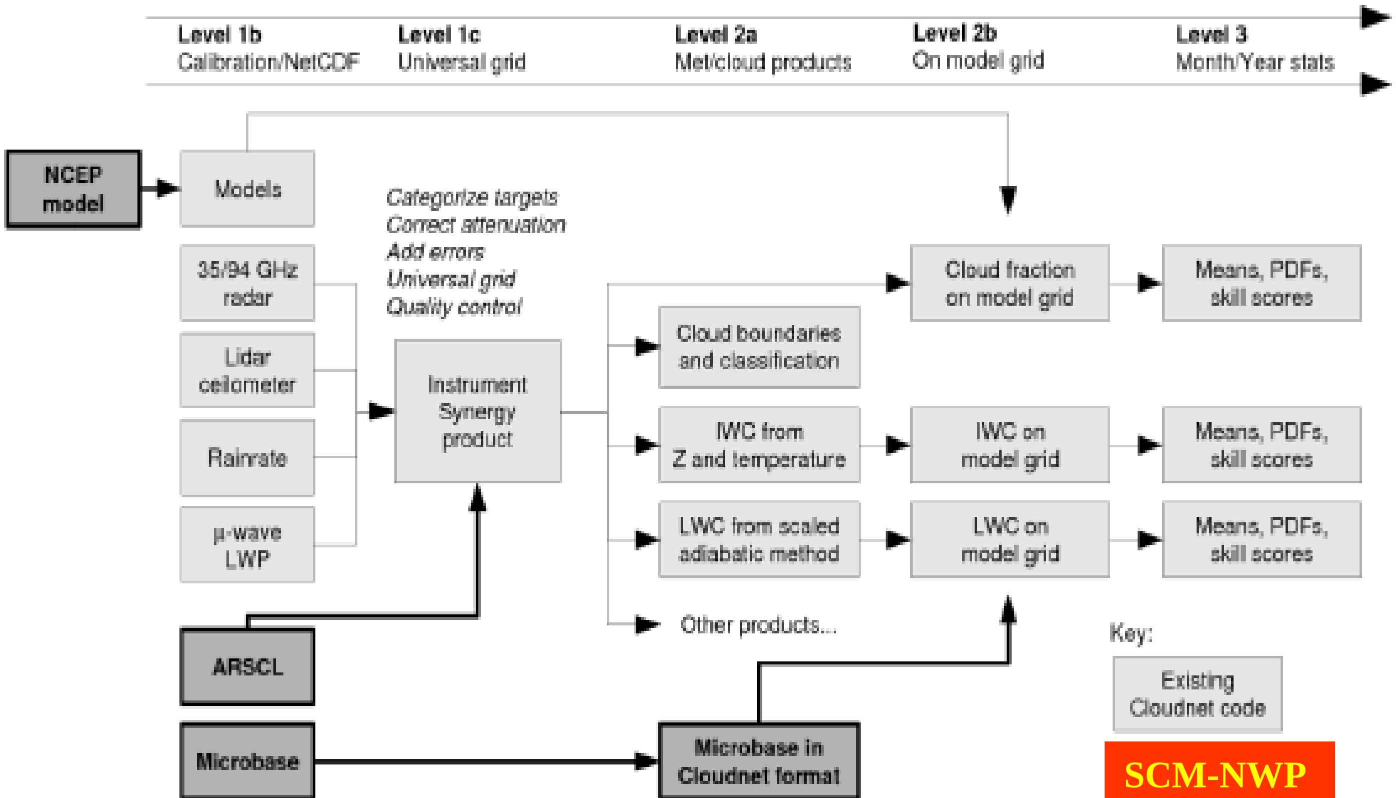
+ Simulation options

+ Summary of SCM experiment settings

Interactive simulation and evaluation/visualization

[Start SCM Experiment]

# NWP-Testbed

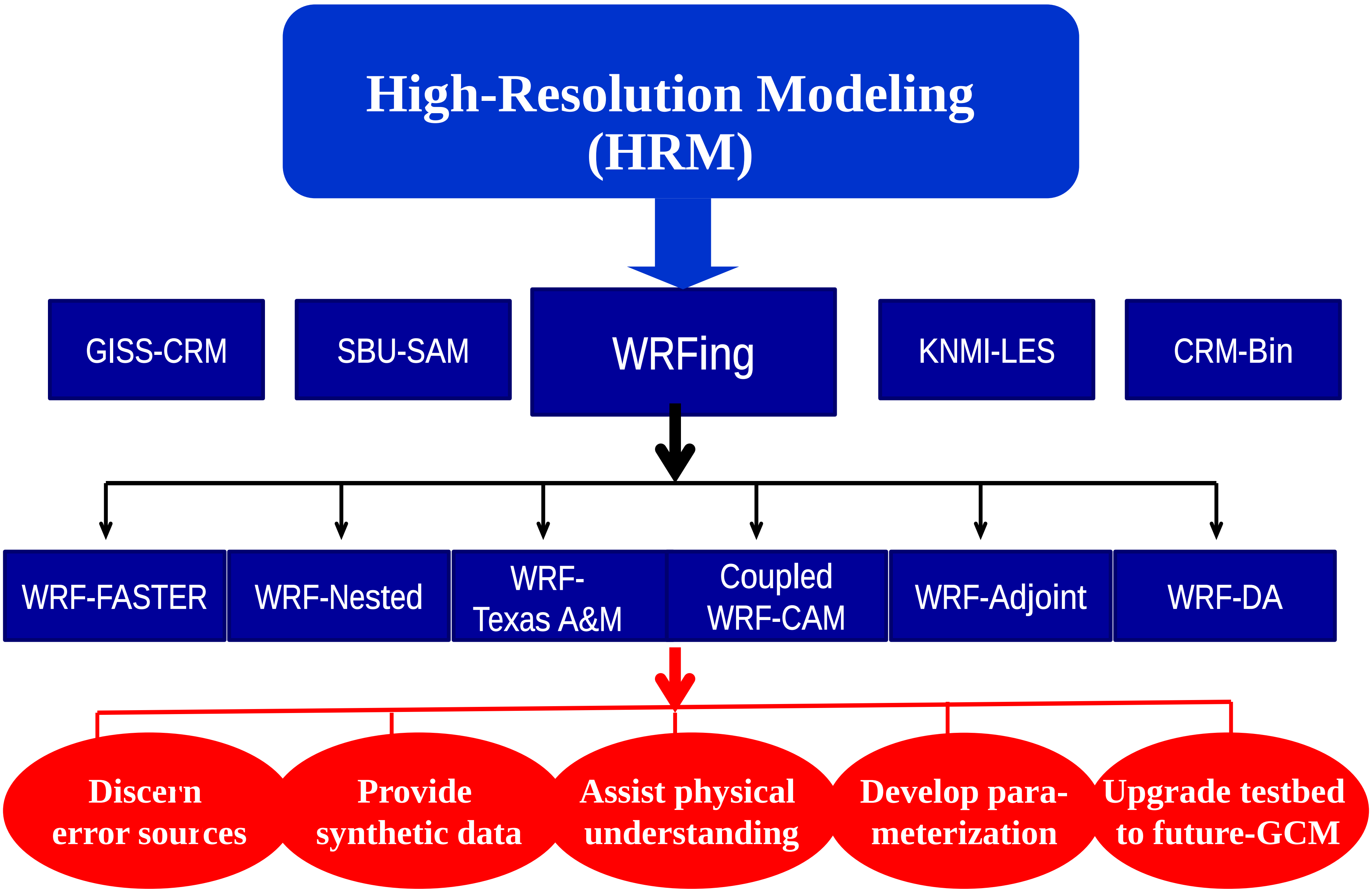



**SCM-NWP Integration**

**The NWP-testbed is built on the EU Cloudnet project and integrates with the other FASTER modeling components, esp SCM**

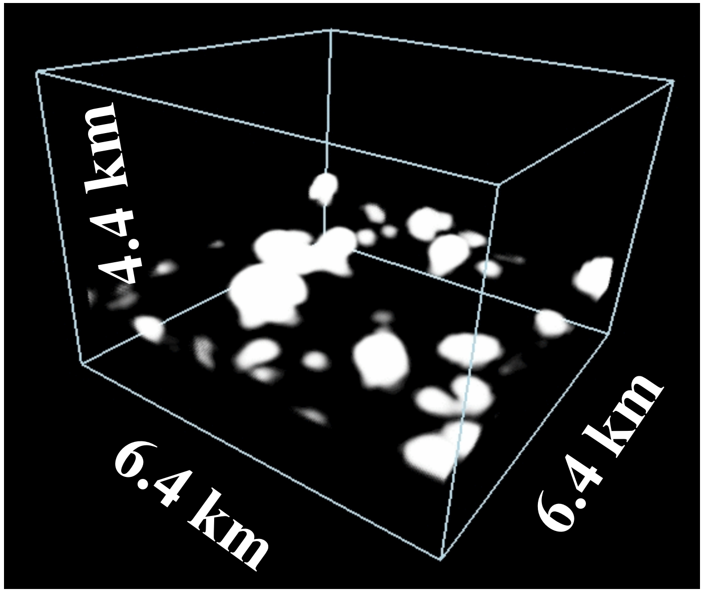
**(Adapted from R. Hogan)**

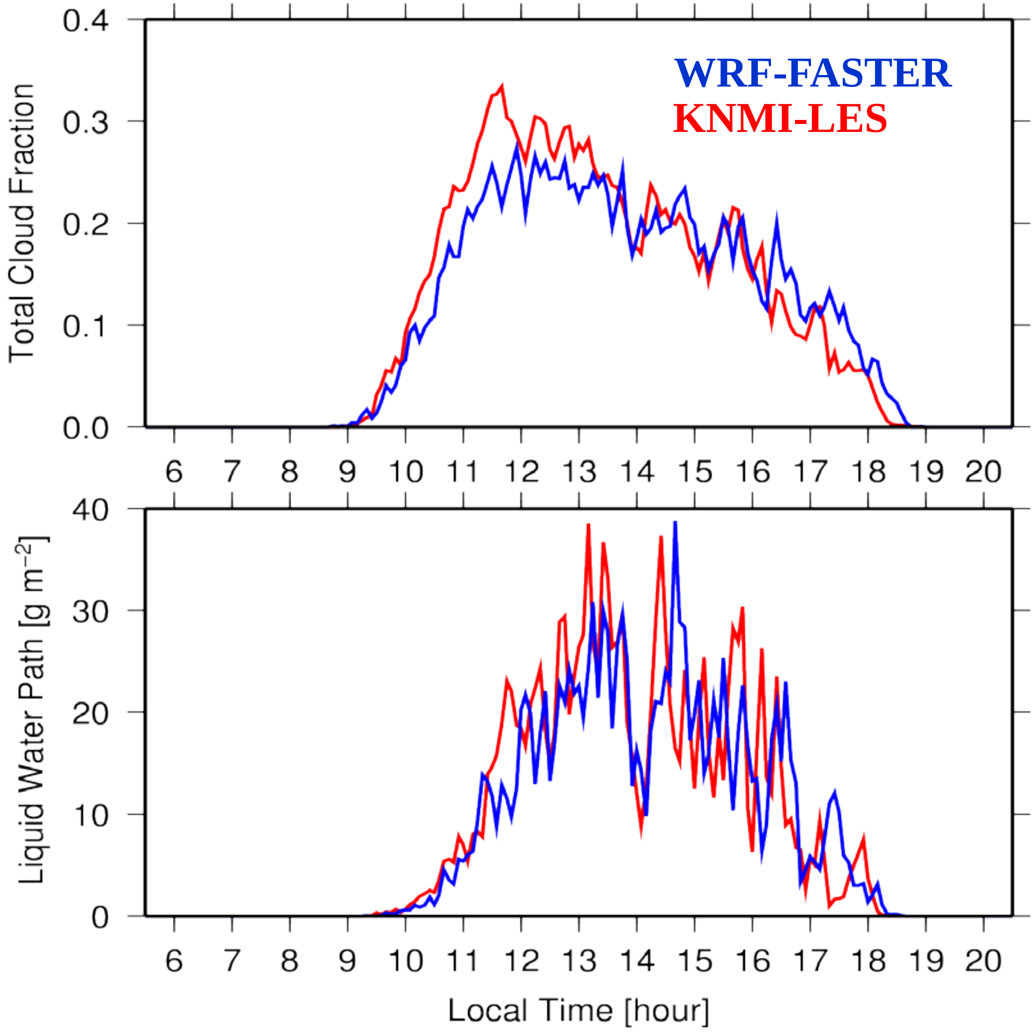
# High-Resolution Modeling Activities



# WRF-FASTER: A New CRM/LES

**WRF reconfigured as a CRM/LES model; validated with well-known models and well-tested cases, FASTER warm-up cases, and CGIL; shown here is cumulus clouds on 21 June 1997 at ARM SGP.**

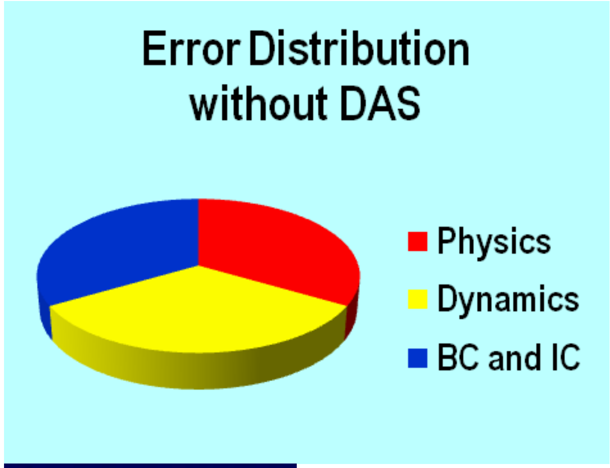


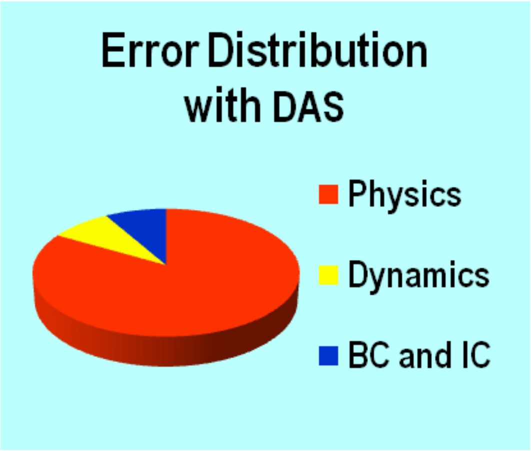

**Movie time: 12 -13 local time**
**Resolution: $\Delta x = \Delta y = 100$ m; $\Delta z = 40$ m; $\Delta t = 0.1$ S**

**(Endo et al., 2012: Mon Wea Rev)**

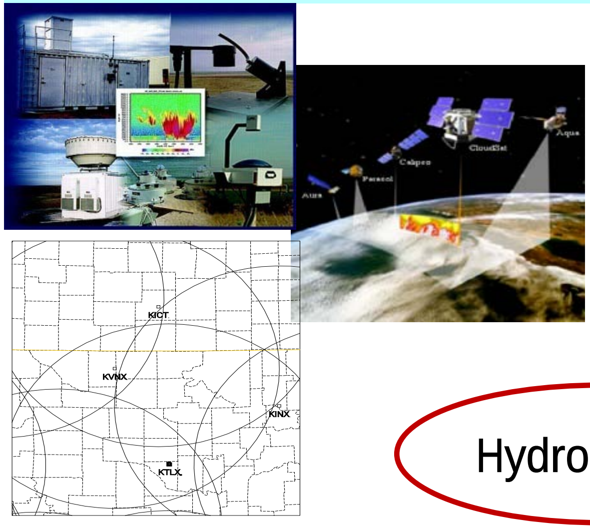
# Multiscale Data Assimilation System




- **Minimize errors in “dynamical” fields & initial and boundary conditions**




- **Help identify parameterization problems in question**




WRF (Chem)
GSI

Land
Surface

Hydrometeor

Multi-Scale
GSI

- **Provide hydrometeor advections;**
- **Aerosol DA-- Supplement aerosol data;**
- **Part of MVES**

GSI = Grid Space Interpolation, NCEP-3DVAR scheme

Multi-Scale GSI = GSI + JPL Multiscale DA System

**Li et al, 2011: Experiments with a multi-scale data assimilation system. *Mon Wea Rev***

# Data Integration

* Infuse available data and tailor to FASTER needs

* Generate new data as needed:

-- CAPE (Convective Available Potential Energy)

-- CIN (Convective Inhibition)

