Relationship between Cloud Fraction and Cloud Albedo in Observations and GCMs

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(Brookhaven National Laboratory)

Motivation and Talk Structure

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

- **Fast processes are *coupled* together in the fast physics *system*;**

- **Investigation of *couplings* calls for examination of *relationships* between key variables;**

- ***Cloud fraction and cloud albedo* are two of the most important variables but often studied *in separation*;**

- **Cloud fraction and cloud albedo are also among the *best and longest* measured/derived quantities by ARM;**

- **The rest is from obs. to models, and from *GCM grid column to global;***

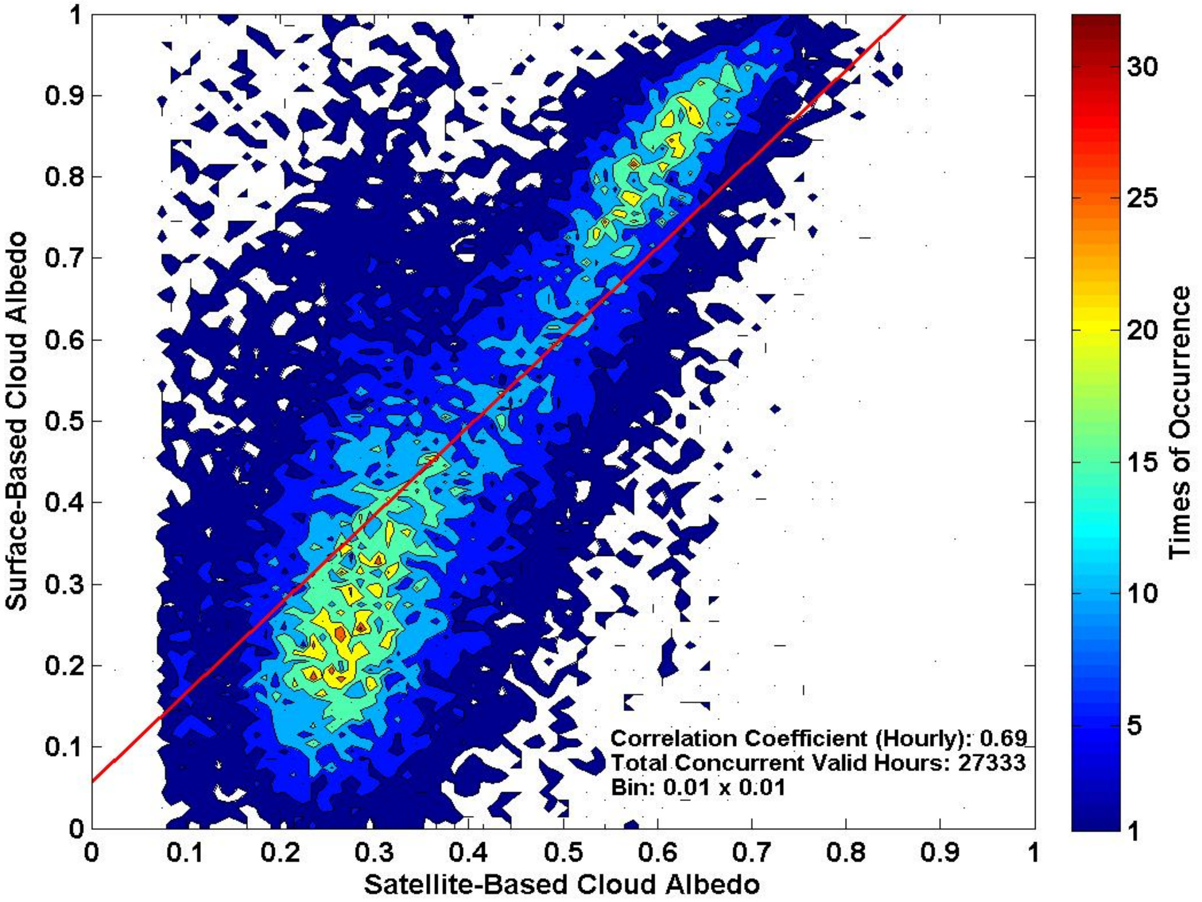
(Please see the other 12 FASTER posters)

A New Surface-Based Method for Measuring Cloud Albedo

- Recently developed an approach to infer cloud albedo from surface-based radiation measurement;
- Encouraging agreement with GOES products;
- Application to other ARM sites is underway;

(Liu et al., ACP, 11, 2011)

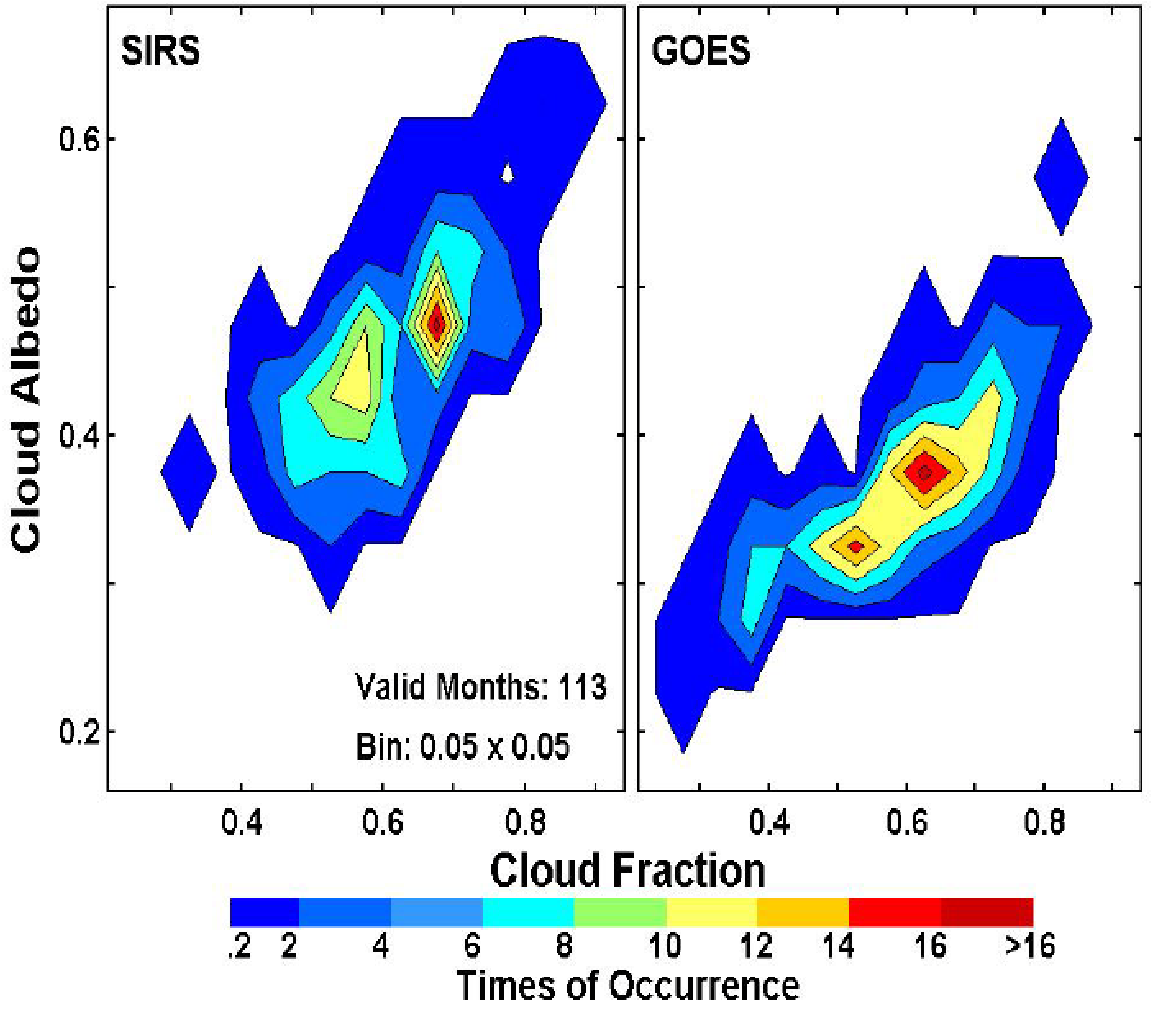
Hourly data from 1997 to 2009 at ARM SGP



Newly derived cloud albedo data, together with ARM cloud fraction measurements & various models, makes my talk possible.

Observational Evidence

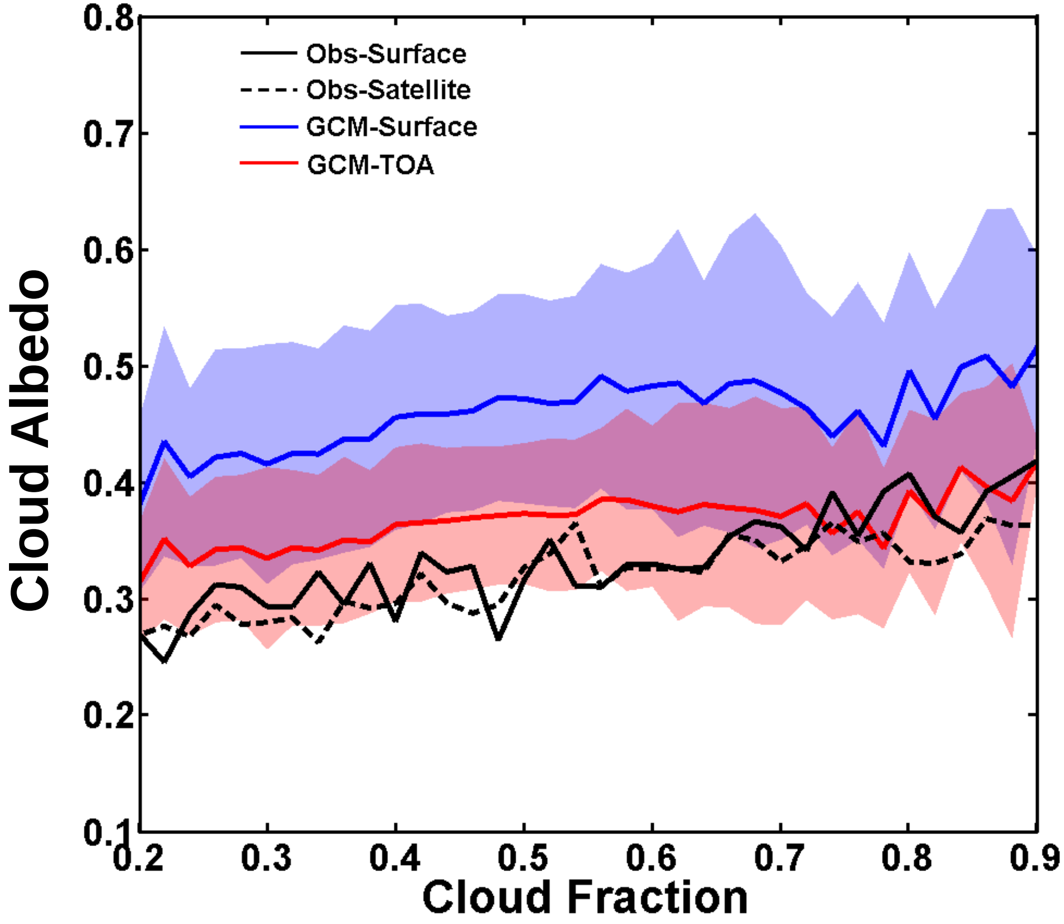
- **12 year monthly data (1997 - 2009) at the ARM SGP site**
- **Two sets of measurements: surface-based Solar Infrared Radiation System (SIRS) and GOES satellite**
- **Joint occurrence of cloud fraction and cloud albedo**
- **Conspicuous positive correlation between cloud albedo and cloud fraction for both GOES and SIRS**



Do GCMs simulate the relationship, and how well ?

