Recent progress in understanding climate feedbacks and forcings

Brian Soden
Rosenstiel School for Marine and Atmospheric Science
University of Miami

Collaborators: Eui-Seok Chung, Katinka Bellomo, Amy Clement, Gabe Vecchi, Isaac Held, Richard Allan, Ramaswamy,

What have we learned that they didn't know?

Manabe

Cess

Hansen

1) **Cloud feedback is not negative (in models)**

2) **High cloud feedback is positive and robust (in models)**

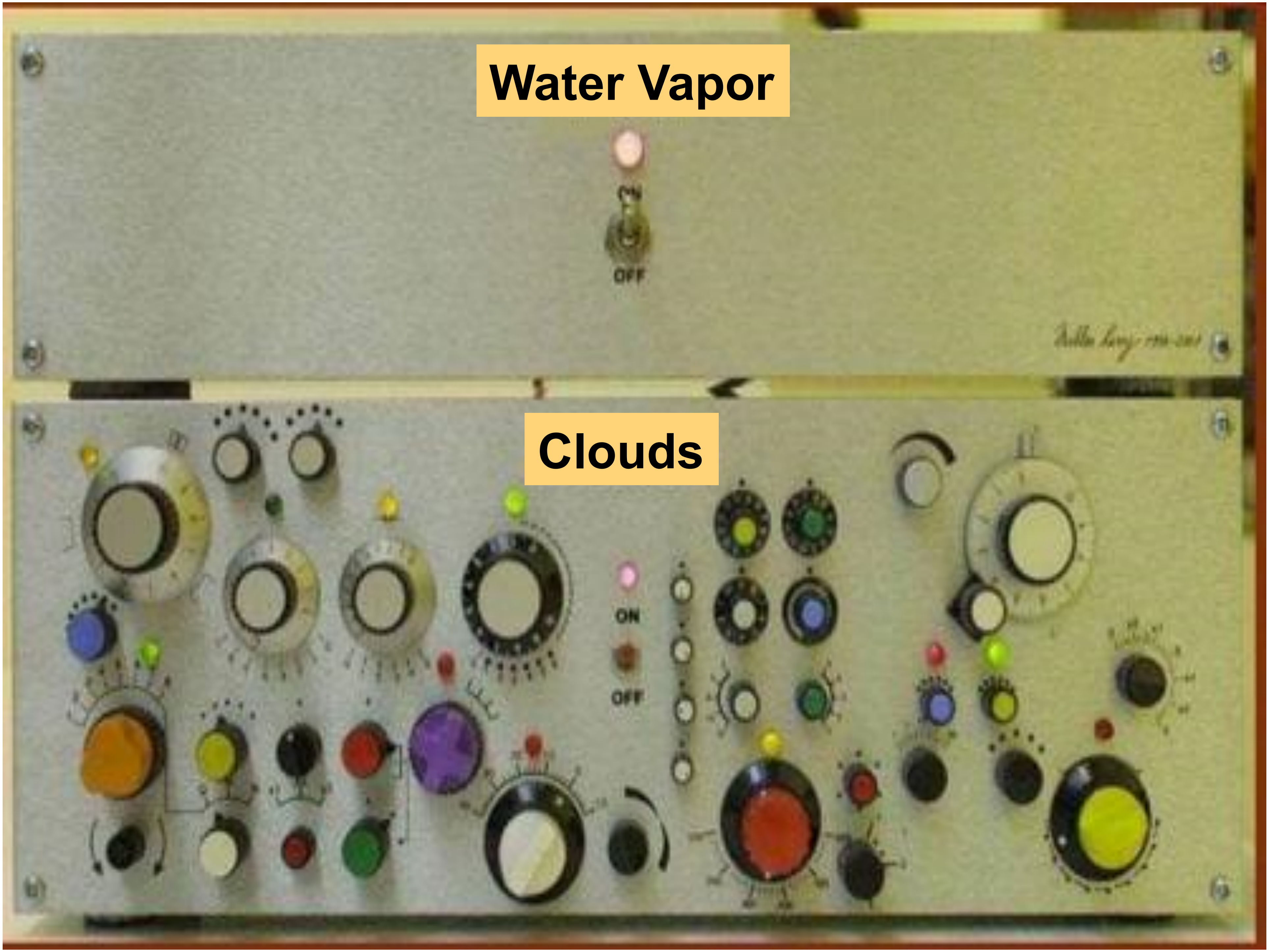
3) **Feedback from low stratocumulus clouds are the main uncertainty (in models)**

Outline

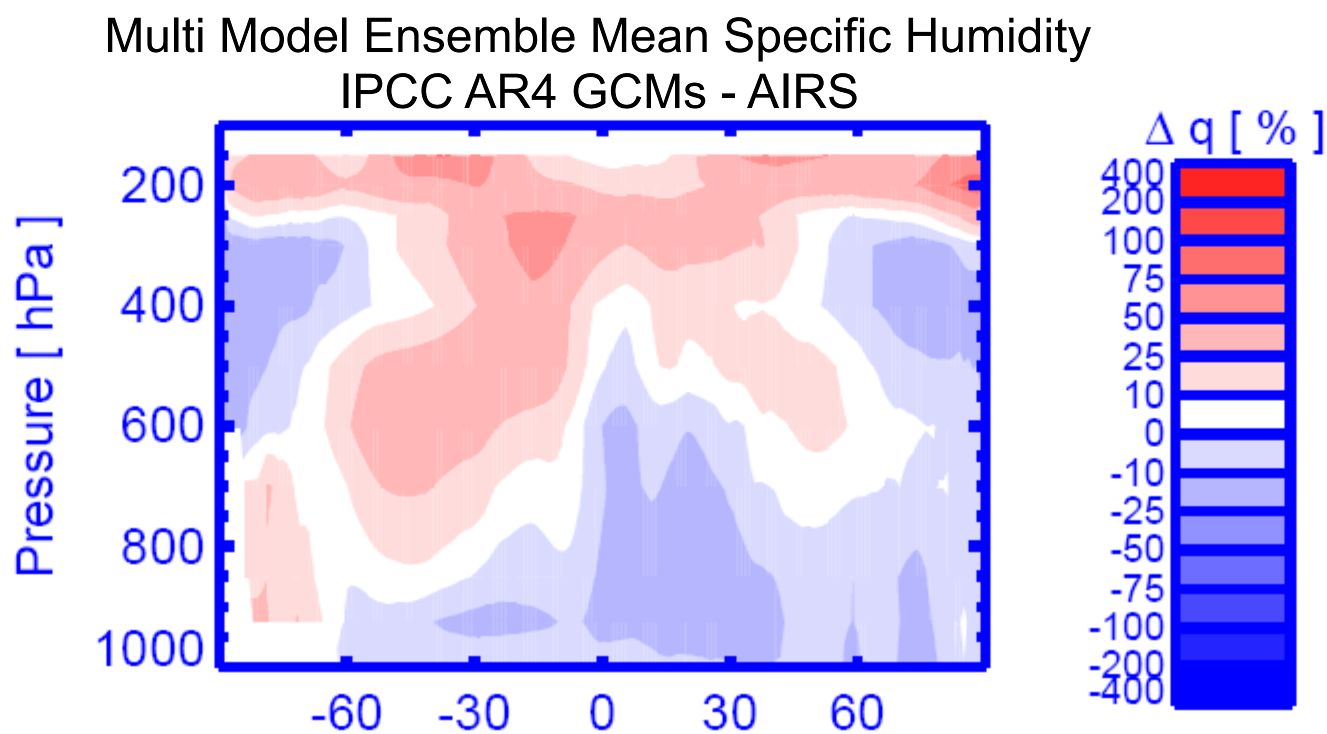
- Progress in understanding cloud feedback (in models)
  - Cloud feedback is not negative
  - High cloud feedback is positive and robust
  - Low cloud feedback is neutral to positive
  - Model spread in low cloud feedback is tied to subtropical stratocumulus regions
  - Possible links to changes in tropical circulation
- Radiative forcing in CMIP3 scenarios
  - Aerosol forcing is a significant contributor to model spread

IPCC Assessments

	Water Vapor Feedback	Cloud Feedback
1990:	"The best understood feedback mechanism is water vapor feedback, and this is *intuitively easy to understand*"	"Feedback mechanisms related to clouds are extremely complex"
1992:	"There is no compelling evidence that water vapor feedback is anything other than positive — *although there may be difficulties with upper trop. water vapor*"	"The effects of clouds remain a major area of uncertainty in the modeling of climate change"
1995:	"Feedback from the redistribution of water vapor *remains a substantial source of uncertainty* in climate models"	"In previous IPCC reports cloud feedback was identified as a major source of uncertainty. Considerable research efforts have further reinforced this conclusion."
2001:	"The balance of evidence *favours a positive clear-sky water vapour feedback* of magnitude comparable to that found in (model) simulations"	"… there has been no apparent narrowing of the uncertainty range associated with cloud feedbacks"
2007:	"Observational and modelling evidence *provide strong support* for a combined water vapour/lapse rate feedback of around the strength found in GCMs"	"Cloud feedback has been confirmed as a primary source of uncertainty."


Water Vapor
ON
OFF
Clouds
ON
OFF

Model Biases in Water Vapor

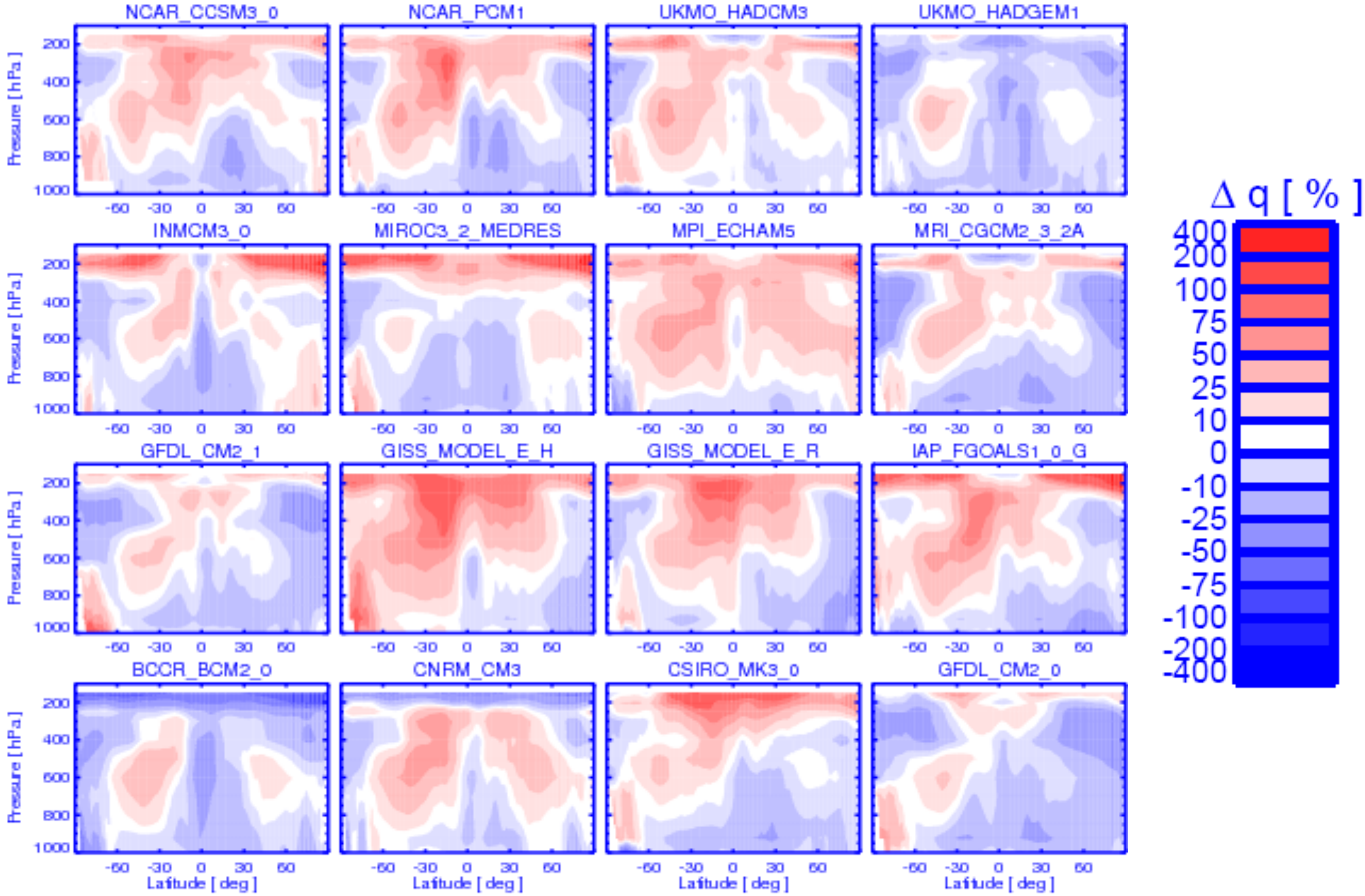


The biases in CMIP3 model simulations are substantial:

- **Moist biases of up to 100% in upper troposphere.**
- **Dry biases of ~25% in lower troposphere.**

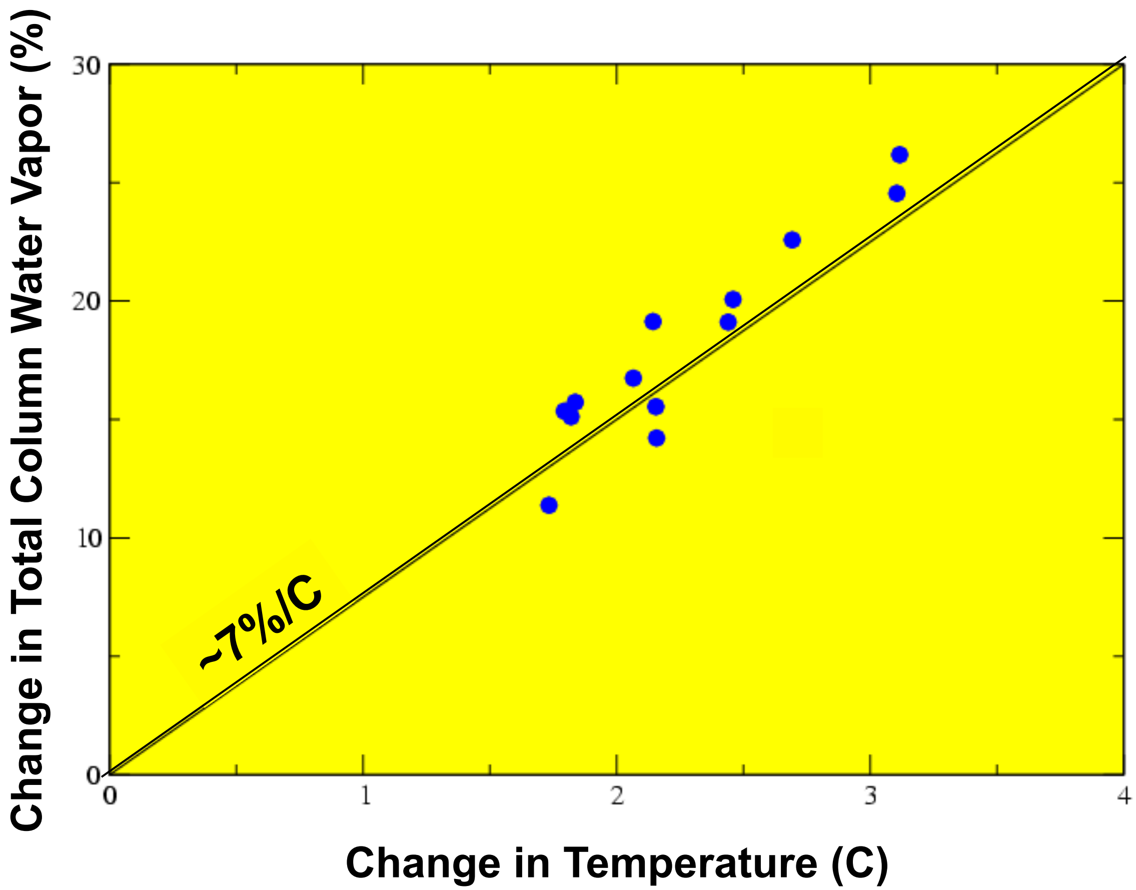
John and Soden 2009

Model Biases in Water Vapor



The biases in water vapor vary substantially from model to model
… yet all have very similar wv feedbacks.