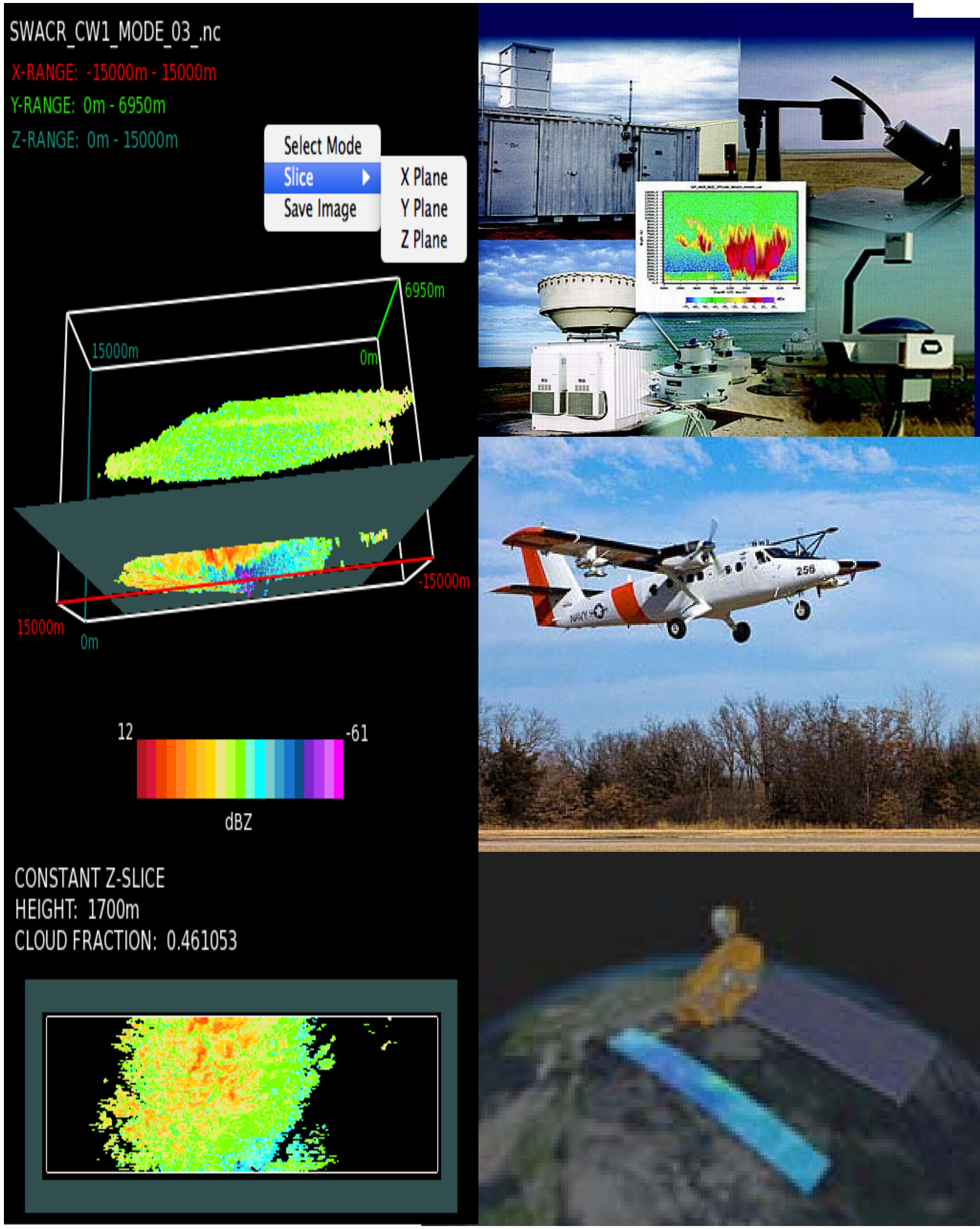
-- Stratiform-Convective Partition

-- Aerosol Properties

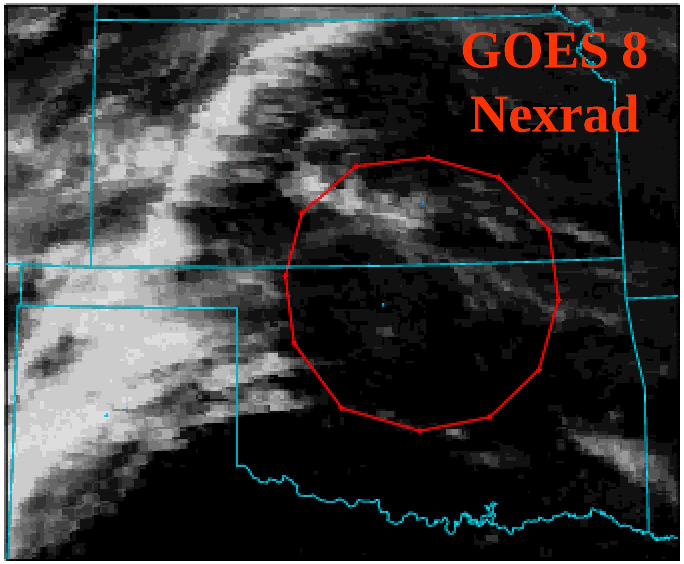
* Model Data

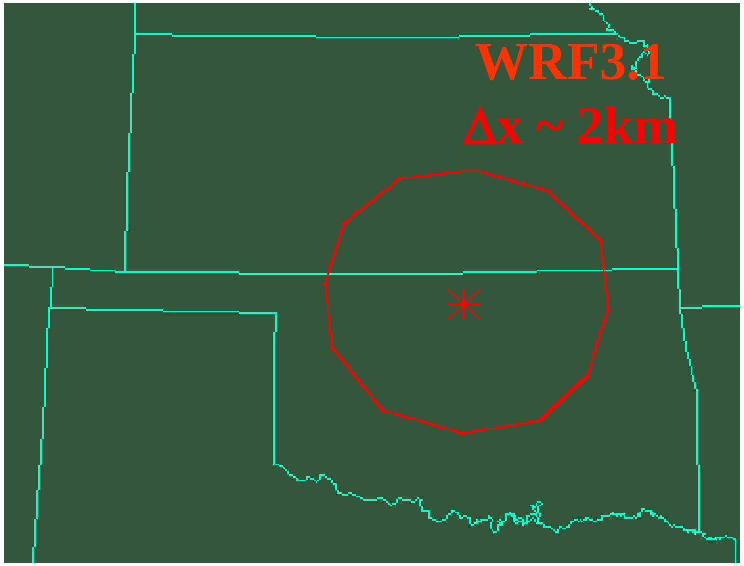
* 4D visualization

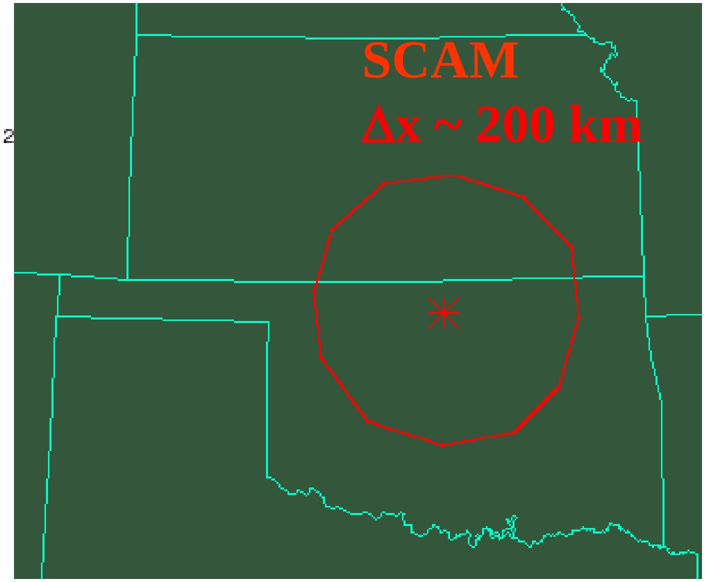
***Multiscale and Multi-Sources***



# Beyond Fried Egg: Multiscale VES



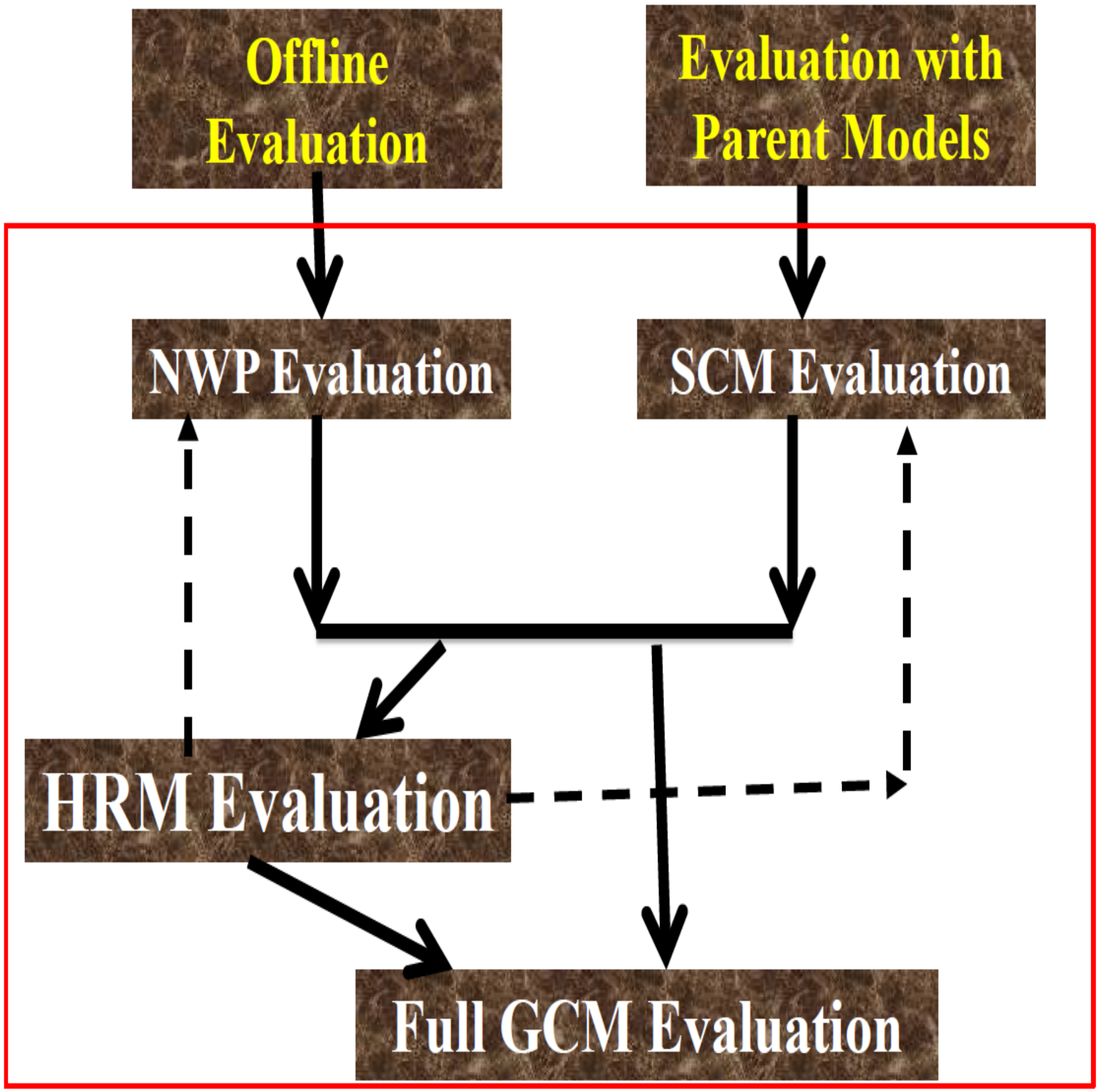




- **Other models e.g., NWP**
- **Evaluation metrics/features**
- **3D**
- **Long-term & real time**
- **Collaboration with computer scientists at BNL and SBU**
- **Growth into a user facility?**

# Evaluation Package, Strategy and Uniqueness

- Long-term statistical , regime, and case study
- Emphasis on coupling and relationship
- Consideration of observational spread
- Metric development
- Model and process ranking/weakest link
- Comprehensive: GCM/SCM, NWP and HRM



# Science Snapshots

# Better Use of ARM Radiation Measurements and New Method for Inferring Cloud Albedo

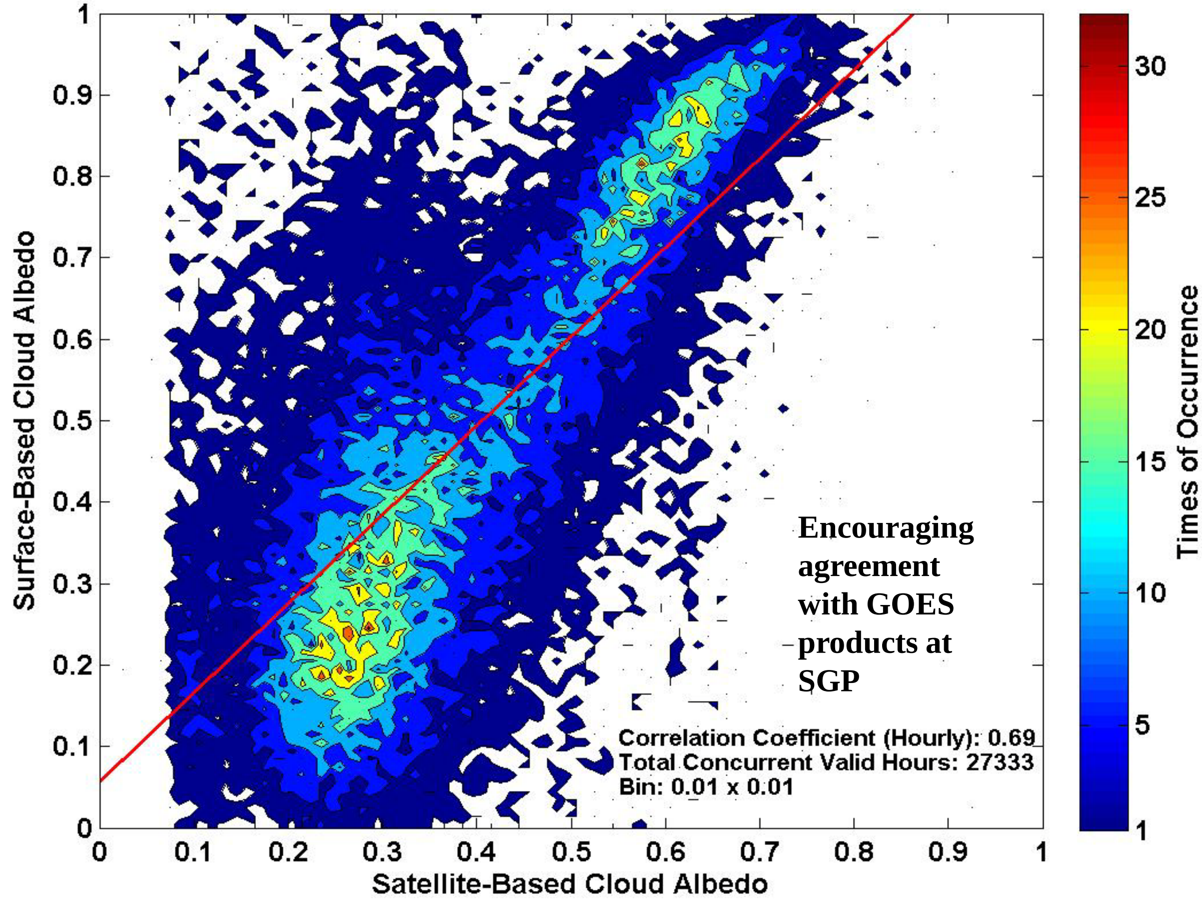
- Analytic relationship between SRCF, cloud fraction and cloud albedo: SRCF = fraction x albedo

- New approach to infer cloud albedo from surface-based radiation measurement;

- Application to other ARM sites;

- PI product to release to the ARM/ASR community

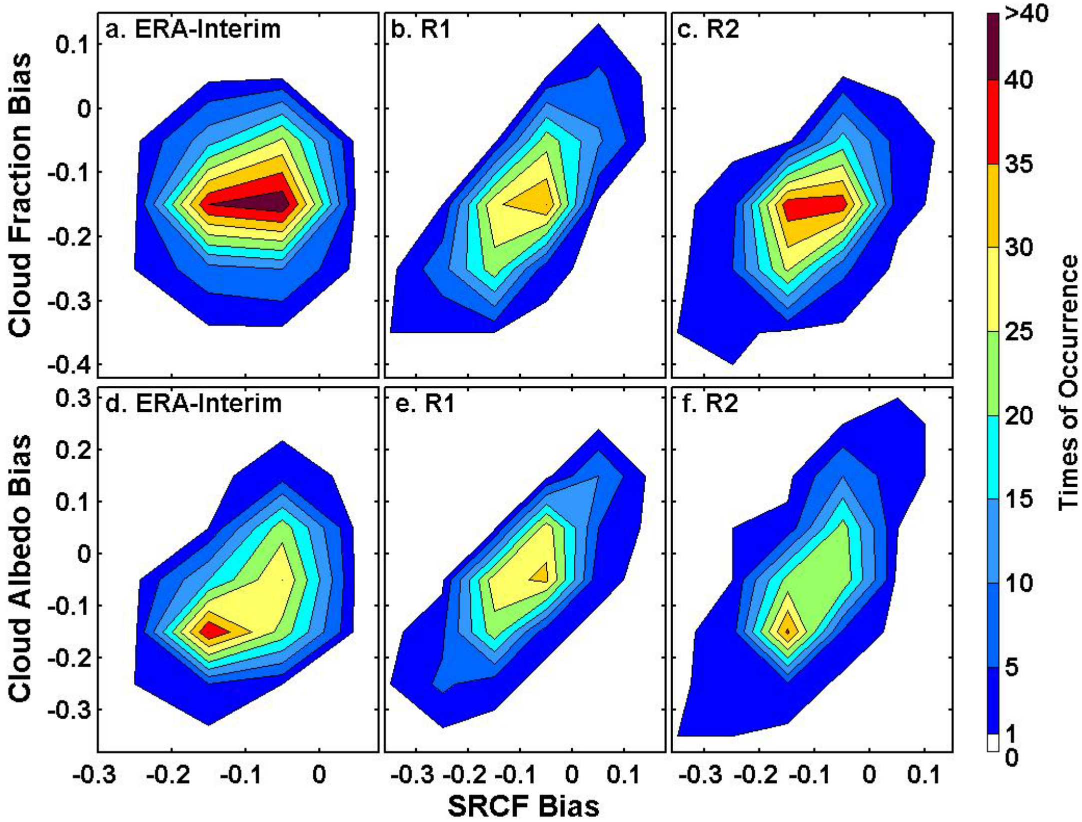
**Hourly data from 1997 to 2009 at ARM SGP**




*Reference: Liu et al., 2011: Relationship between cloud radiative forcing, cloud fraction and cloud albedo, and new surface-based approach for determining cloud albedo. Atmos. Chem. Phys., 11, 7155-7170 .*

# Evaluation of NWP Reanalysis & Analysis

- **Widespread use**
- **Use in ARM large-scale forcing and merged sounding VAP**
- **Cloud properties not assimilated; errors from model physics;**
- **Three major reanalysis products evaluated;**
- **Model negative biases in cloud properties.**



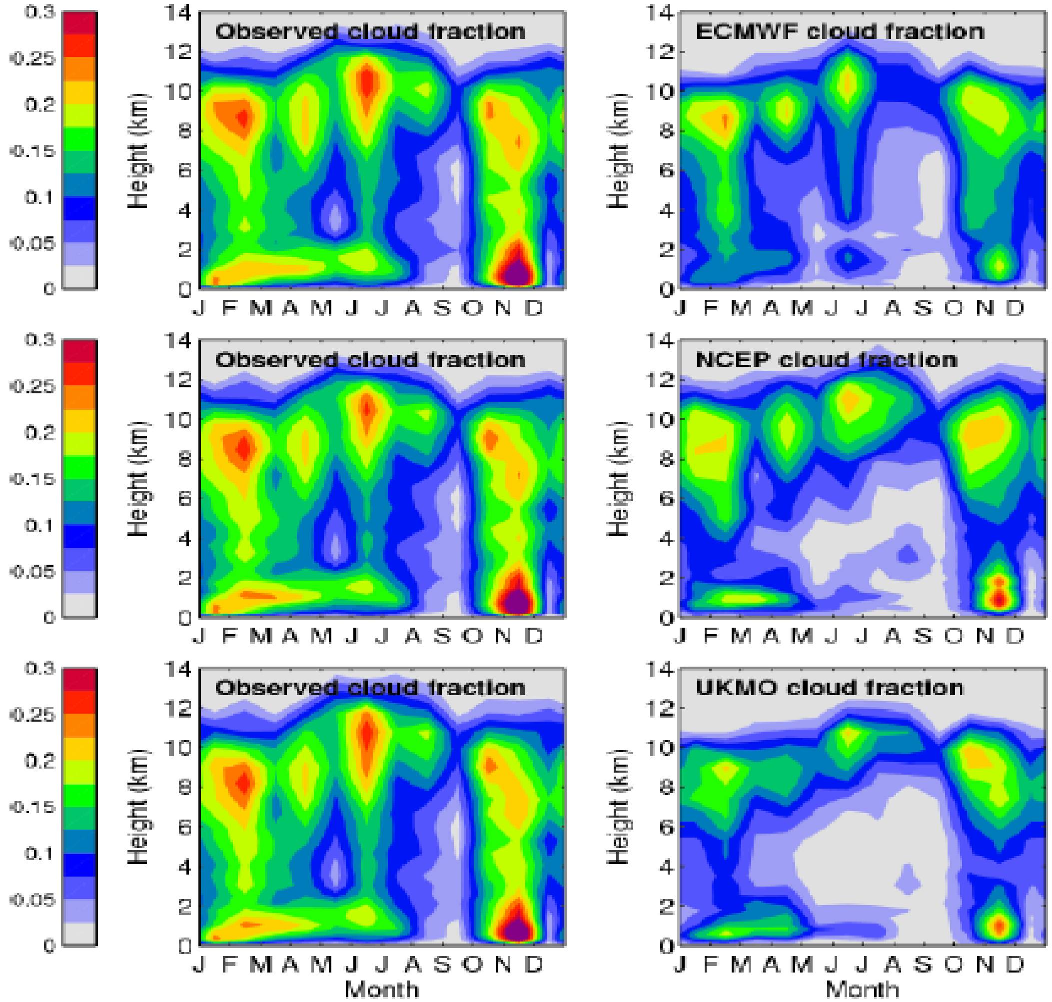

**Coupling between cloud properties and near surface meteorology, especially relative humidity likely via PBL processes (not shown)**

