Climate Radiative Responses and Clouds: What we are learning from CMIP3

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with thanks to S. Bony, B. Soden, and others

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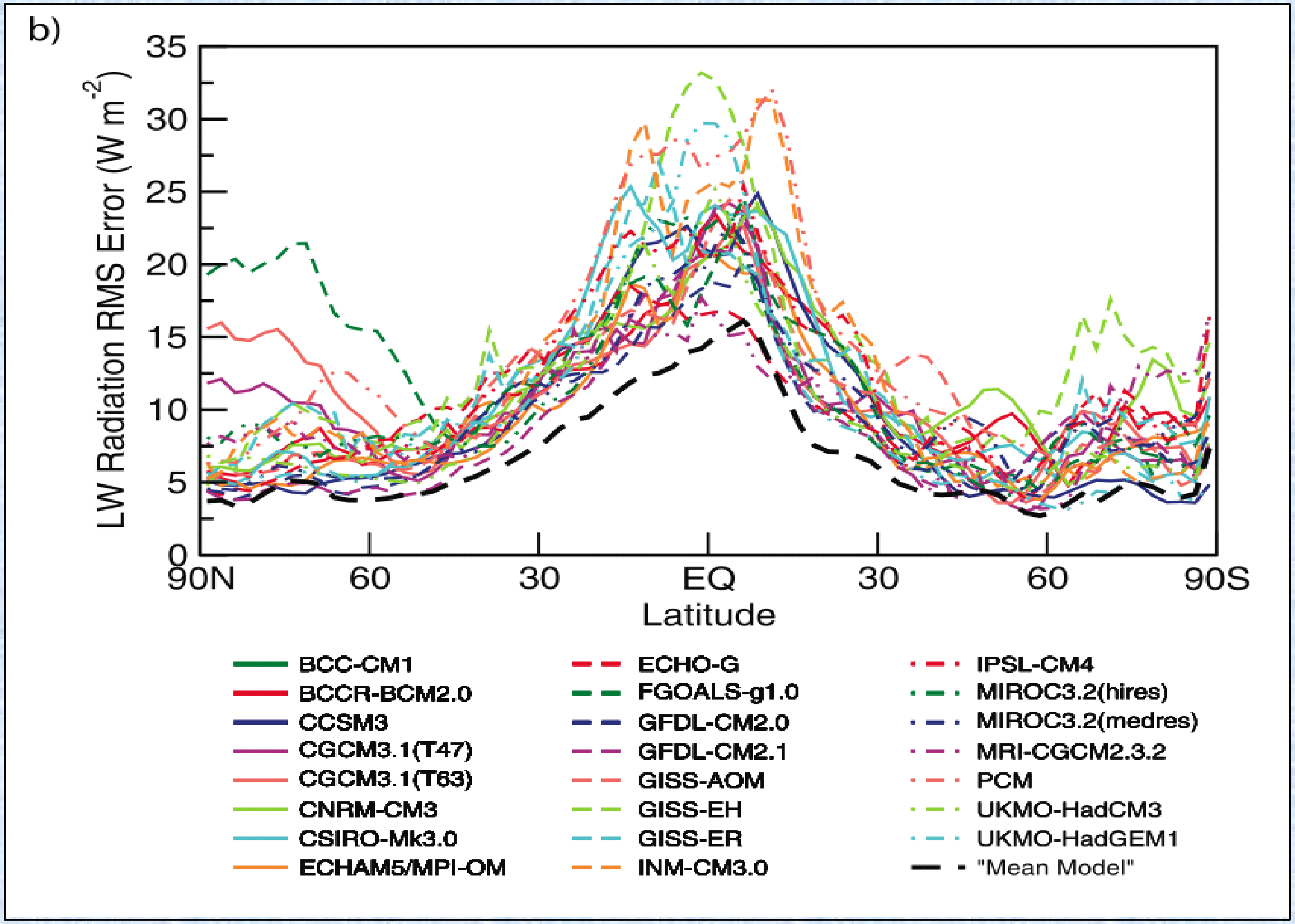
CMIP3 terminology and background

- CMIP = Coupled Model Intercomparison Project
- Simulations performed in support of IPCC's Fourth Assessment Report (AR4)
- WCRP's WGCM & CMIP panel coordinated activity
- PCMDI archived and made available model output (funded by DOE)
- 17 climate modeling centers (23 models) performed 12 expts. each
- CMIP3 impact:
  - → Has resulted in more than 300 publications
  - → Provided basis for 4 of the 7 figures appearing in the IPCC WG1 "Summary for Policy Makers"
  - → Provided basis for about 3/4 of the more than 100 figures in chapters 8-11.