The Consistency of Water Vapor Feedback



- The absorption by water vapor increases in proportion to the logarithm of its concentration.
- Consistent fractional changes = consistent feedback from water vapor.

Is there a Clausius-Clapeyron for clouds?

Radiative Kernels

$$\Delta T_s = \frac{G}{\lambda}$$

R = net radiation at TOA

G = radiative forcing (W/m^2)

λ= climate sensitivity parameter (radiative damping $W/m^2/K$)

$$\lambda = \frac{\delta R}{\delta T}\frac{dT}{dT_s} + \frac{\delta R}{\delta W}\frac{dW}{dT_s} + \frac{\delta R}{\delta C}\frac{dC}{dT_s} + \frac{\delta R}{\delta \alpha}\frac{d\alpha}{dT_s}$$

+ higher order terms

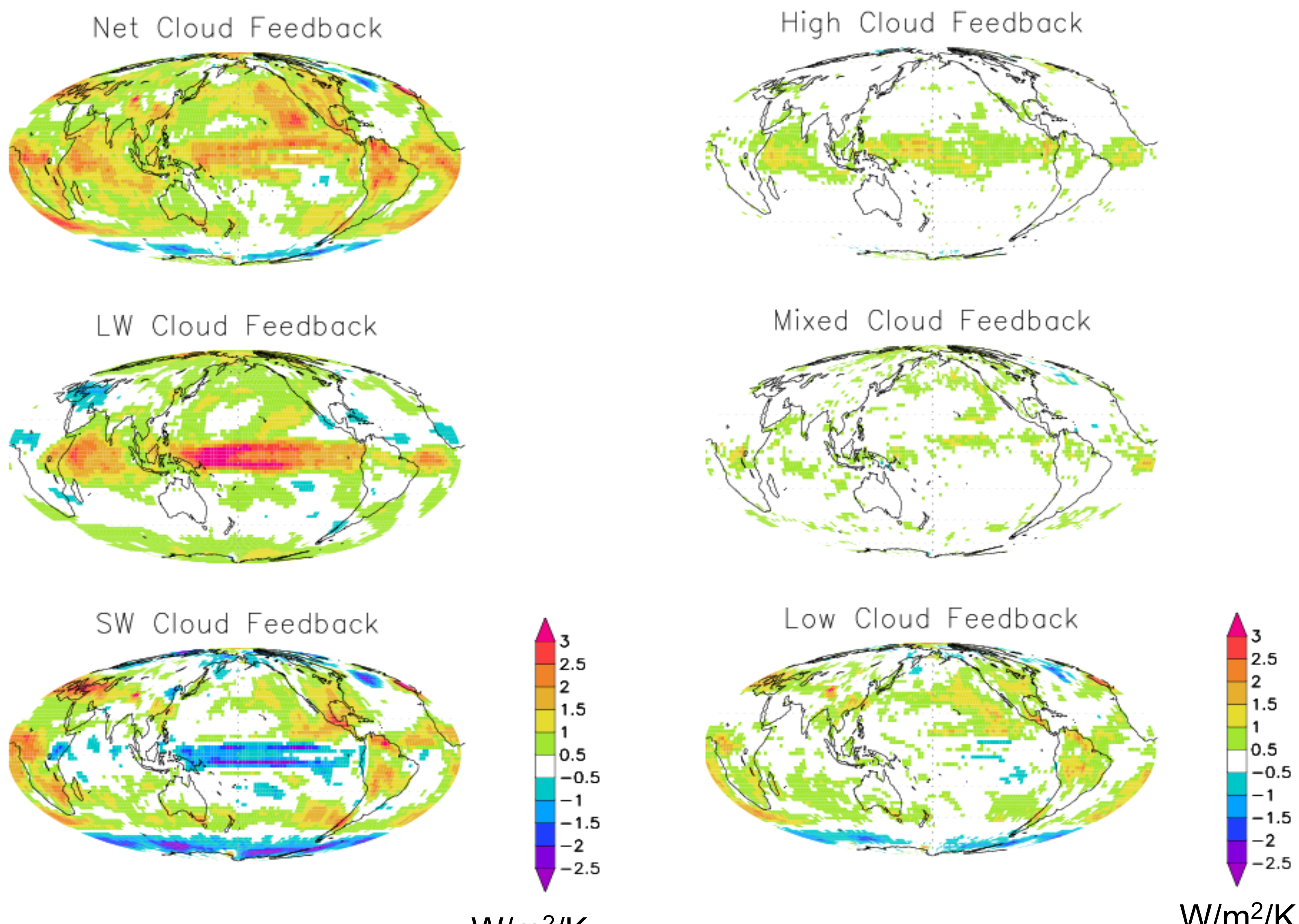
Temperature Feedback | Water Vapor Feedback | Cloud Feedback | Sfc Albedo FeedbacK

Climate Feedback = $\delta R/\delta X$ X dX/dT_s

Radiative Transfer

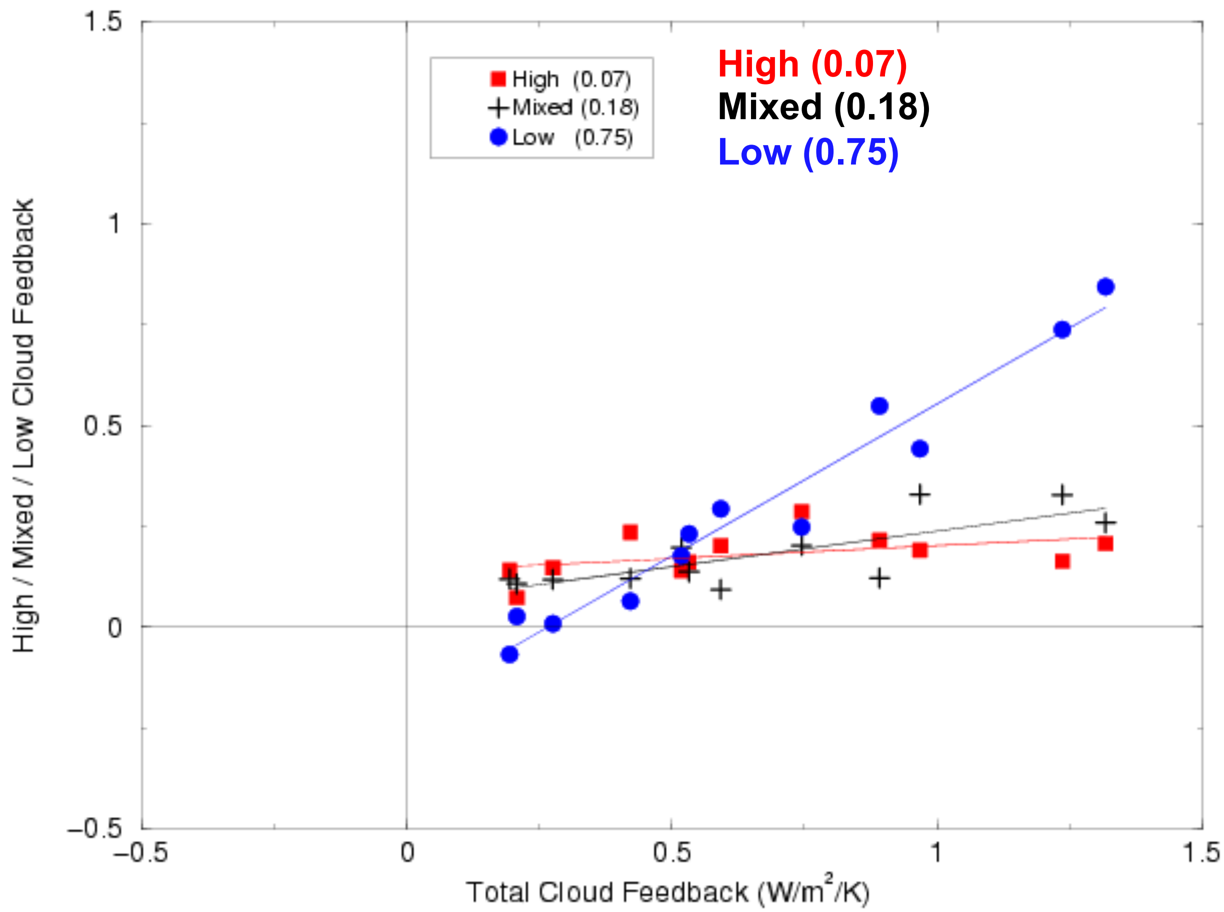
Climate Response

Ensemble Mean Cloud Feedback: CMIP3



Soden and Vecchi (2011)

Intermodel Spread in Cloud Feedback: CMIP3



High cloud feedback is positive and robust.

Low cloud feedback is highly variable (~75% of total spread)

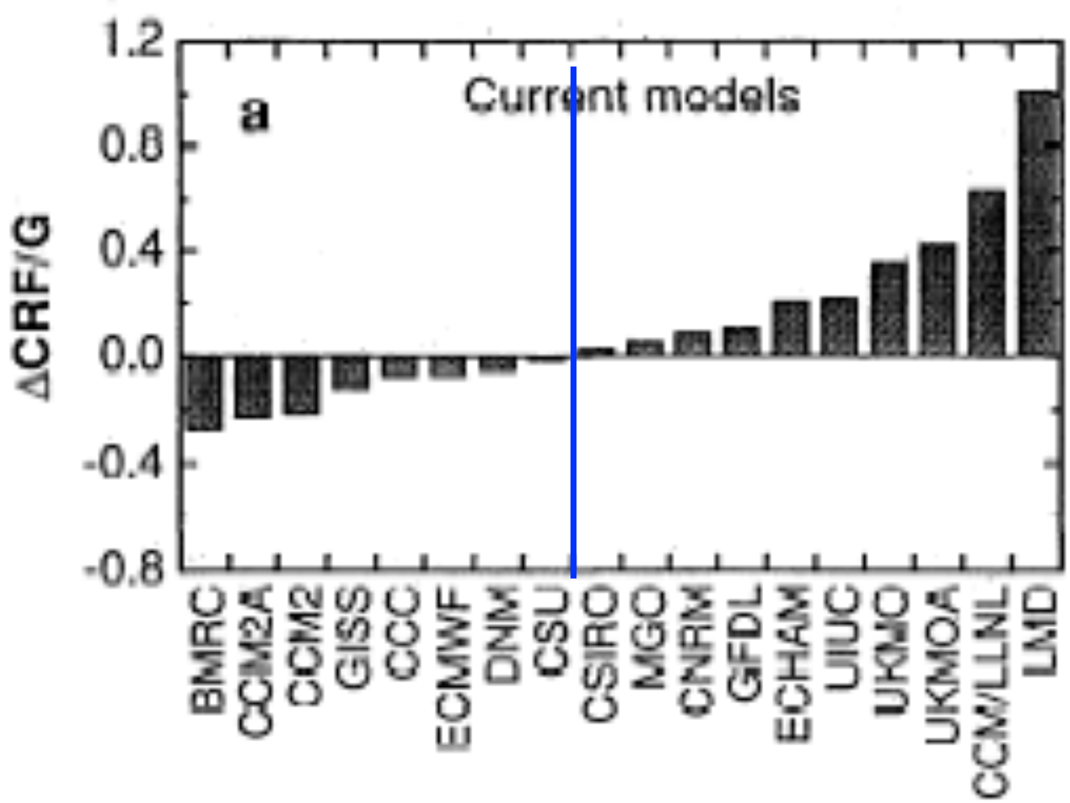
but not negative.

Soden and Vecchi (2011)

Why is cloud feedback positive?

Interpretation of Cloud-Climate Feedback as Produced by 14 Atmospheric General Circulation Models

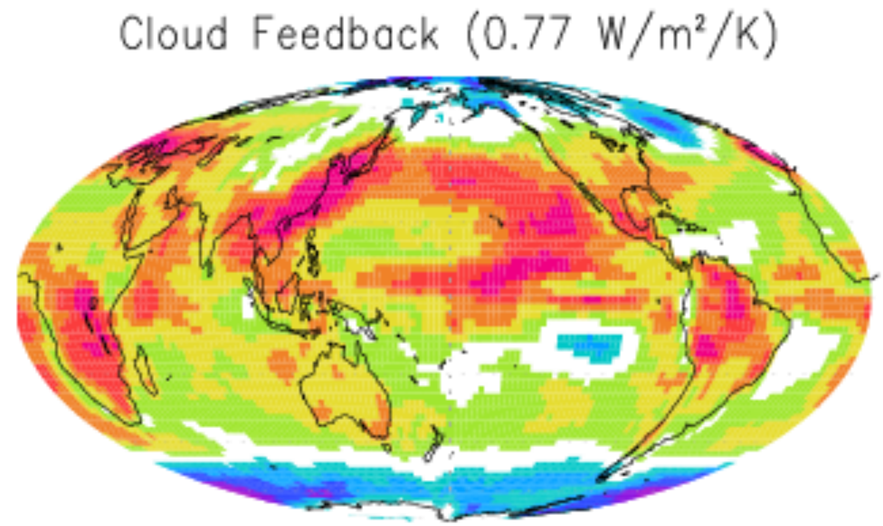
R. D. Cess, G. L. Potter, J. P. Blanchet, G. J. Boer, S. J. Ghan, J. T. Kiehl, H. Le Treut, Z.-X. Li, X.-Z. Liang, J. F. B. Mitchell, J.-J. Morcrette, D. A. Randall, M. R. Riches, E. Roeckner, U. Schlese, A. Slingo, K. E. Taylor, W. M. Washington, R. T. Wetherald, I. Yagai

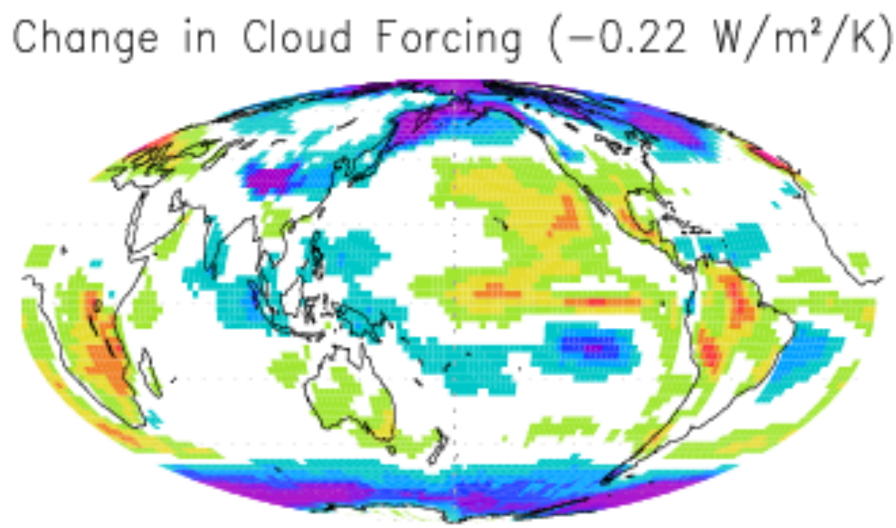


Cess et al. (1989)