***Ref: Wu et al, 2012: Observational-based evaluation of major NWP reanalyses against ARM measurements over the SGP site. J. Geophys. Res (revised)***

# Evaluation of NWP Forecasts

- SGP 2001 to 2010
- Darwin 2005 to 2009
- SGP2004 example
- Qualitative agreement
- Underestimated clouds, esp., low-level clouds
- Consistent with reanalysis

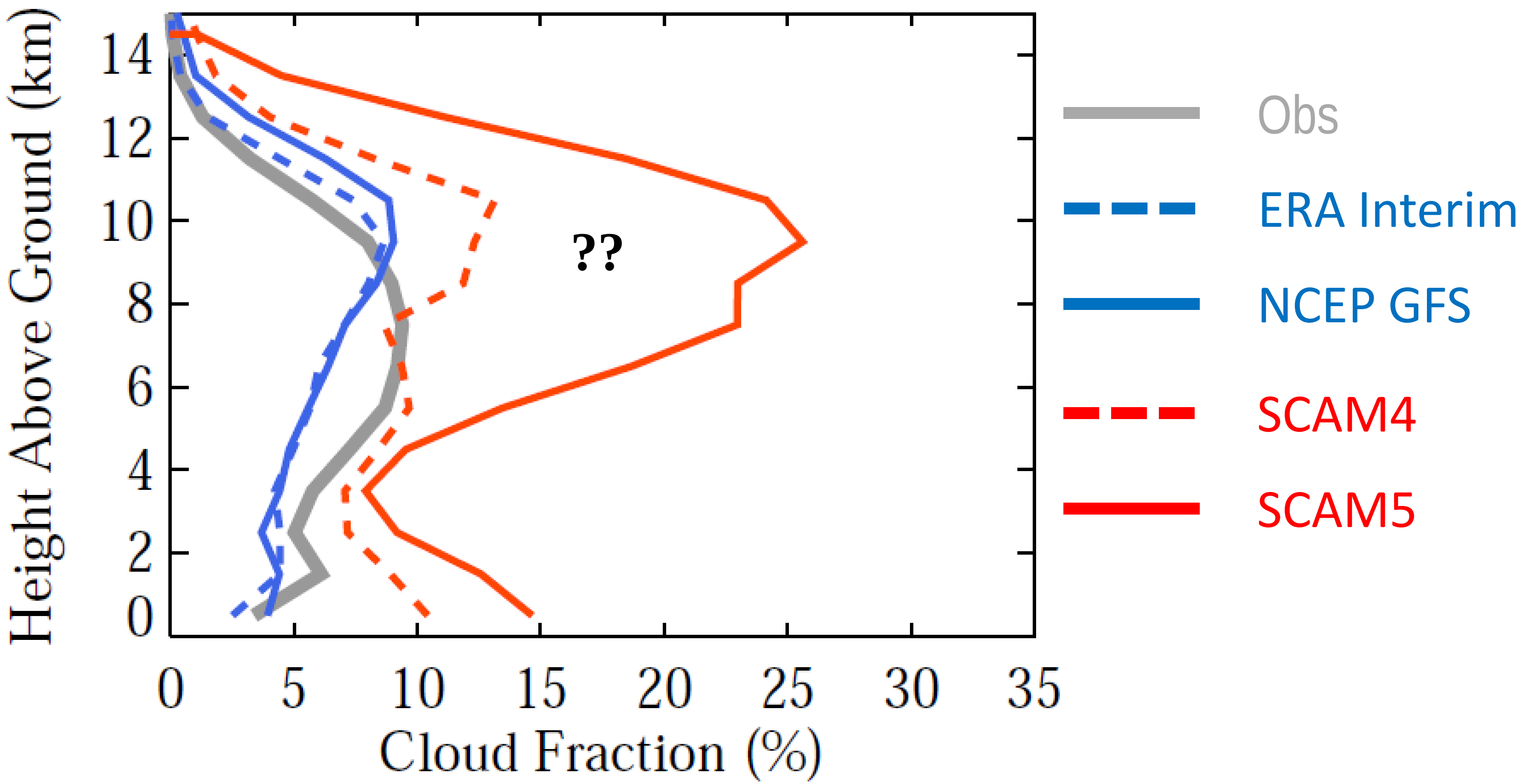
SGP 2004




*Barrett et al 2009: Geophys. Res. Lett, 36, L17811.*

# SCM-NWP Integration

## 2004-2008 Annual Mean Cloud Fraction over SGP



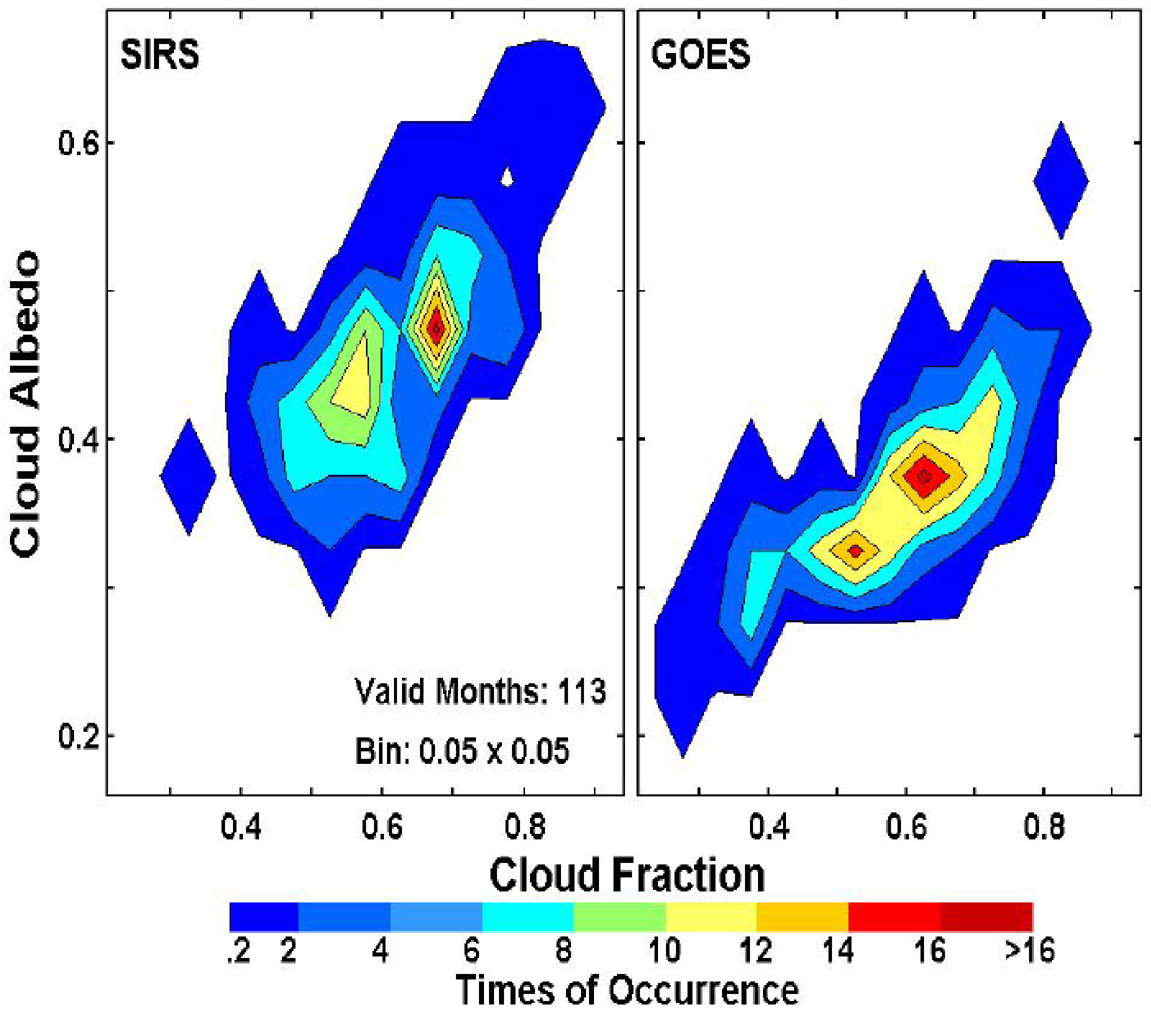
# Relation between Cloud Albedo and Fraction

- 12 year monthly data (1997 - 2009) at the ARM SGP site

- Two sets of measurements: surface-based Solar Infrared Radiation System (SIRS) and GOES satellite

- Joint occurrence of cloud fraction and cloud albedo

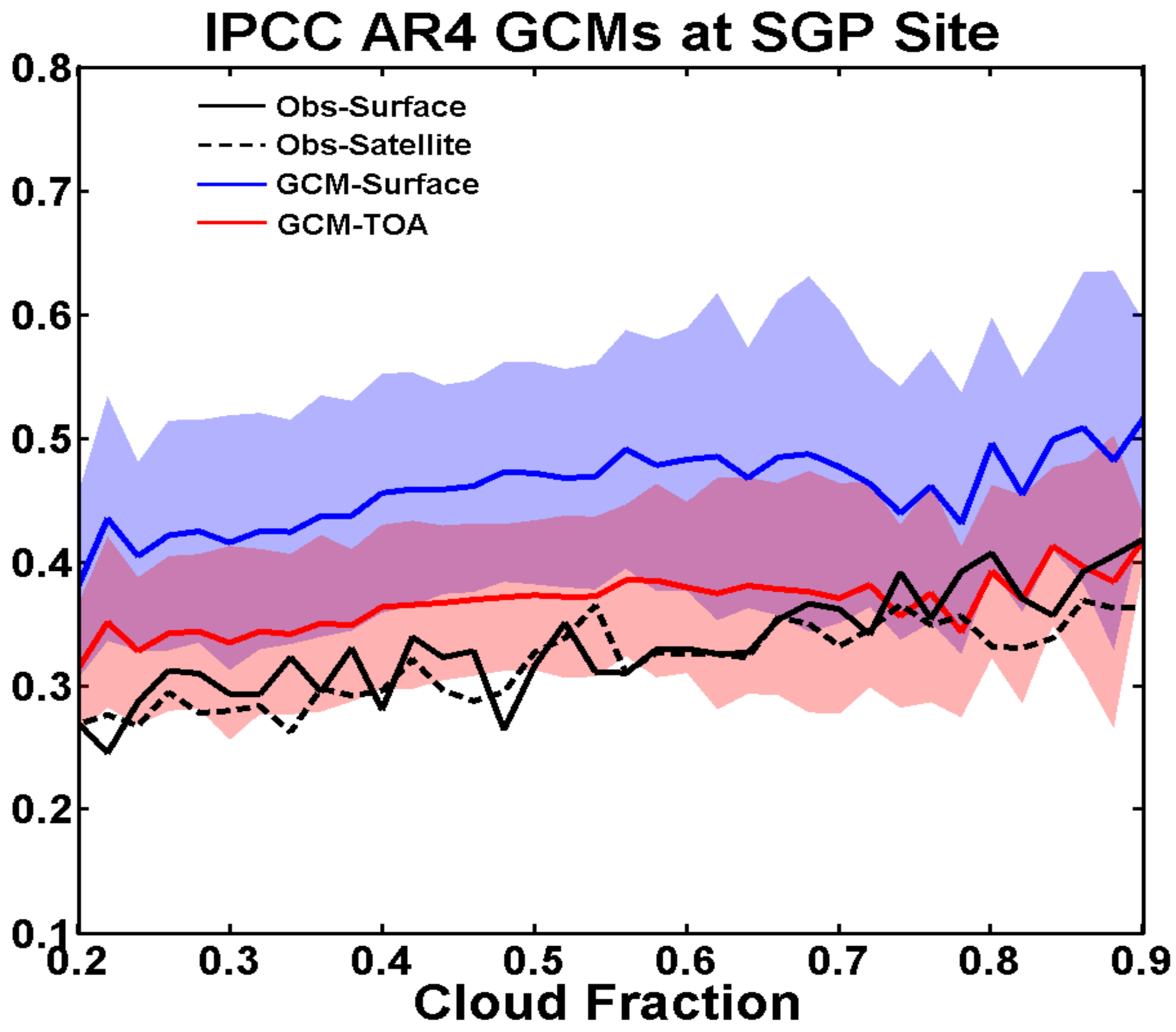
- Conspicuous positive correlation between cloud albedo and cloud fraction for both GOES and SIRS




**Do GCMs simulate the relationship, and how well ?**

# Comparison between GCMs and Observations

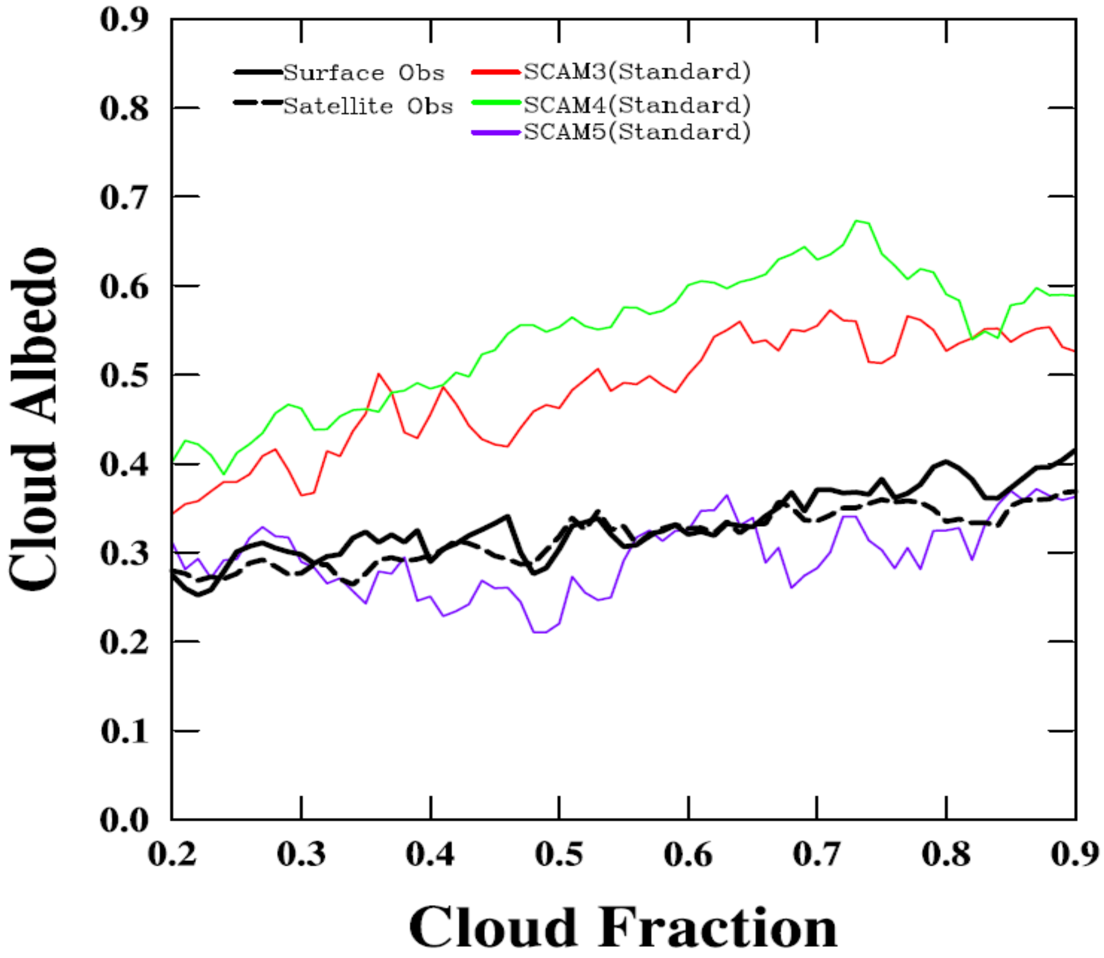
- General positive correlation
- Large inter-model spread
- Difference between TOA and surface-based cloud albedo



# SCM Investigation

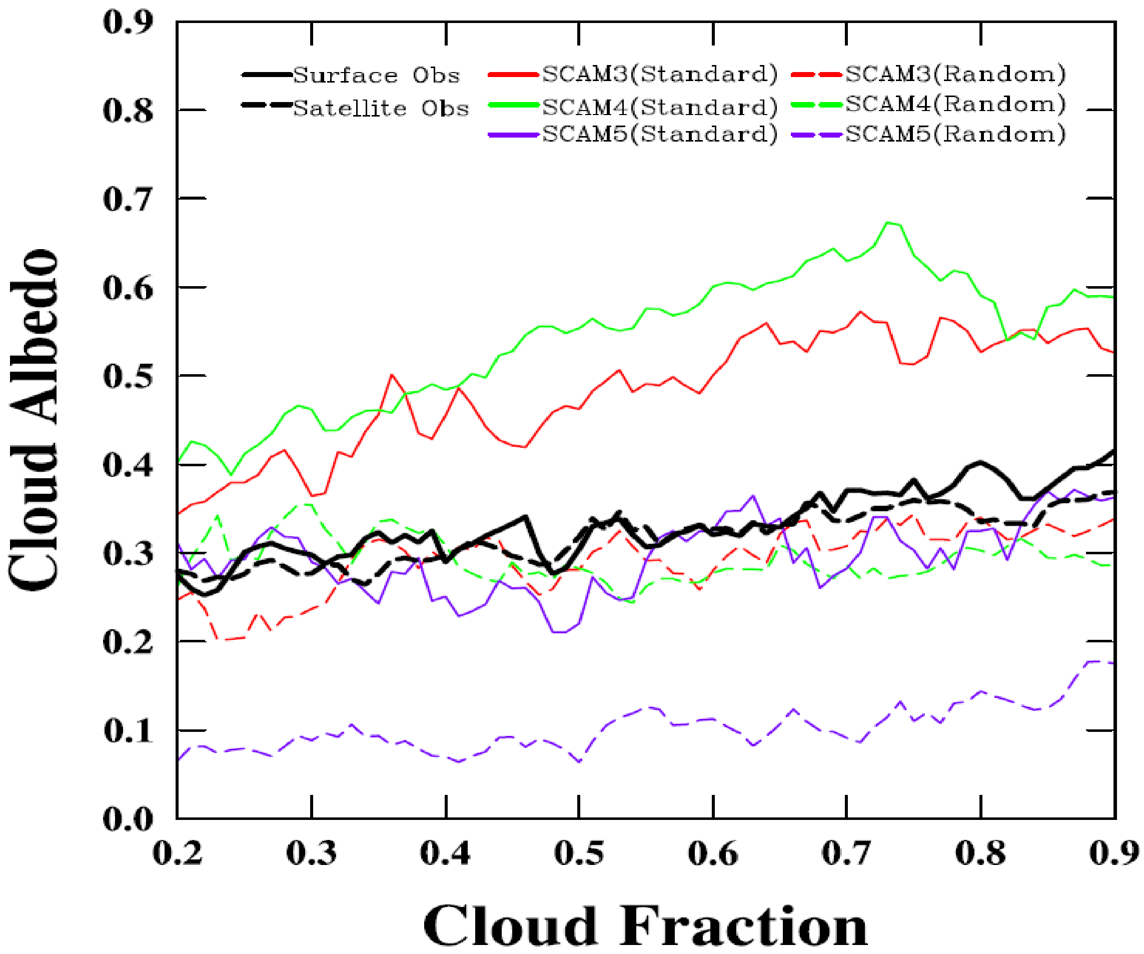
✓ **Different physics: SCAM3, SCAM4, and SCAM5;**

✓ **SCAMs produce general positive correlation, with SCAM5 best simulating the observations;**



# SCM Investigation

- ✓ Different physics: SCAM3, SCAM4, and SCAM5;
- ✓ SCAMs produce general positive correlation, with SCAM5 best simulating the observations;
- ✓ Different cloud overlaps: standard (solid) and random (dashed);
- ✓ Differences can arise from model physics and/or cloud overlap assumptions.