Comparison between GCMs and Observations

- **IPCC AR4 GCM grid column near SGP**
- **General positive correlation**
- **Large inter-model spread**
- **Difference between TOA and surface-based cloud albedo**

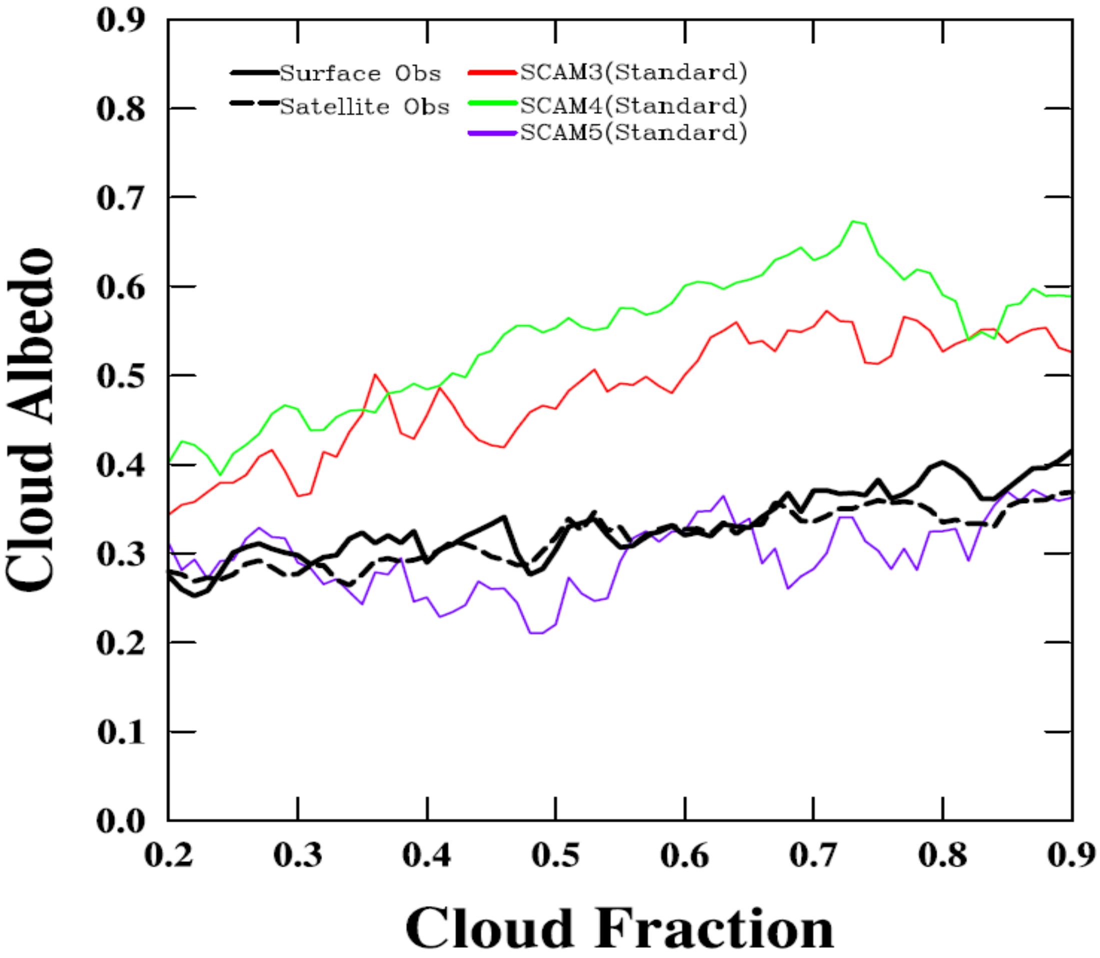


GCMs generally simulate the relation between the pair, but with intermodel and model-obs differences. Further questions are what determines the relationship and what causes the differences ?

SCM Investigation

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

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



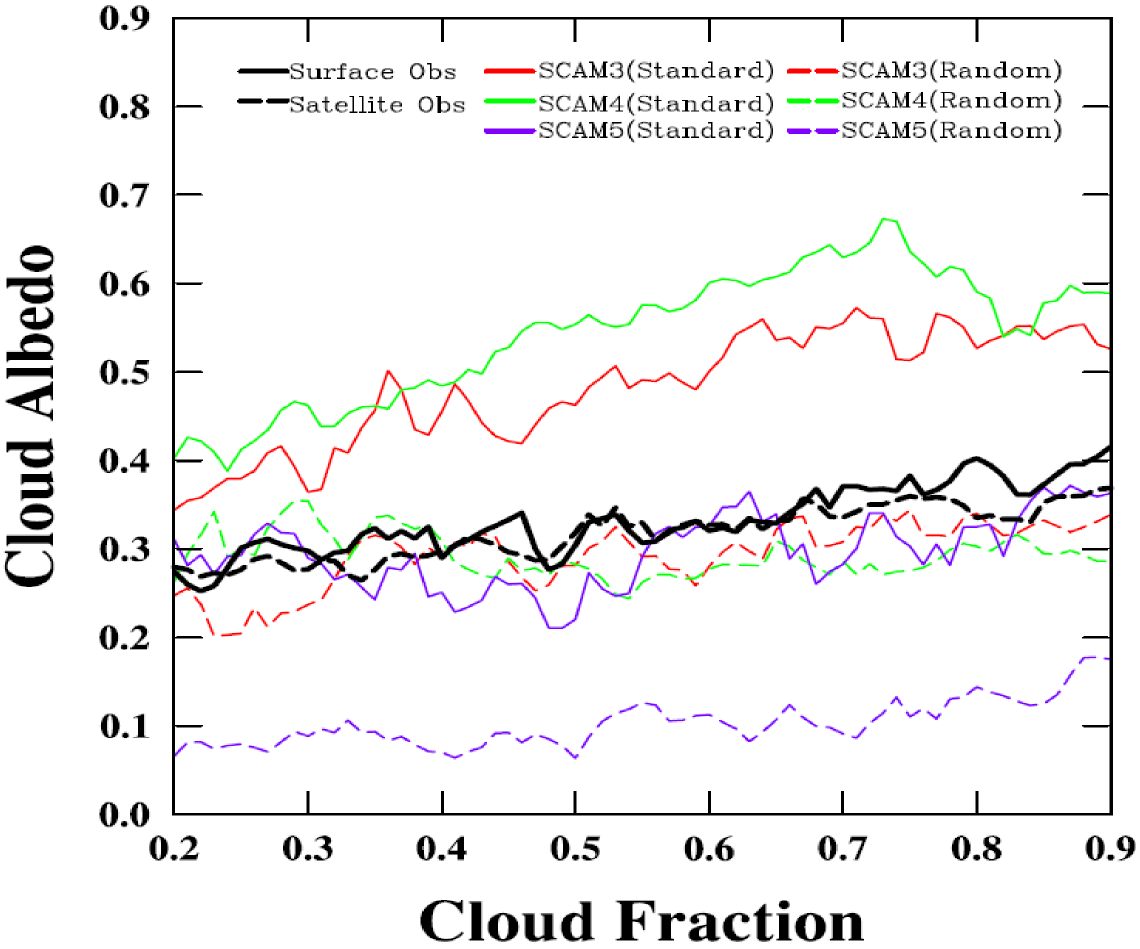
SCM Investigation

✓ 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 :**

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

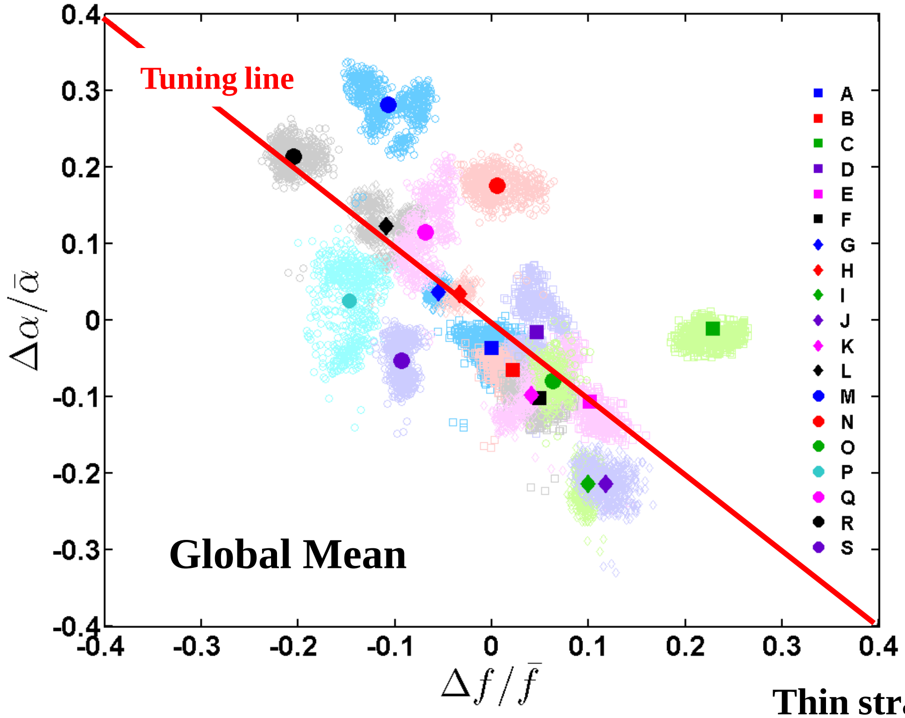
- **A more accurate expression is**

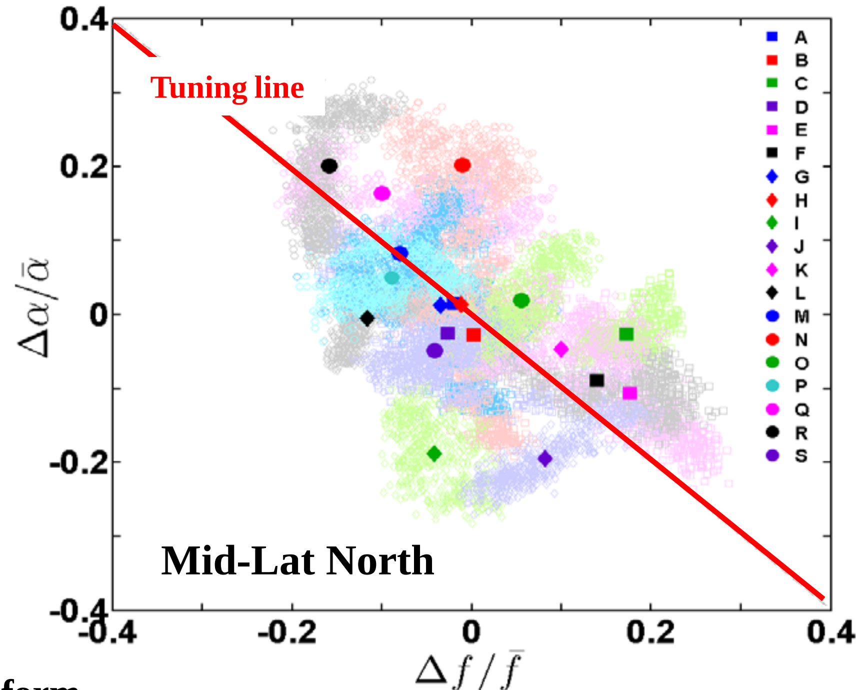
$$\frac{\Delta\alpha}{\alpha} = -\frac{\Delta f}{f}$$