Changes in CRF are biased estimates of cloud feedback

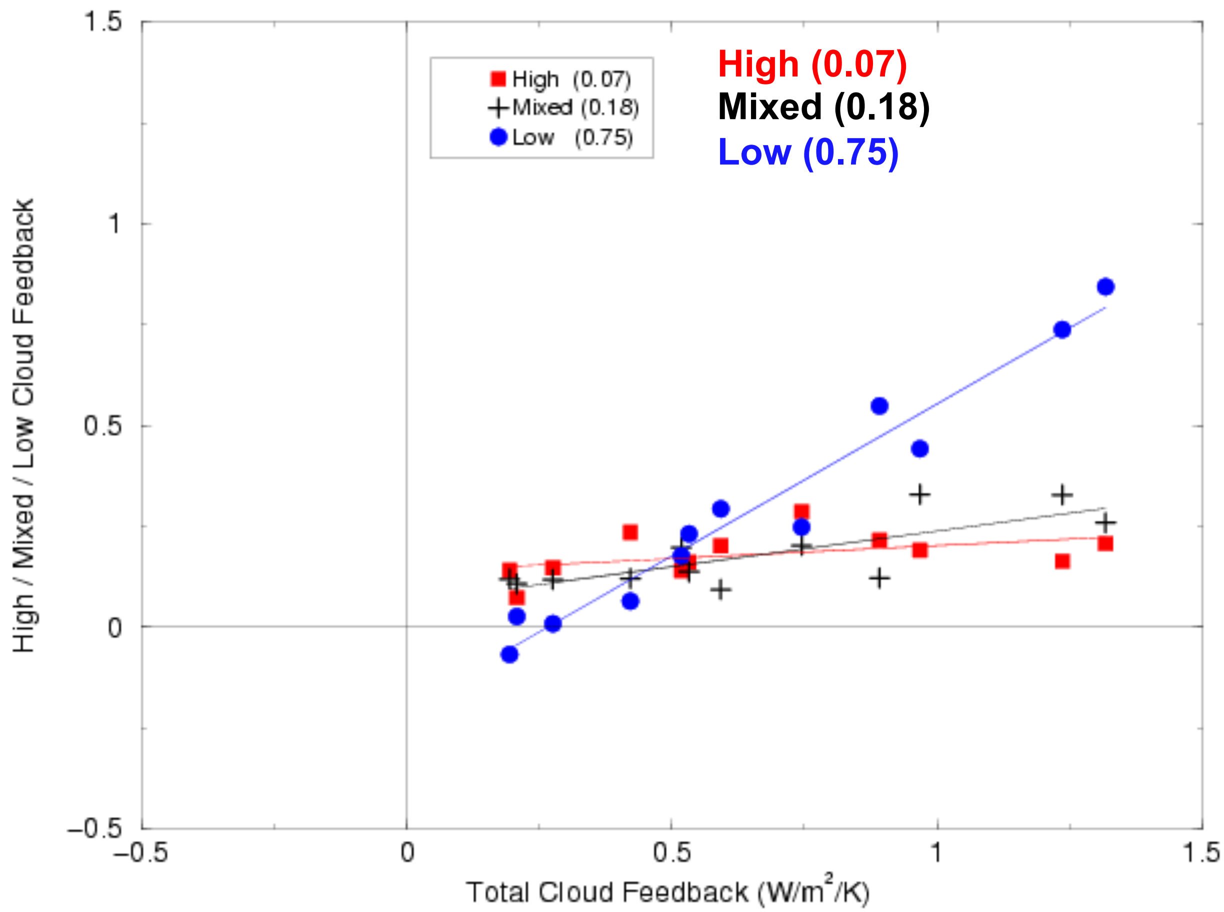
Cloud Feedback vs Δ Cloud Forcing





$CRF = R_{clr} - R$

Intermodel Spread in Cloud Feedback: CMIP3



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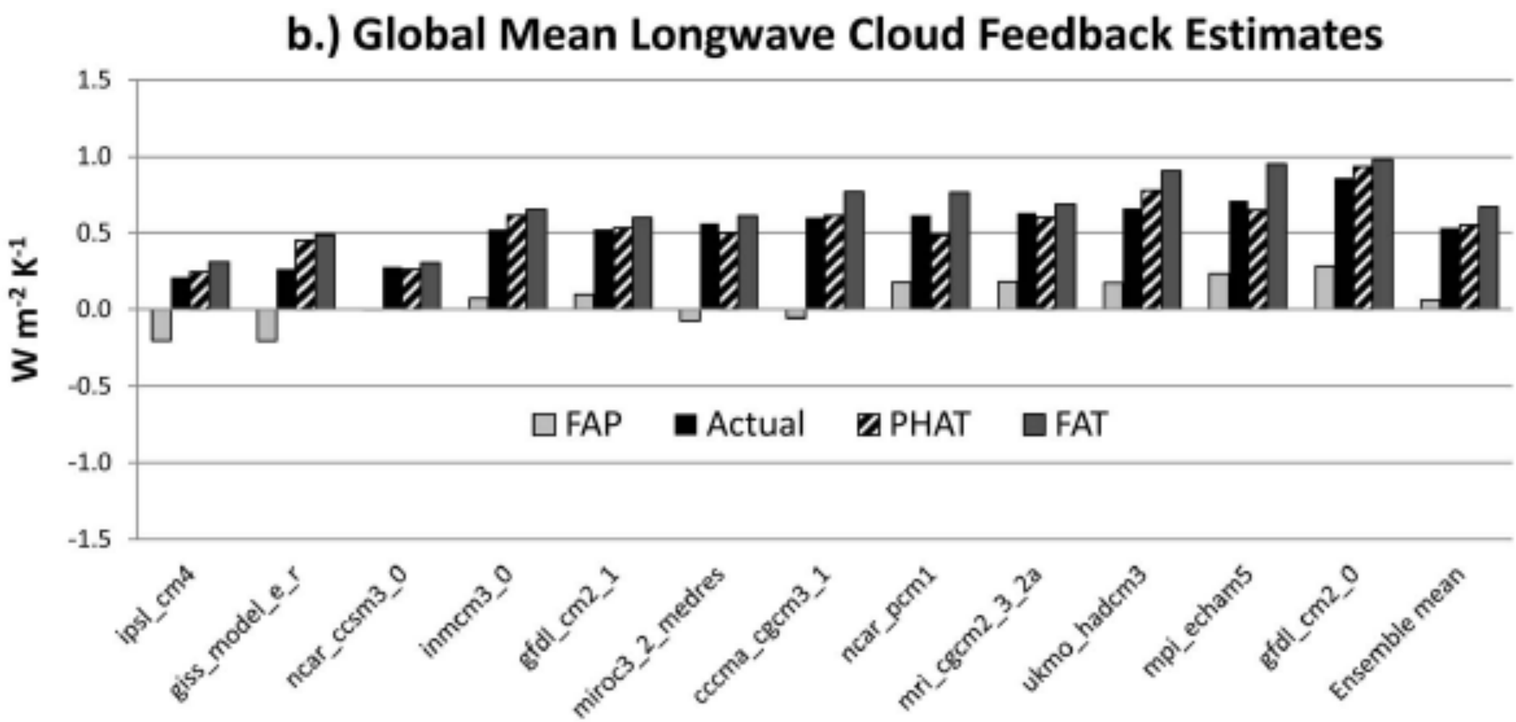
Soden and Vecchi (2011)

Why is High Cloud Feedback Positive and Robust?

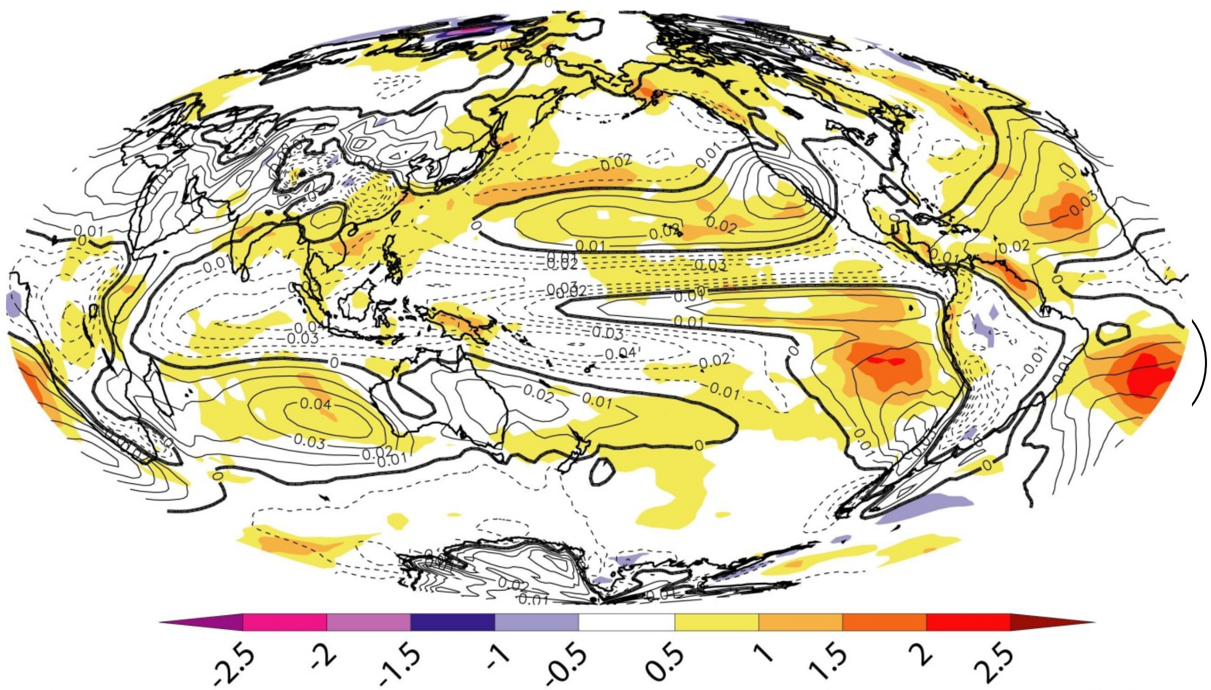


High cloud changes in GCMs follow a nearly constant temperature (rather than constant altitude).

This behavior is supported by observations (Z&H 20011)

Zelinka and Hartmann (2010)

Local contribution to intermodel spread in cloud feedback

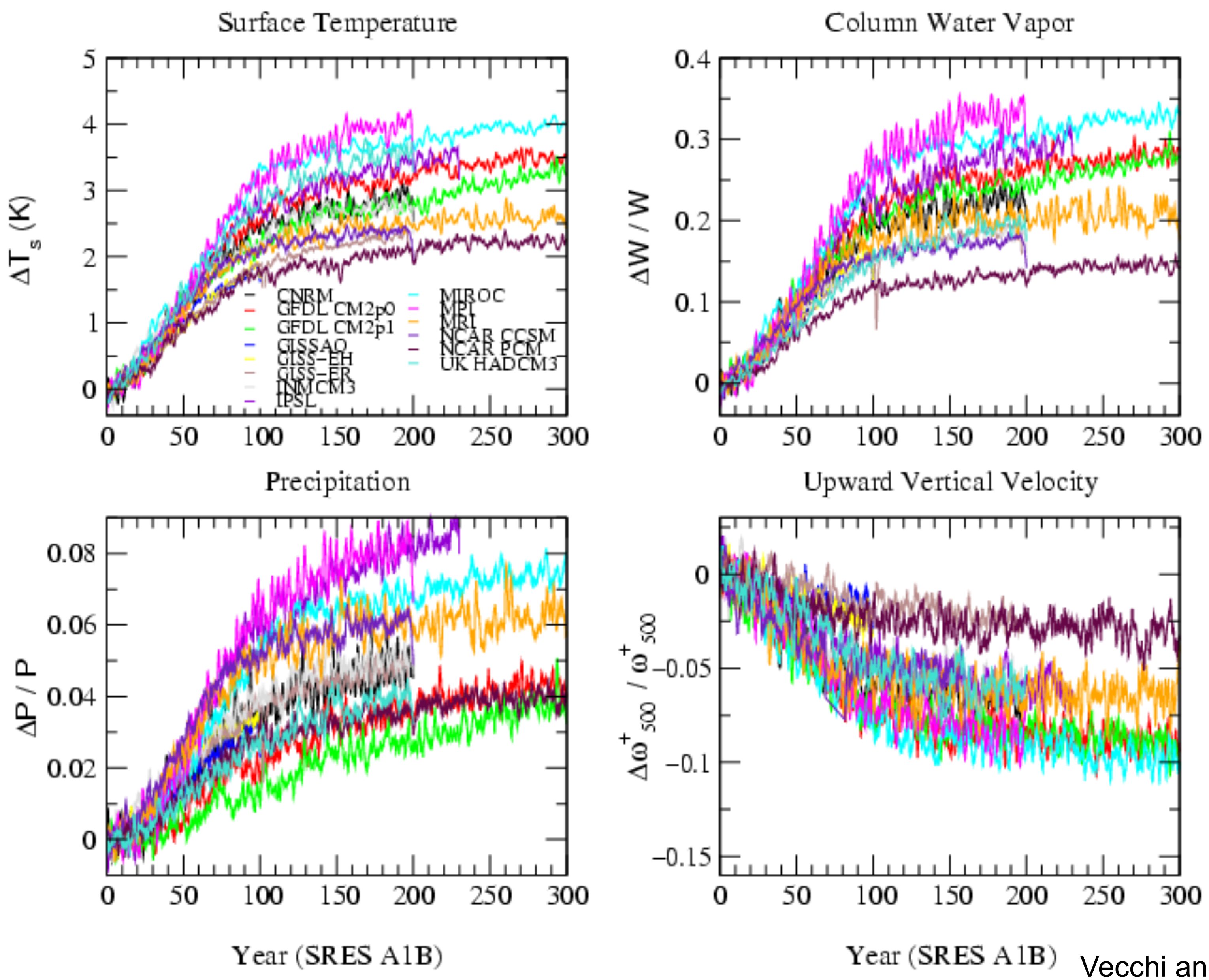


Shade: Regression of Local Cloud Feedback to Global-mean Cloud Feedback ($W \cdot m^{-2} \cdot K^{-1}$)
Contour: Background 500hPa Pressure Velocity ($Pa \cdot s^{-1}$)

- **Most of intermodel spread arises from low stratocumulus/cumululs regions**
- **Possible links to atmospheric circulation**

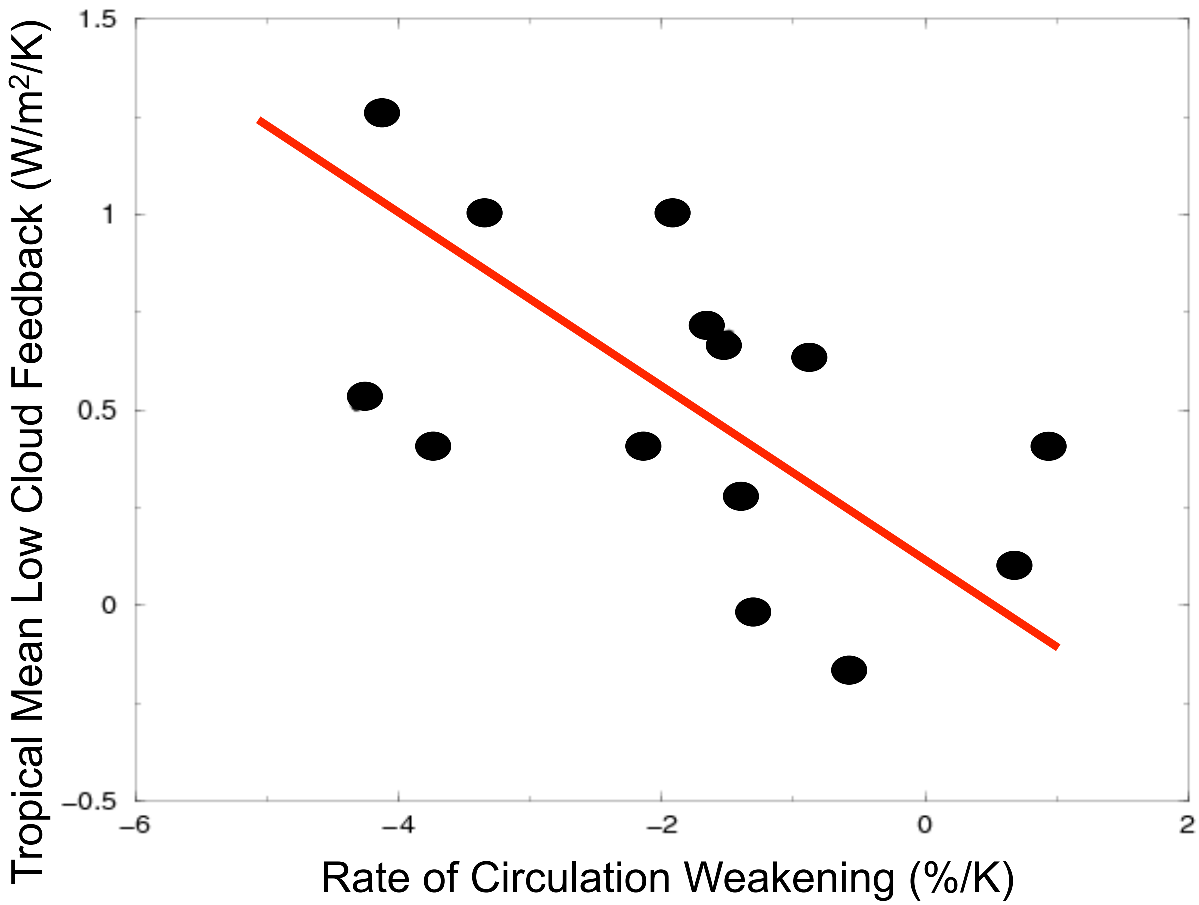
Soden and Vecchi (2011)