**The relationship between cloud albedo and cloud fraction, along with the fact that model physics and/or overlap assumption can lead to comparable results, calls for consideration of coupling and consistency issues in development of fast physics parameterizations!**

# Tuning and Compensating Errors — Analysis

- **Tuning to the same TOA energy budget leads to an inverse relationship between cloud fraction f and cloud albedo α :**

$$\alpha f \sim \text{constant}.$$

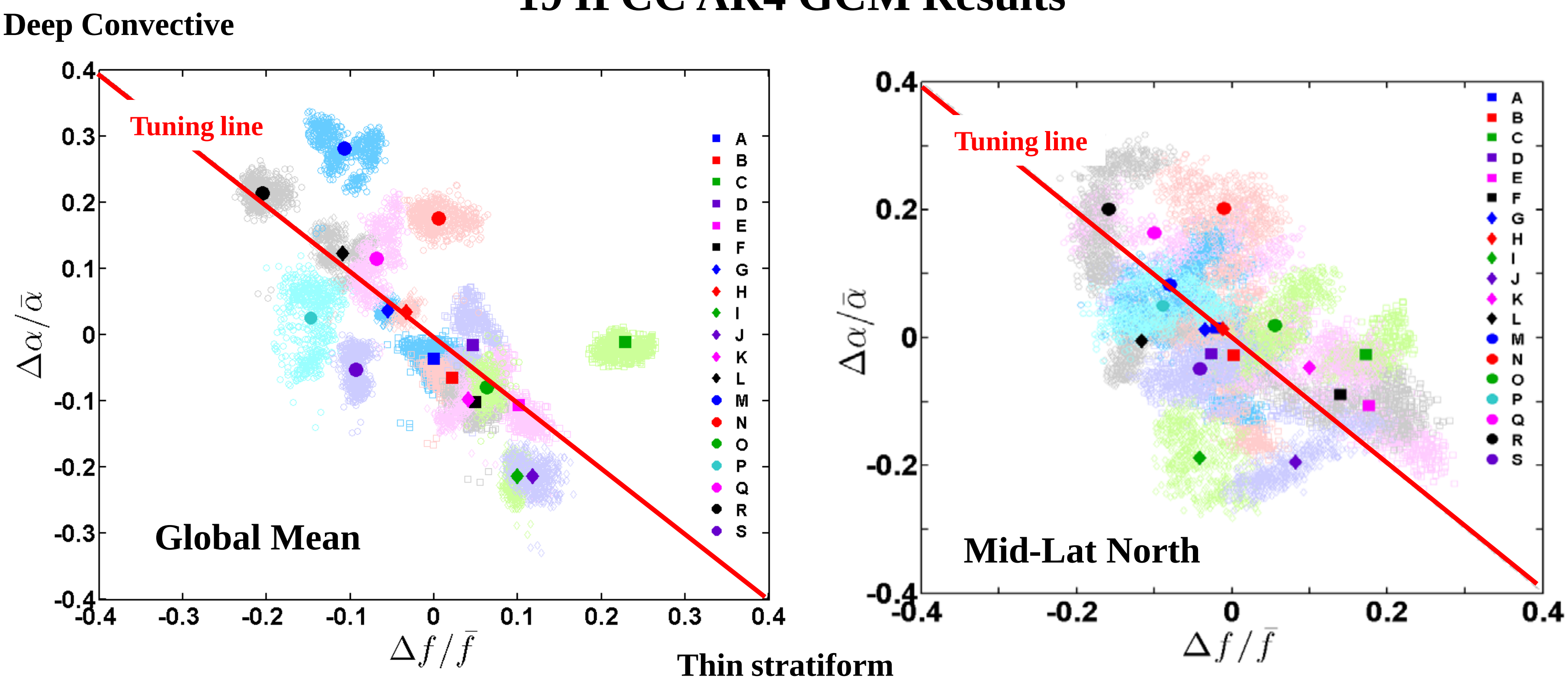
- **A more accurate expression is**

$$\frac{\Delta\alpha}{\alpha} = -\frac{\Delta f}{f}$$

**(Liu et al., ACP, 11, 7155-7170, 2011)**

# Tuning and Compensating Errors — Evidence

## 19 IPCC AR4 GCM Results




**These results demonstrate that "tuning" parameterizations to observations lead to serious compensating errors, even distinct cloud regimes; we should derive parameterizations from first principles and reduce the number of tunable parameters as much as possible, and meantime look for smart objective "tuning" !!**

# Compensating Errors in Precipitation

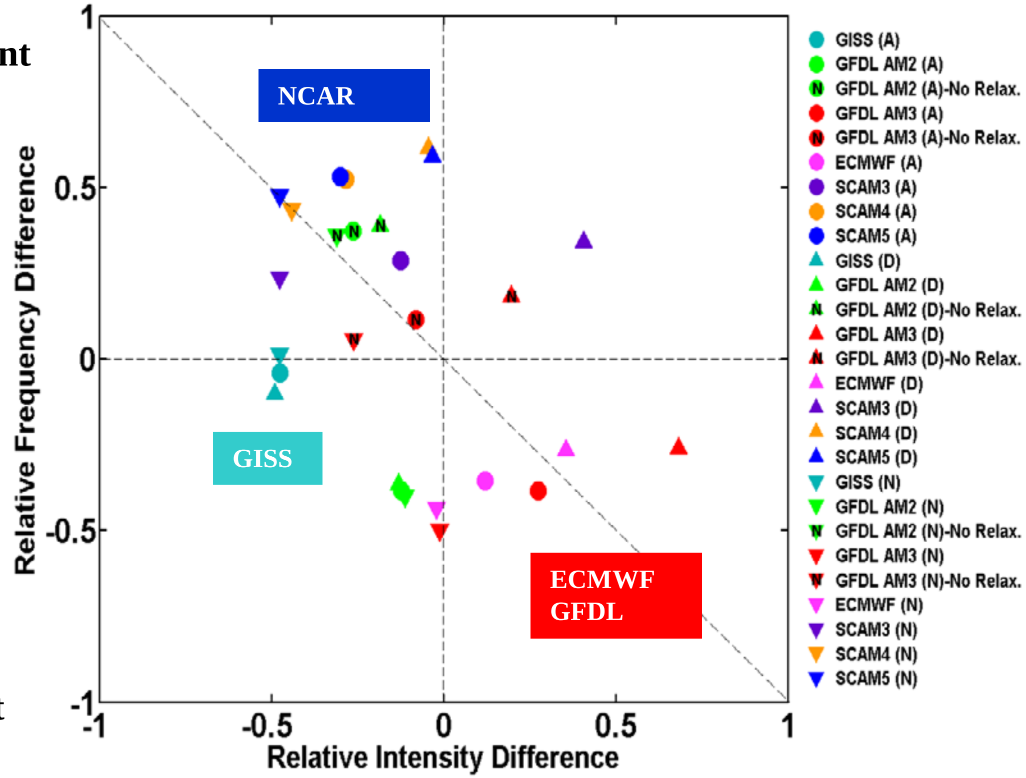
$$\mathbf{P} = \overline{\mathbf{p}}\,\mathbf{N}$$

$$\frac{\Delta\overline{p}}{\overline{p}} = -\frac{\Delta N}{N}$$

P = Total precipitation
N = Number of event
$\overline{\mathbf{p}}$ = Event mean

More Frequent

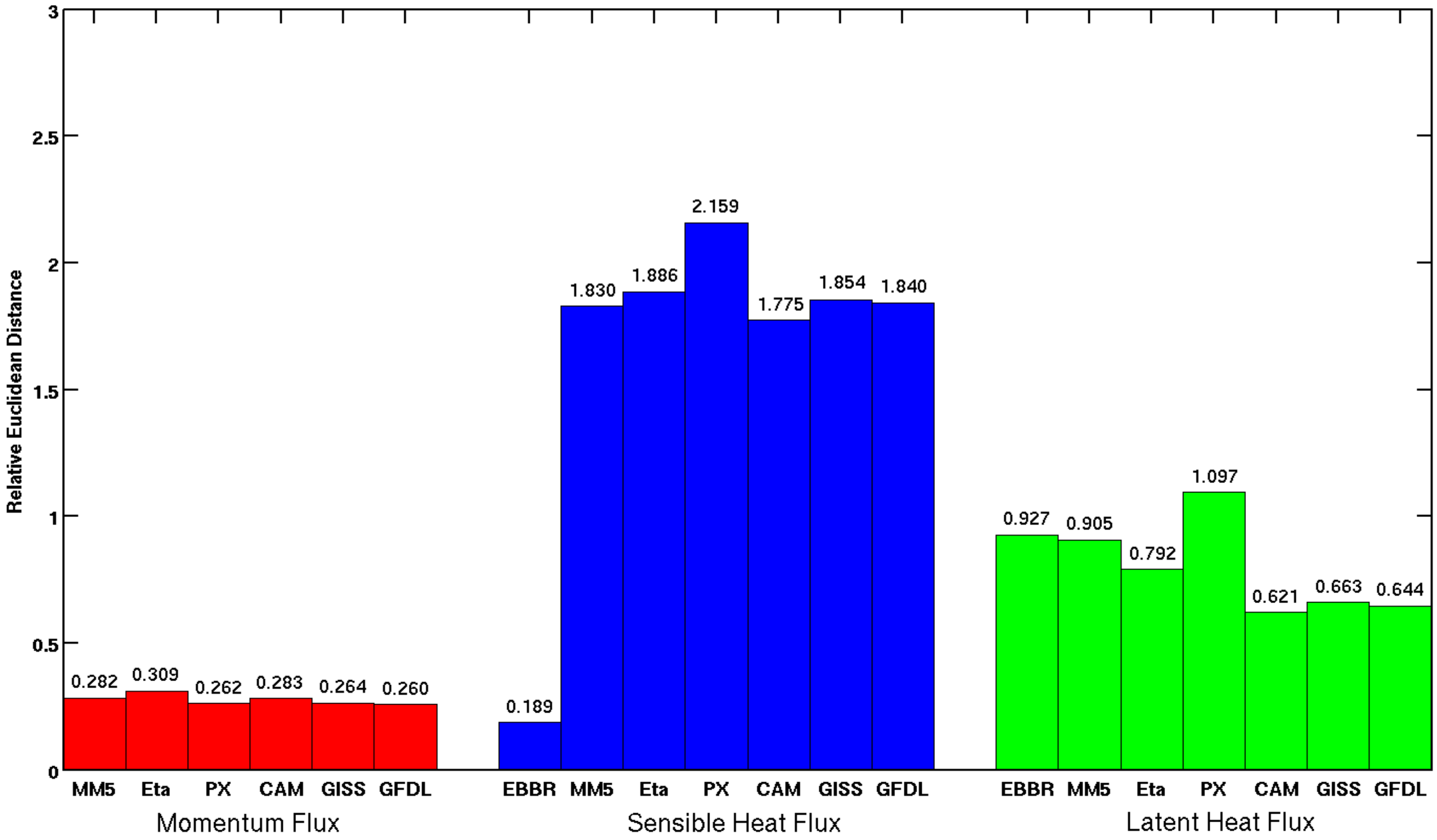
Less Frequent




Weaker Precipitation → Stronger Precipitation

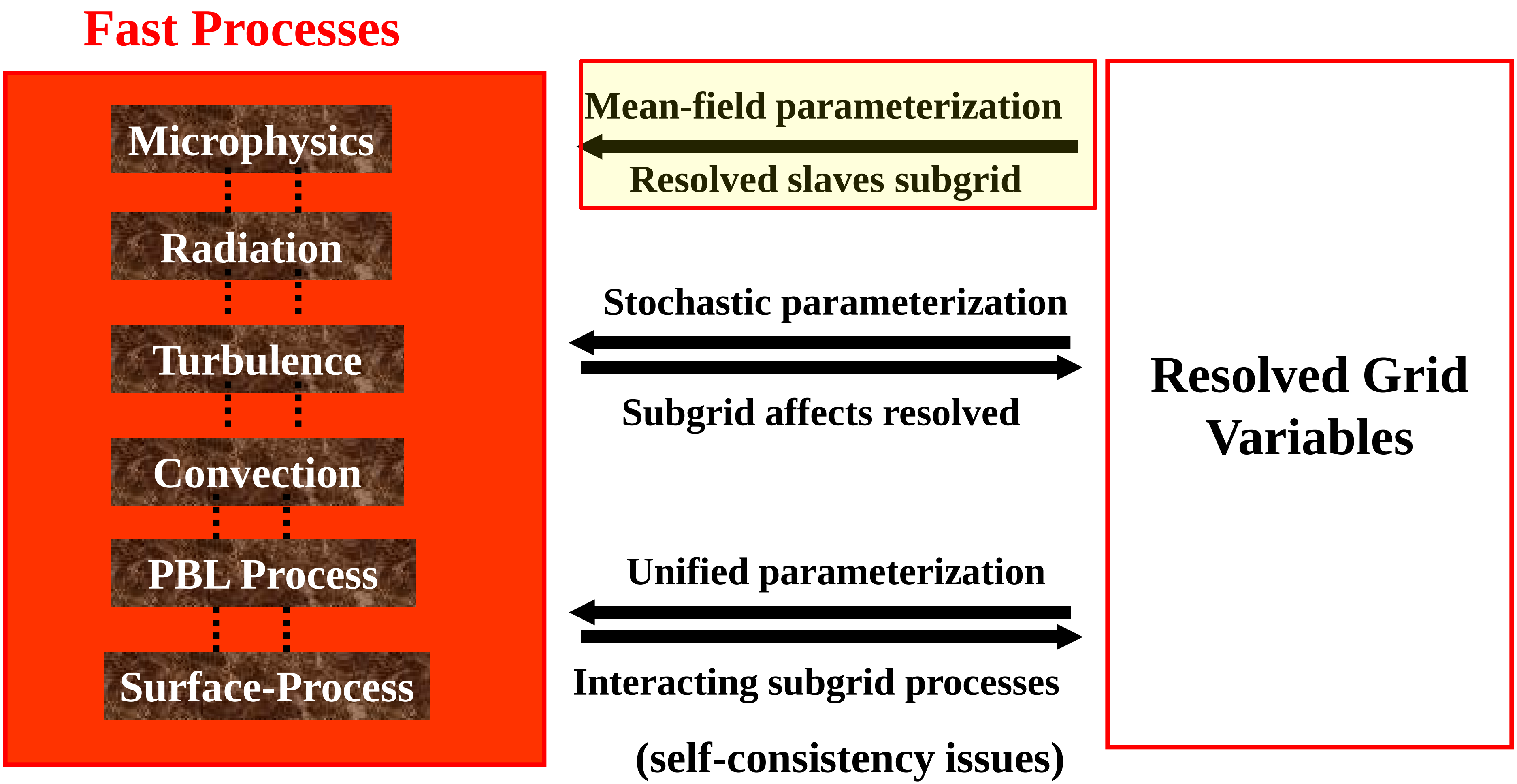
**Crucial message: large scale forcing controls SCM total precipitation more, however, from different compensating errors in different GCMs >> convection trigger vs strength?**