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

Tuning and Compensating Errors — Evidence

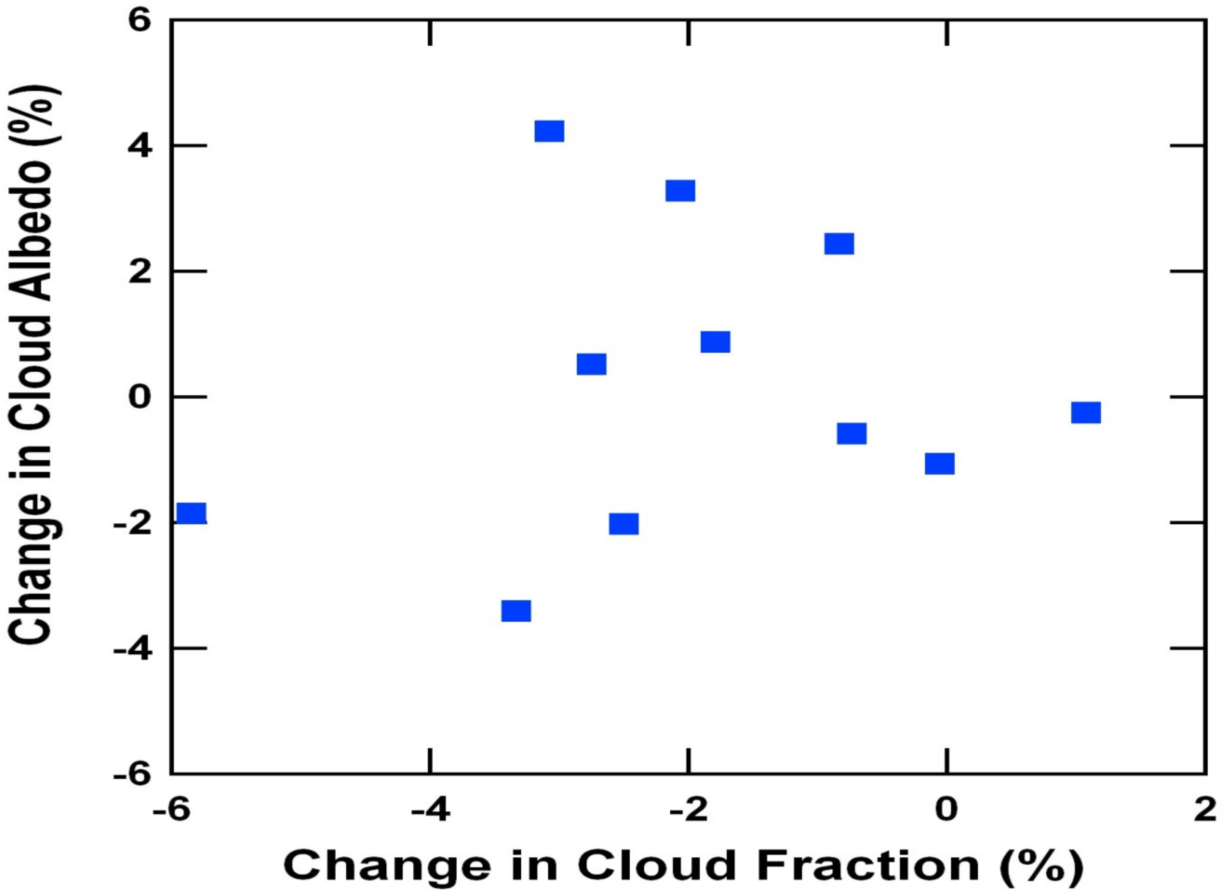
19 IPCC AR4 GCM Results





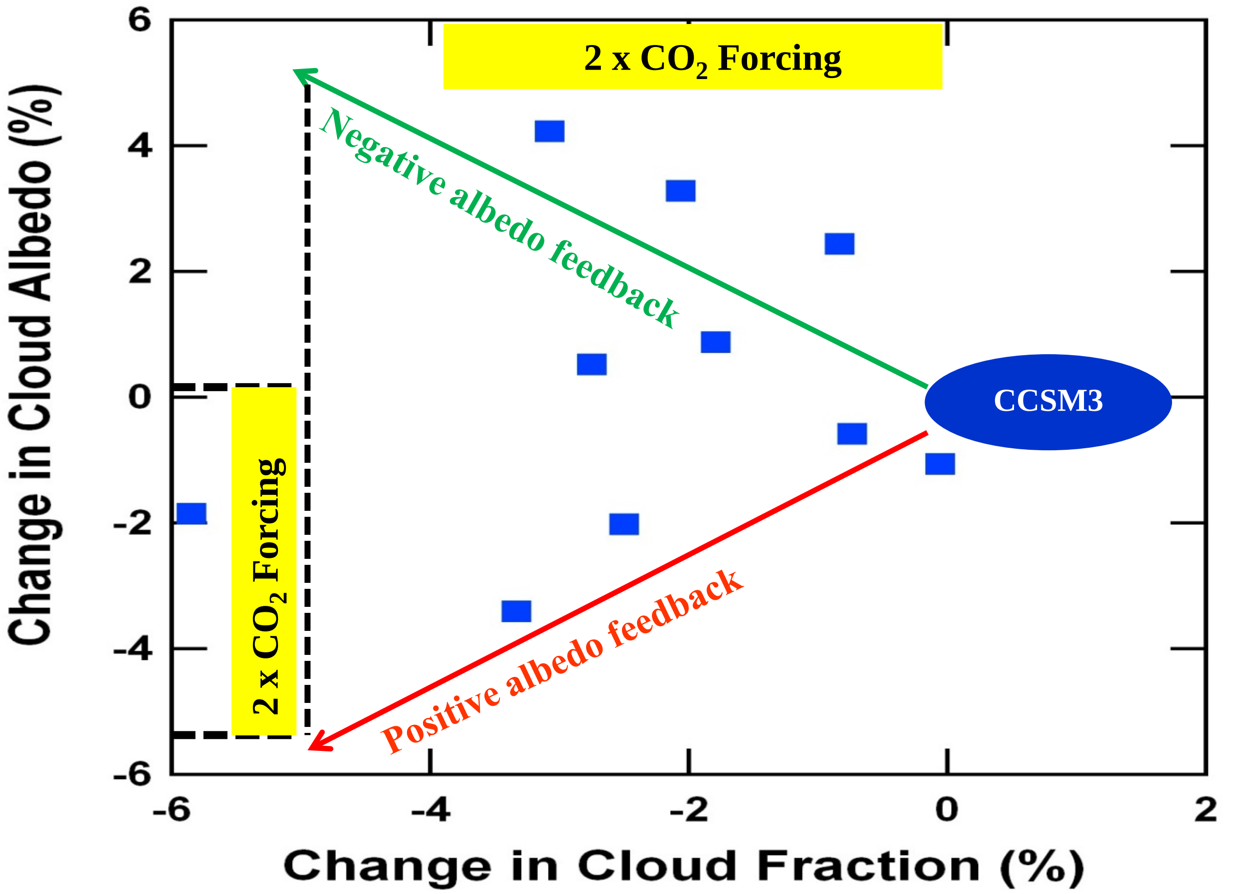
These results demonstrate that "tuning" parameterizations to observations lead to serious compensating errors, even distinct cloud regimes; we should derive parameterizations from first principles and reduce the number of tunable parameters as much as possible, and meantime look for smart objective "tuning"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

Cloud Feedback Triangle



Cloud Feedback Triangle

- **All but CCSM3 have smaller cloud fraction for doubled CO2;**
- **Changes of cloud albedo differ among GCMs (- 6% to + 6%) more than those of cloud fraction (-6% to +2%);**
- **Two albedo feedback branches: CO2-induced albedo warming and CO2-induced cooling.**

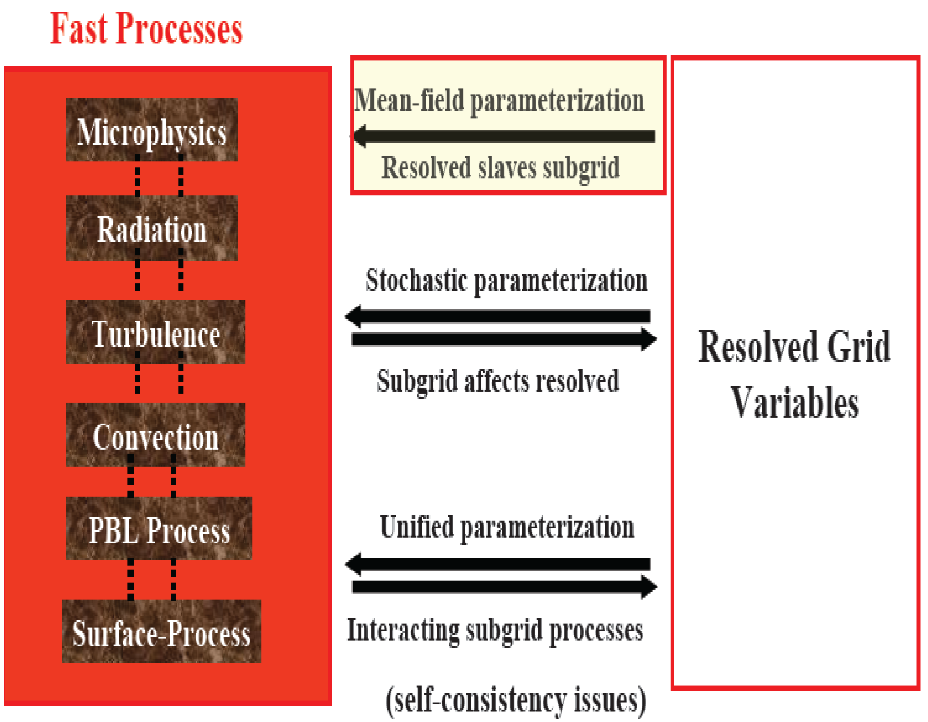


The finding that most GCMs but CCSM3 produces positive cloud fraction feedbacks whereas cloud albedo feedbacks varies from positive to negative suggests more needs for reducing albedo spread!

Future Model Evaluation and Parameterization Development

- Coupling, Coupling, Coupling, …
- Relation, Relation, Relation, …
- Consistency, Consistency, Consistency, …
- Theory, Theory, Theory, …
- Unifying, Unifying, Unifying, …

(PDF-overlap, copulas-based approach …)



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

Take-Home Messages

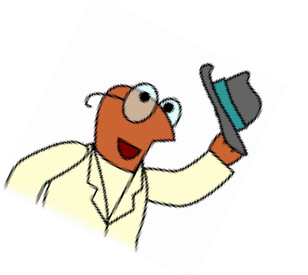
• **Physics tends to generate *positive correlation* between cloud fraction and cloud albedo;**

• **"Tuning" to match energy budgets tends to generate *negative correlation* between the pair, strong compensating errors, and even distinct cloud regimes;**

• **Relationship analysis is extremely useful to unravel model deficiencies; more is needed and underway;**

• **Multiple ways forward to fix the problems:**

-- Self-consistent, unifying parameterizations
-- More & better observations to constrain models;
-- Objective "tuning" (optimization)
-- Data assimilation



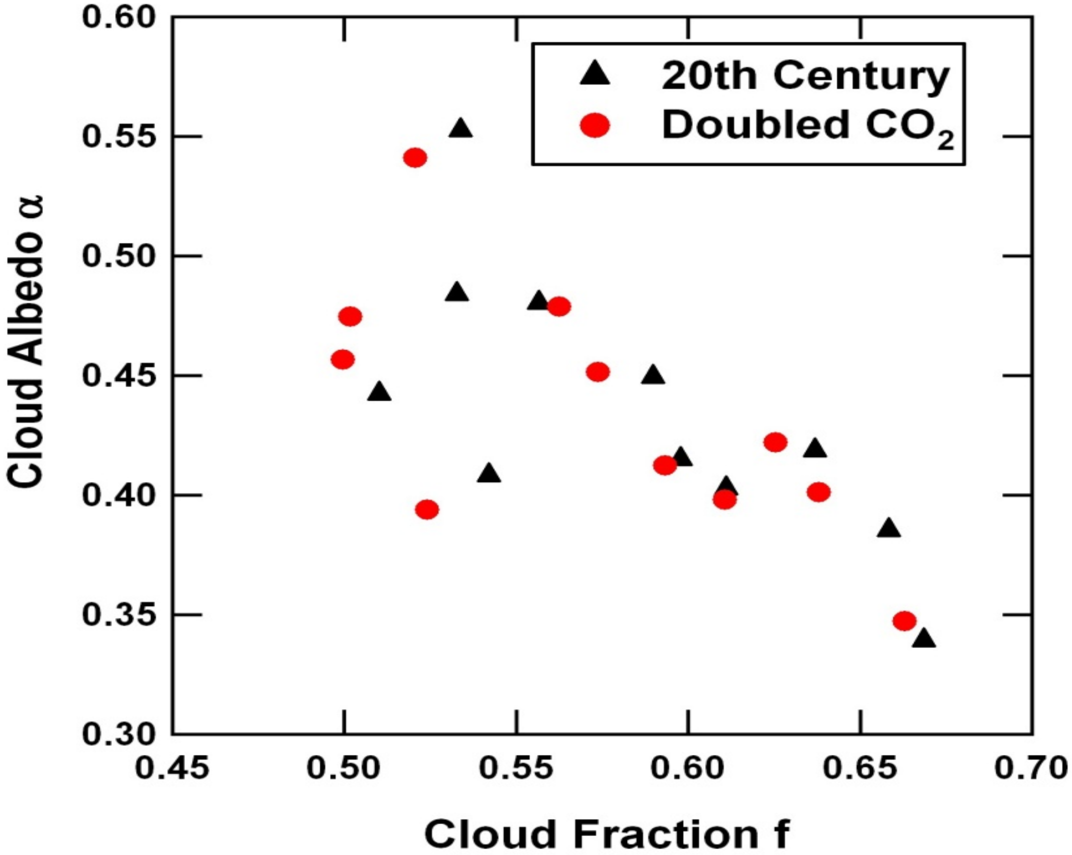
Backup Slides

Physics Underlying the Relationship ?