Weakening of the Tropical Circulation: CMIP3



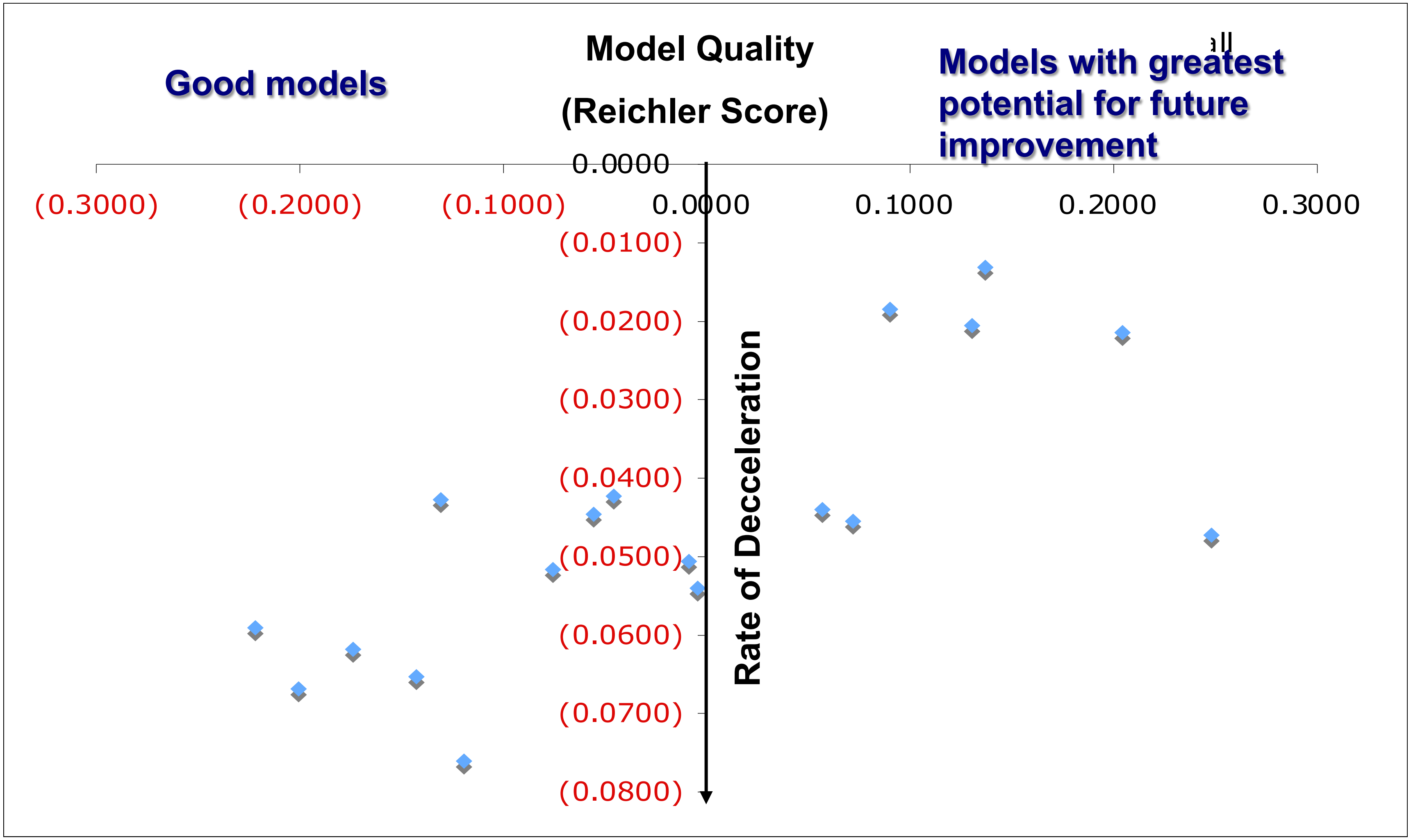
Vecchi and Soden 2007

Weakening of Circulation and Tropical Low Cloud Feedback



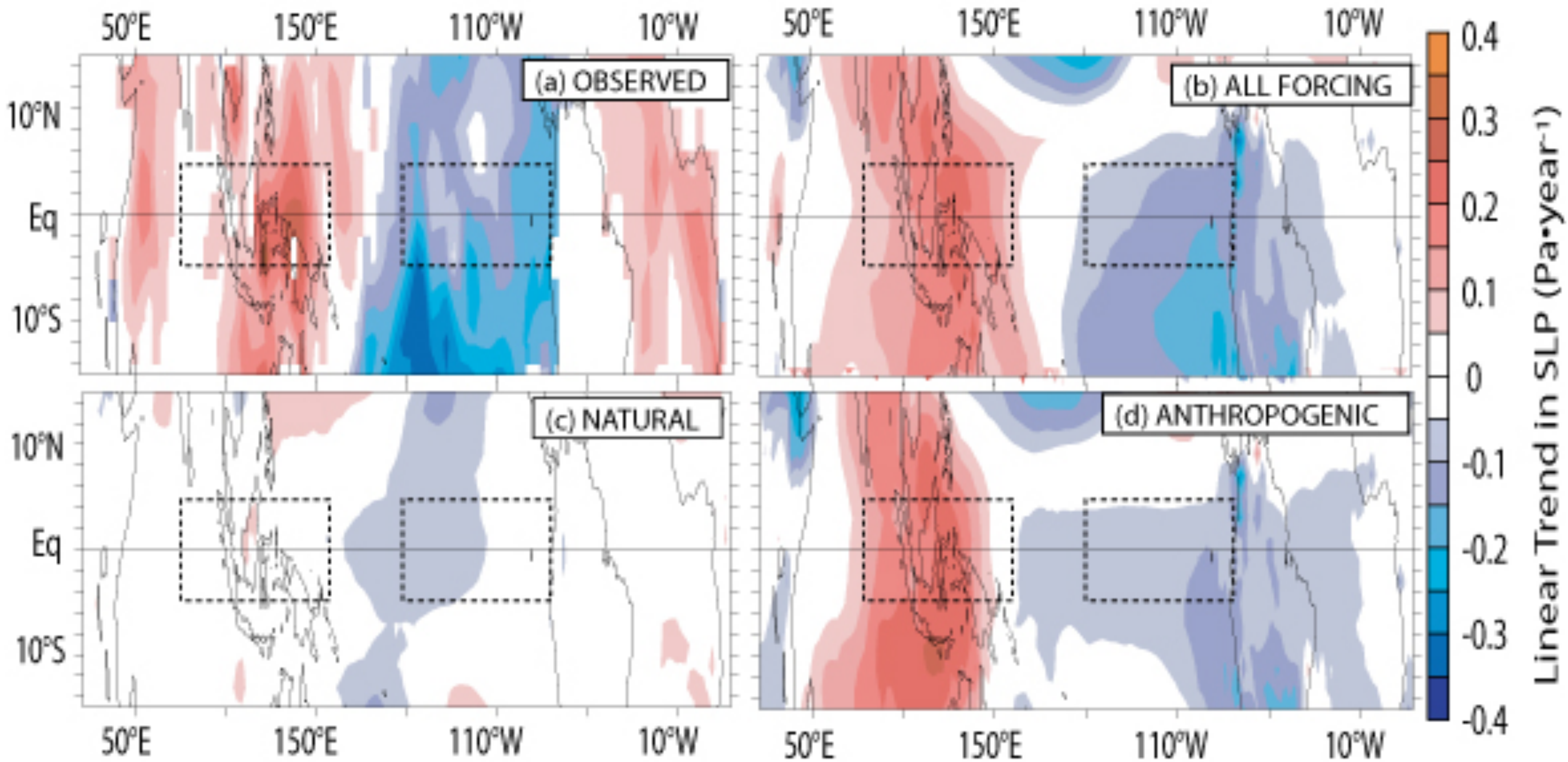
Models with greatest weakening have largest low cloud feedback

“Best” Models Tend to Show Greater Weakening



Reichler Score developed by Thomas Reichler
(U. Utah) to quantify quality of climate simulation

Historical Trends in SLP: 1861-2000

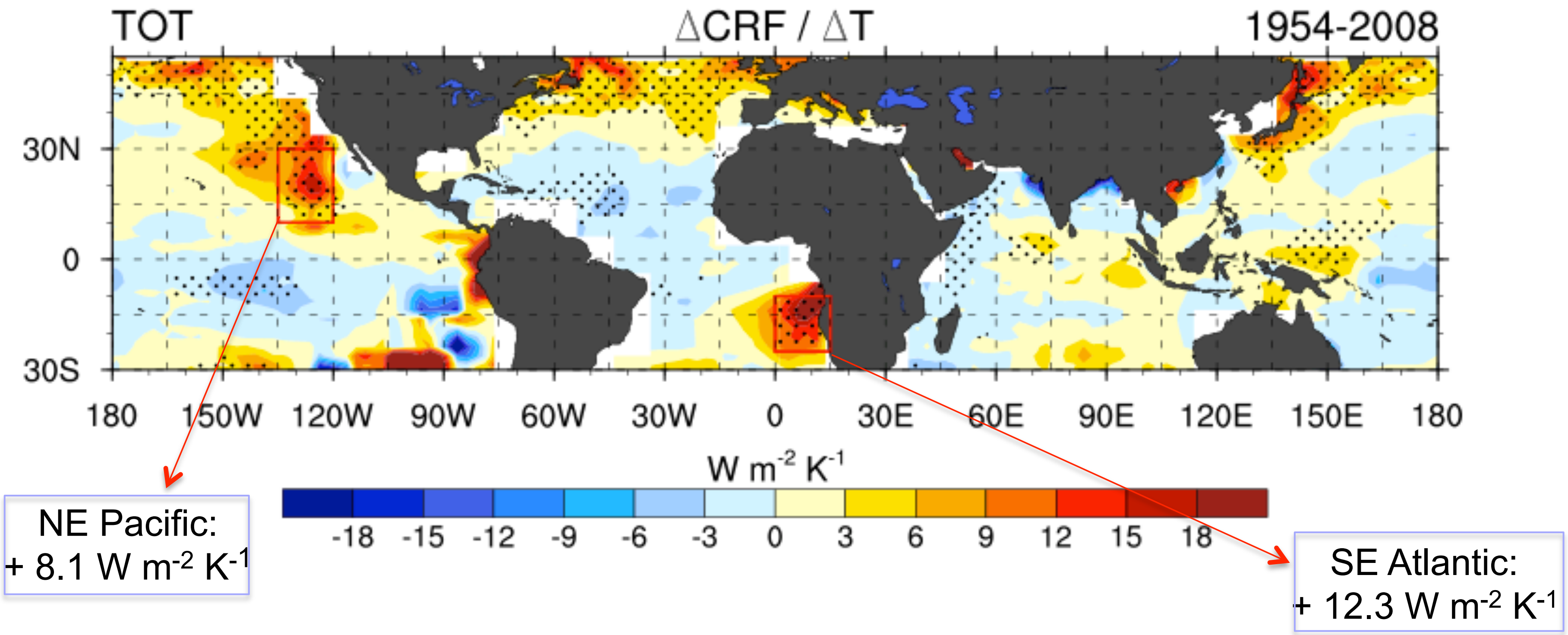


- Observations suggest that Walker Circulation has weakened over the past century due to anthropogenic forcing.

- Models suggest that we should expect to see a reduction in subtropical low cloud.

Vecchi et al. 2006

Observational Estimates of Cloud Feedback



- ΔCRF -> obtained by regressing ISCCP net radiative flux at TOA and multiplying the regression coeff. by H&W <u>total cloud</u> cover, ΔT = +0.47^{o} (from 1954 to 2008).
- NE Pacific and SE Atlantic: CRF increases and the total cloud feedback parameter is **positive** over this period.

Katinka Bellomo (RSMAS)

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Radiative Forcing in CMIP3 Model Scenarios

- **Most modeling centers do not provide (calculate?) the radiative forcing for different emission scenarios.**

- **Those that do calculate the radiative forcing usually do so differently from one group to the next.**

- **We use "radiative kernels" (Soden et al., 2008) to estimate clear-sky radiative forcing.**

Estimating Radiative Forcing using “Kernels”

Consider the Change in Net Clear-sky Flux at TOA: ***dR***

$$dR = \left(\frac{\delta R}{\delta T}\frac{dT}{dT_s} + \frac{\delta R}{\delta W}\frac{dW}{dT_s} + \frac{\delta R}{\delta \alpha}\frac{d\alpha}{dT_s}\right)dT_s \quad + G \quad + \dots$$

Temperature Feedback | **Water Vapor Feedback** | **Sfc Albedo FeedbacK**

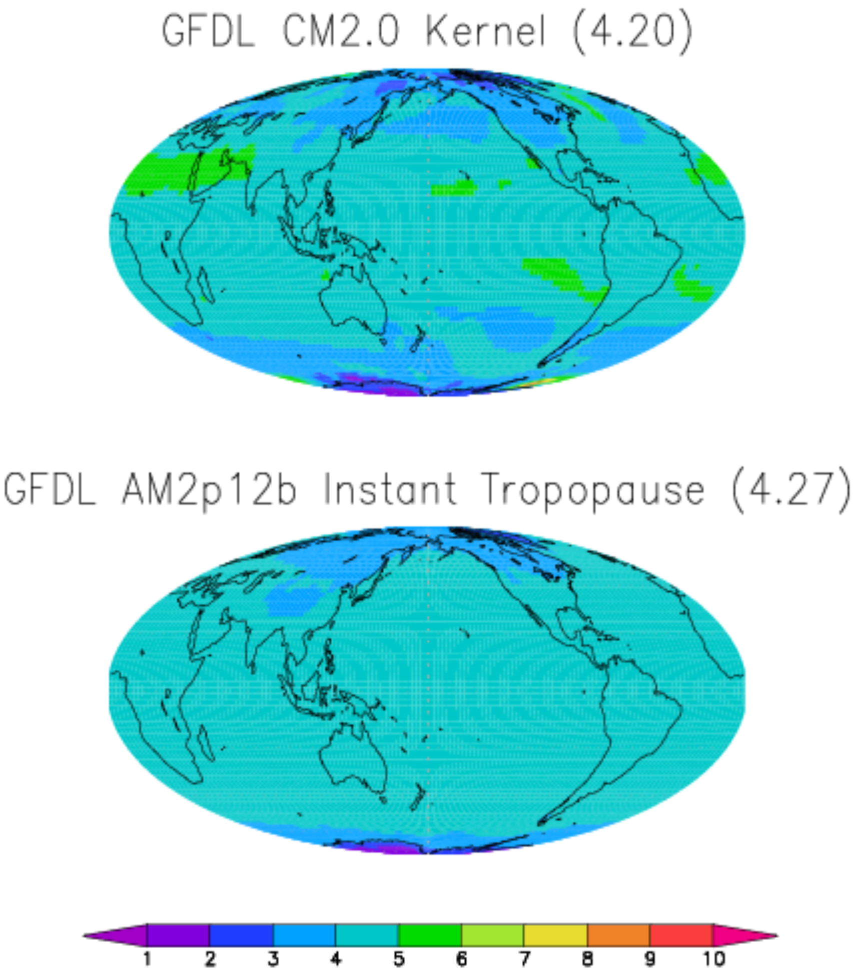
GCM Output

Linear response of radiative flux to feedbacks (computed from kernels)