# Offline Evaluation of Surface Flux Parameterization Using 7-Year ARM Observations



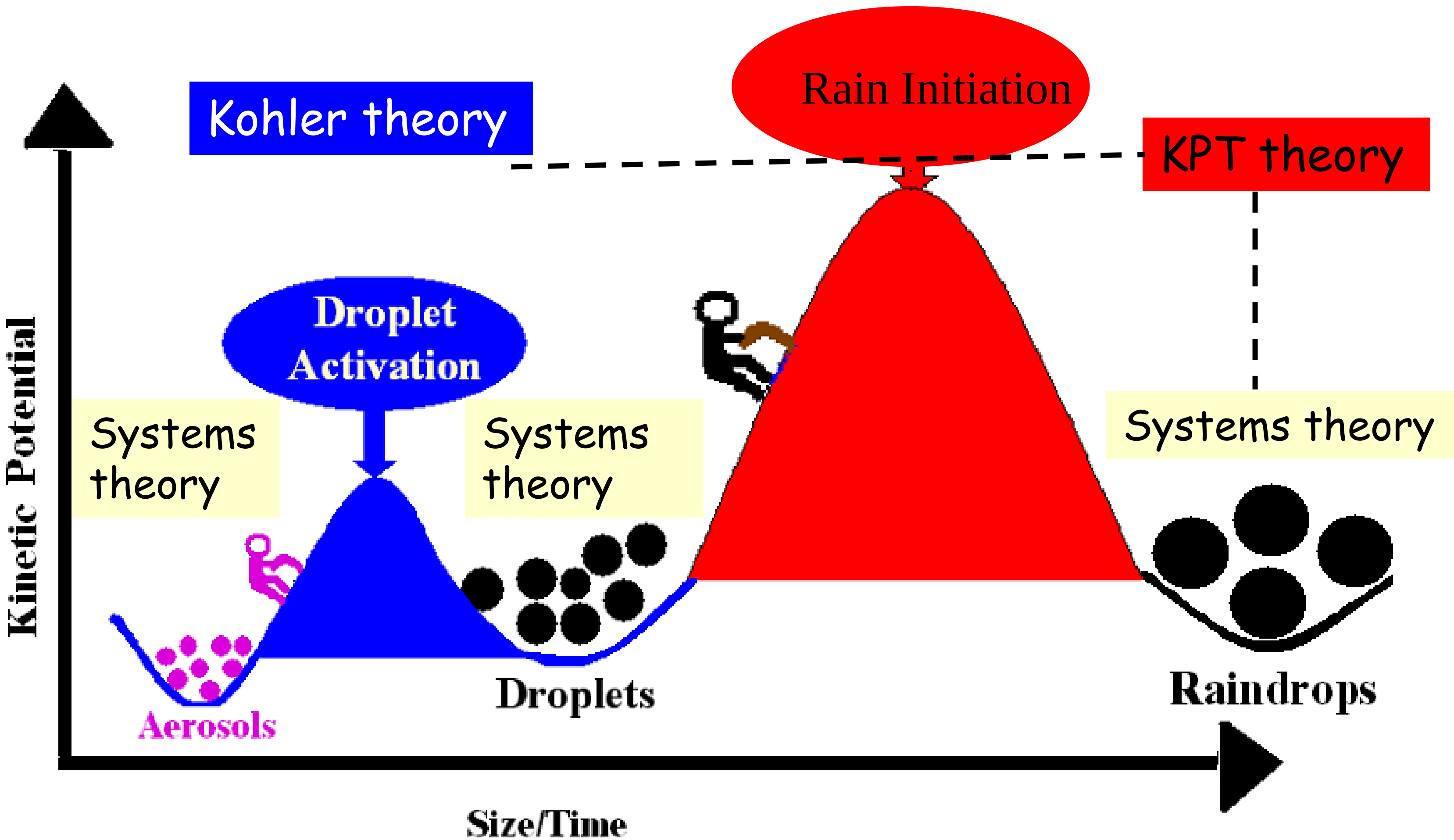

**(Liu et al, Mon Wea Rev, 2012)**

# Three Levels of Parameterization



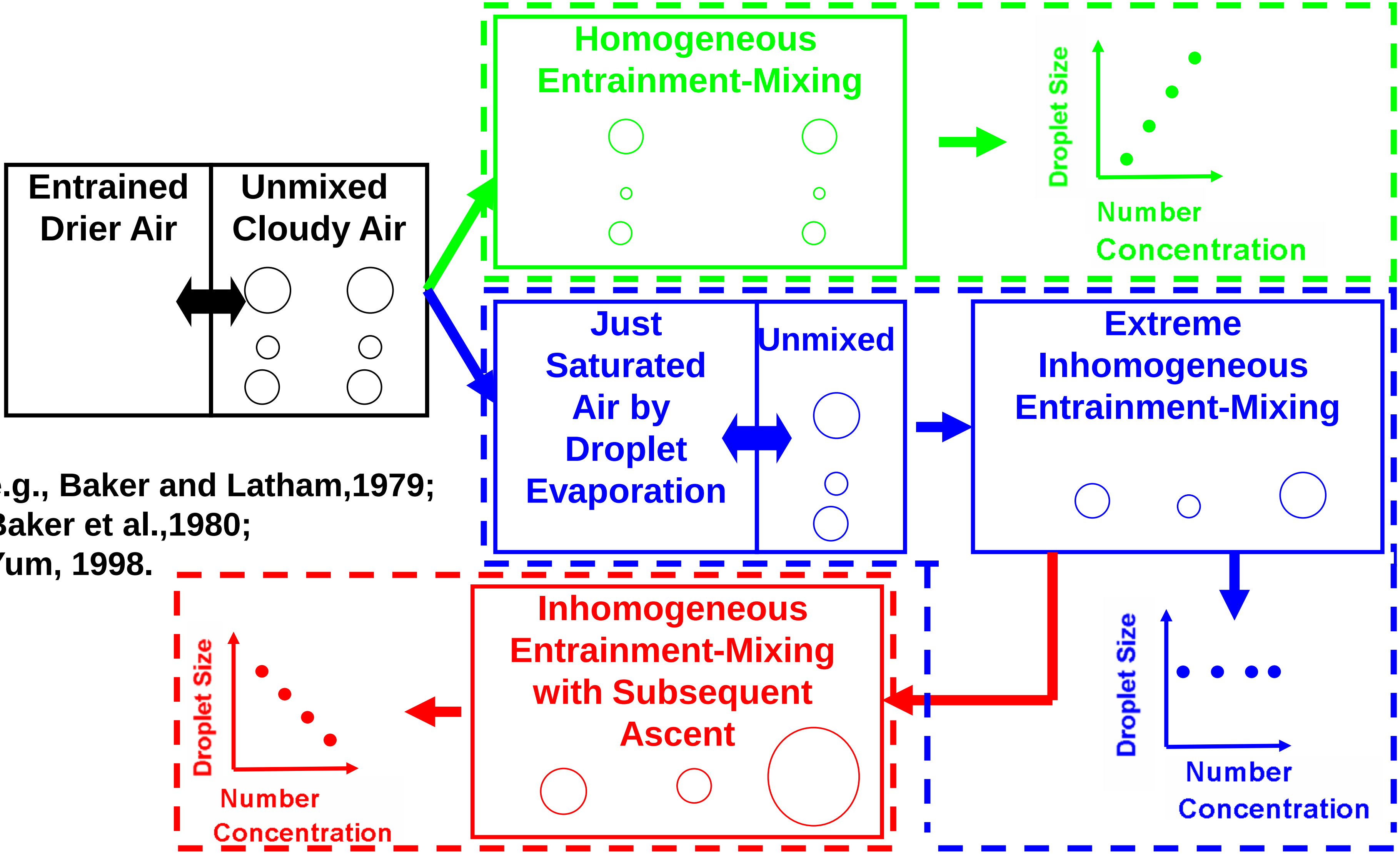

***Parameterization is not just practical necessity, but deep theoretical underpinning of scale-interactions within the multiscale system.***

# Systems theories for representing all aerosol/cloud/precipitation processes




*Three-moment scheme for aerosol-cloud-precipitation continuum Liu et al., (2002, 2004, 2006, 2007, 2009) on clouds and precipitation.*

# Entrainment-Mixing Mechanisms




e.g., Baker and Latham,1979;
Baker et al.,1980;
Yum, 1998.

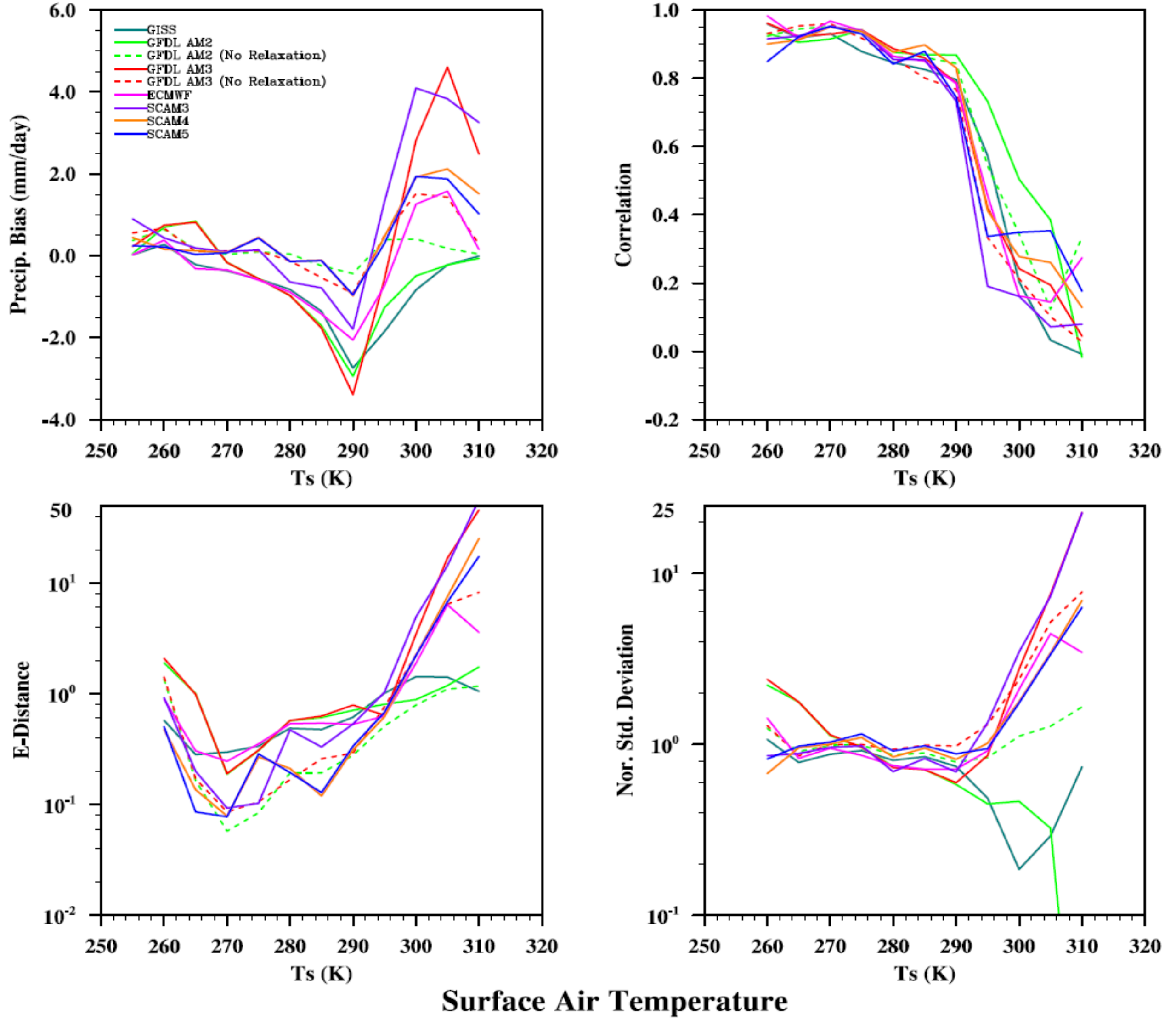
**A journey of thousand miles starts with a single step**

**Suggestions & Collaborations ?**

**Thanks so much !**

# Evaluation of SCMs with ARM Measurements

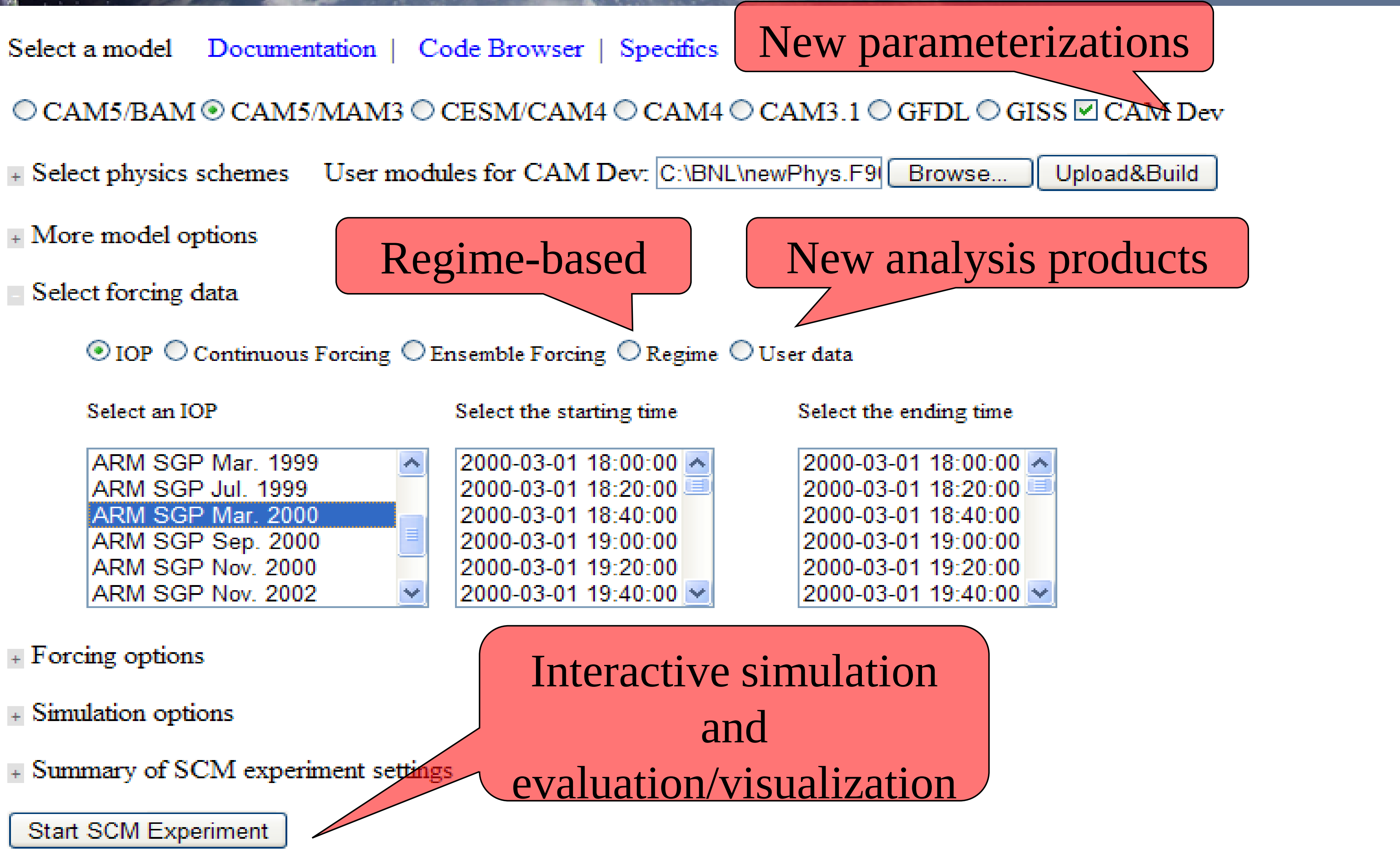
- **4 major SCMs;**
- **Different versions;**
- **3 year (1999 -2001) runs with hourly resolution**
- **Model performance as a function of surface temperature**
- **Deficient parameterizations related to convection**
- **More results next**



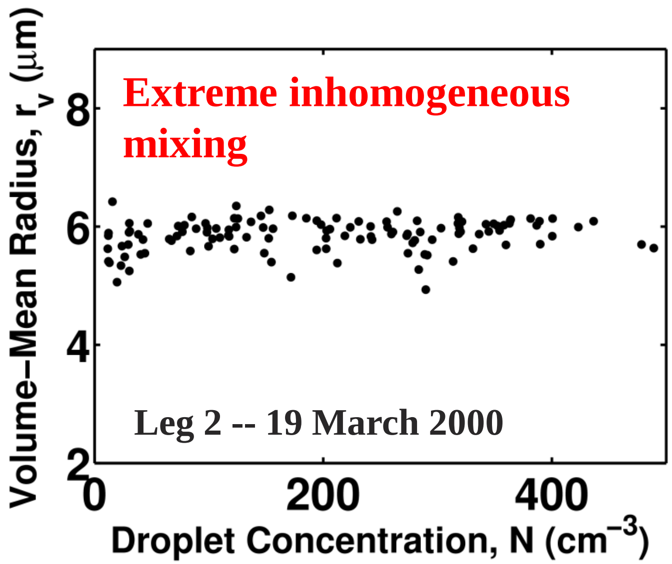

***Ref: Song et al, 2012: Observational-based evaluation of major NWP reanalyses against ARM measurementsP site. J. Geophys. Res (to be submitted)***