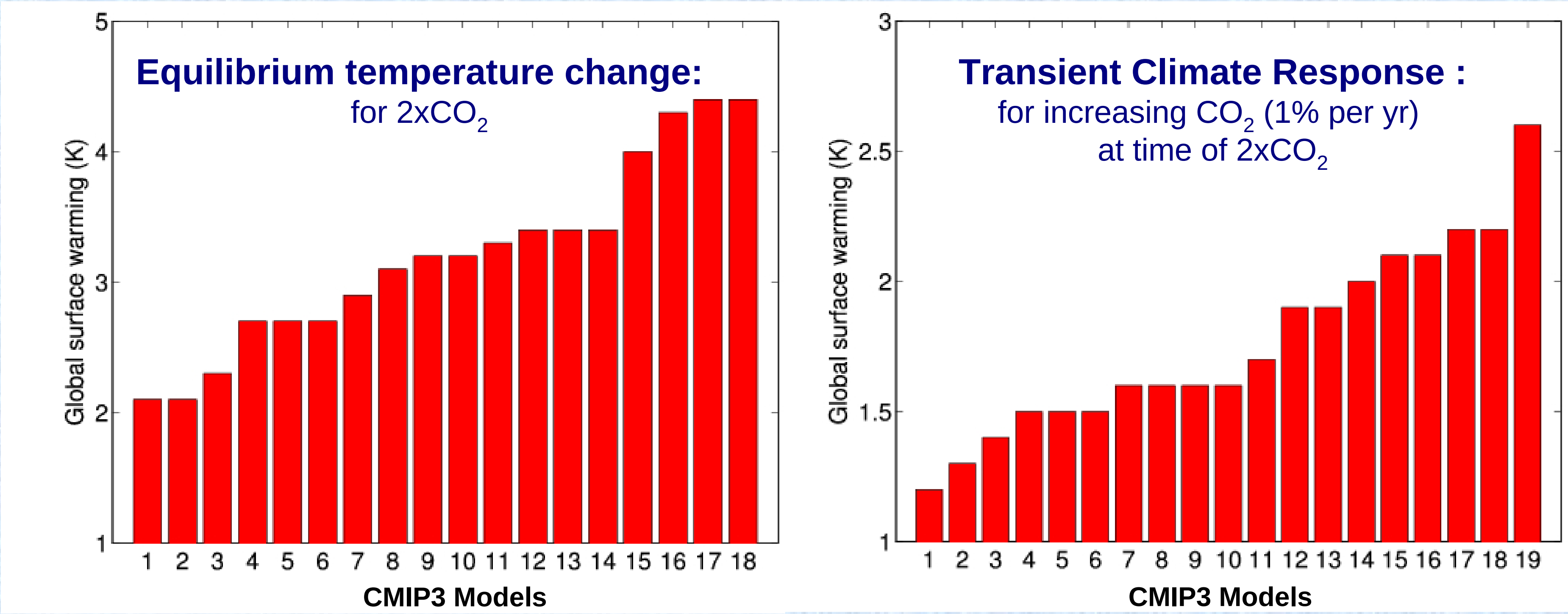
RMS error in simulating outgoing longwave radiation

Error computed over all longitudes and 12 climatological months



IPCC AR4 Chpt. 8

Climate sensitivity estimates from CMIP3 GCMs

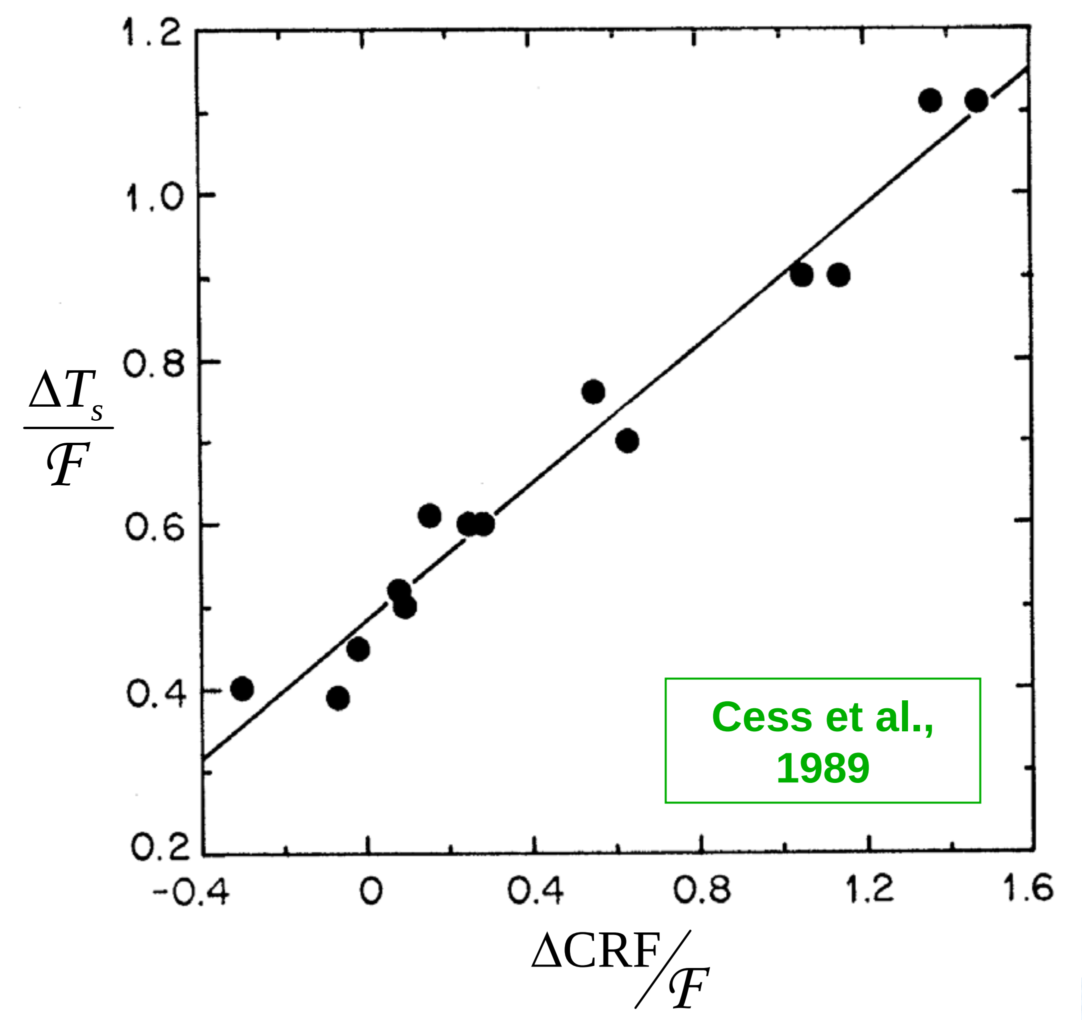


Courtesy of S. Bony

What explains the range of results?

What's the right answer?

In 1989 the range of climate sensitivities was only slightly broader and was explained largely by clouds.