- Principle of Fluid Continuity: Taller clouds tend to be wider.
-

Constrained with observations/physical principles, tunable parameterizations may lead to compensating errors; we should develop and use parameterizations from first principles as much as possible.

"Tuning" Seen in 2 x CO_2 Experiment



Outline

- **FASTER is an ESM effort to bridge ESM and ASR sciences by fully utilizing ARM measurements to evaluate parameterizations of cloud-related fast processes in climate models;**

- **ARM measurements at SGP**

- **Model results and SCM investigation**

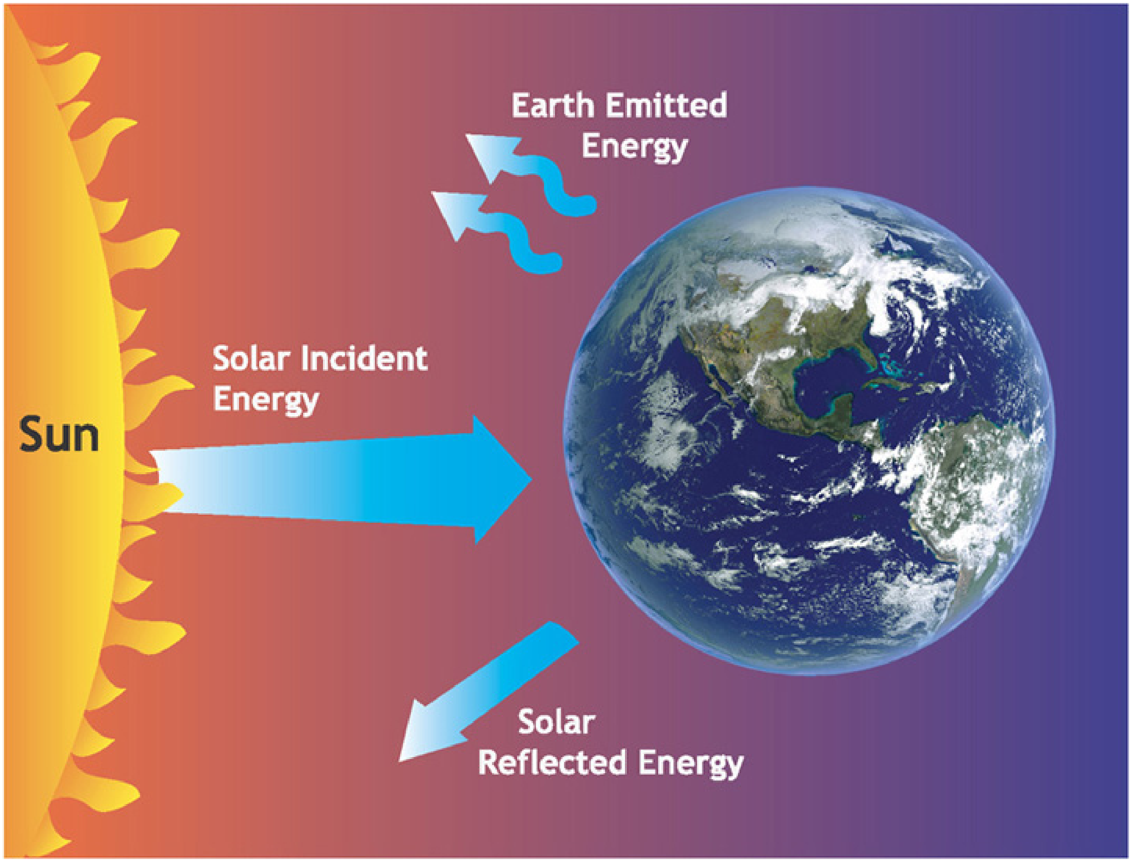
- **Application to global GCMs**
  -- Compensating errors and "tuning"
  -- Cloud feedbacks

FASTER Pyramid

Pyramid level	
Better global climate model	Ultimate goal
Acceleration of 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

21+ investigators

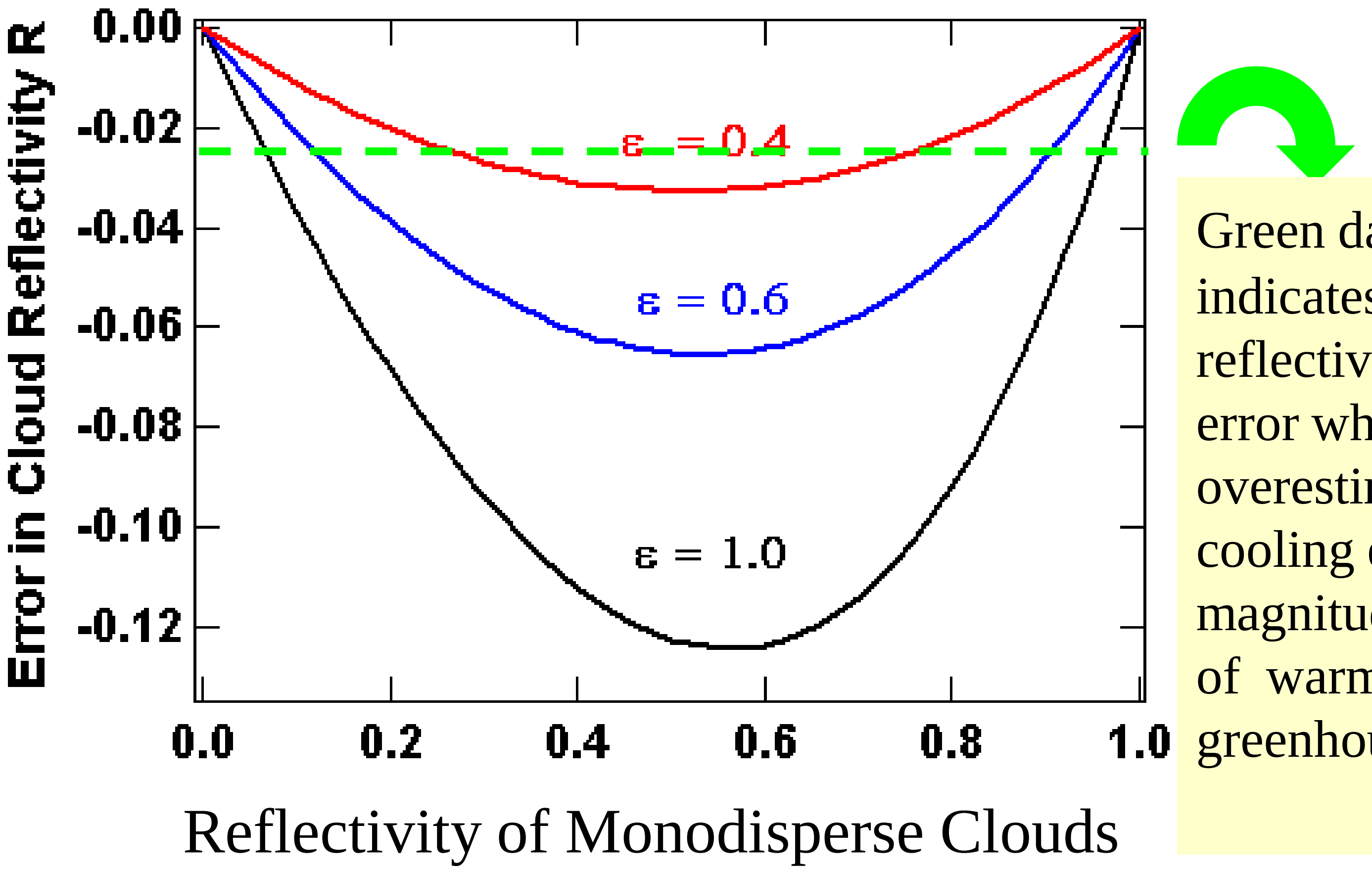
Why on Cloud Albedo and Cloud Fraction ?



Planetary albedo is determined by cloud albedo A and cloud fraction f:

$$A_p = Af + (1-f)A_0 \sim Af$$

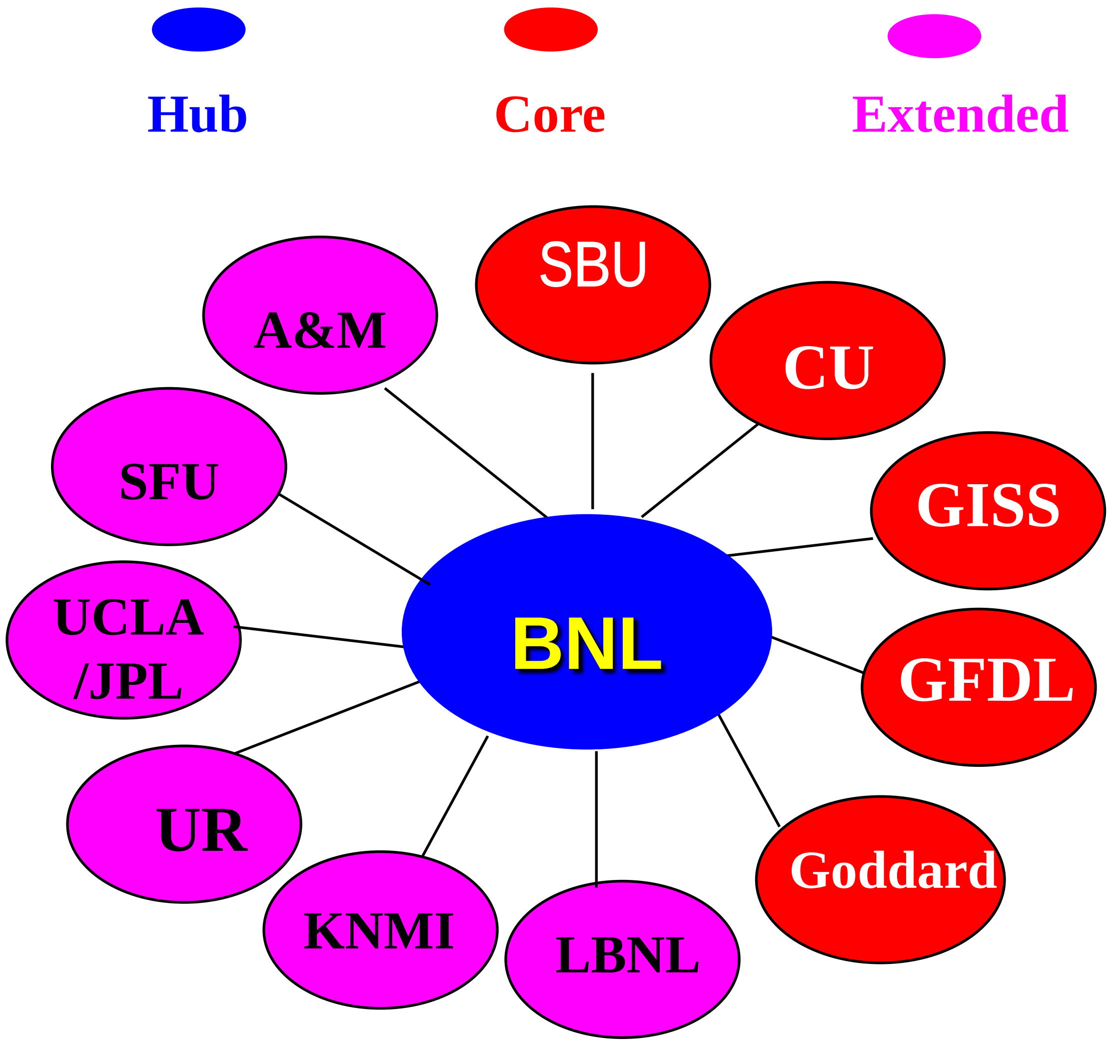
Neglect of dispersion effect significantly overestimates cloud reflectivity



Green dashed line indicates the reflectivity error where overestimated cooling equals to the magnitude of warming by greenhouse gases.

Neglecting dispersion can cause errors in cloud reflectivity, which further cause errors in temperature larger than warming by greenhouse gases. Dispersion may be a reason for overestimating cloud cooling effects by climate models.

FASTER Team



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

What is FASTER?