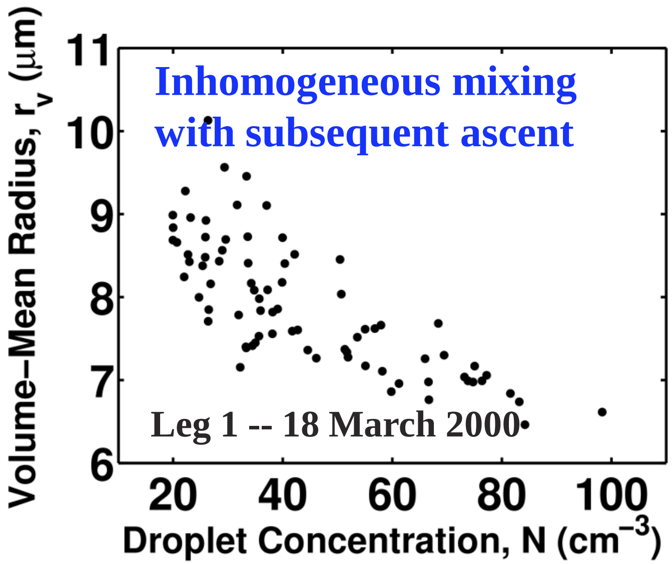
# Web-Based FASTER Testbed

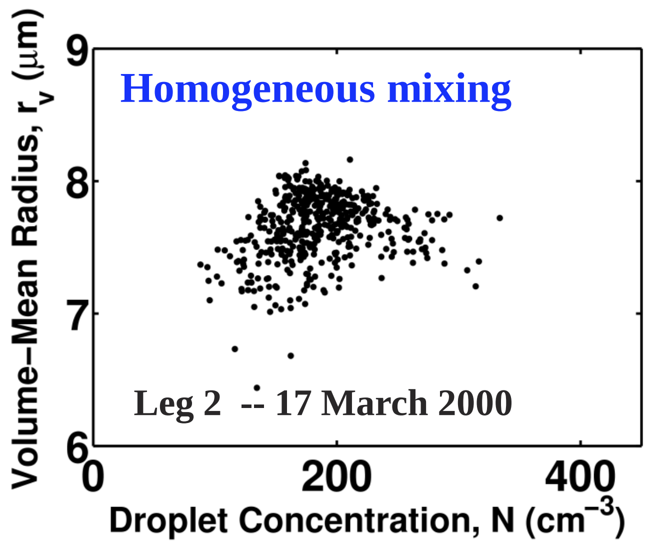
FASTER Gateway: http://www.bnl.gov/esm

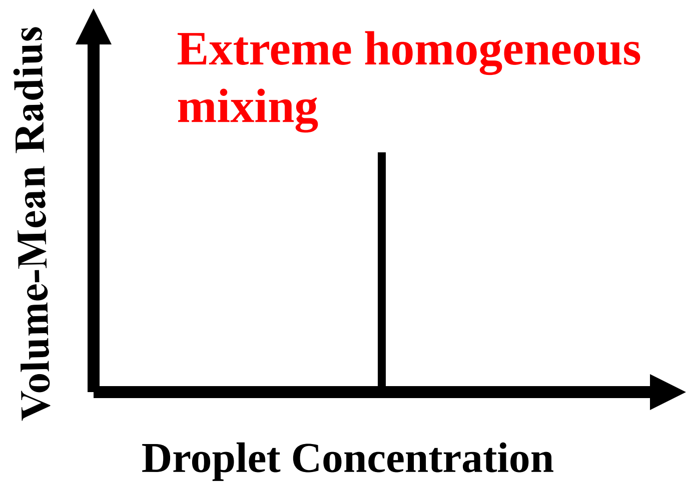


# Entrainment-Mixing Processes & Microphysics



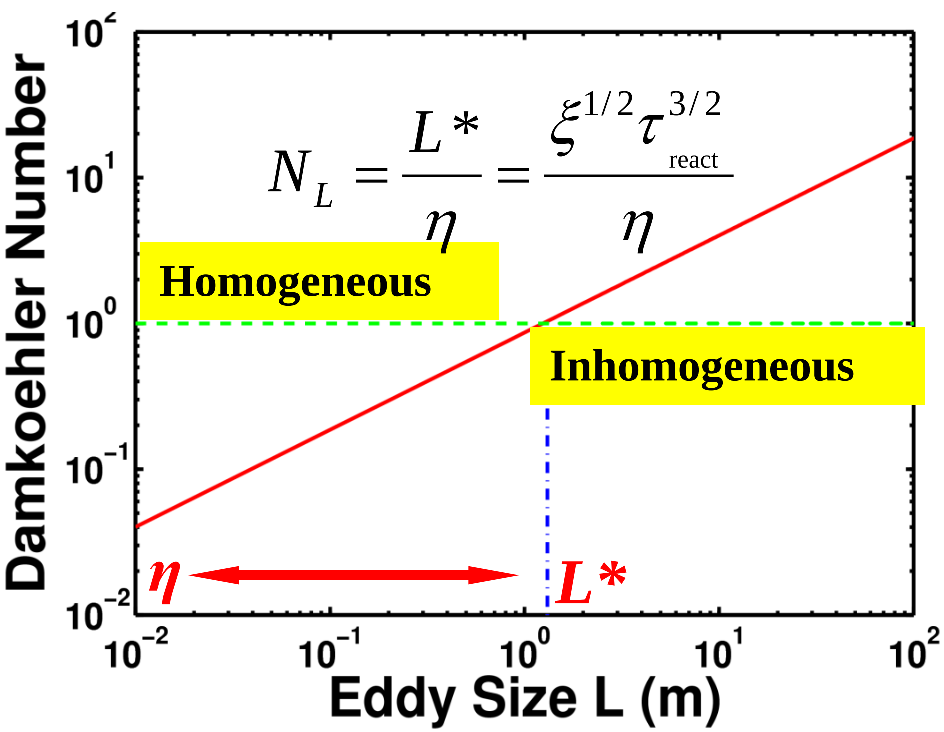



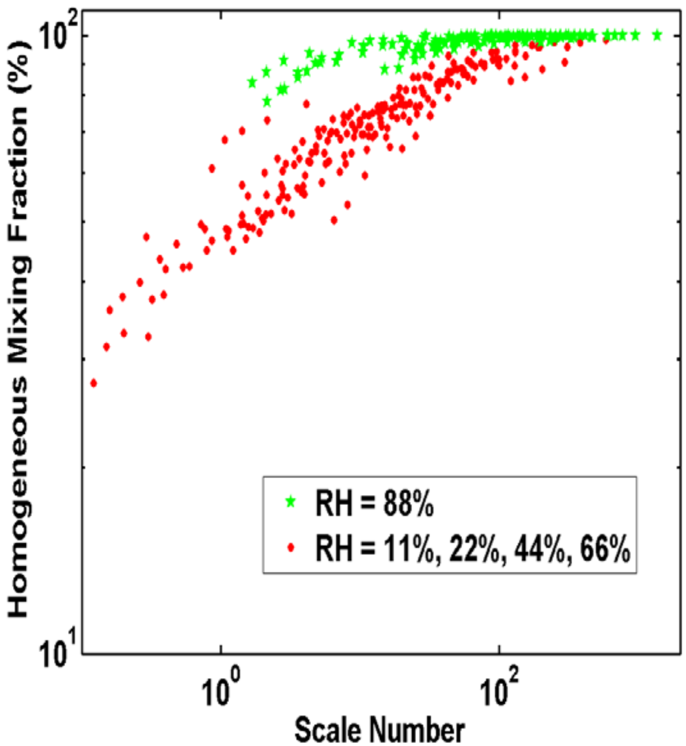



# Homogeneous Mixing Fraction

$\eta$: Kolmogorov scale; $L^*$ transition scale; $N_L$ transition scale number



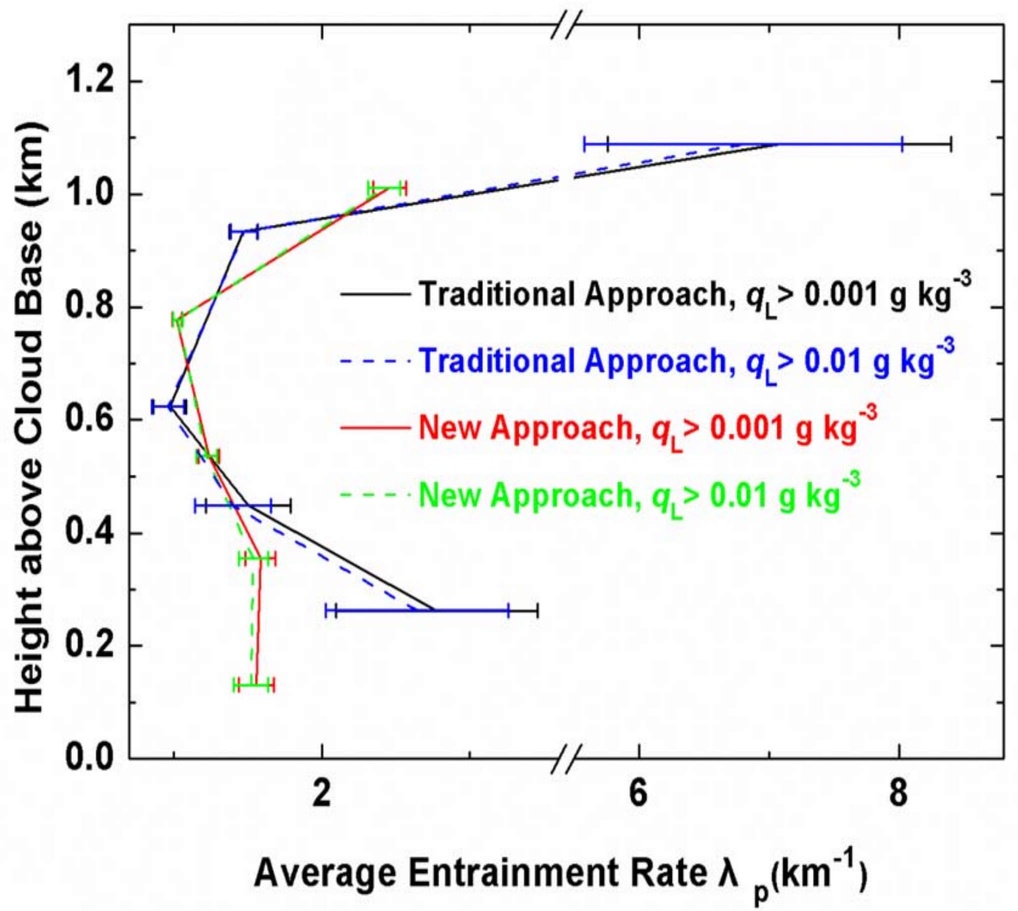




Further parameterization of the scale number leads to a much needed parameterization for homogeneous mixing fraction.

*Lu et al 2011: Examination of turbulent entrainment-mixing mechanisms using a combined approach. J. Geophys. Res.; 2012: Relationship between homogeneous mixing fraction and transition scale number, Environ. Res. Lett.*

# Entrainment-Mixing Processes: New Approach for Estimating Entrainment Rate

- **Elimination of need for in-cloud measurements of temperature and water vapor**
- **Smaller uncertainty**
- **Potential for a parameterization that directly links microphysical effects of entrainment mixing with entrainment rate**
- **Potential for a remote sensing technique to measure entrainment rate for ARM**

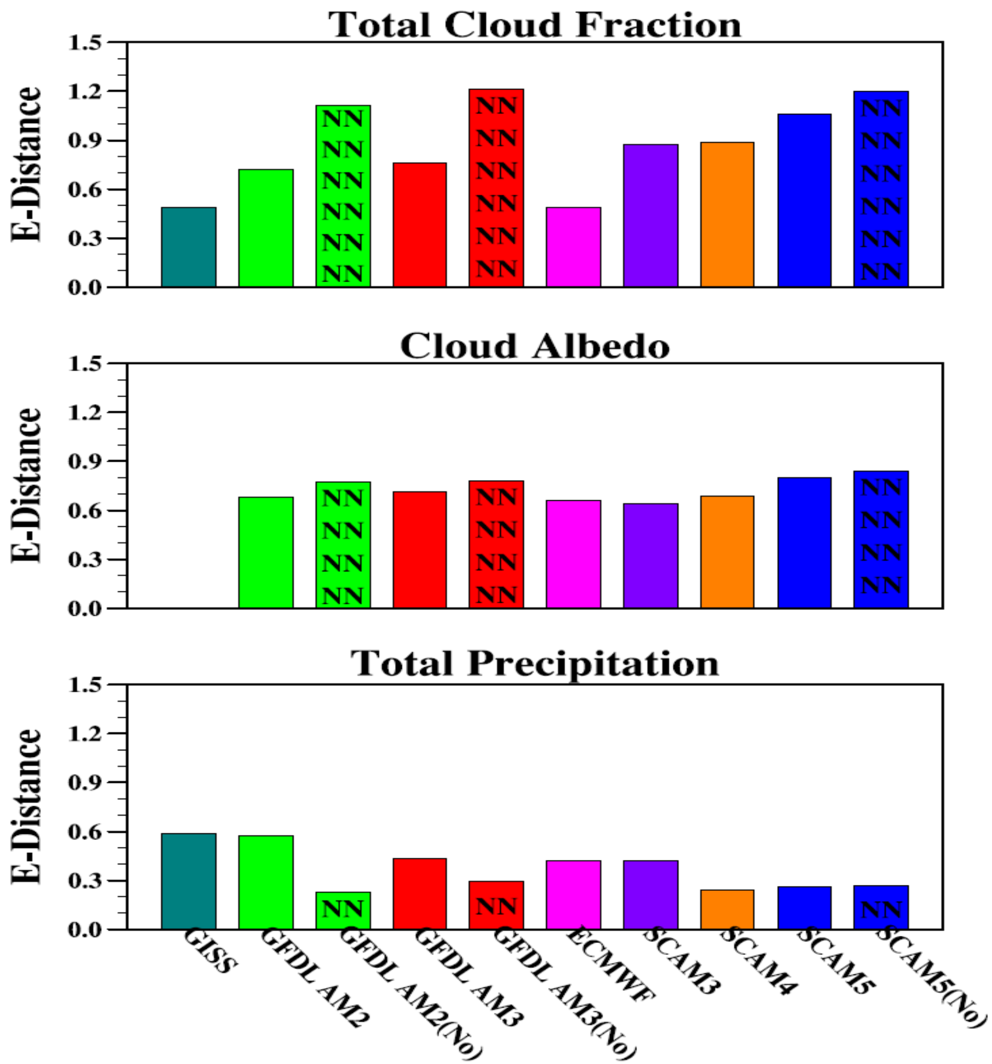



*Lu et al 2012: A new approach for estimating entrainment rate. Geophys. Res. Lett.*

# New Metric – Relative Euclidean Distance

- **Traditional statistical measures: bias, standard deviation difference, correlation coefficient r**
- **A new metric that (1) measures overall performance and (2) can be used to compare not just different models but different quantities: Relative Euclidean Distance:**

$$D = \sqrt{\left[\frac{(\overline{M}-\overline{O})}{\overline{O}}\right]^2 + \left[\frac{(\sigma_M-\sigma_O)}{\sigma_O}\right]^2 + (1-r)^2}$$




**Decrease of D from cloud fraction to precipitation is consistent with that SCM precipitation is better constrained by large scale forcing.**

# Evaluation of Surface Flux Schemes

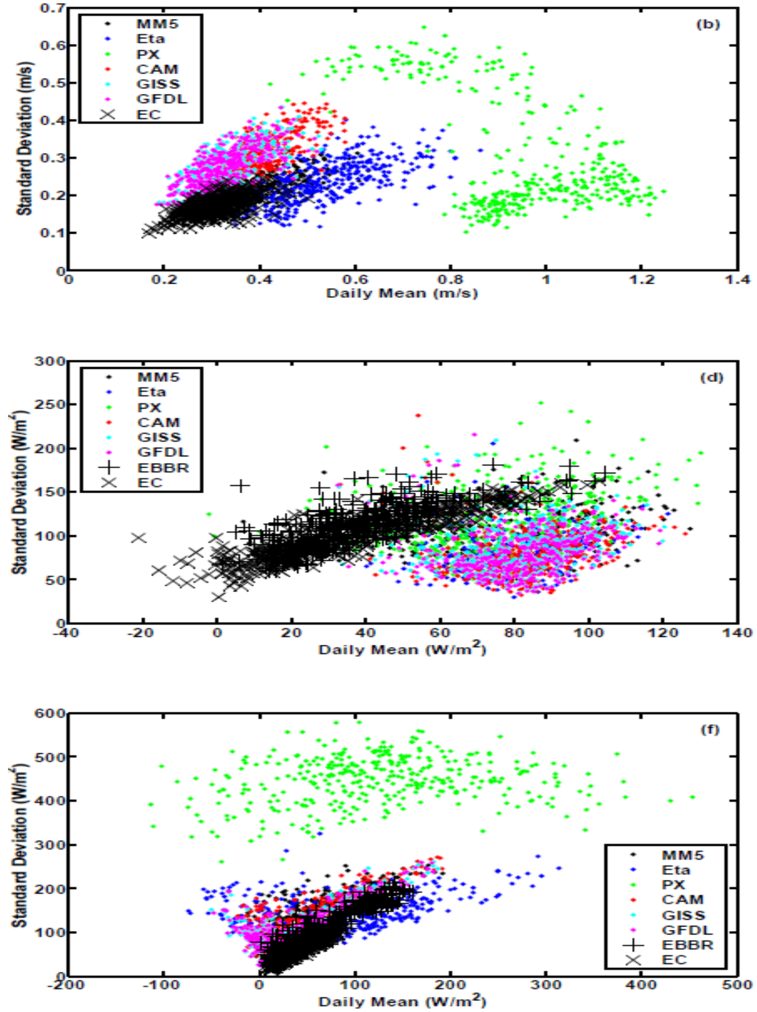
• 5 major schemes in GCM and WRF

• 7 year SGP measurements

• Model performance in terms of relation between daily mean and standard deviation

• Parameterizations can be wrong in mean, standard deviation, or both

**Standard Deviation**




**Momentum flux**

**Sensible heat flux**

**Latent heat flux**

**Daily Mean**

*Liu et al 2012: Evaluation of surface flux parameterizations using long-term ARM measurements. Mon. Wea. Rev. (Revised)*

# Evaluation of Aerosol Cloud Interactions

## Overview:

- Observations from ARM IOPs are being utilized to evaluate the interactions between clouds and aerosols in the NASA GISS ModelE.

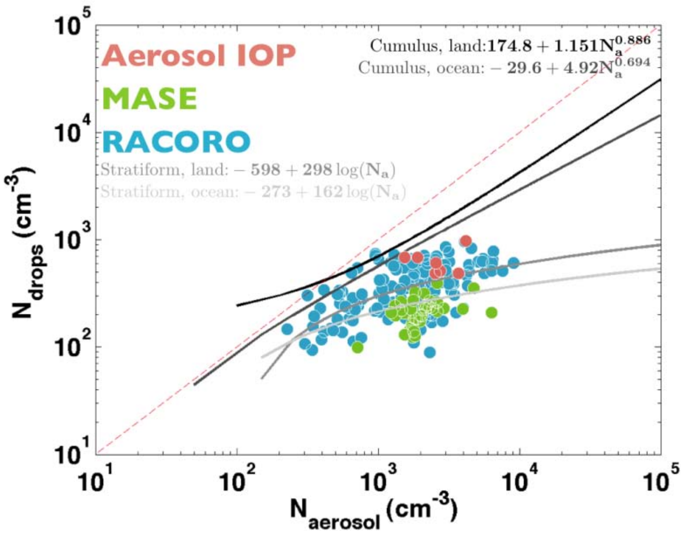
- Parameterizations of droplet activation, droplet effective radius, and relationships between surface aerosol and cloud properties are tested.

## Highlights:

- Simulated droplet activation generally follows observations.

- Effective radius parameterizations result in significantly different values – the impact of these differences on climate are currently being evaluated.


**Campaigns Utilized**



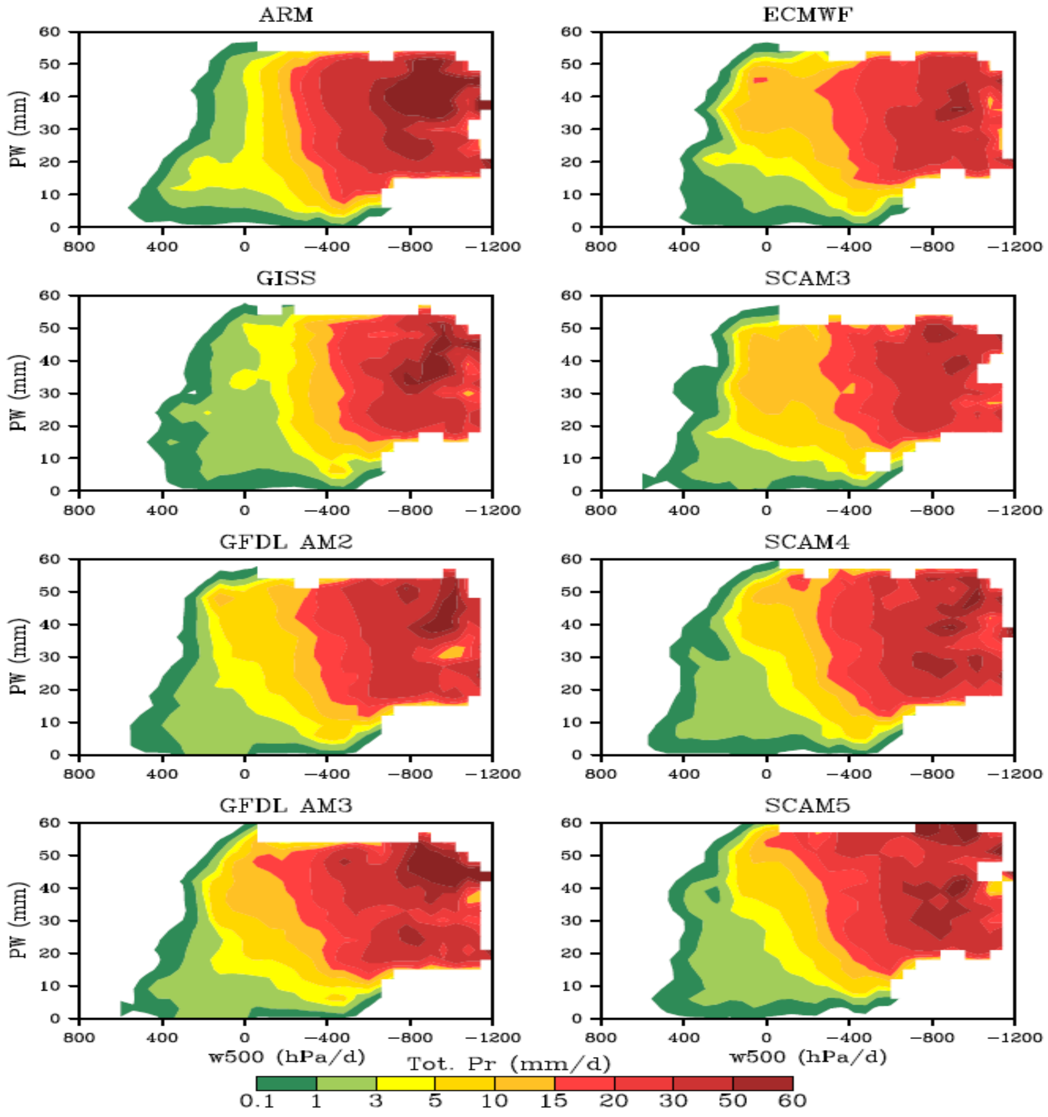

**Droplet Activation**

## Reference:

de Boer, G., S. Menon, S.E. Bauer, T. Toto, A. Vogelmann and M. Cribb (2012): Evaluation of aerosol-cloud interactions in the GISS ModelE using ARM Observations, *Atmos. Phys. Chem.*, in preparation

# Evaluation of SCMs with ARM Measurements

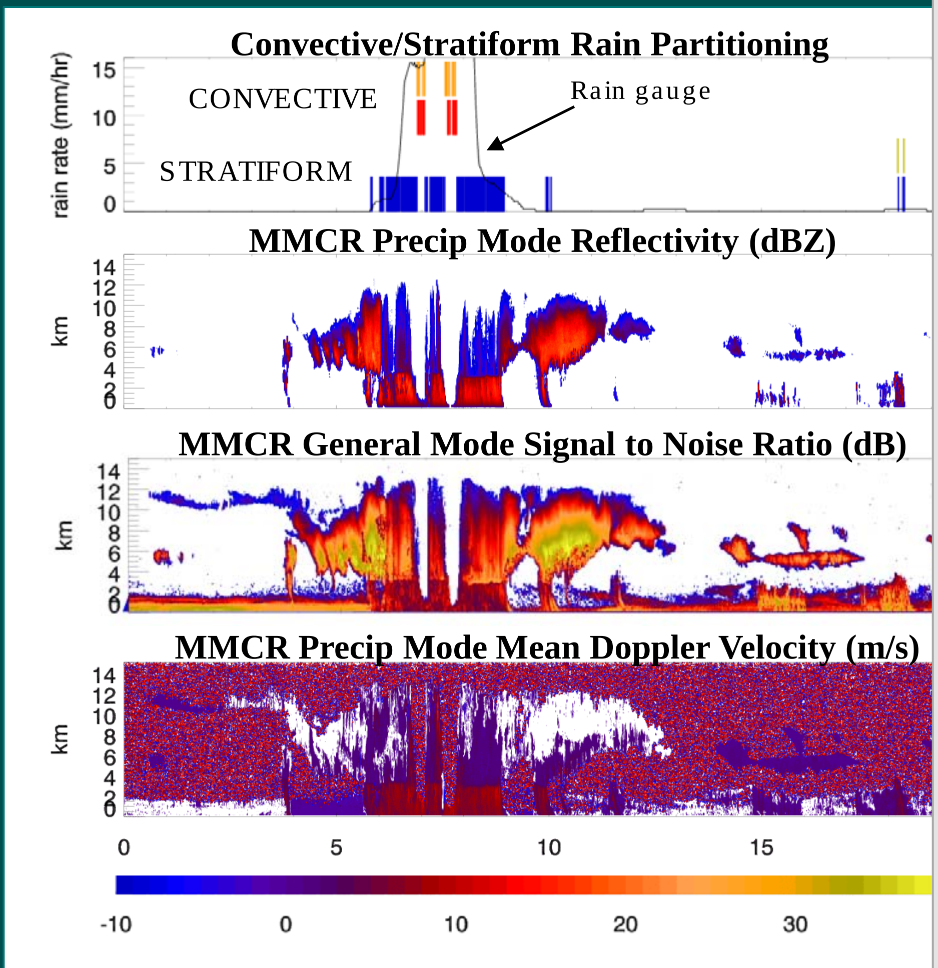
- **4 major SCMs;**
- **Different versions;**
- **3 year (1999 -2001) runs with hourly resolution**
- **Model performance as a function of surface temperature**
- **Deficient parameterizations related to convection**
- **More results next**