ARM was shaped by the recognition that in models, clouds were mostly responsible for producing a range of climate sensitivities

- The discussions which led to ARM in the late 80's originally focused primarily on radiation.
- "Based on the peer review [in 1989], … the scope [of ARM] was broadened beyond radiative transfer to include clouds and cloud processes represented in general circulation models, …"
- The perspective provided by the multi-model ensemble was partly responsible for this broadening of emphasis.

http://www.arm.gov/about/history.stm

OUTLINE

- A modified framework for discussing "forcing" and "feedbacks" in climate models
- New approaches for diagnosing feedbacks in climate models
- Examples of what we've learned from the CMIP3 multi-model ensemble
- Future directions

Formulation for quantifying feedbacks

- Focus on the global, annual mean energy budget

(perturbation from initial equilibrium):

$$\frac{\partial E}{\partial t} = F_{\text{TOA}}$$

- Why?
  - → To zeroth order, climate is determined by energy flow across TOA
  - → Processes that strongly affect TOA flux have strong influences on climate
  - → Perturbations to the net TOA flux largely determine thermosteric changes in sea level.
  - → From TOA flux, we can estimate surface temperature changes (if we also monitor uptake of heat by the oceans).

"Radiative response" is a generalization of the concepts of "forcing" and "feedback"

(perturbation from initial equilibrium):

$$\frac{\partial E}{\partial t} = F_{\text{TOA}}$$

- Define "radiative response"
  - → Any change in the system that ***directly*** affects F_{TOA}
    - e.g., clouds, water vapor, surface albedo, [CO_2]
  - → Definition excludes changes that only ***indirectly*** impact F_{TOA}
    - e.g., changes in atmos. transport or evaporation (even though these affect water vapor and clouds)
- "Radiative response" makes no fundamental distinction between "forcing" and "feedback".

Distinguish between "fast" and "slow" radiative responses

$$F_{\text{TOA}} = \underbrace{\mathcal{F}}_{\text{"fast"}} + \underbrace{\mathcal{S}}_{\text{"slow"}}$$

- "Fast" radiative responses (commonly called "forcing")
  - → Evident before "climate" has changed
  - → Seen instantaneously or within a few months of imposed perturbation
  - → e.g., direct radiative impact of [CO_2] changes; stratospheric adjustment
- "Slow" radiative responses (commonly called "feedbacks")
  - → e.g., "Planck response", water vapor, surface albedo
  - → Traditionally assumed proportional to global mean temperature change:

$$\mathcal{S} \approx -\lambda \Delta T$$

Feedback analysis: resolve radiative responses into components and monitor them as climate evolves

$$\frac{\partial E}{\partial t} = F_{\mathrm{TOA}} = \sum_i \mathcal{F}_i + \sum_j \mathcal{S}_j$$

- Express each radiative response component as a product, e.g.:

$$\mathcal{S}_j = \frac{\partial F_{\mathrm{TOA}}}{\partial x_j} \Delta x_j$$

  - → x_j represents all the variables that can affect TOA radiation.
  - → Similar equation applies to "fast response" components
  - → More generally, above equations contain nonlinear interaction terms, which are usually small.

- **Relative size of each flux component is some measure of its importance to climate response**

Note: By this approach, we avoid several limitations of the conventional feedback framework.

- No requirement that system be linear
- No need to assume that feedbacks are proportional to global mean temperature perturbation
- Avoids somewhat artificial distinction between "feedback" and "forcing"
- Scraps any fundamental reliance on the (artificial) so-called "Planck response" (or "Planck feedback parameter")
- Enables, within the same framework, a more natural analysis of additional feedbacks (e..g, carbon cycle feedbacks)

How are components of "slow radiative response" (feedback) evaluated in models?

- Change in cloud radiative forcing (e.g., Cess et al., 1989)
- Partial radiative perturbation (PRP) approach (e.g., Manabe & Wetherald, 1988; Colman, 2001)
- Approximate PRP
  - → Tune a simple model to mimic each GCM (Taylor et al., 2000, 2007)
  - → "kernel" method: use a GCM as a partial surrogate for other GCM's (Soden & Held, 2006)

$$S_j = \frac{\partial F_{\mathrm{TOA}}}{\partial x_j} \Delta x_j$$

In model of interest:

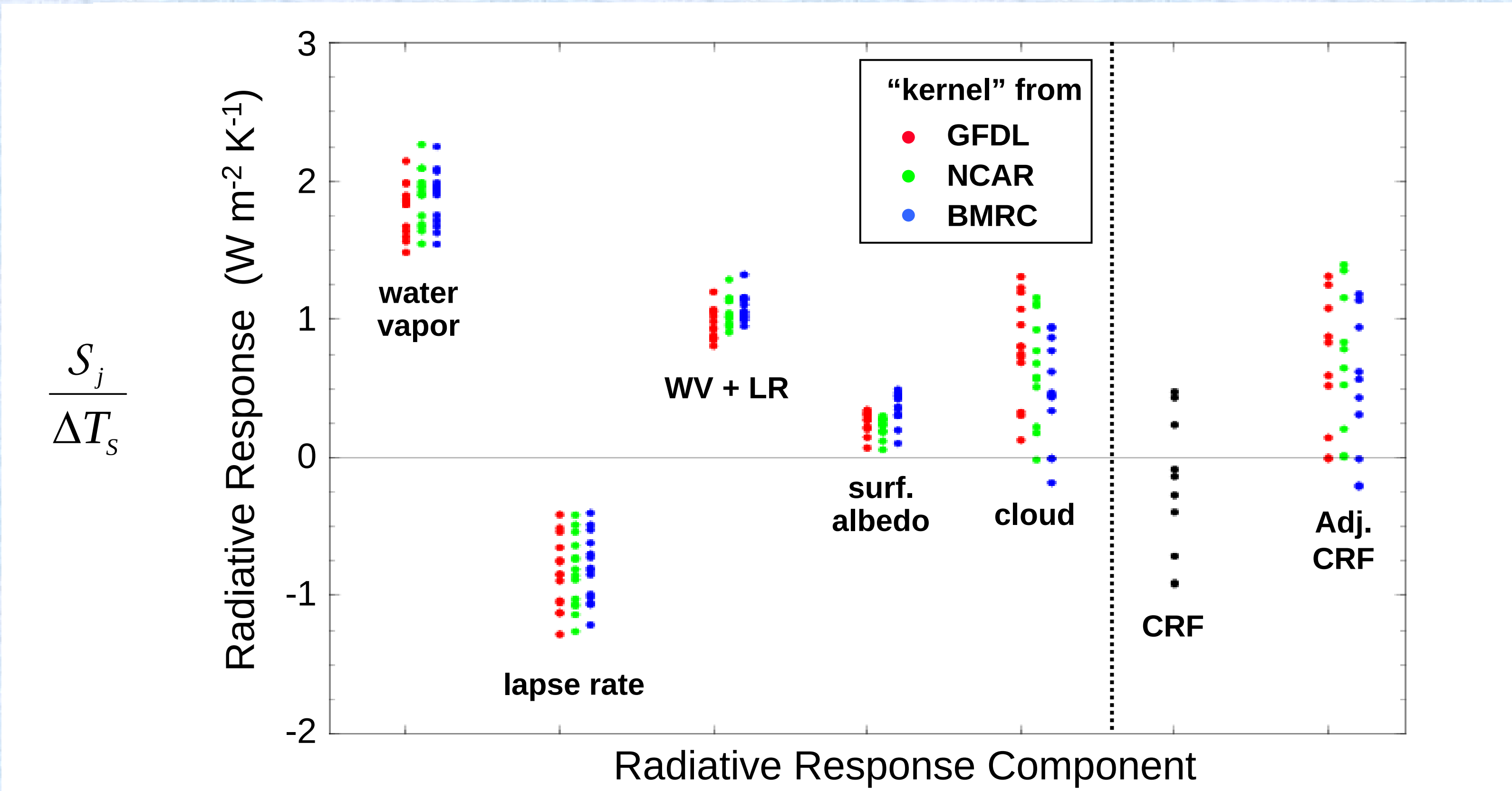
radiative response (S_j)

"kernel" from surrogate GCM ($\frac{\partial F_{\mathrm{TOA}}}{\partial x_j}$)

Change in variable affecting radiation (Δx_j)

Normalized radiative response differences among 14 CMIP3 models are larger than differences due to radiative "kernels".

Δx_i from SRES A1B scenario: (2100-2110) - (2000-2010)

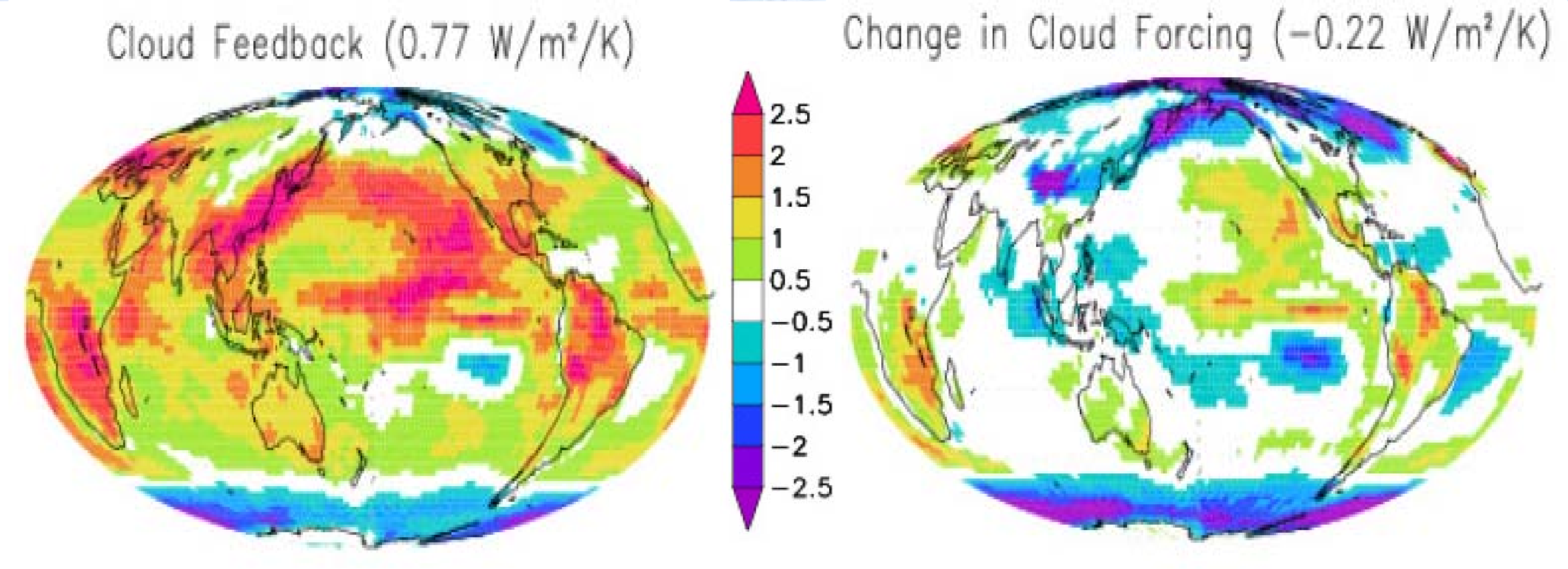


Soden et al., 2008

The "kernel" method successfully isolates true cloud "feedback" from "cloud masking" effects