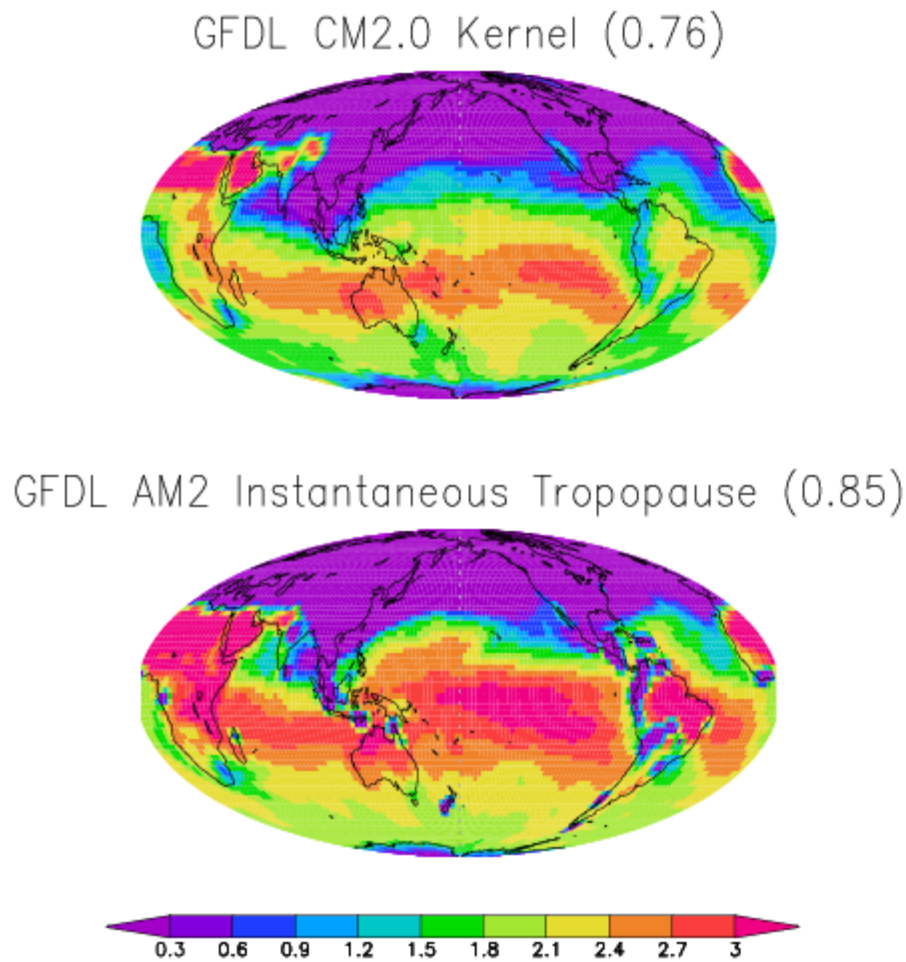
Clear-Sky Radiative Forcing

Radiative Forcing: Kernel vs. Direct Calculation

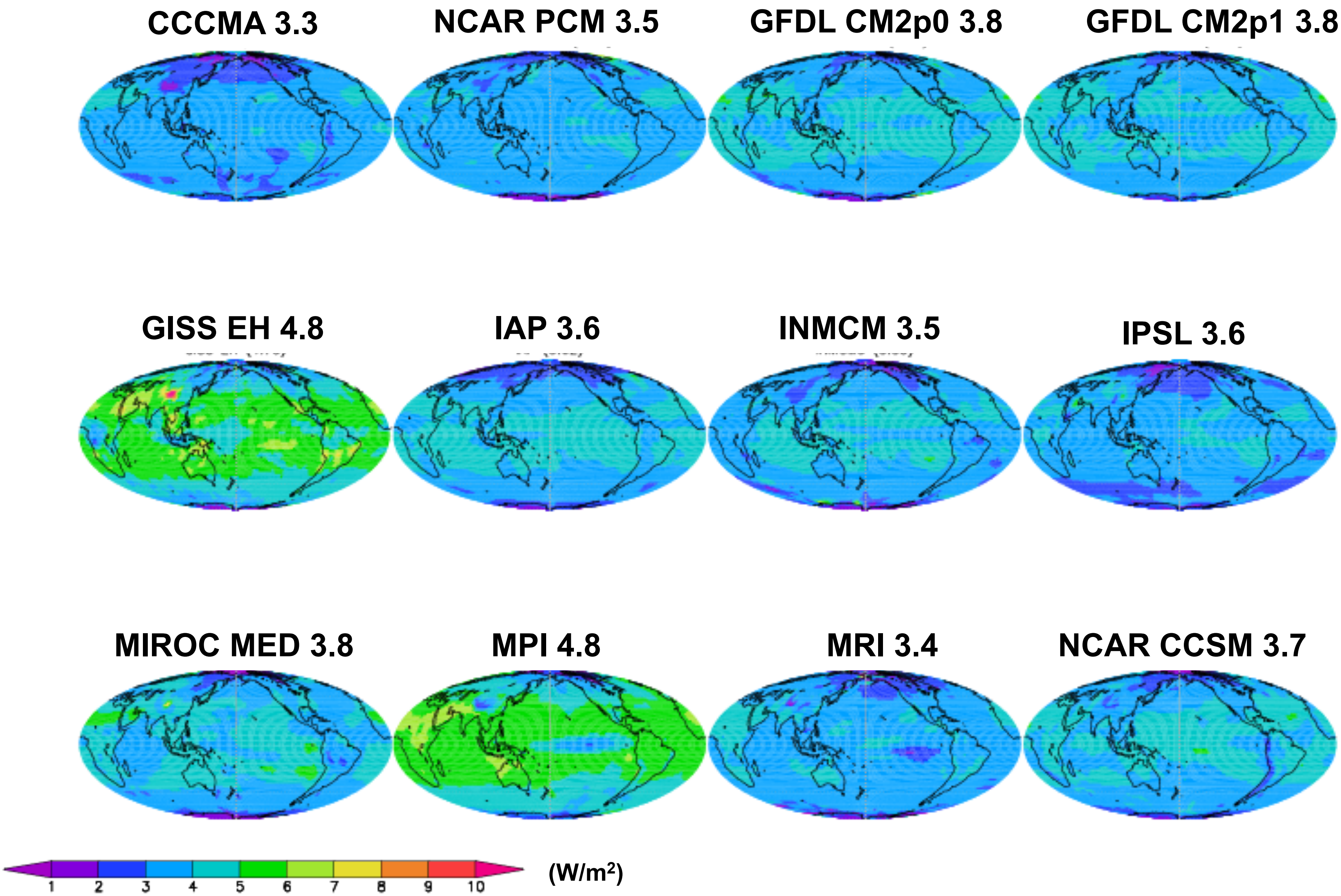
2x CO2



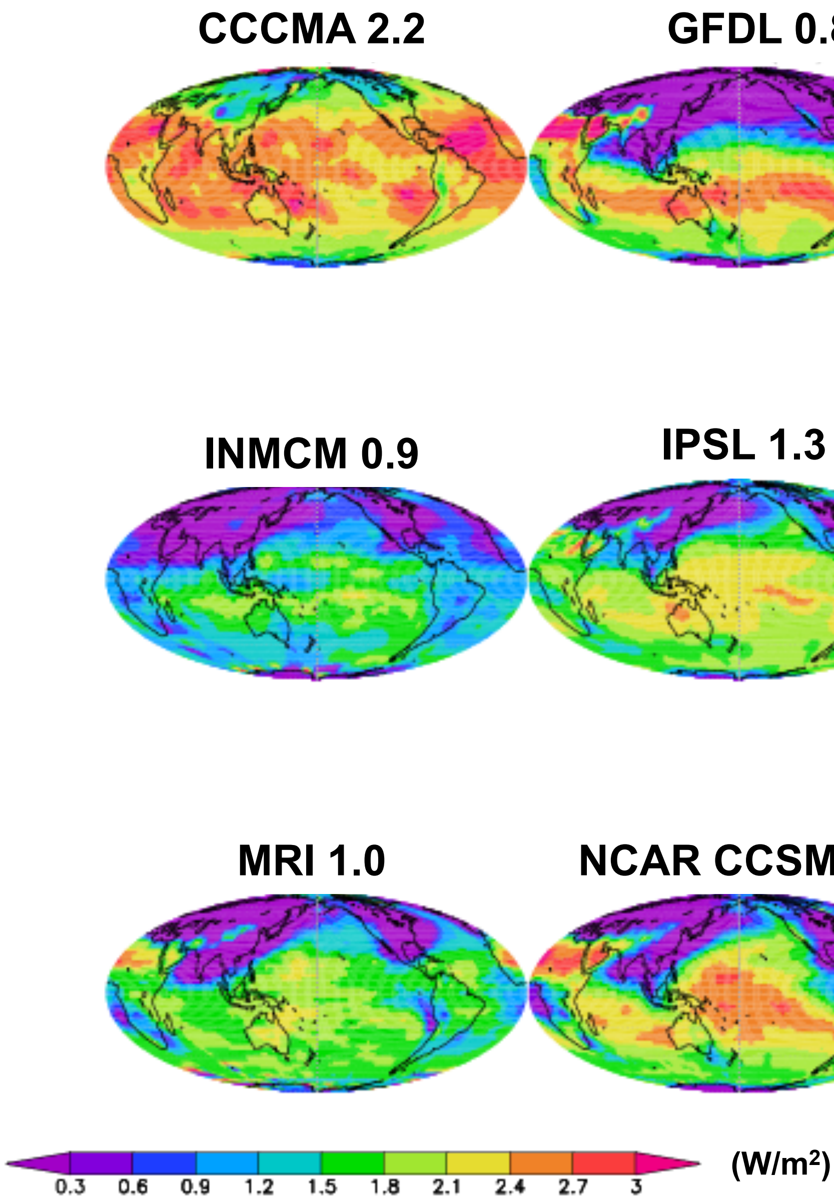
20C3M



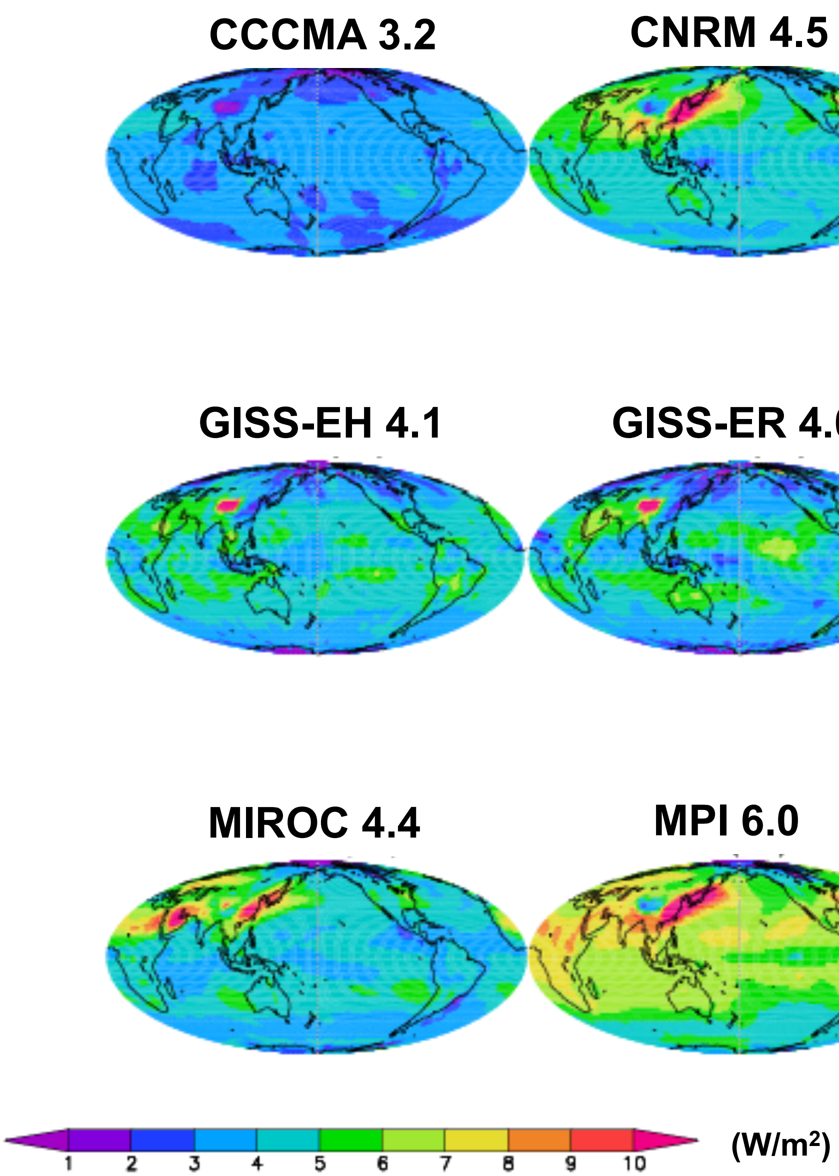
Clear-sky Radiative Forcing: IPCC AR4 2xCO2



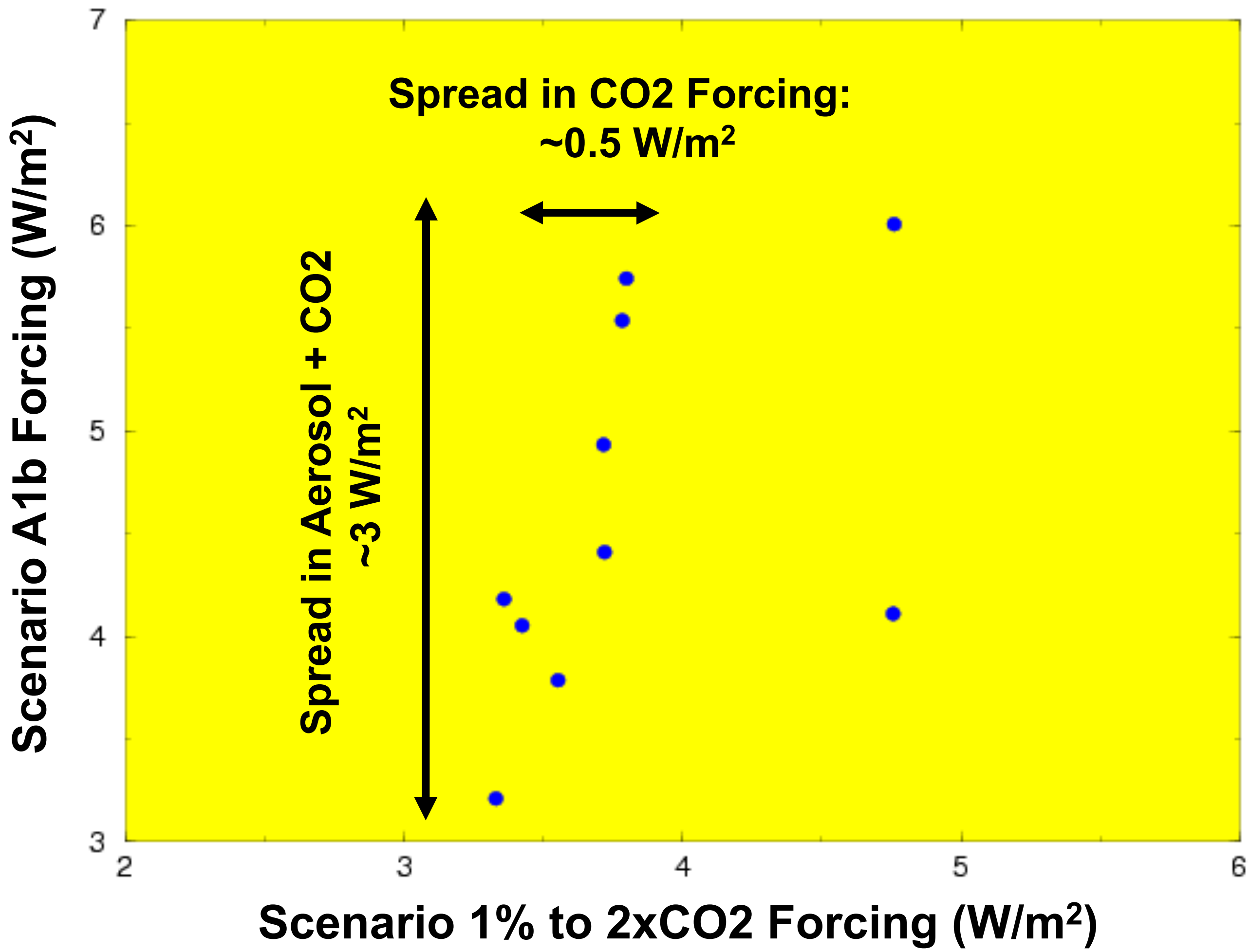
Clear-sky Radiative Forcing: IPCC AR4 20C3M