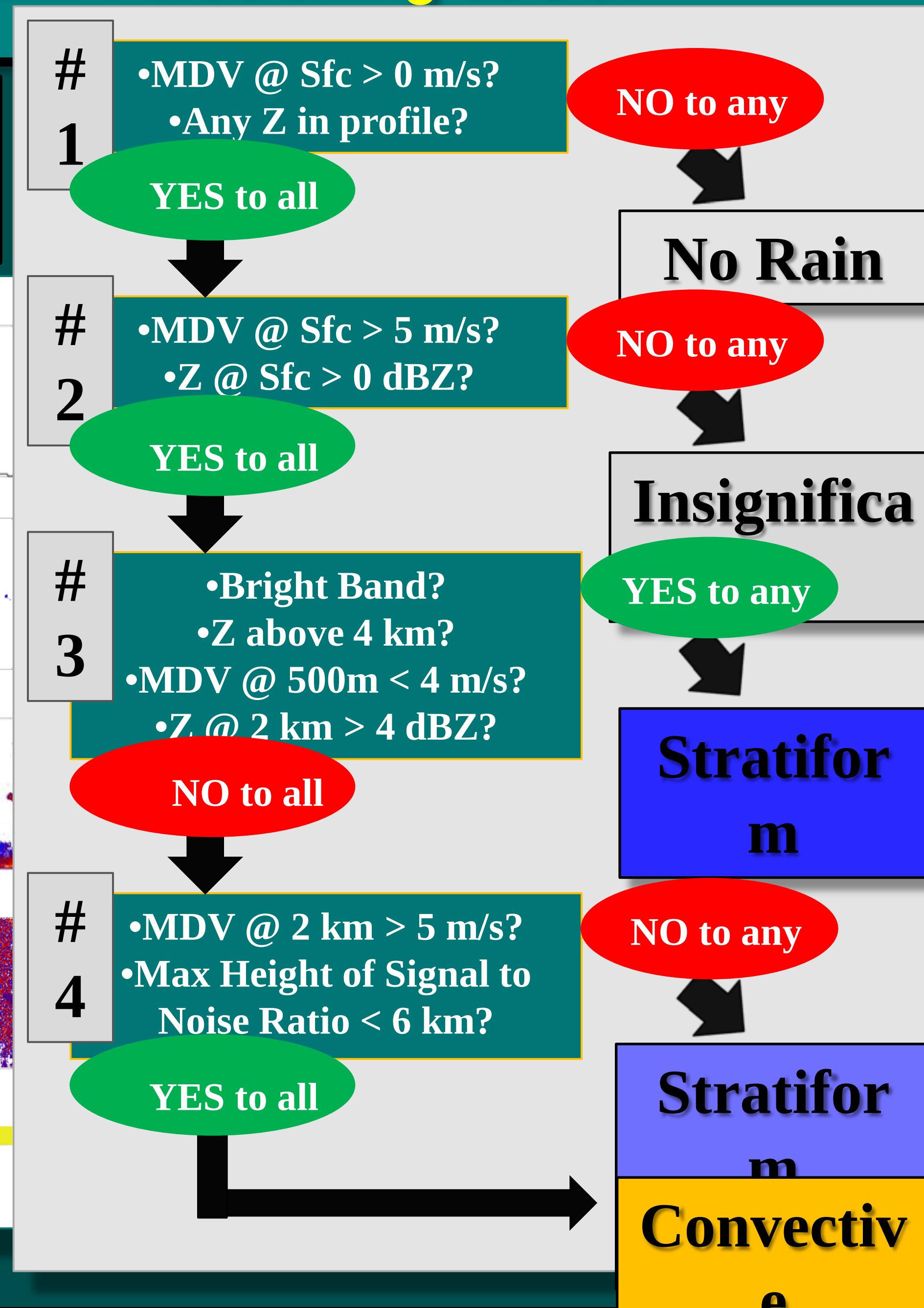



***Ref: Song et al, 2012: Observational-based evaluation of major NWP reanalyses against ARM measurementsP site. J. Geophys. Res (to be submitted)***

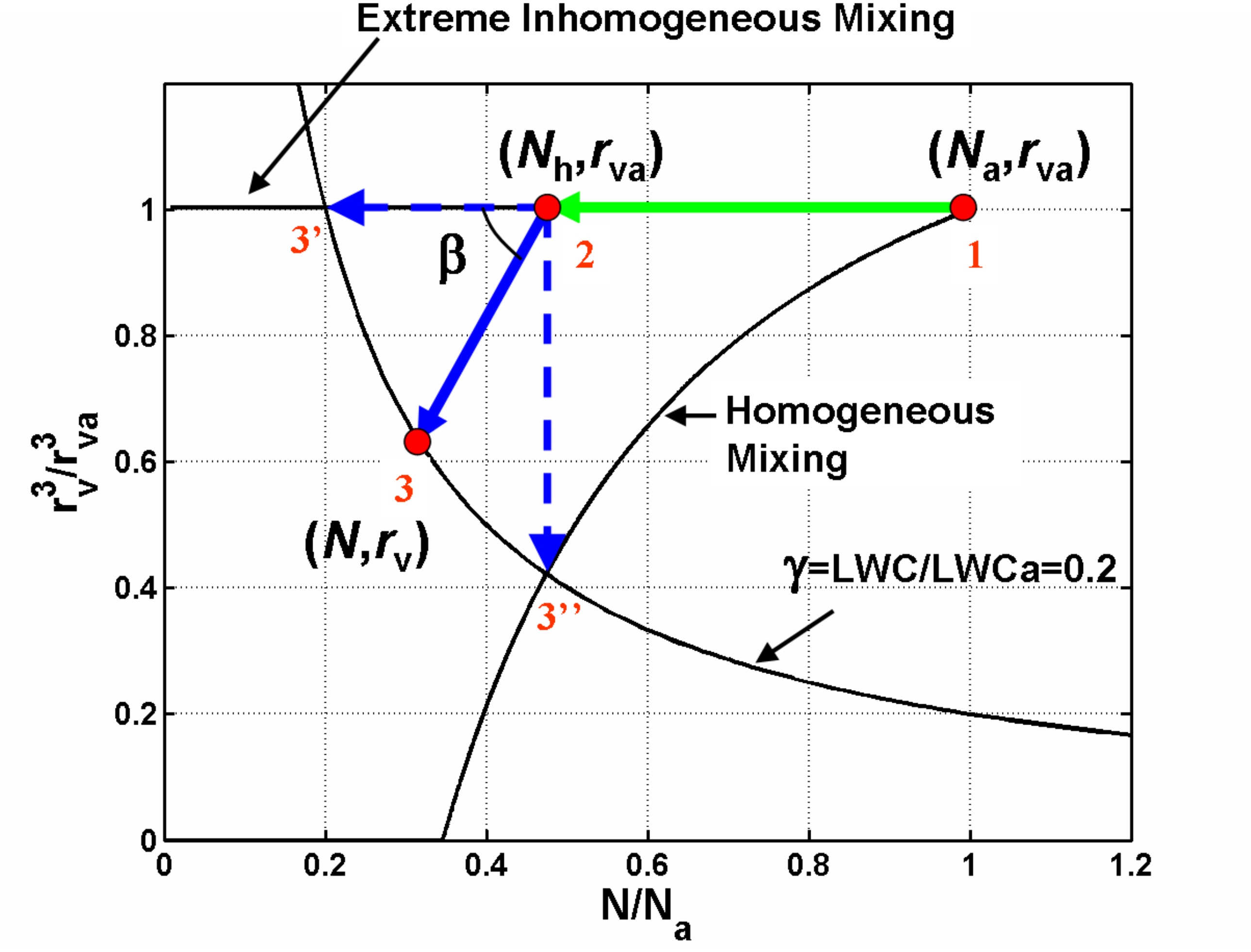
# Convective/Stratiform Rain Partitioning at SGP

Available for:
2000 - 2007



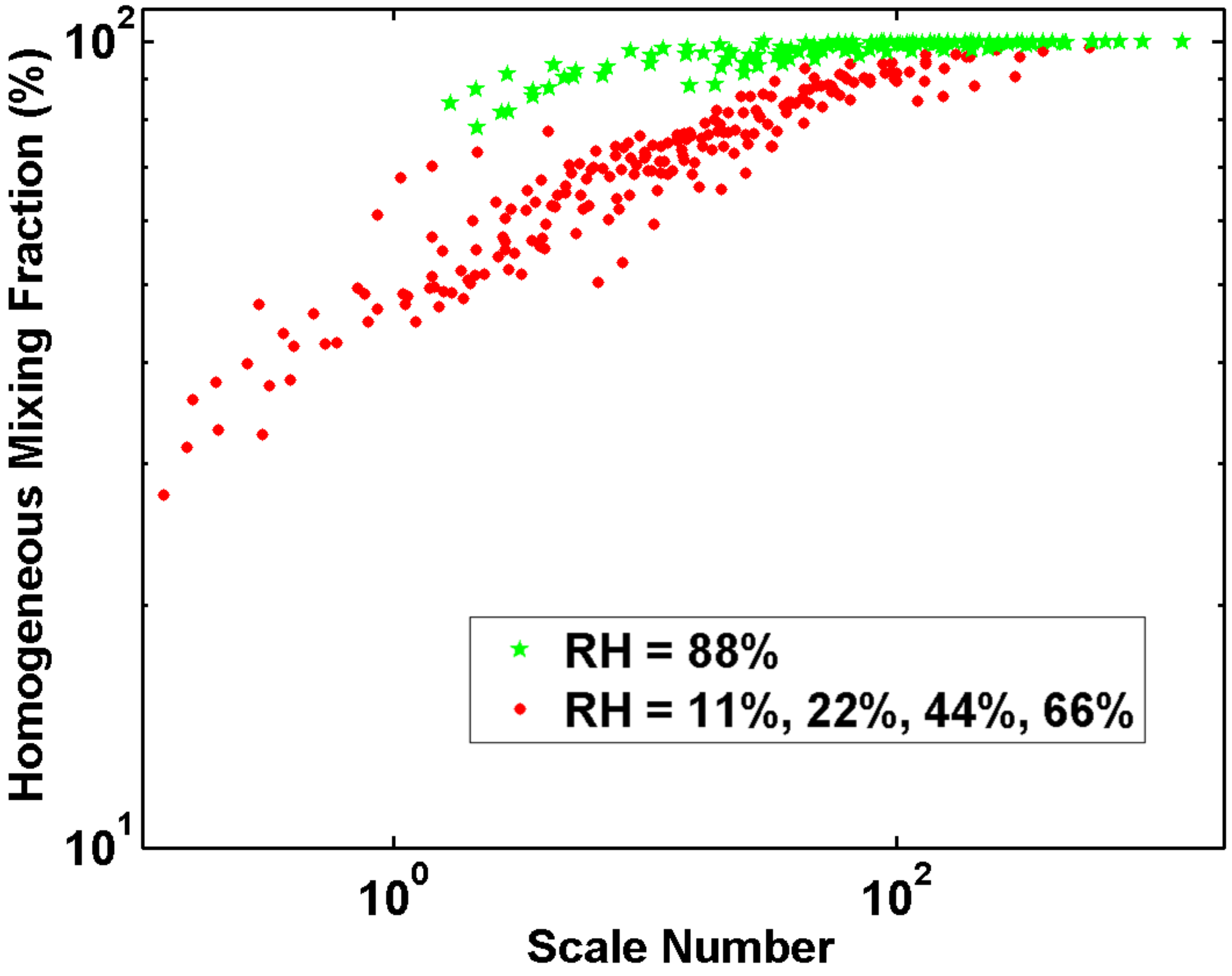



# Three Definitions of Homogeneous Mixing Fraction --- $\Psi_1$



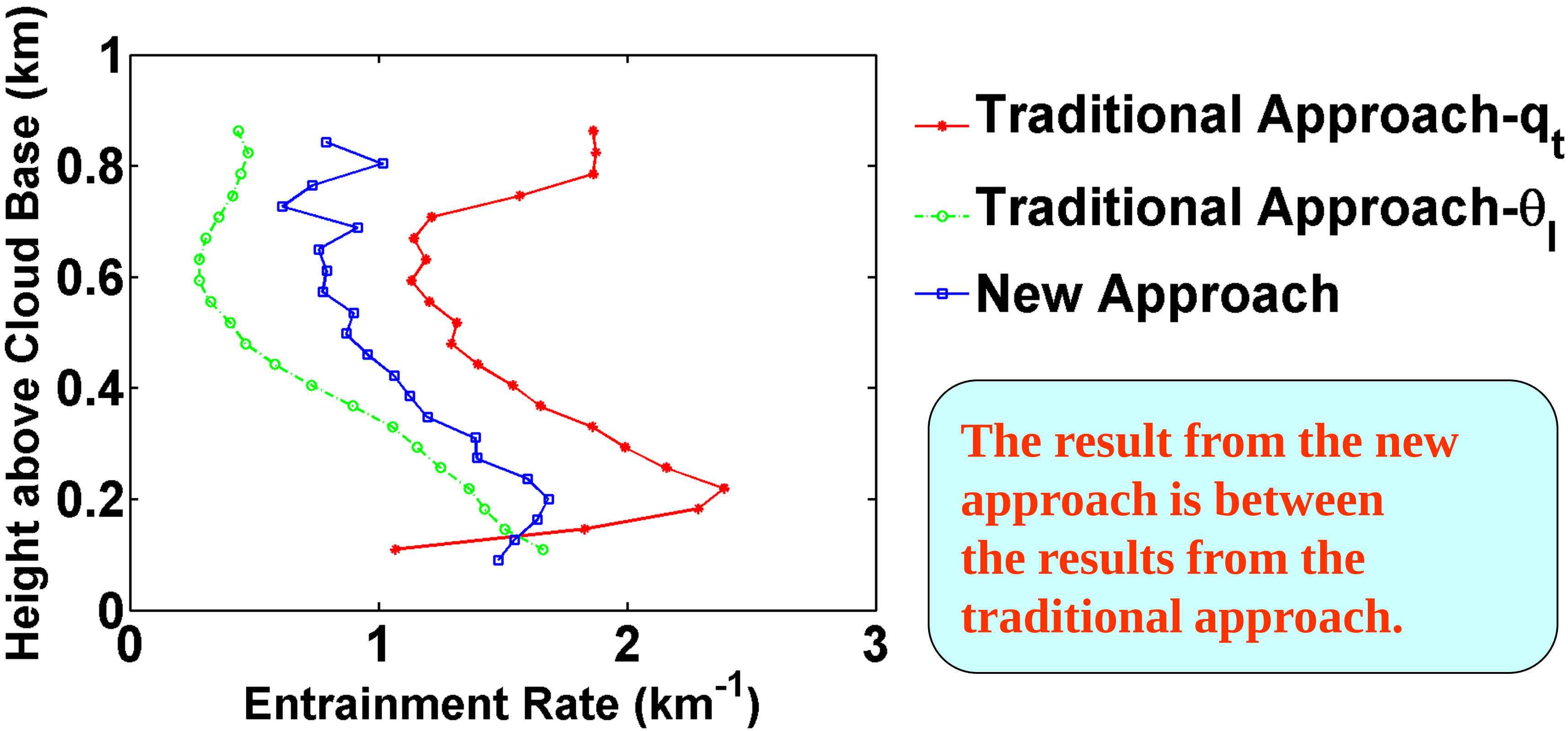

$$\psi_1 = \frac{\beta}{\pi / 2}$$

# Dependence of Homogeneous Mixing Fraction on Transition Scale Number



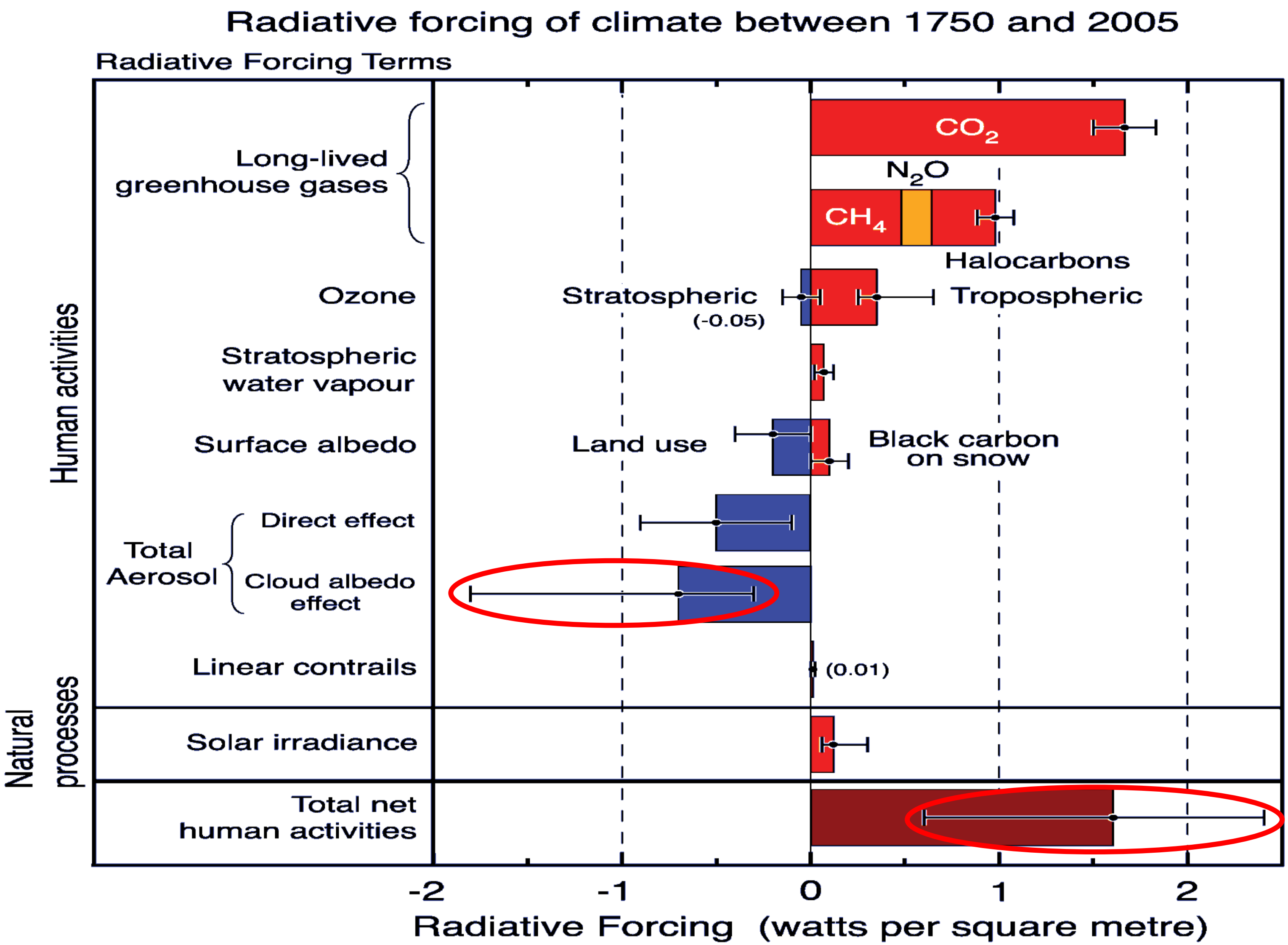
# Validation with LES Results

A benchmark case over the SGP site simulated by an LES model, WRF-FASTER (Endo et al., 2011)