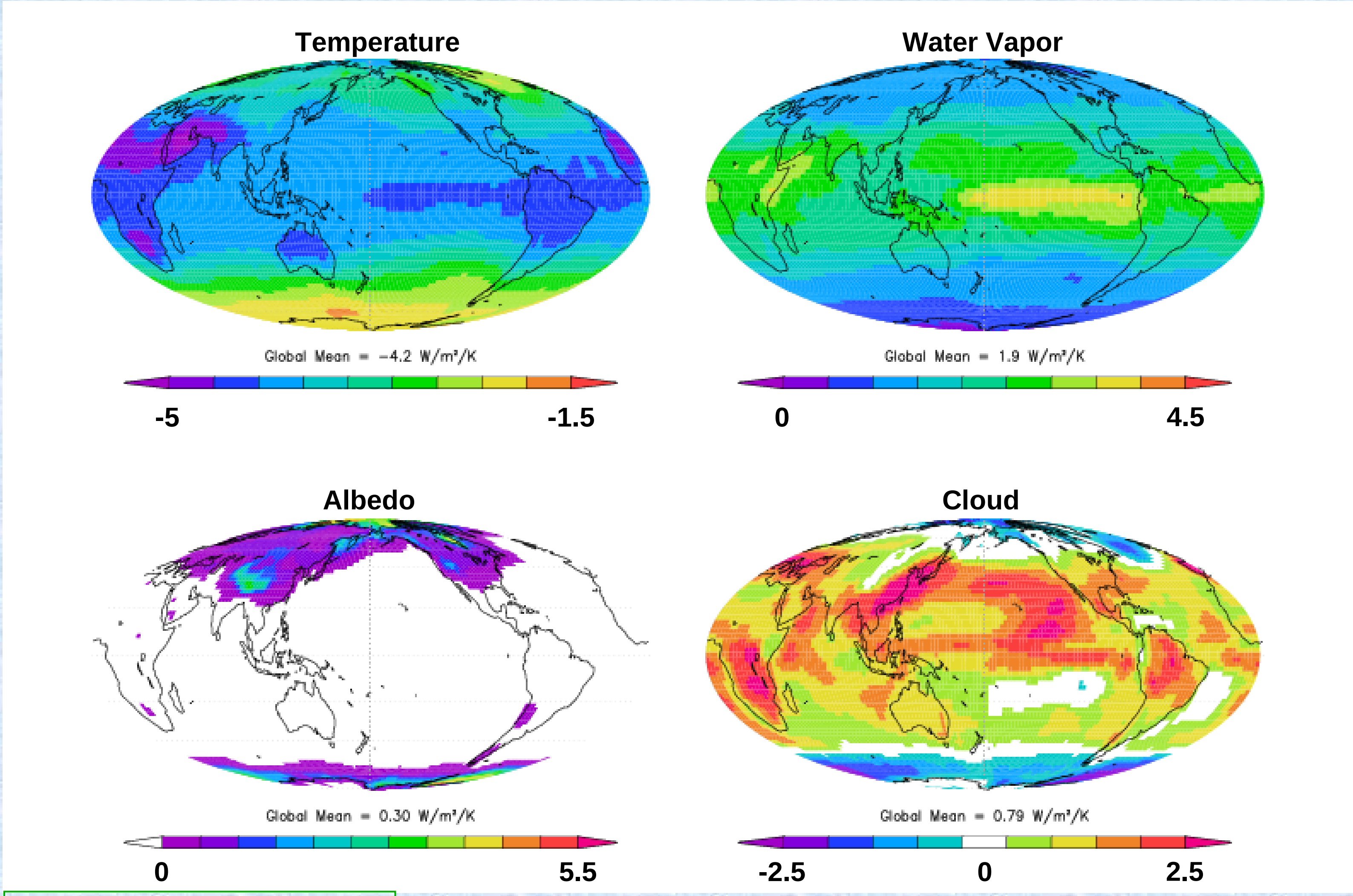
Mean Result from CMIP3 Multi-Model Ensemble

(based on GFDL "kernel")



Soden et al., 2008

CMIP3 multi-model mean normalized radiative response:
[based on SRES A1B scenario: (2100-2110) - (2000-2010)]



Soden et al., 2008

Are there cloud responses evident even in the absence of climate change (i.e., for global mean $\Delta T_s \approx 0$)?

- Empirically, we find that for any given model, climate sensitivity is somewhat independent of the forcing mechanism.
  - → Given the climate sensitivity we can estimate global mean temperature response from radiative "forcing" alone.
  - → We often "cheat" to maintain this relationship; e.g., we
    - allow the stratosphere to adjust
    - invoke "indirect" aerosol effects
- In reality the radiative responses we call "forcings" are distinguished from other radiative responses by being
  - → independent of surface temperature (loosely speaking)
  - → Associated with shorter time-scales: normally less than a few months

It is often assumed that a simple relationship relates "forcing" and temperature response.

- Assume each slow radiative response is proportional to temperature change:

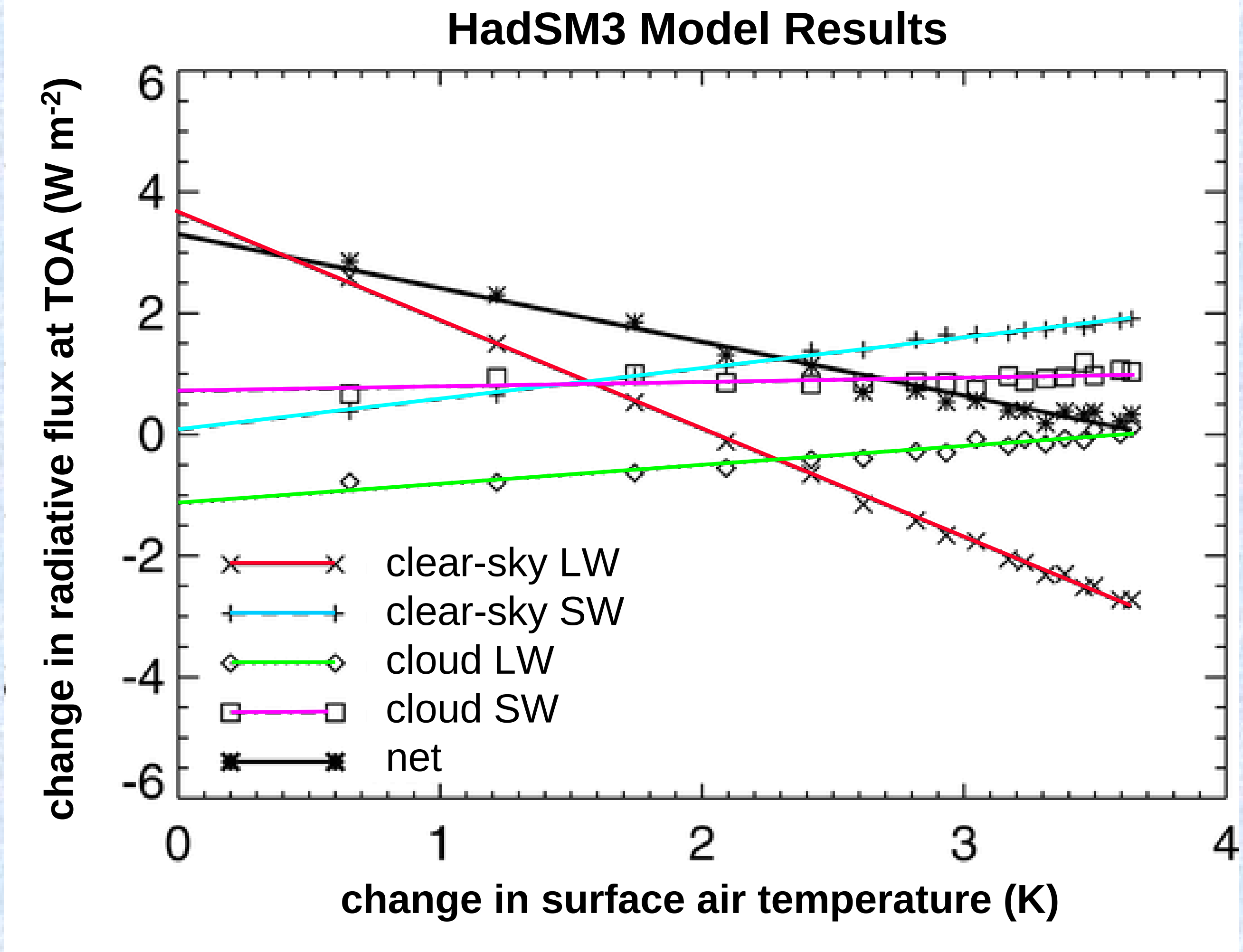
$$\mathcal{S} = \sum_j S_j = \sum_j \lambda_j \Delta T$$

- then

$$F_{\text{TOA}} = \mathcal{F} + \mathcal{S}$$
$$\sum_j \lambda_j \Delta T = F_{\text{TOA}} - \mathcal{F}$$

- In climate change experiments with constant forcing (e.g., instantaneous doubling of CO_2), Gregory et al. (2004) show that both $\mathcal{F}$ and λ_i can be estimated.

In 2xCO2 expts., there appears to be both LW & SW fast cloud responses, which alter the "forcing".



Gregory & Webb, 2008

Conclusions concerning "fast" responses in slab ocean versions of the CMIP3 models include:

- "Fast" cloud radiative responses
  - → Increase SW effective forcing by ~0.6 W/m^2
  - → Decrease LW effective forcing by ~0.2 W/m^2
  - → Appear to be partly explainable in terms of a decrease in clouds
  - → The global mean decrease in clouds, however, is a residual of positive and negative changes in different regions.
- Hint of "fast" decrease in atmos. water vapor content too
- Among CMIP3 models, differences in "fast" radiative responses account for some of the spread in projections.
- It may be easier to validate the "fast" cloud responses from available observations (compared to slow responses associated with climate change itself)

Based primarily on:
Gregory & Webb (2008);
Andrews & Forster (2008)

There may be other "fast" climate responses not captured by considering radiative responses alone.