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

connotations and guiding principles

— system

— testbed and research

— evolve with GCMs

— faster evaluation of fast physics

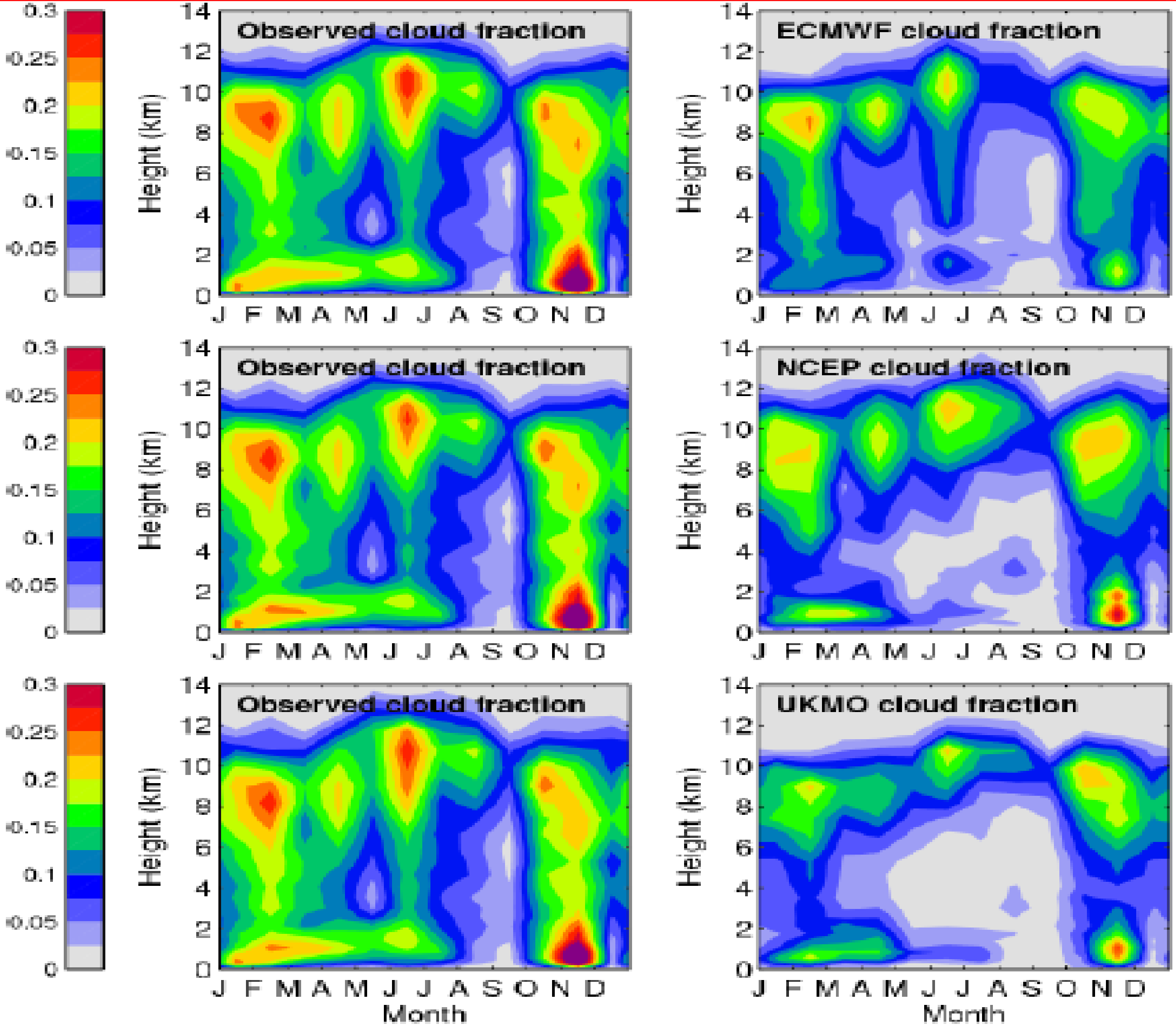
- **Result from ESM proposal "*Continuous Evaluation of Fast Processes in Climate Models Using ARM Measurements*"**

- **Funded by DOE ESM at ~ 3M/year for 5 years**

- **Co-managed by DOE ESM and ASR programs**

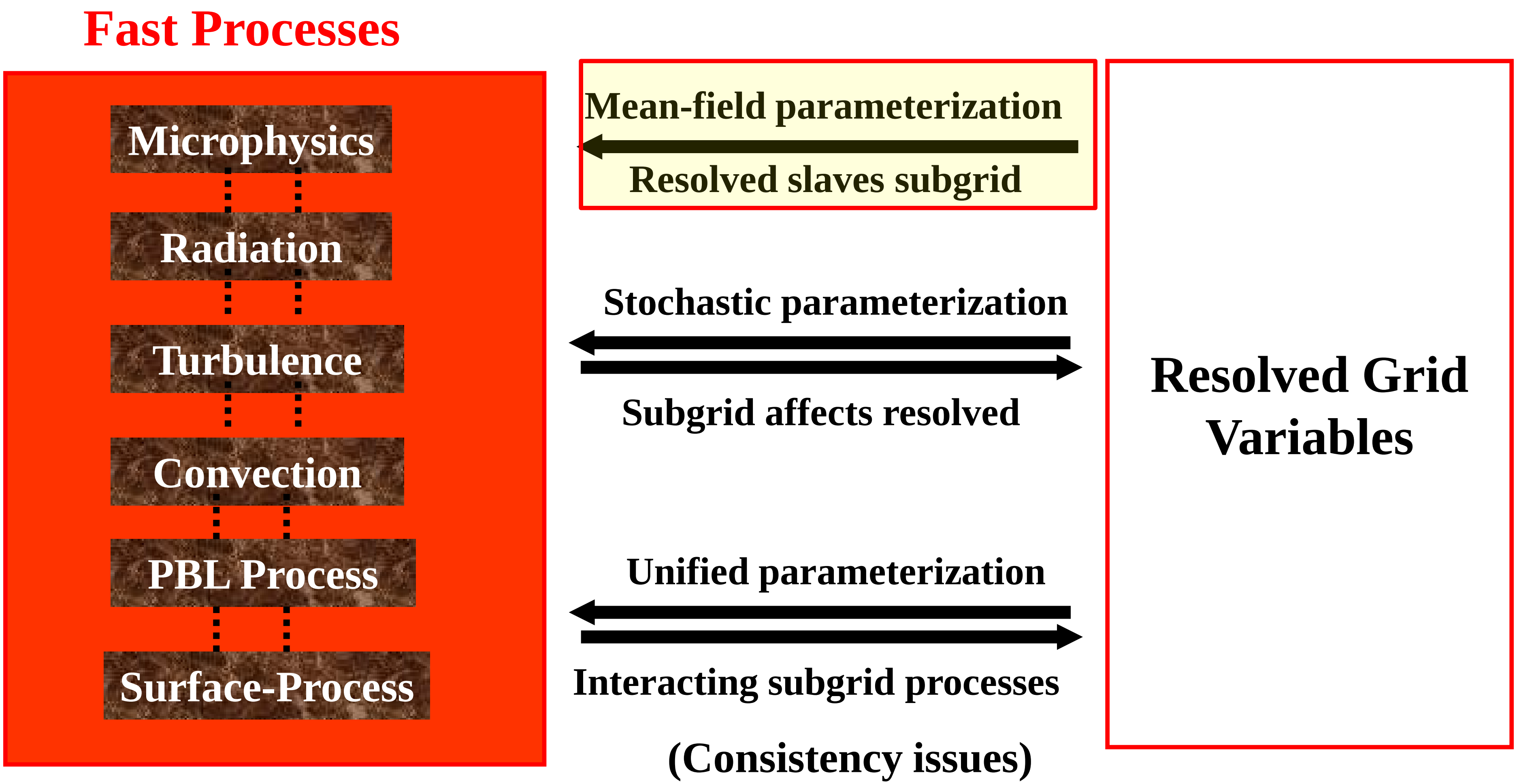
FASTER is a new DOE effort to *bridge ESM and ASR* sciences by fully utilizing *ARM* measurements to accelerate/improve evaluation and parameterization of cloud-related fast processes in global climate models.

Cloud Fraction in NWPs



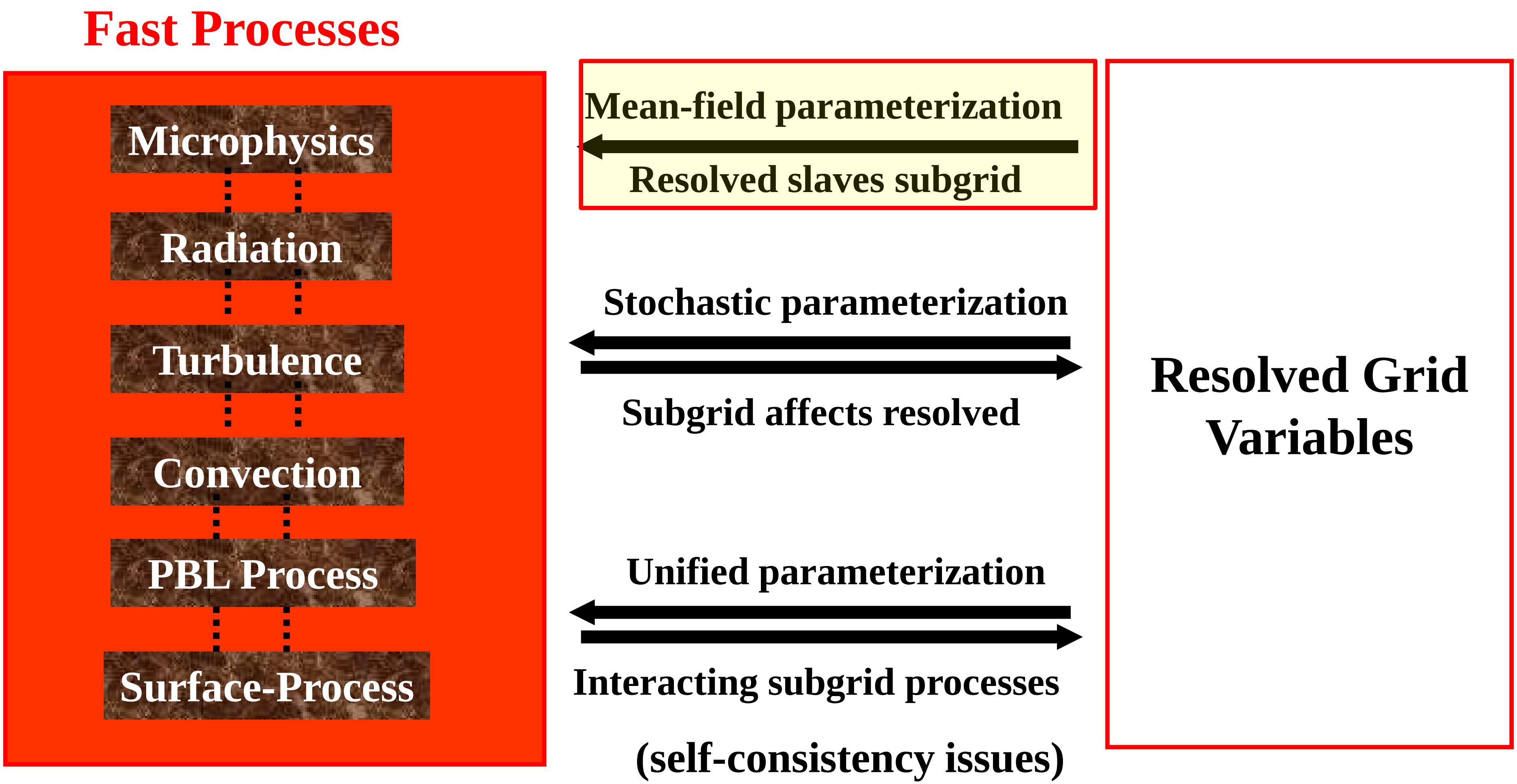
SGP 2004: Underestimated Low-Level Clouds