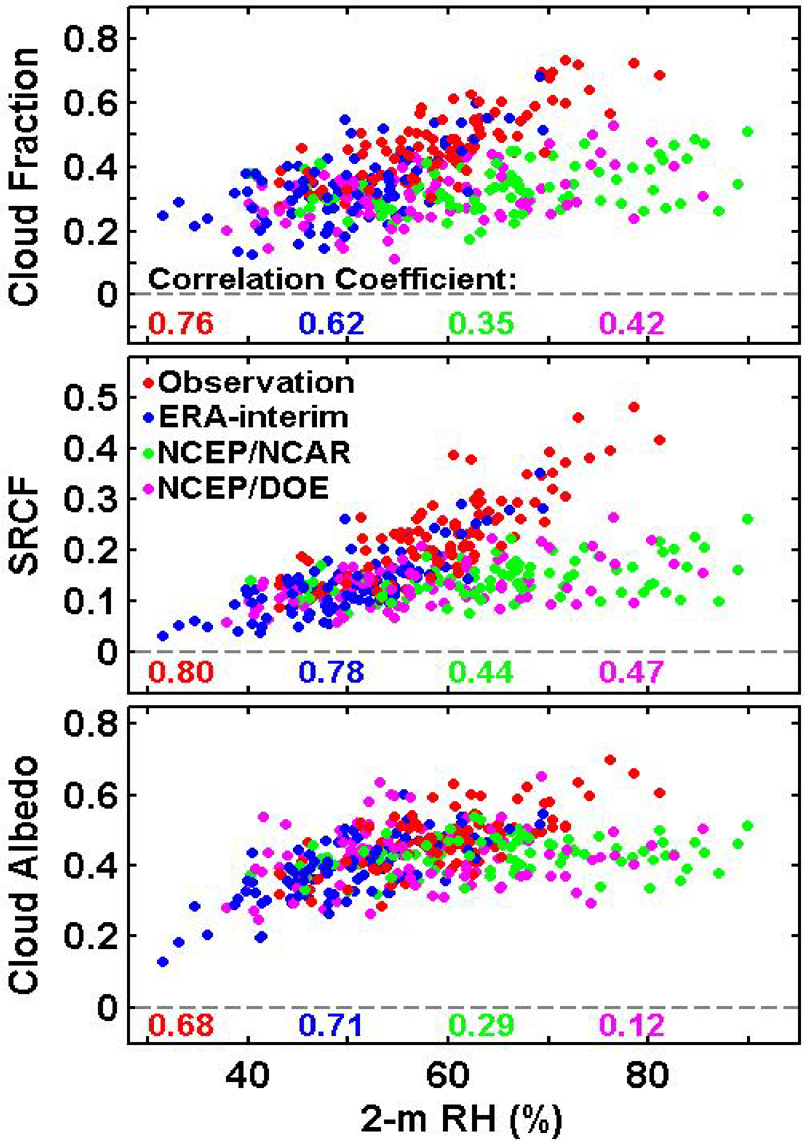



The result from the new approach is between the results from the traditional approach.

# Aerosol indirect effects constitute the major uncertainty in climate forcing!



# Cloud Properties vs 2-m RH (monthly)



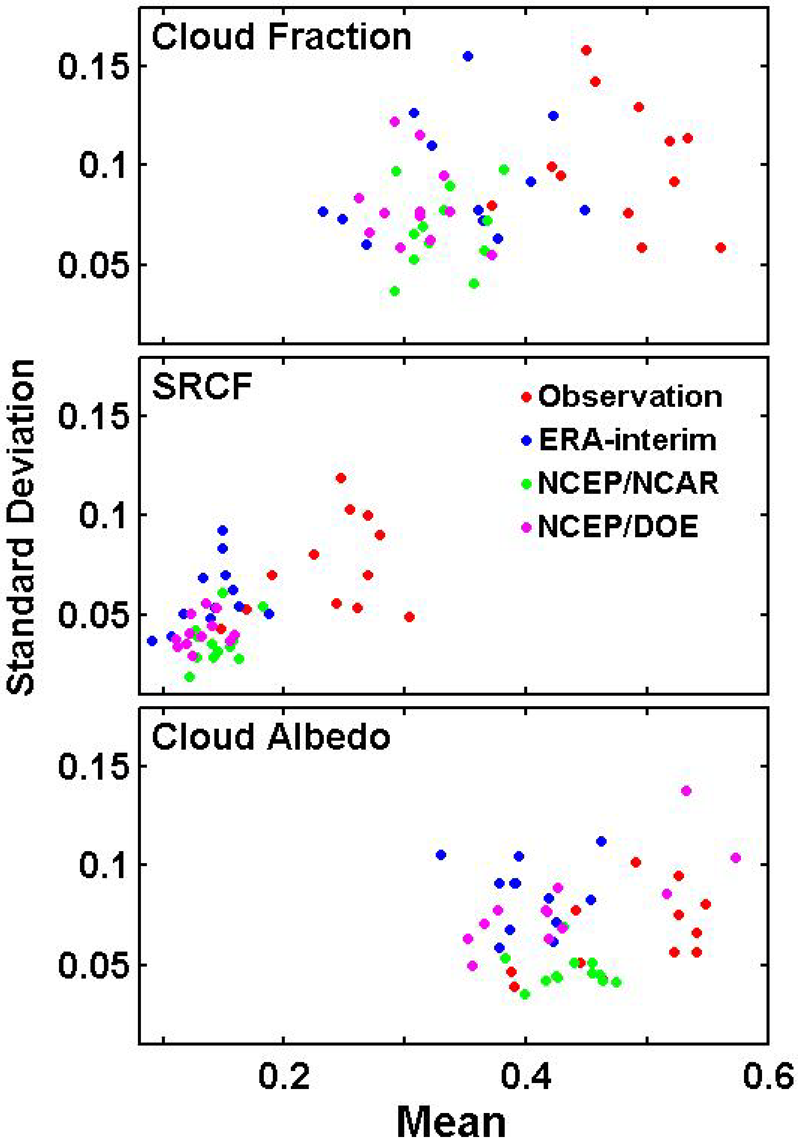

**Obs**
**ERA-Interim**
**NCEP/NCAR**
**NCEP/DOE**

**The cloud properties strongly link to the relative humidity (RH):**

- **Obs/ERA-Interim: strongest, with correlation [0.62, 0.80]**
- **R2: slightly stronger than R1 on the link between cloud fraction (or SRCF) and the RH**
- **R1/R2: relatively weak on the link between cloud albedo and the RH**

**!!! Strong link between the cloud properties and RH !!!**

# Standard Deviation vs Mean (monthly)




Obs
ERA-Interim
NCEP/NCAR
NCEP/DOE

**The standard deviation and mean of the cloud properties :**

- **Obs: overall largest mean/std for the cloud properties**
- **ERA-interim: overall second largest mean/std for cloud fraction, and second largest std for SRCF and cloud albedo**
- **R1/R2: overall similar mean/std, except R2 cloud fraction (albedo) std is slightly (significantly) larger than R1**

**!!! Observations show the largest mean/std !!!**

# Three Definitions of Homogeneous Mixing Fraction --- $\Psi_3$

$$\psi_3 = \frac{\ln N - \ln N_i}{\ln N_h - \ln N_i} = \frac{\ln r_v^3 - \ln r_{vi}^3}{\ln r_{vh}^3 - \ln r_{vi}^3}$$

**This definition, $\Psi_3$, turns out to be related to $\alpha$:**

$$\psi_3 = 1 - \alpha$$

**where $\alpha$ was defined by Morrison and Grabowski (2008):**

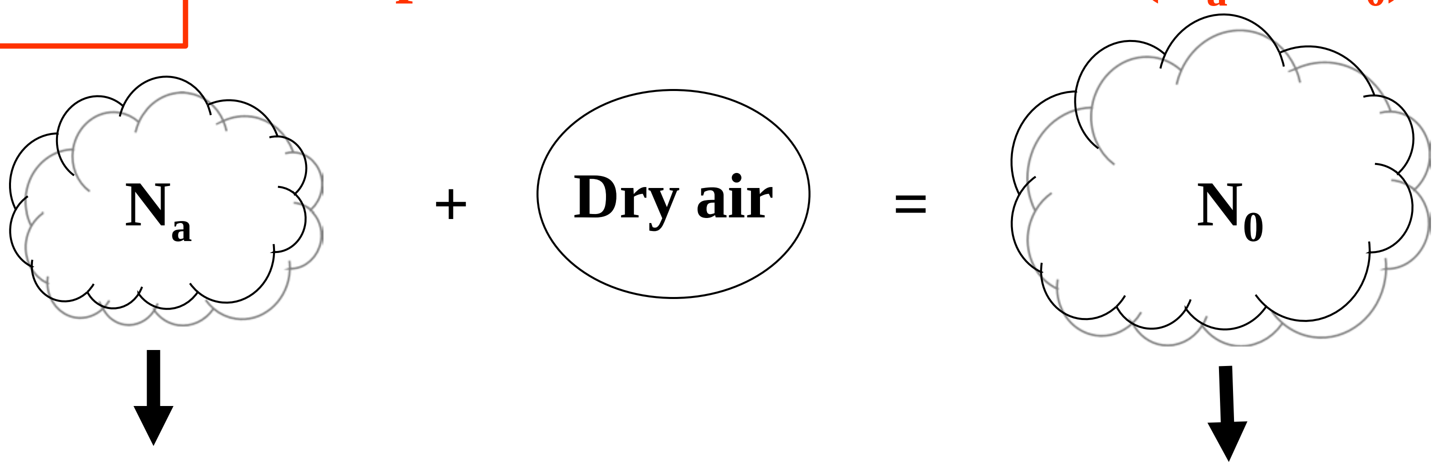
$$N = N_0 \left(\frac{q}{q_0}\right)^{\alpha}$$

# Two Transition Scale Numbers (2)

**$\tau_{react}$ is based on:**

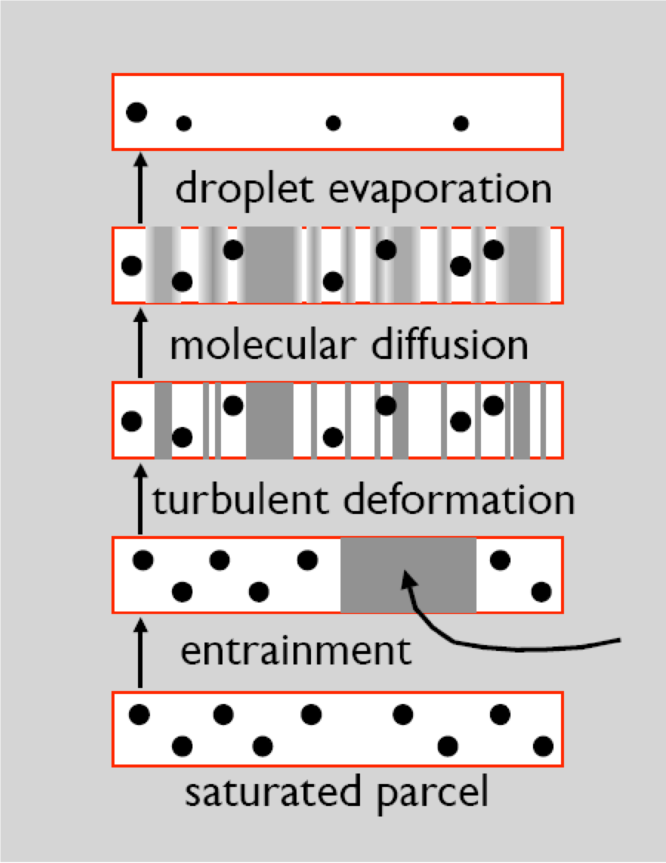
$$\begin{cases} \dfrac{dr}{dt} = A\dfrac{s}{r} \\ \dfrac{ds}{dt} = -Brs \end{cases}$$

***r*: droplet radius;**
***s*: supersaturation;**
***A*: a function of pressure and temperature;**
***B*: a function of pressure, temperature and droplet number concentration ($N_a$ or $N_0$).**




**Scale Number $N_{La}$** **$N_{L0}$**

# Explicit Mixing Parcel Model (EMPM)




**Krueger (2008)**

**Domain size:**

**20 m× 0.001 m × 0.001 m ;**

**Adiabatic Number Concentration:**

**102.7, 205.4, 308.1, 410.8, 513.5 c**

**Relative humidity:**

**11%, 22%, 44%, 66%, 88%;**

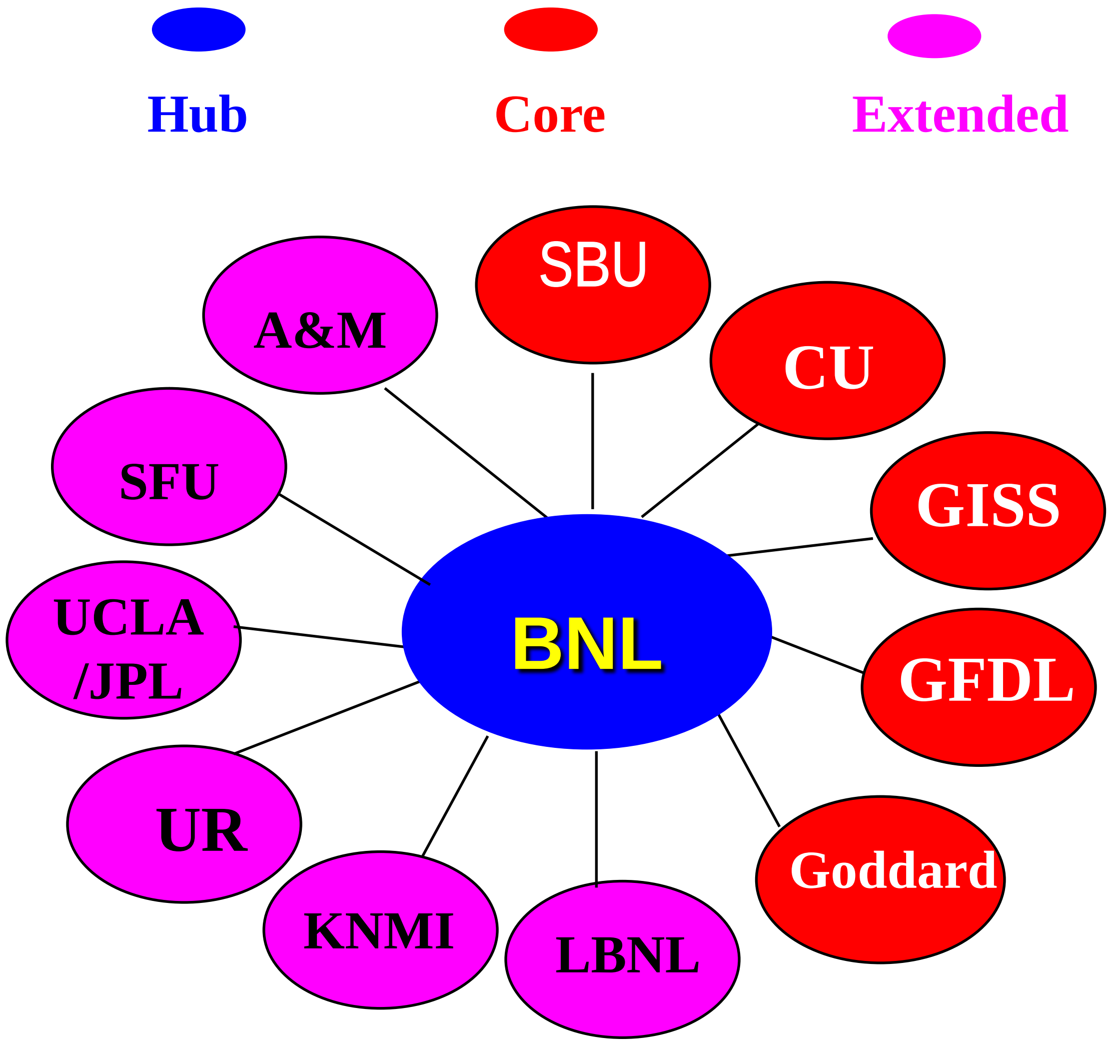
**Dissipation rate:**

**1e-5, 5e-4, 1e-3, 5e-3, 1e-2, 5e-2 m**

**Mixing fraction of dry air:**

**0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9.**

# FASTER Team

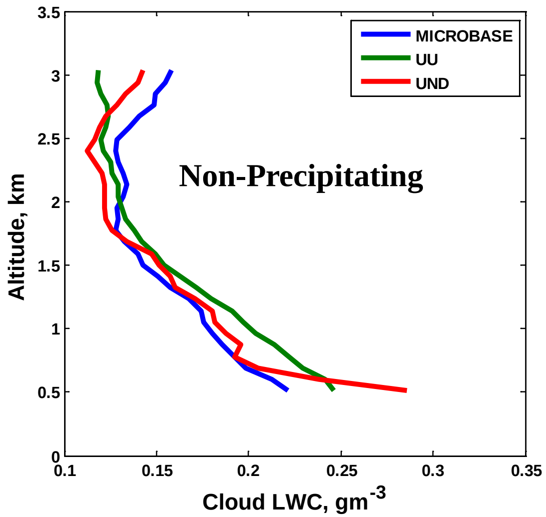


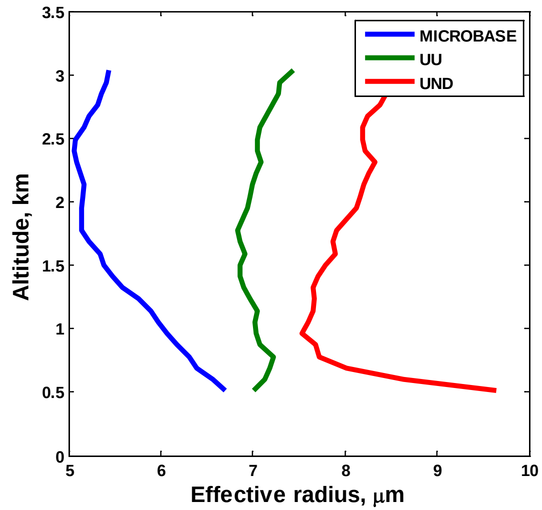

- 12 Institutions
- 24 + investigators with combined areas of expertise needed
- Major GCMs/SCMs
- **Major NWP models**
- **WRF model**
- **CRM/LES models**
- **Observations**

# Uncertainty/Spread of ARM Measurements

- **Large differences, esp. effective radius;**
- **Large difference for cloud fraction products**
- **Consideration of product spread in model evaluation;**

**Microphysical retrievals from 1998 to 2006 at SGP**




**Consistent definition of cloud fraction**

- **Possible way out:**

Single radar lacks enough Information such as droplet concentration → Use period with dual frequency radar (2006-2008) to train → Calibrate existing Micro-retrievals (e.g., MICROBASE)

***References: Huang et al., 2012: An intercomparison of radar-based liquid cloud microphysics retrievals and implication for model evaluation studies. Atmos. Mea. Tech, submitted. In press***