Clear-sky Radiative Forcing: IPCC AR4 A1b



Clear-sky Radiative Forcing: 2xCO2 vs. A1b

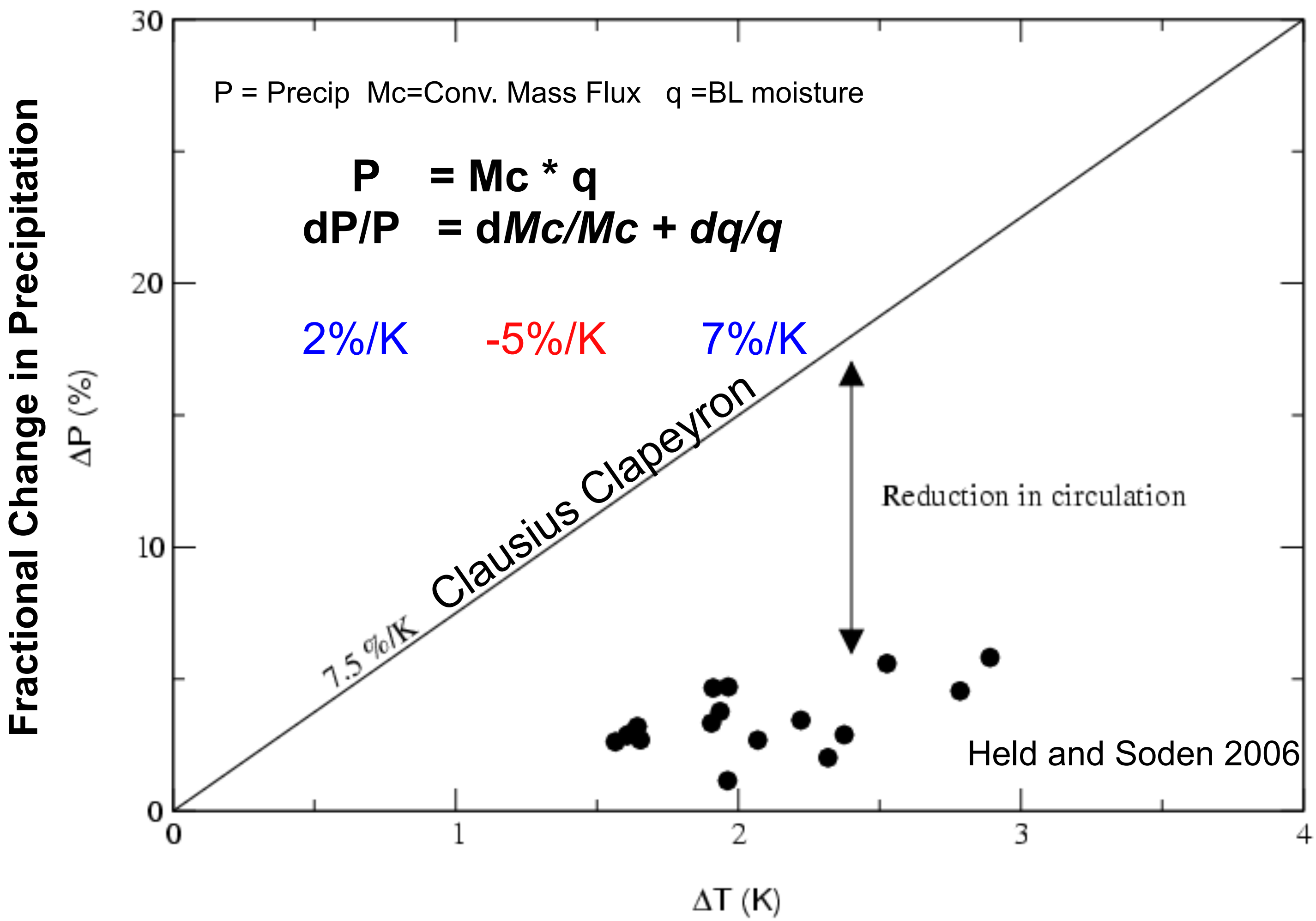


Remaining Challenges

- Why is low cloud feedback positive in models?
- What role do changes in the large-scale circulation (subsidence) regulate low cloud changes in the tropics?
- What other factors besides subsidence are important?
- Is there observational evidence to support any of this?

Extra Slides

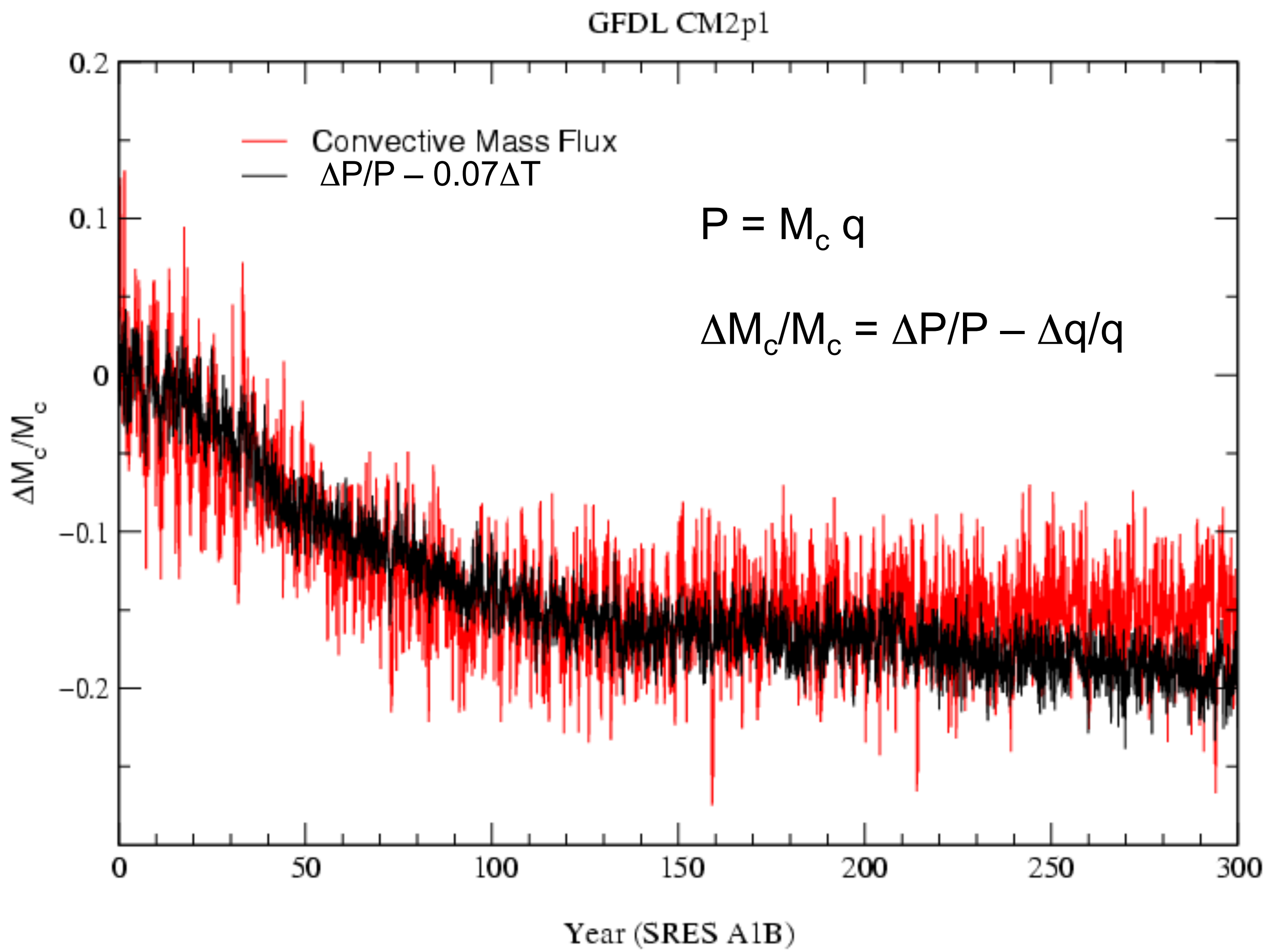
Strengthening of Hydrological Cycle and Weakening of Circulation



ΔP ~2% due to limit on water vapor emission (Stephens and Ellis, 2008)

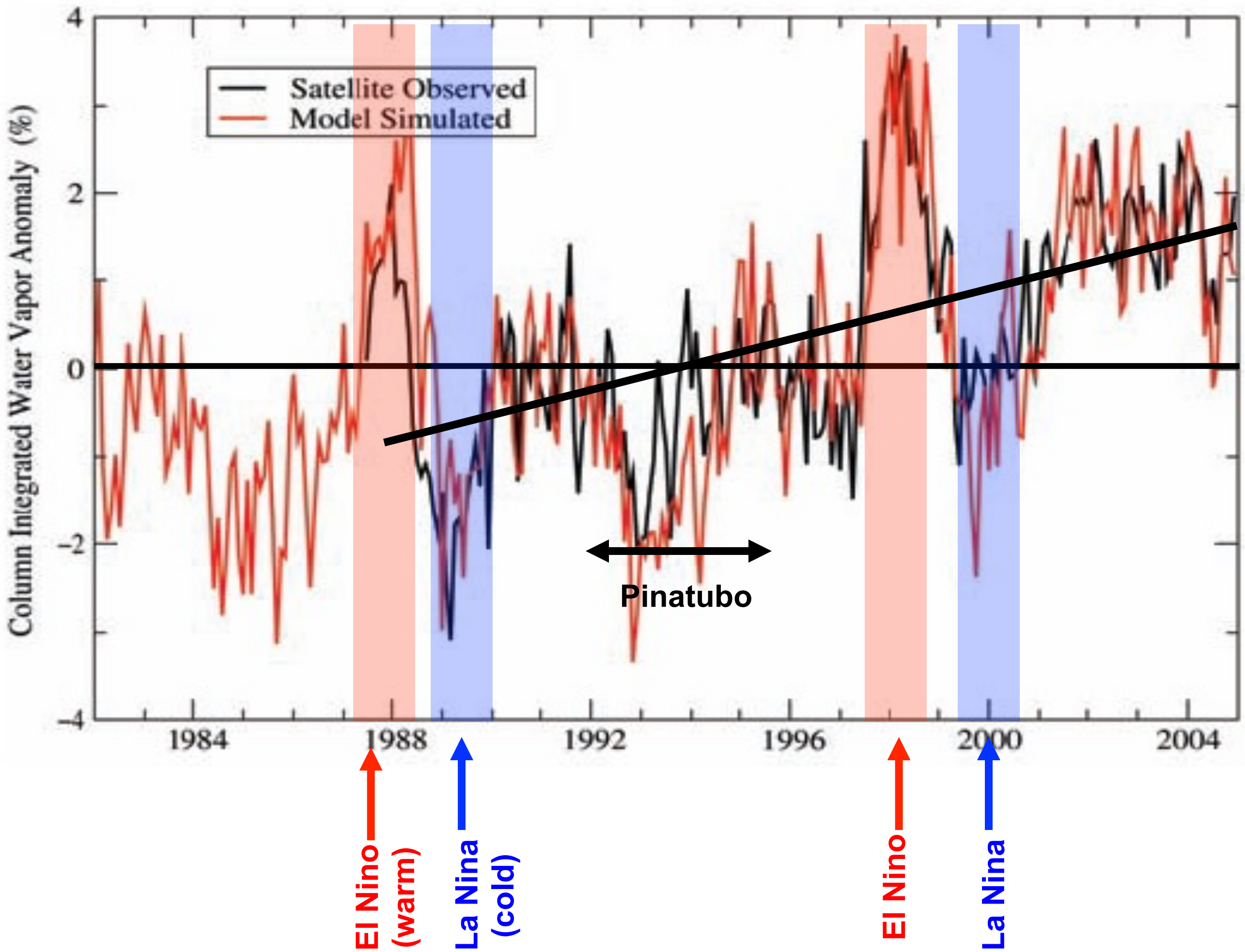
Change in Convective Mass Flux

Fractional Change in Convective Mass Flux



Held and Soden 2006

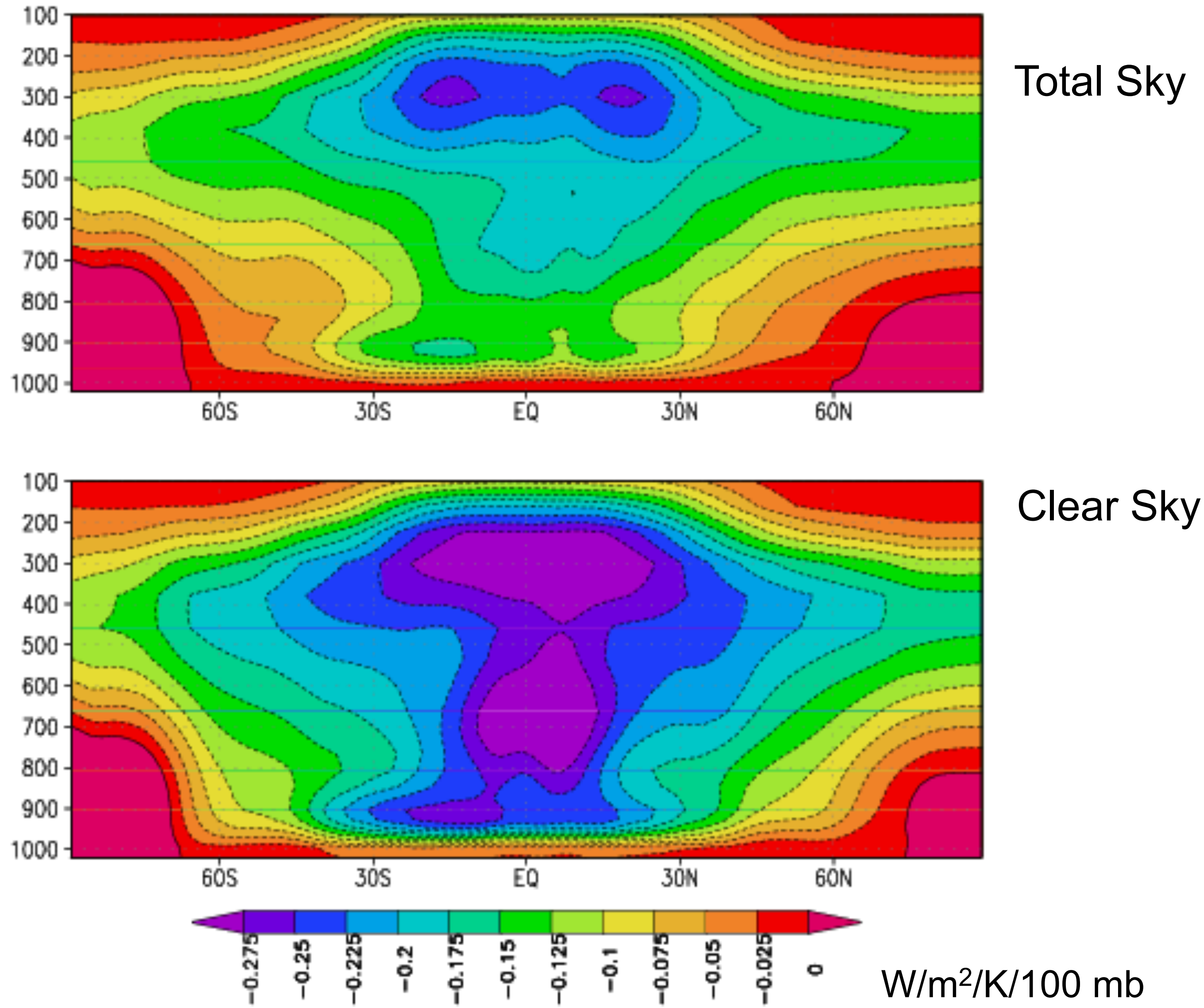
Satellite-Observed and Model-Simulated Changes in Atmospheric Water Vapor



- There is abundant observational evidence in support of a strong water vapor feedback

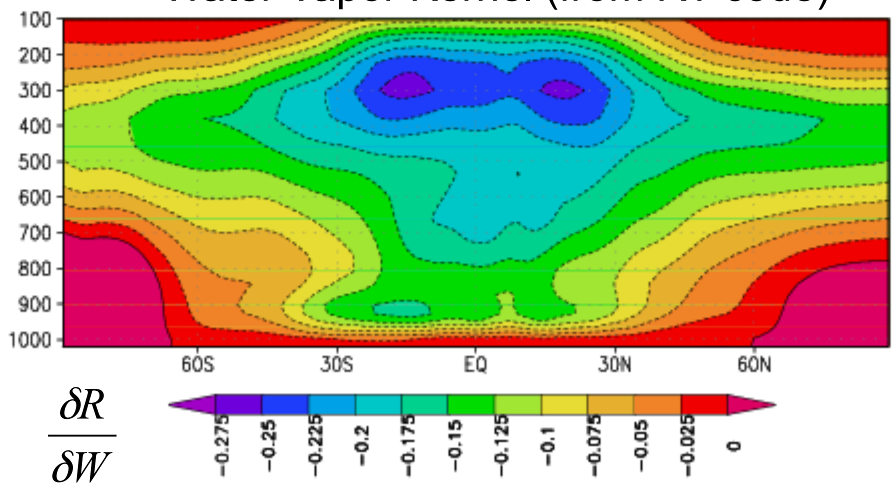
Water Vapor Kernel
(zonal, annual mean)