Scale-Dependent Parameterizations



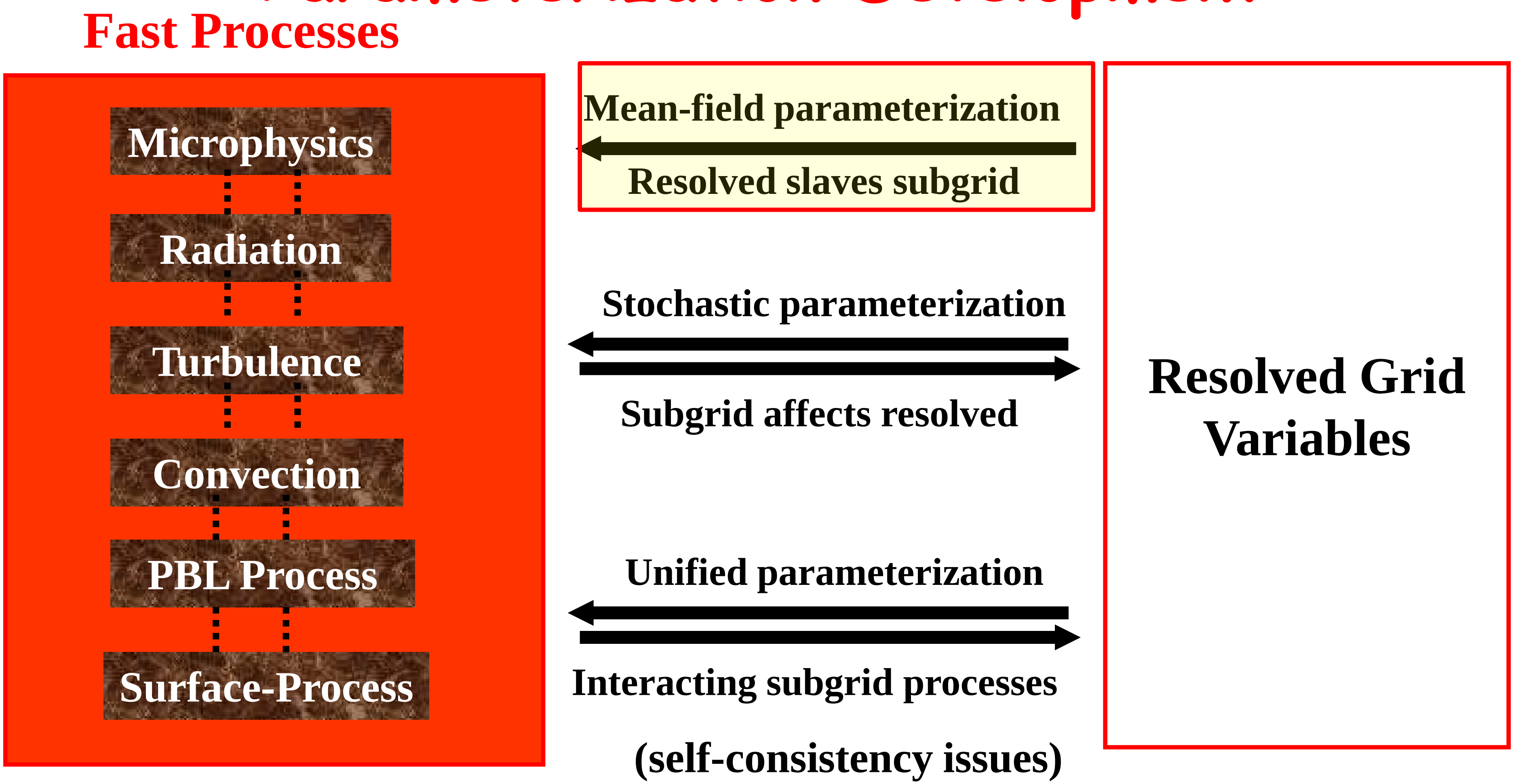
Parameterization is not just practical necessity, but deep theoretical underpinning of scale-interactions within the multiscale system.

Dynamics-Physics Coupling



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

A Mahatan Project for Model Evaluation and Parameterization Development



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

Rich History of Cloud Physics Here

THE PHYSICS OF
CLOUDS

BY

B. J. MASON, D.Sc., F.R.S.

DIRECTOR-GENERAL METEOROLOGICAL OFFICE
FORMERLY PROFESSOR OF CLOUD PHYSICS
IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY, LONDON

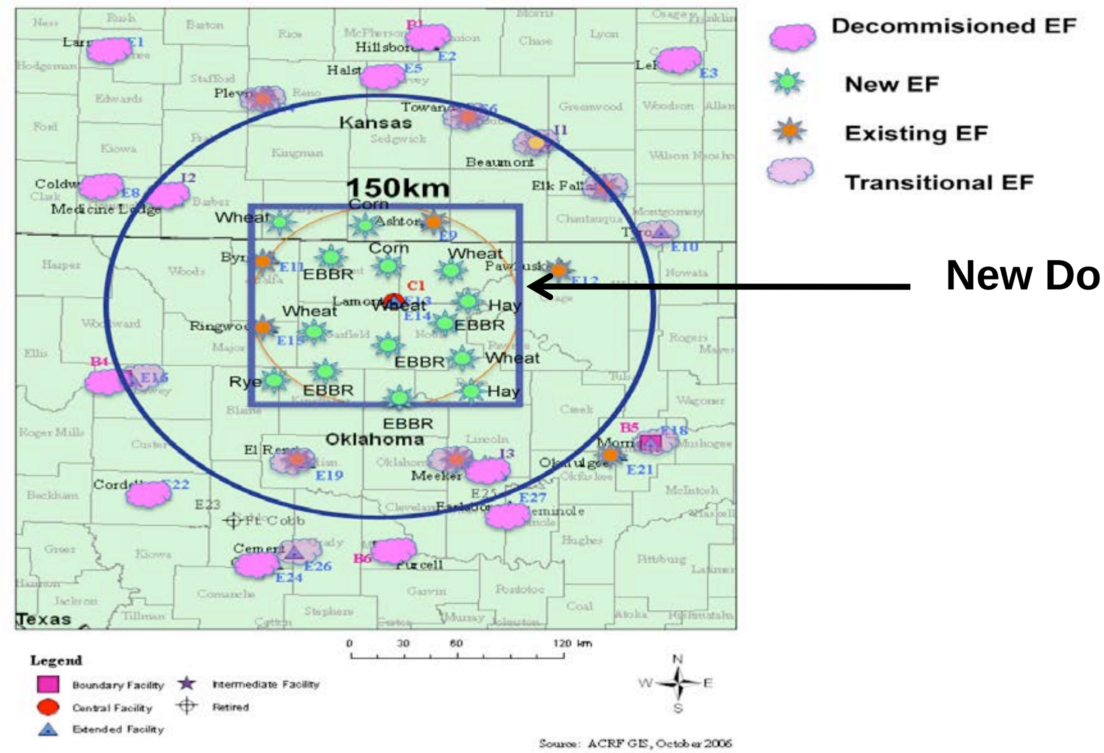
B. J. Mason
Formerly Prof. of Cloud Physics
Imperial College of Science and Technology (1948 – 1965)

"Progress in cloud physics has been hindered by a poor appreciation of these interactions between processes ranging from nucleation phenomena on the molecular scale to the *[turbulent]* dynamics of extensive cloud systems on the scale of hundreds of thousands of kilometers"

(Quote from 1st ed. preface, 1957)

The SGP Domain Reduced

- ACRF is shrinking SGP to a smaller domain (150x150 km) with increased density of surface stations
- Two forcing datasets will be generated for future IOPs: one at current domain and one at the reduced domain

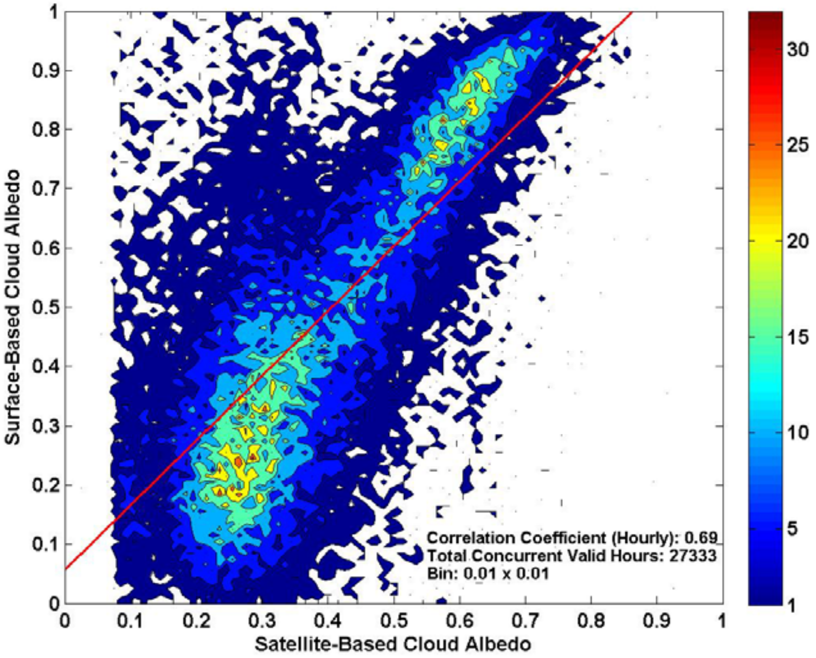


New Domain

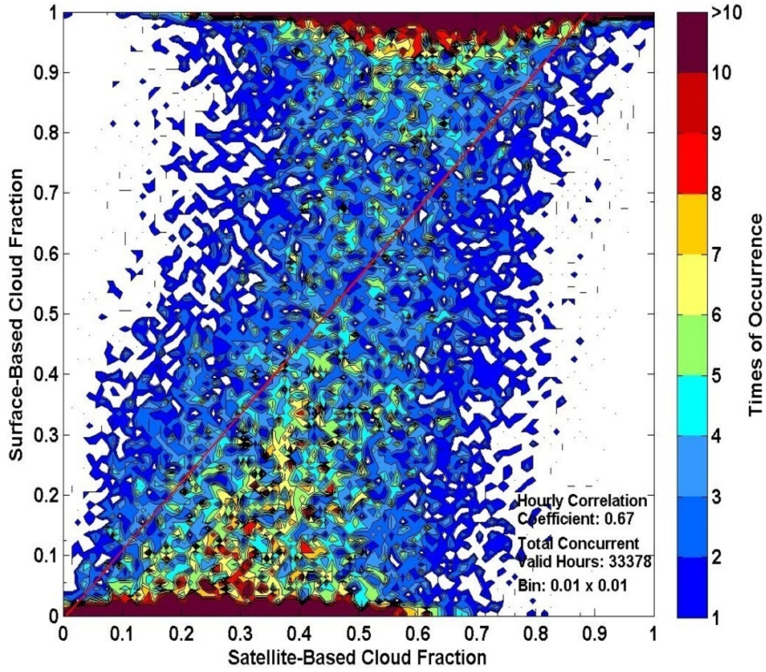
New Surface-Based Method for Measuring Cloud Albedo

Hourly data from 1997 to 2009 at SGP

Cloud Albedo



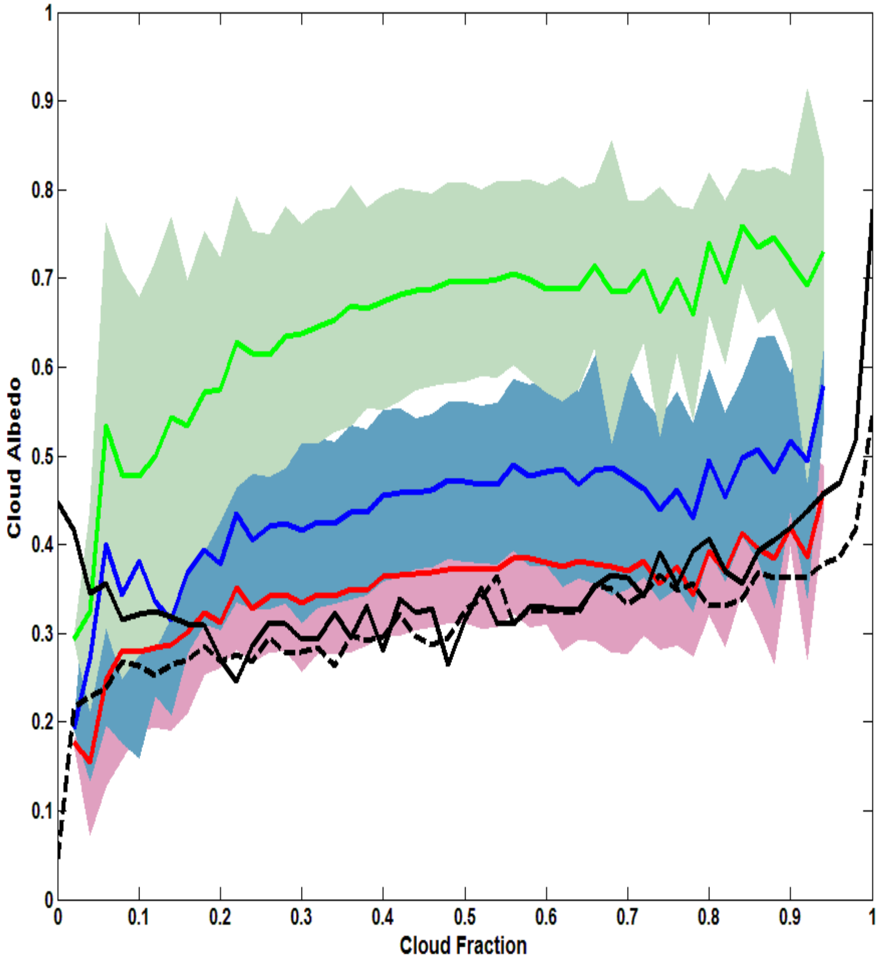
Cloud Fraction



The differences in cloud albedo and cloud fraction seem similar between GOES-based and surface-based Results, why?