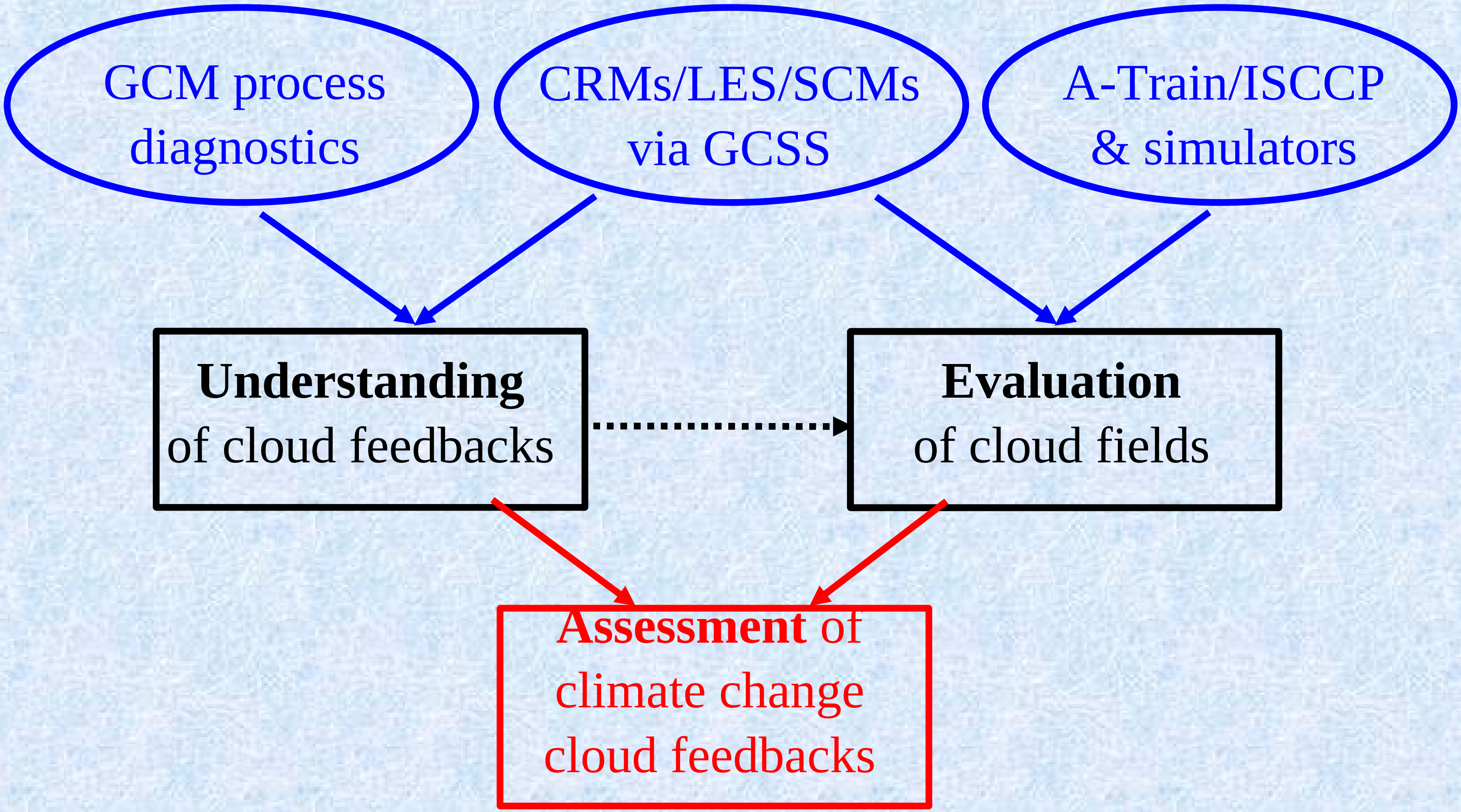
- Embargoed by PNAS

Bala, Duffy & Taylor (submitted)

We know that clouds remain largely responsible for the spread in model projections of climate change. What's next?

- Cloud Feedback Model Intercomparison Project (CFMIP)
- Routine application of new diagnostics (e.g., ISCCP and CALIPSO simulators)
- Analysis of regimes or of individual cloud types (e.g., based on vertical motion, or ISCCP optical-depth/CTP category)
- Evaluation of parameterizations based on LES/CRM/SCM models
- Metrics for evaluating clouds and gauging improvements (e.g., Pincus et al., 2008)
- Metrics for weighting model projections
- CMIP5

Cloud Feeback Model Intercomparison Project strategy



http://www.cfmip.net

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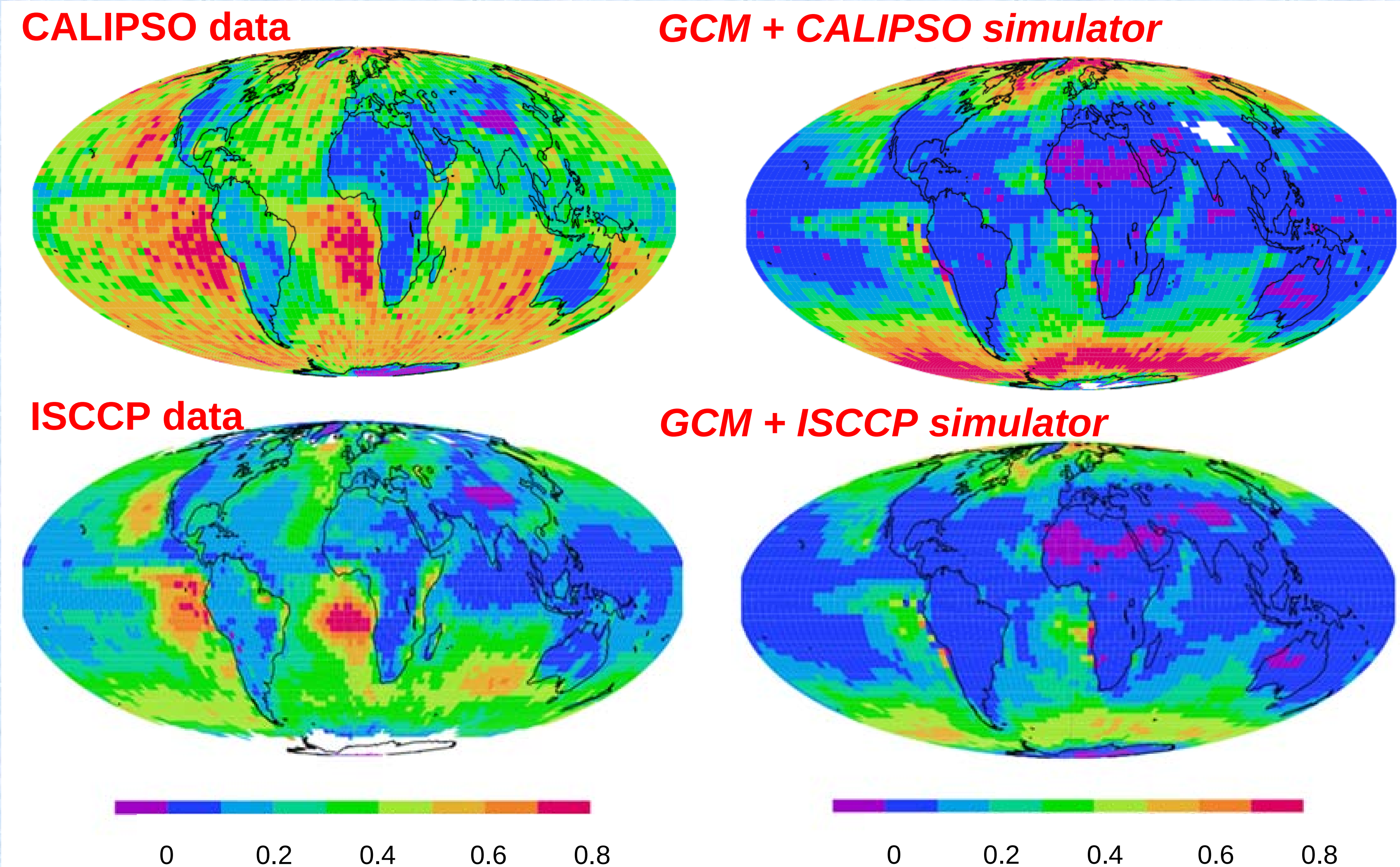
Comparison of Sept/Oct/Nov low level cloud fraction (Ptop > 680 hPa)