Change in OLR due to constant RH increase in water vapor



Water Vapor Feedback using Kernels

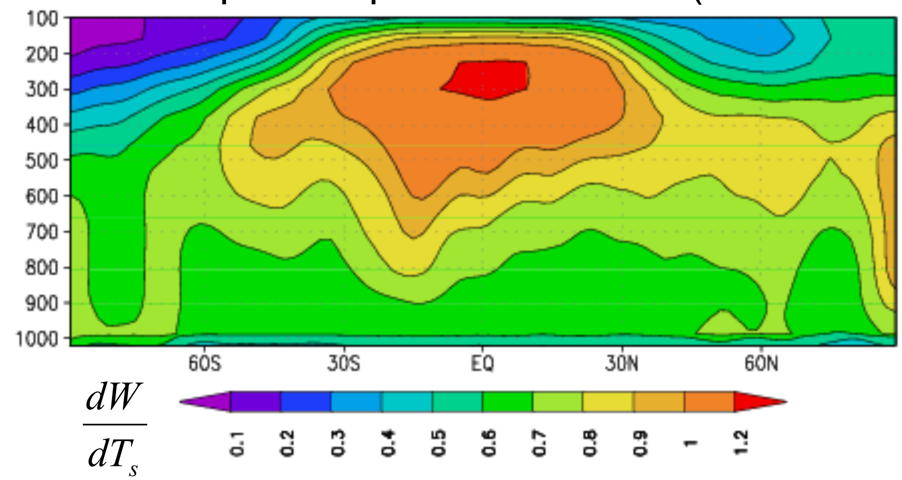
Water Vapor Kernel (from RT code)



$$\frac{\delta R}{\delta W}$$

x

Water Vapor Response to 2xCO2 (from GCM)



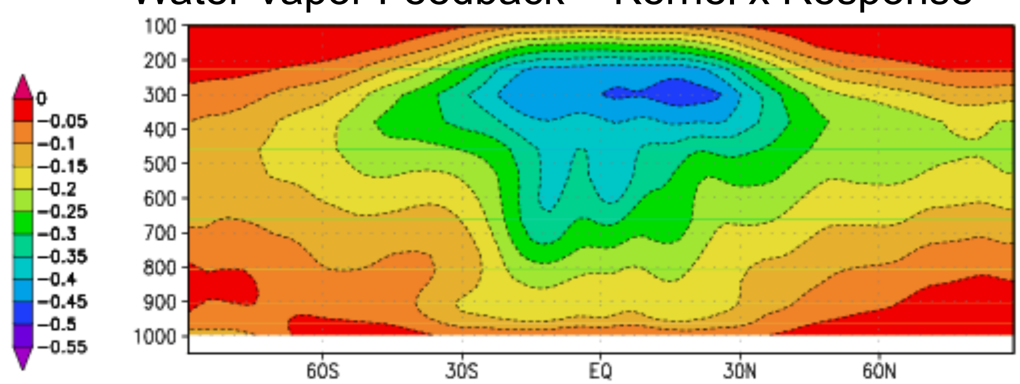
$$\frac{dW}{dT_s}$$

Radiation is most sensitive to upper troposphere because clouds mask contributions from lower levels

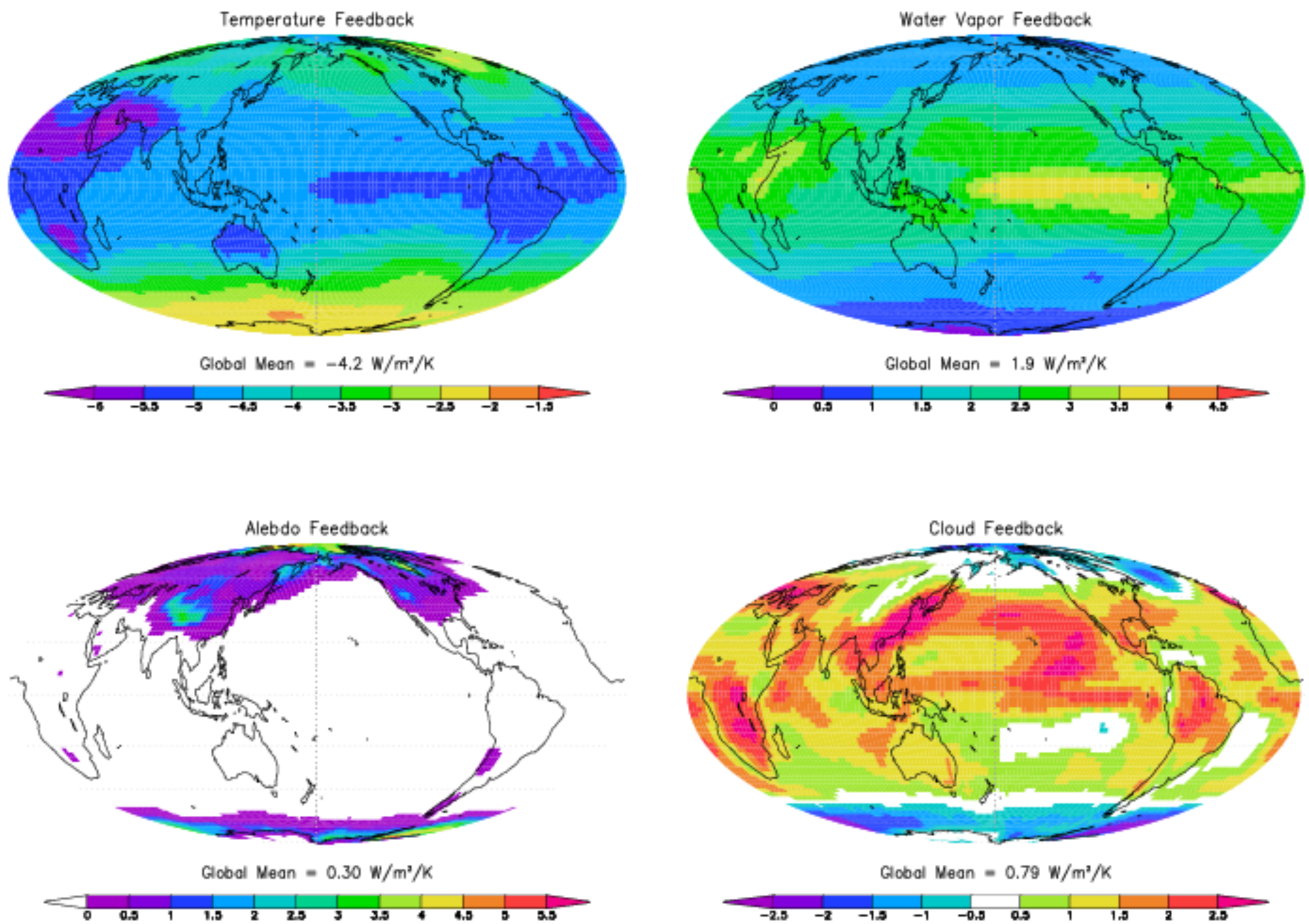
Fractional changes in water vapor are also largest in upper troposphere due to C-C and moist adiabatic response.

=

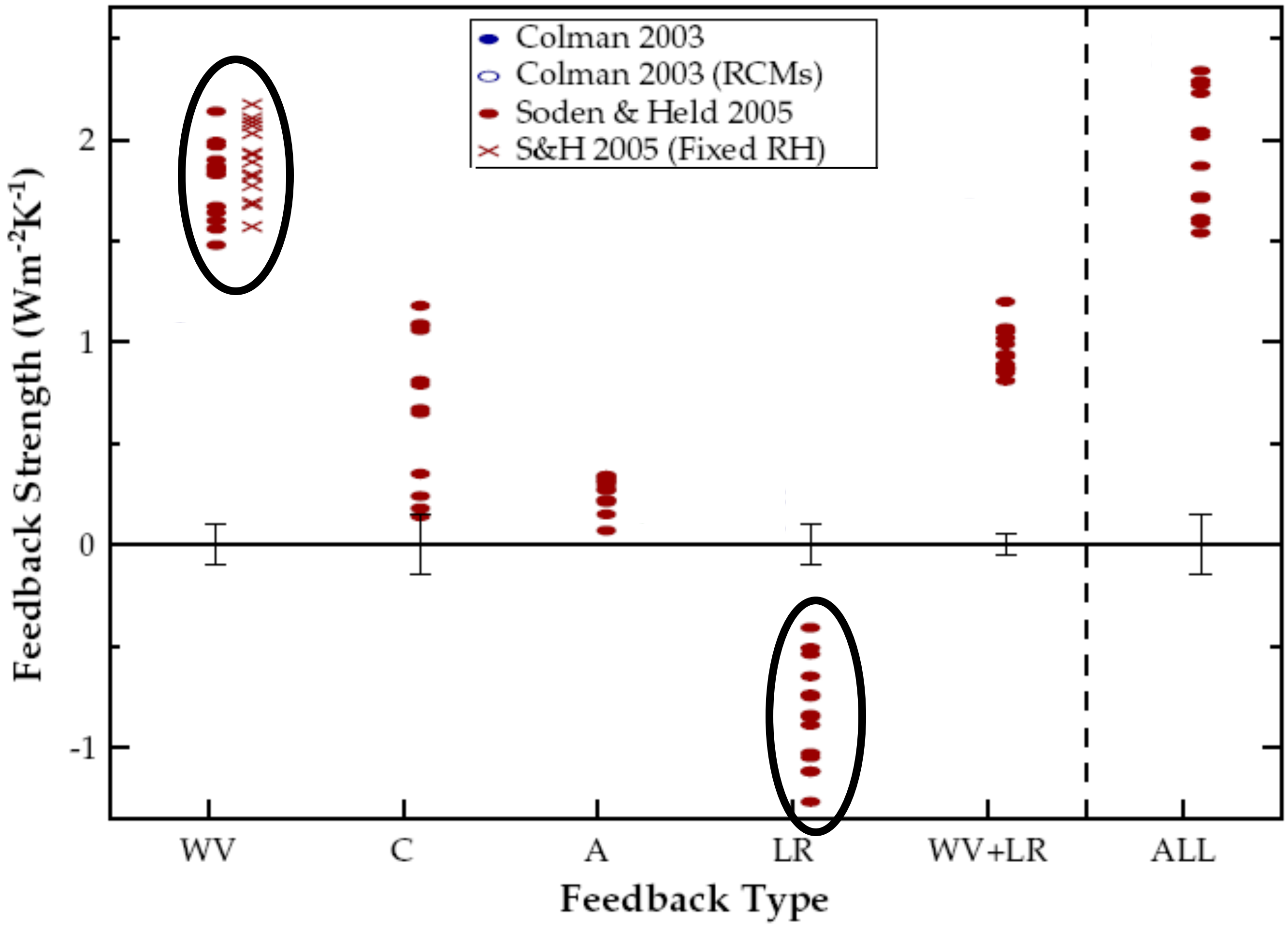
Water Vapor Feedback = Kernel x Response



Ensemble Mean Feedbacks: IPCC AR4 GCMs



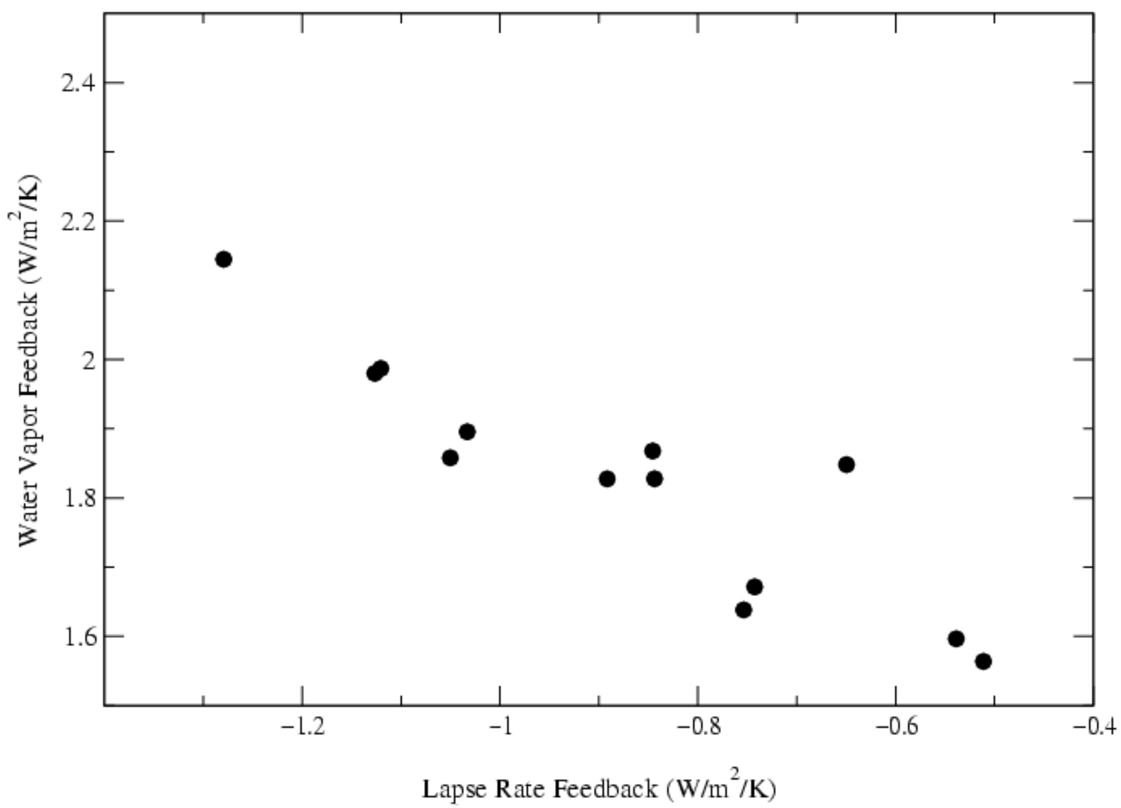
Climate Feedbacks in IPCC Models



Bony et al. 2006

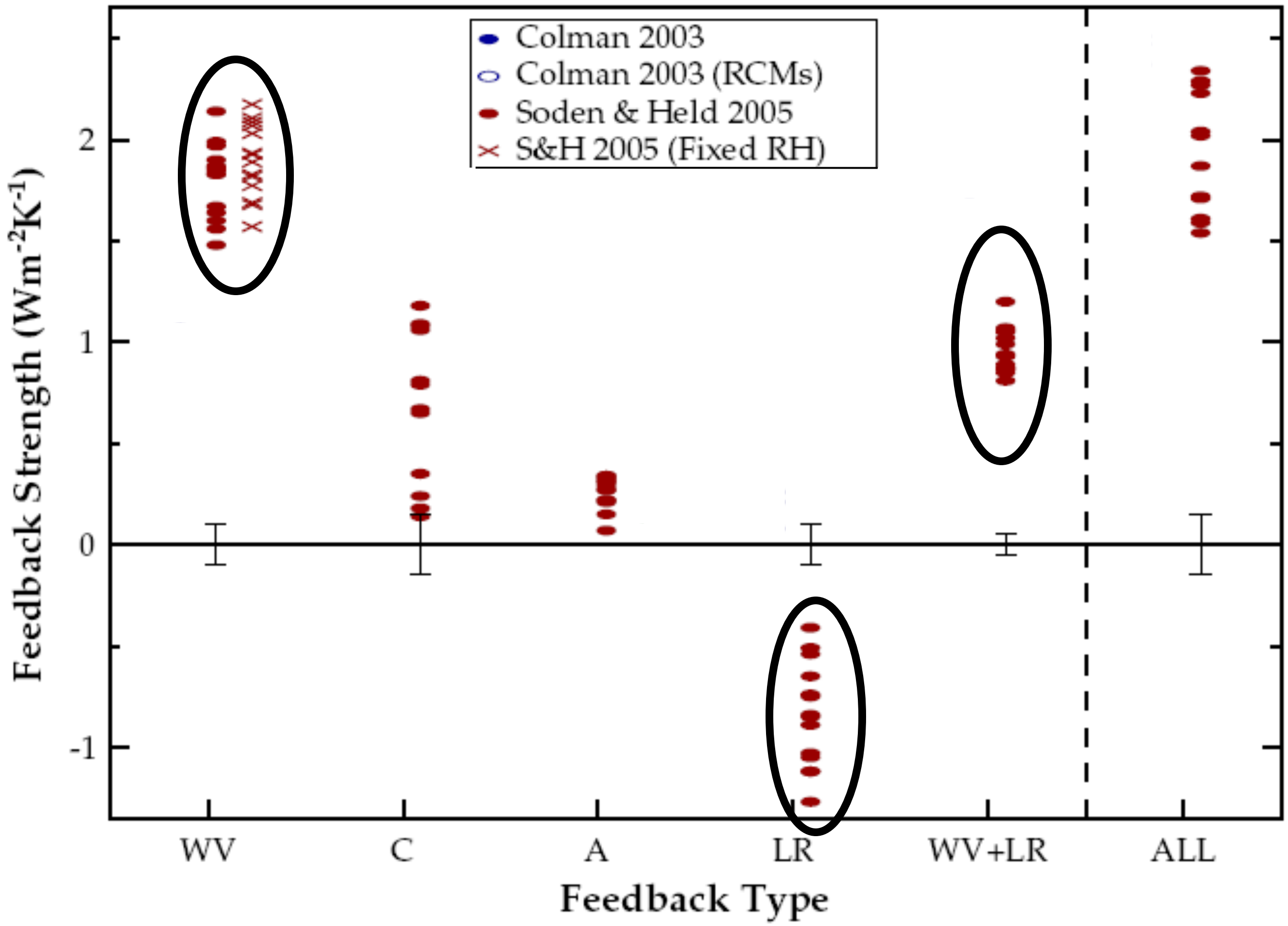
- **Water vapor provides the strongest positive feedback in GCMs.**
- **There is no model with a negative cloud feedback.**