Cloud Albedo, Cloud Fraction and Their Relationships: Physics and Tool

IPCC AR4 GCM Results



- Black curves – observations
- Color schemes – GCMs

Green = total water path;
Blue = surface radiation;
Red = TOA radiation

- Positive correlation, esp. for cloud fraction between 0.2 and 0.9
- SCM shows either physics and/or overlap schemes lead to similar results
- Theoretical demonstration
- How about NWP results?
- Compensating errors & tuning issues?

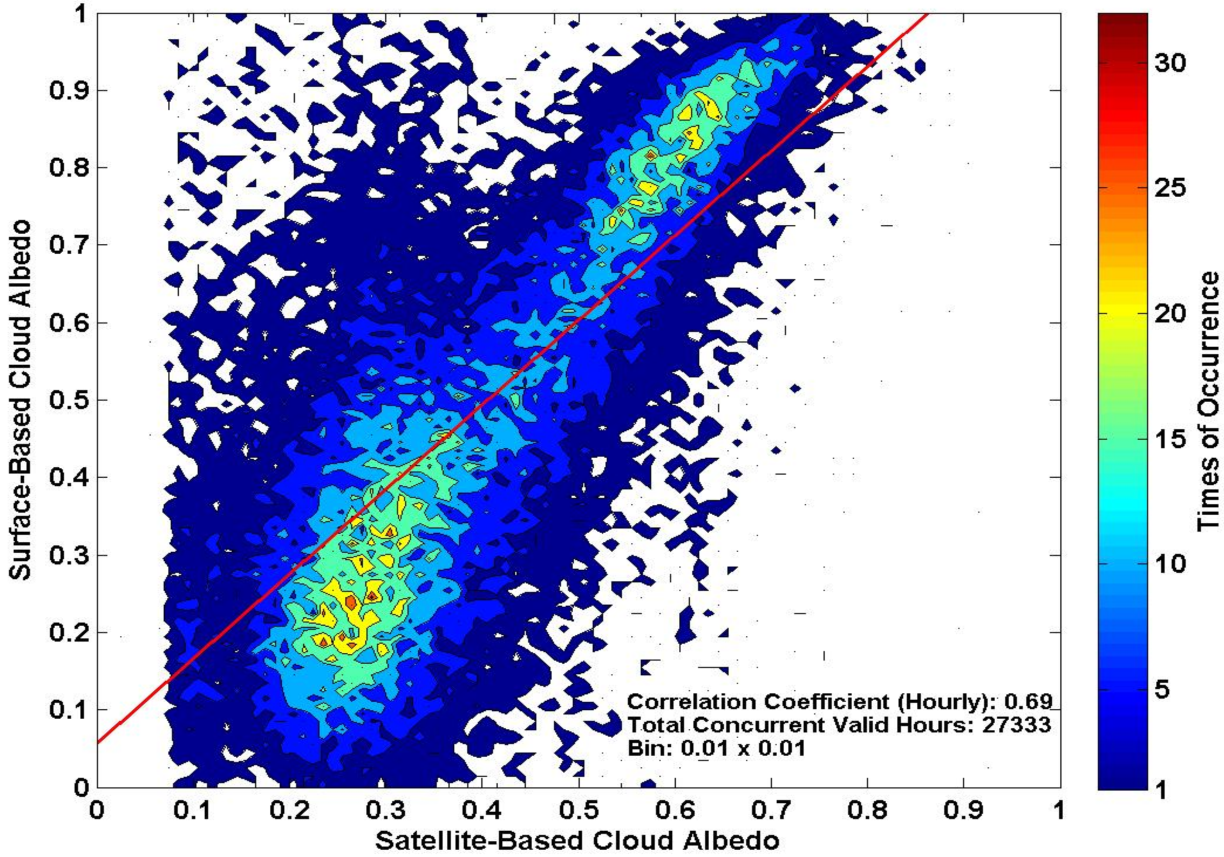
New Surface-Based Method for Measuring Cloud Albedo

- First quantities targeted are cloud albedo and cloud fraction due to their importance in determining radiation budget, widespread use in model evaluation, and availability of ARM measurements.

- Seek new application of ARM surface-based radiation measurements

(Liu et al., ACP, tentatively accepted)

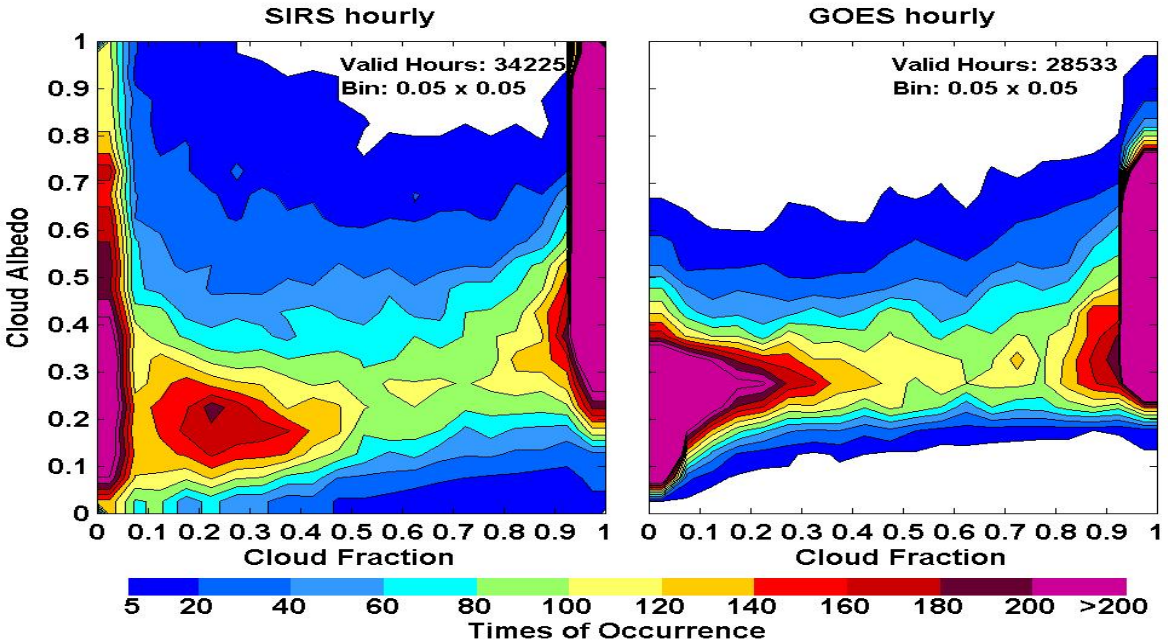
Hourly data from 1997 to 2009 at SGP



$$\text{Surface – Based Cloud Albedo} = \frac{\text{Effective Cloud Albedo}}{\text{Cloud Fraction}}$$

$$\text{Cloud Effective Albedo} = \frac{\text{Clear Sky Downward SW Radiation - All Sky Downward SW Radiation}}{\text{Clear Sky Downwward SW Radiation}}$$

Observational Evidence



- Two sets
site: GOE
radiation

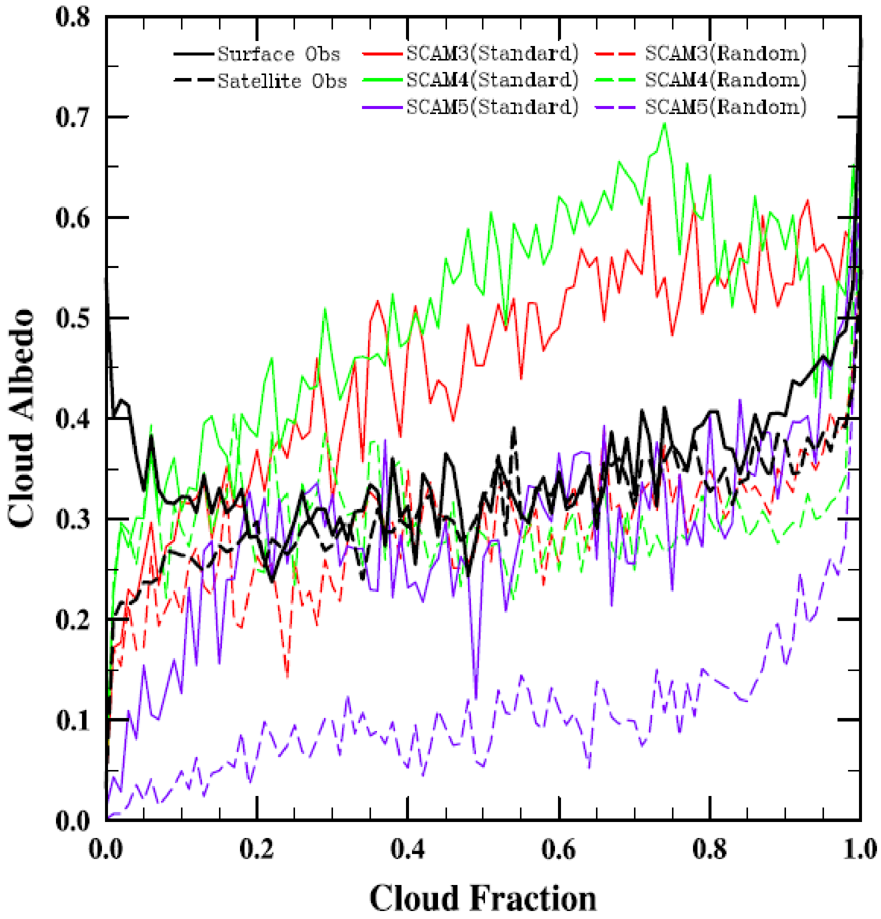
- Hourly (

-

A positive correlation is evident for the GOES data and for the SIRS data with cloud fraction from 0. 2 and 0.9.

SCM Investigation

- Different physics: SCAM3, 4, and 5;
- Different cloud overlaps: standard (solid) and random (dashed);
- SCMs produce general positive correlation;
- Differences can arise from model physics and/or cloud overlap assumptions.

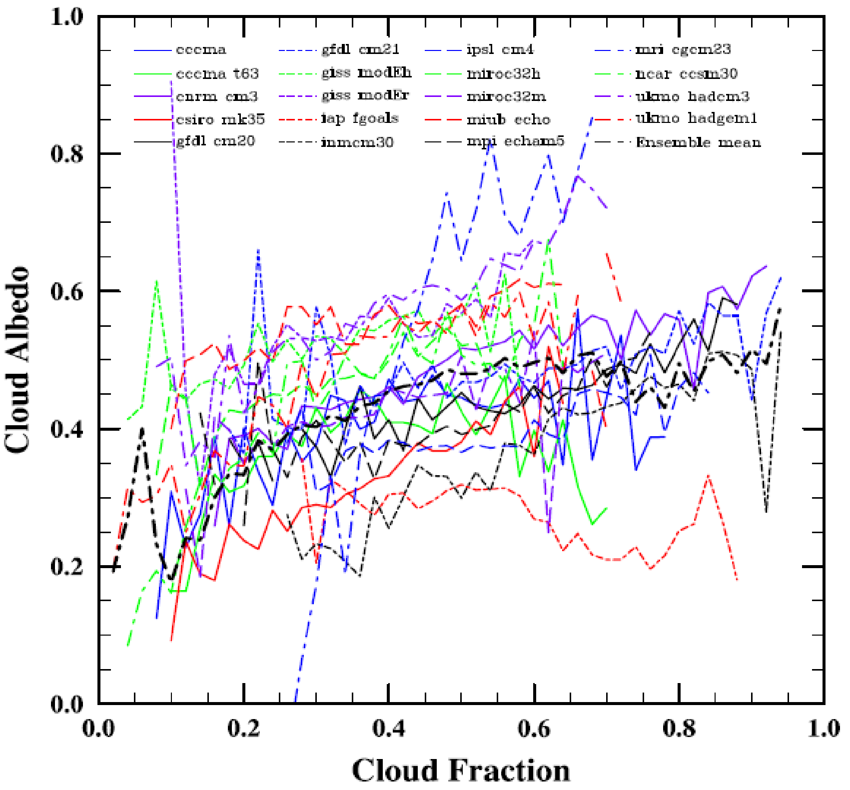


The relationship between cloud albedo and cloud fraction, together with the fact that either model physics or overlap assumption, poses new challenges to parameterization development: coupling and consistency!