Chepfer et al., submitted

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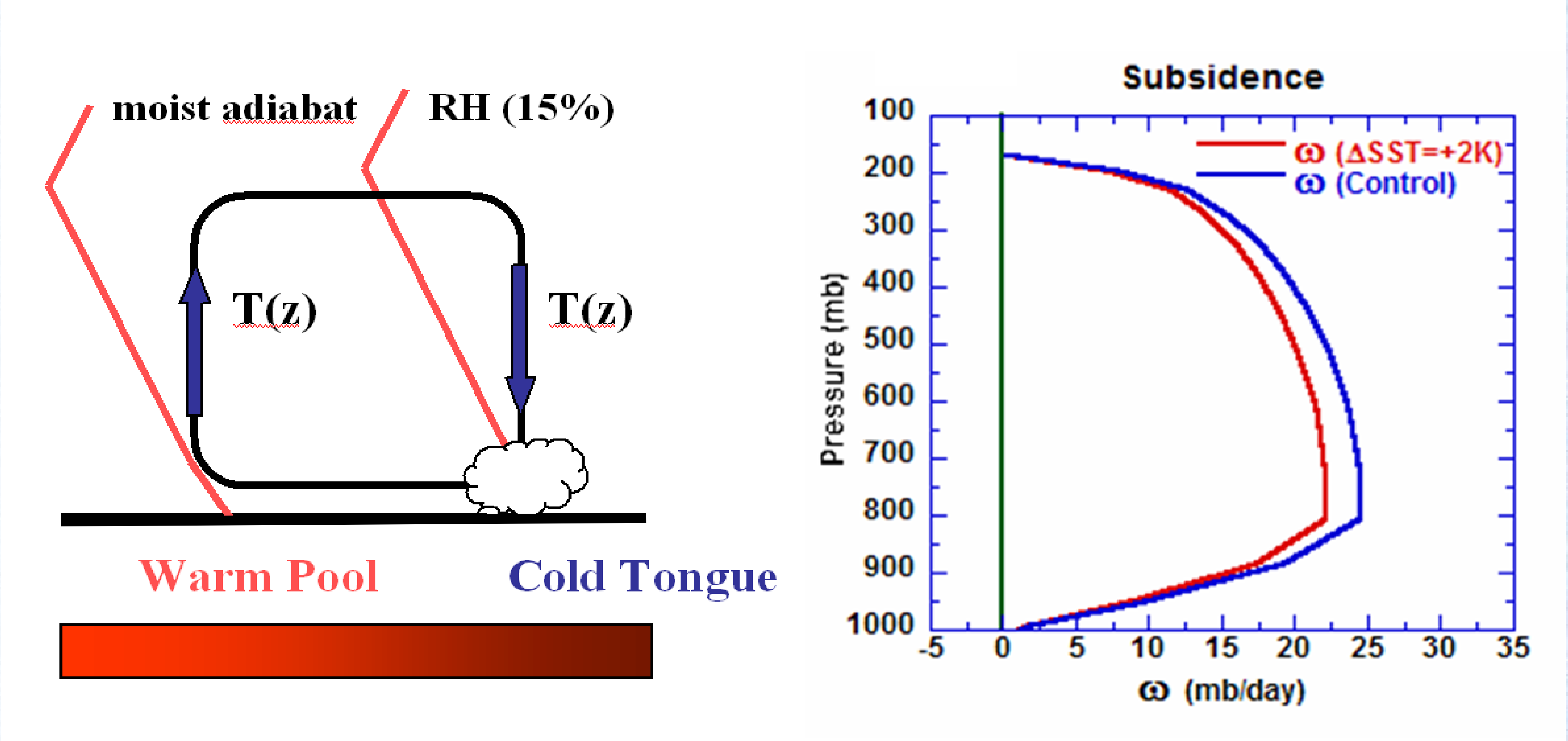
LES/CRM/SCM models will be externally forced to examine cloud responses and provide a reference "dataset" to evaluate climate model parameterizations.



Zhang & Bretherton, 2008

PCMDI

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Summary (1)

- A modified framework for evaluating cloud radiative responses has been developed which
  - → Accommodates cloud responses unrelated to global mean temperature change
  - → Shows that clouds continue to be responsible for much of the spread in model climate sensitivity
  - → Suggests differences in “fast” responses account for some of this spread
- New techniques for evaluating cloud feedbacks can unambiguously remove misleading “cloud masking” effects.
- “Fast” climate responses may have important implications for the hydrological cycle.

Summary (2)

- The CMIP3 multi-model ensemble has led to a number of new results and identified which results are robust across models:
  - → Water vapor and lapse rate feedbacks are intimately related and partially compensating.
  - → Cloud feedbacks are positive in nearly all models.
  - → Cloud feedbacks are on average just a little less important than water vapor plus lapse rate feedback
- We have not shown, but publications based on CMIP3 indicate:
  - → Cloud feedback is positive because LW cloud feedback is strongly positive.
  - → The intermodel spread in cloud feedback arises principally from the spread in SW feedback (ranges from modestly negative to strongly positive)
  - → The model spread in SW feedback originates primarily in regions of subtropical subsidence (marine boundary layer clouds clouds).