Comparison between GCMs and Observations

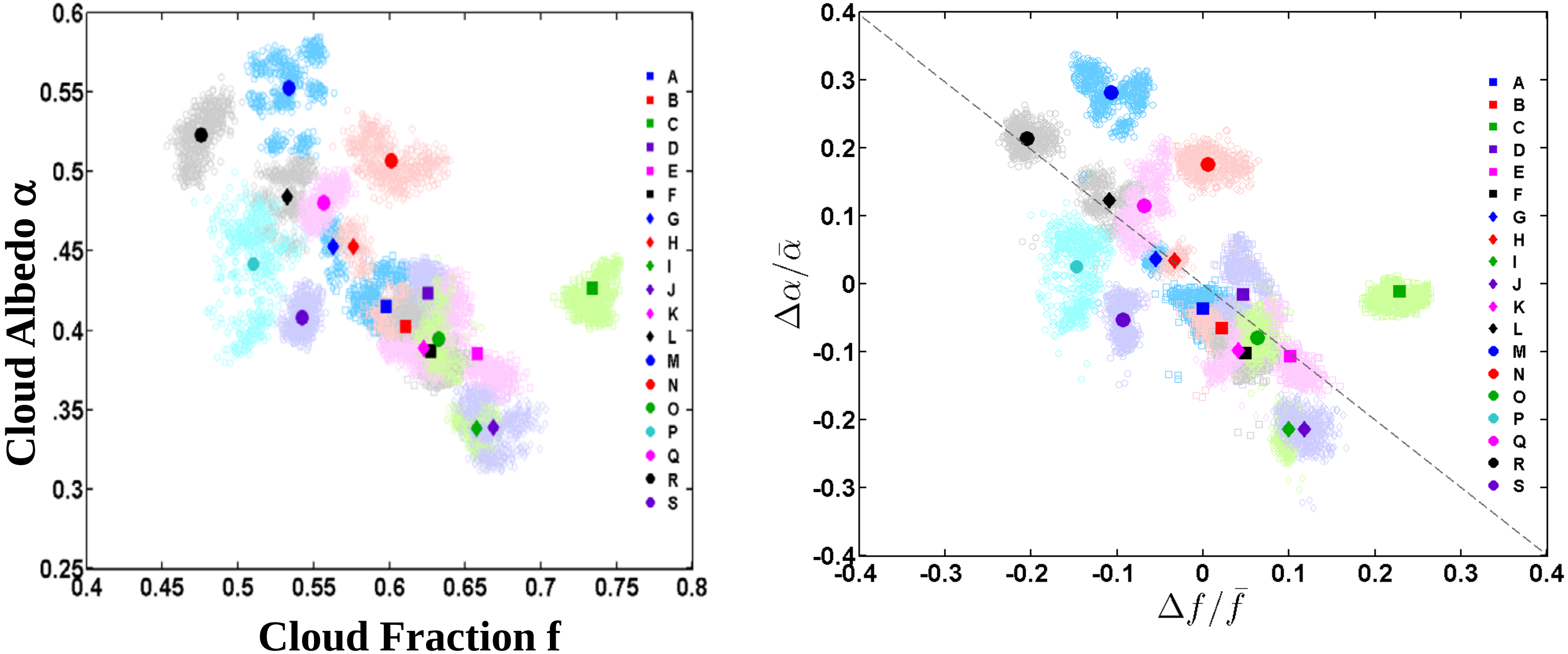
- General positive correlation
- Large inter-model spread
- Difference between TOA and surface-based cloud albedo

IPCC AR4 GCMs at SGP



Tuning and Compensating Errors — Evidence

19 IPCC AR4 GCM Results



Constrained with observations/physical principles, tunable parameterizations may lead to compensating errors; we should develop and use parameterizations from first principles as much as possible.

Tuning and Compensating Errors — Evidence

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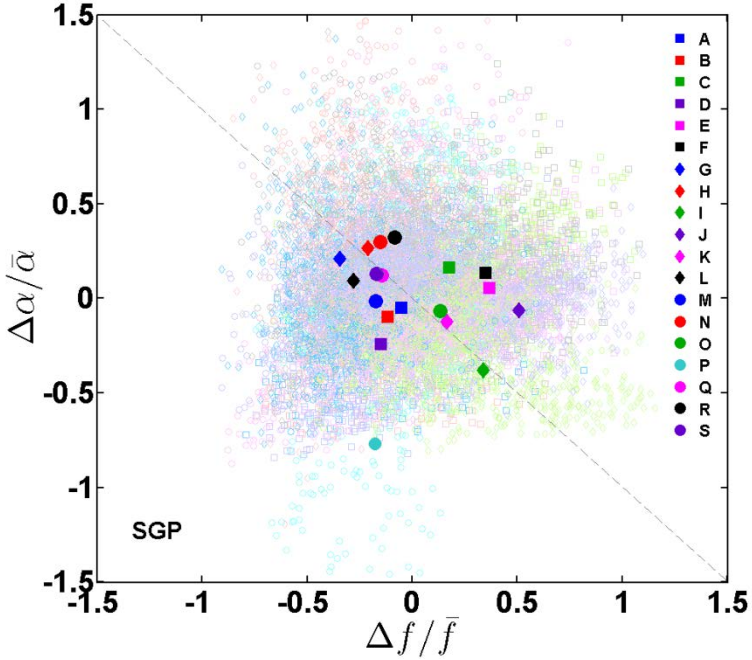
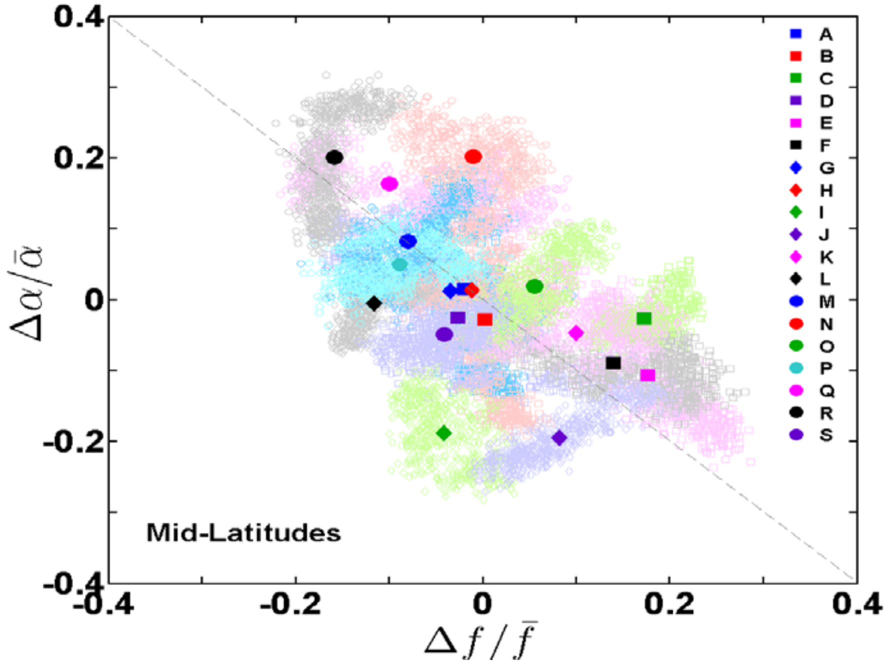




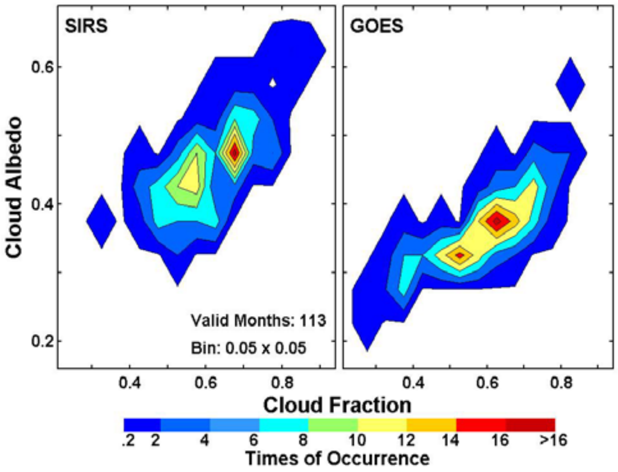
Constrained with observations/physical principles, tunable parameterizations may lead to compensating errors; we should develop and use parameterizations from first principles as much as possible.

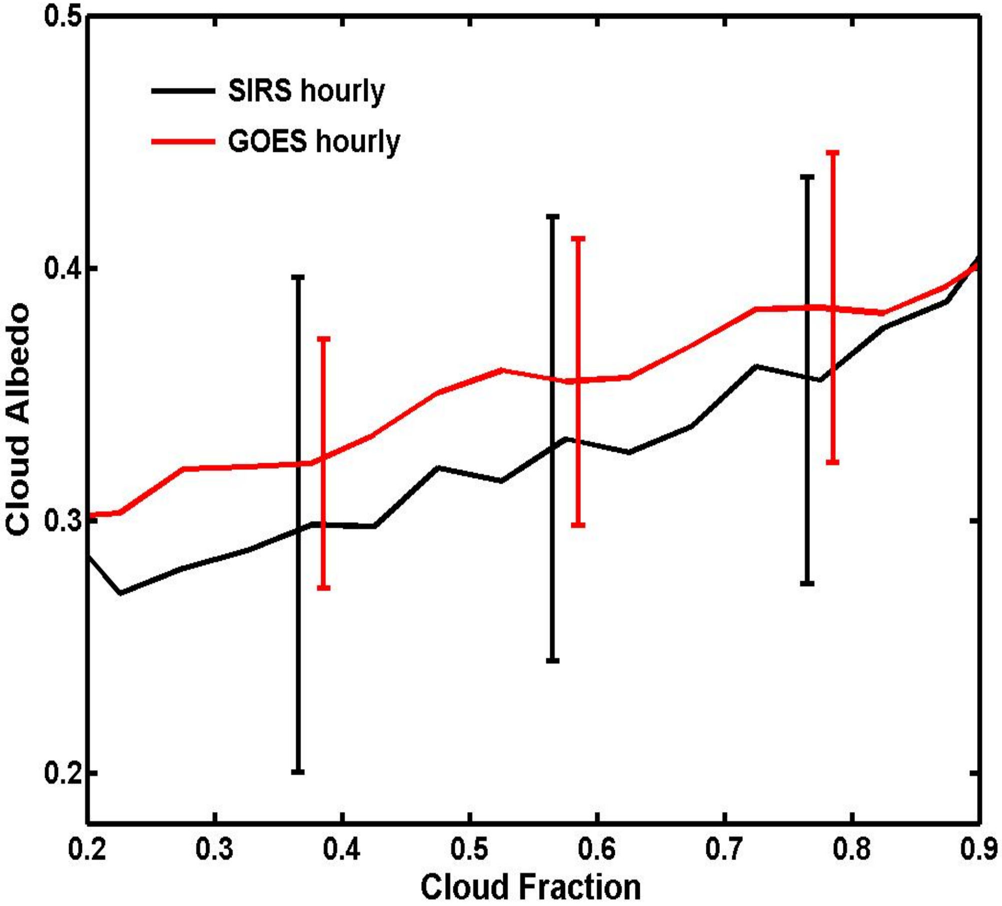
Observational Evidence

• 12 year hourly data (1997 to 2009) at the ARM SGP site;

• Two sets of measurements: GOES satellite and surface-based radiation system (SIRS);

Monthly Mean





Issue of statistical method ?

Positive correlation is evident for both the GOES data and for the SIRS data.

Taking up these opportunities & challenges will lead us to an ever better future !

A journey of thousand miles starts with a single step

Suggestions & Collaborations ?

Thanks so much !