Lapse Rate and Water Vapor Feedbacks:
IPCC AR4 GCMs



Water vapor feedback is larger in models with greater warming in the upper troposphere

Climate Feedbacks in IPCC Models



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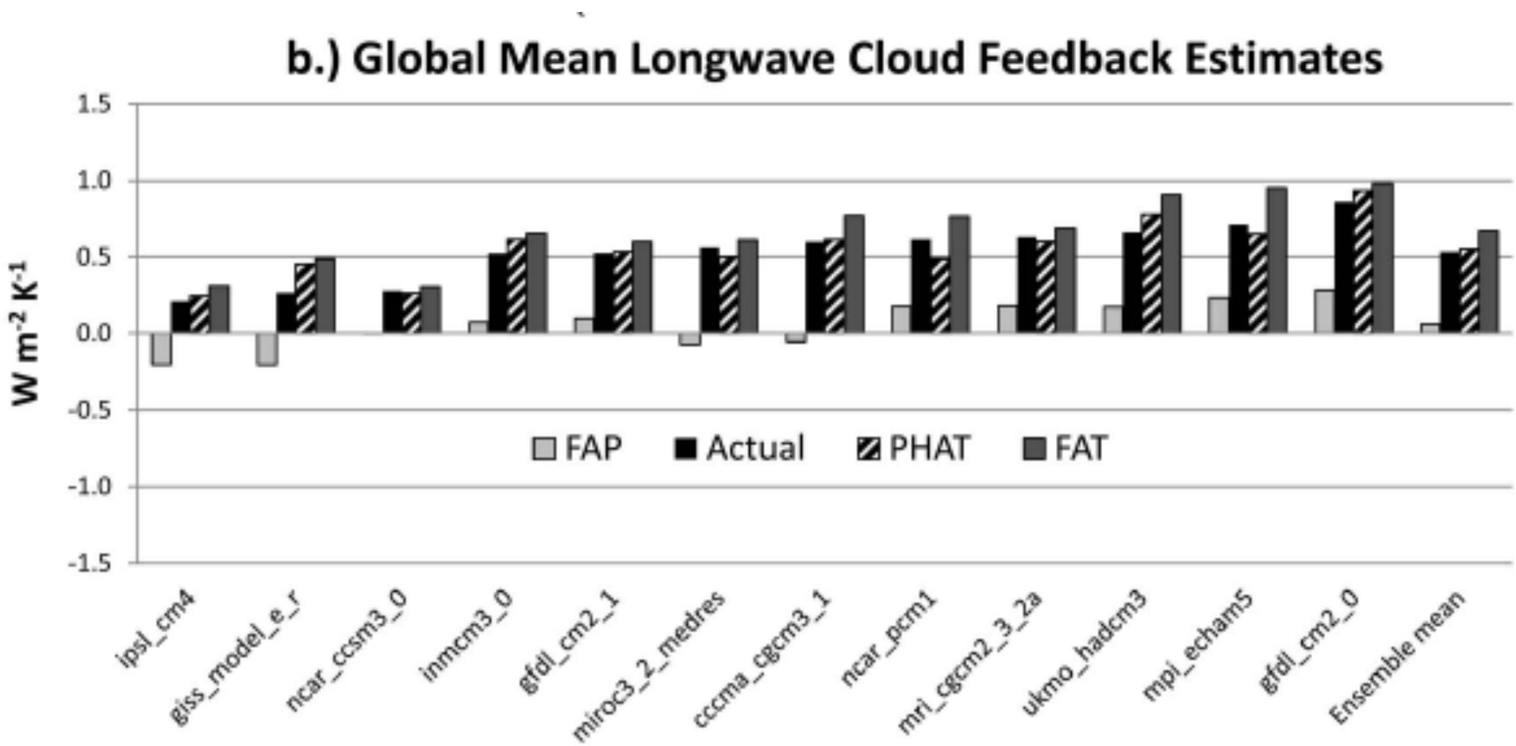
Why is High Cloud Feedback Positive?

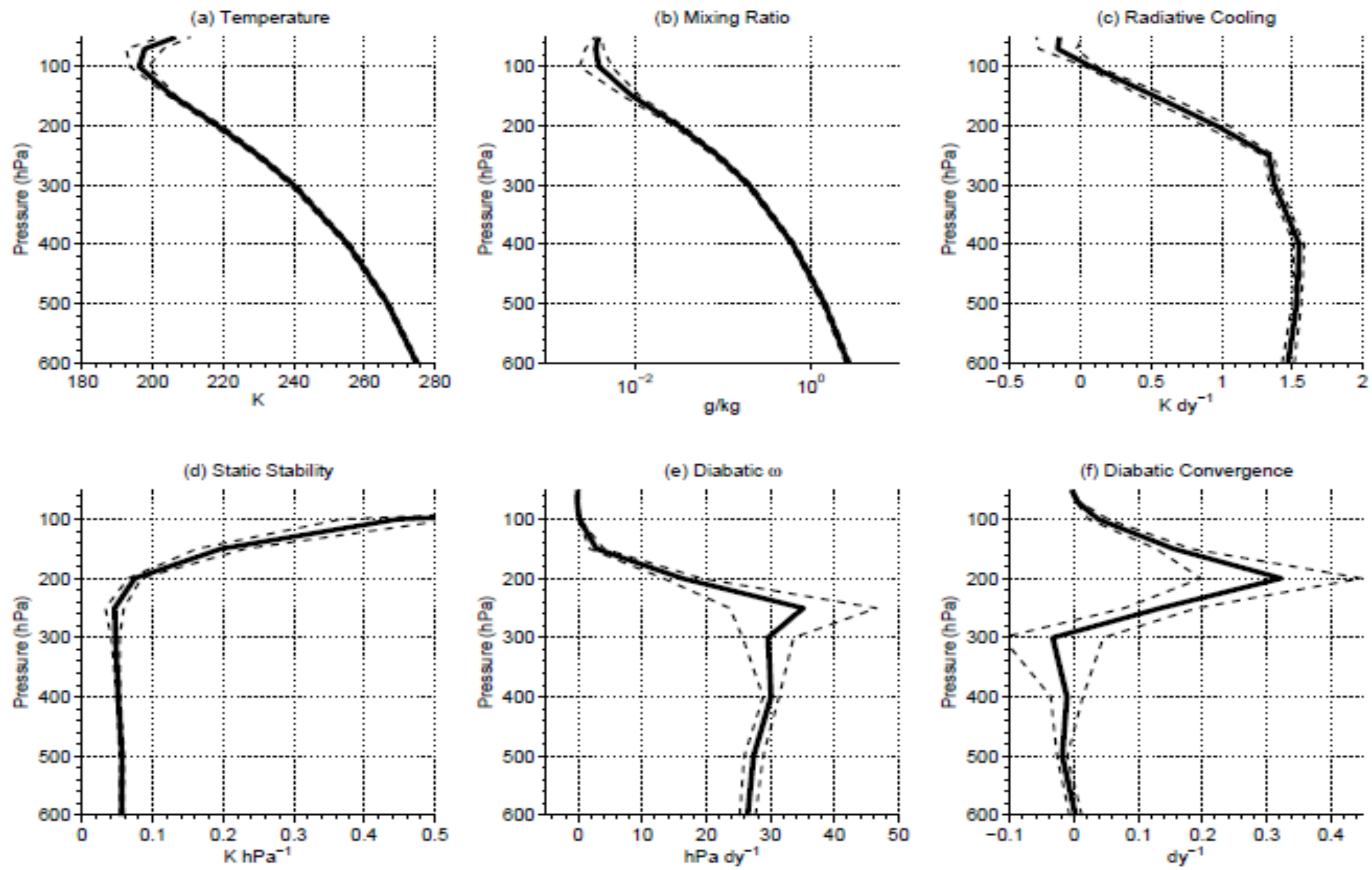


• High cloud changes in GCMs follow a nearly constant temperature (rather than constant altitude).

•This behavior is supported by observations

Zelinka and Hartmann (2010)

Why is High Cloud Feedback Positive?



Zelinka and Hartmann (2010)

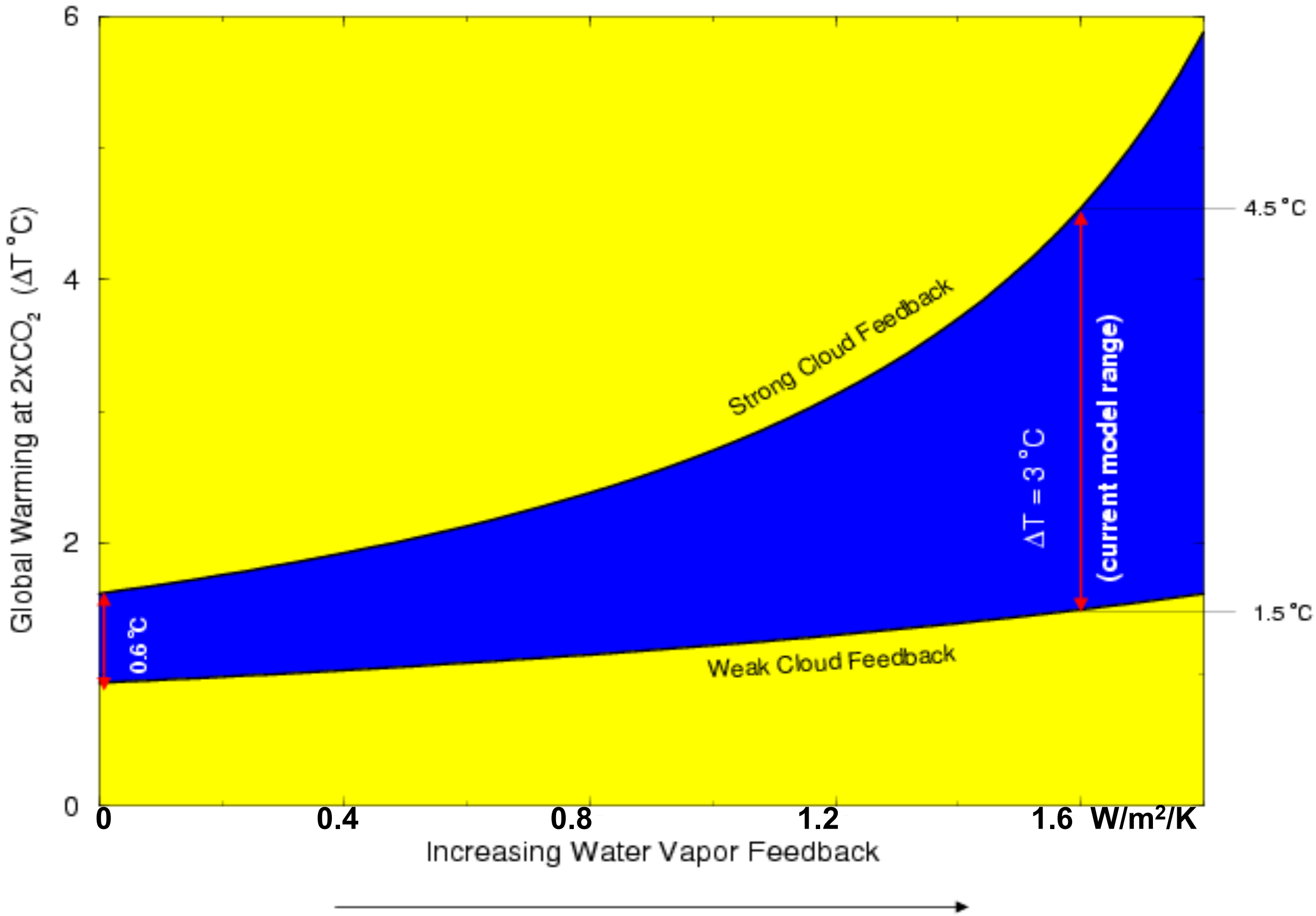
$$\sigma = \frac{\kappa T}{p} - \frac{\partial T}{\partial p},$$

$$\omega = \frac{Q_R}{\sigma}.$$

$$conv \equiv -\nabla_H \cdot \mathbf{U} = \frac{\partial \omega}{\partial p}.$$

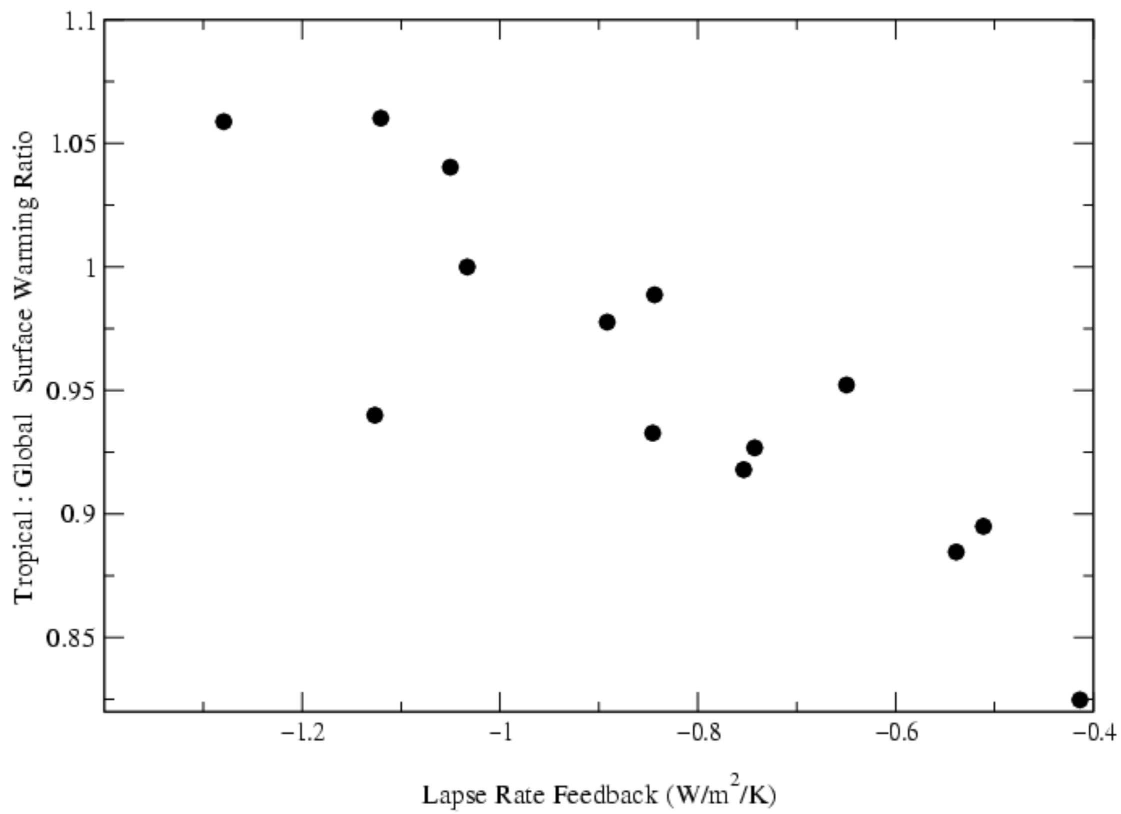
As climate warms, there is an upward shift in the level of divergence (and Q_R) due to increased water vapor

Importance of Water Vapor Feedback



• Positive feedbacks mutually amplify their impact on climate sensitivity.

Lapse Rate Feedbacks:
IPCC AR4 GCMs



Models with greater low-latitude warming have larger lapse-rate feedback.

Observational Evidence for PHAT

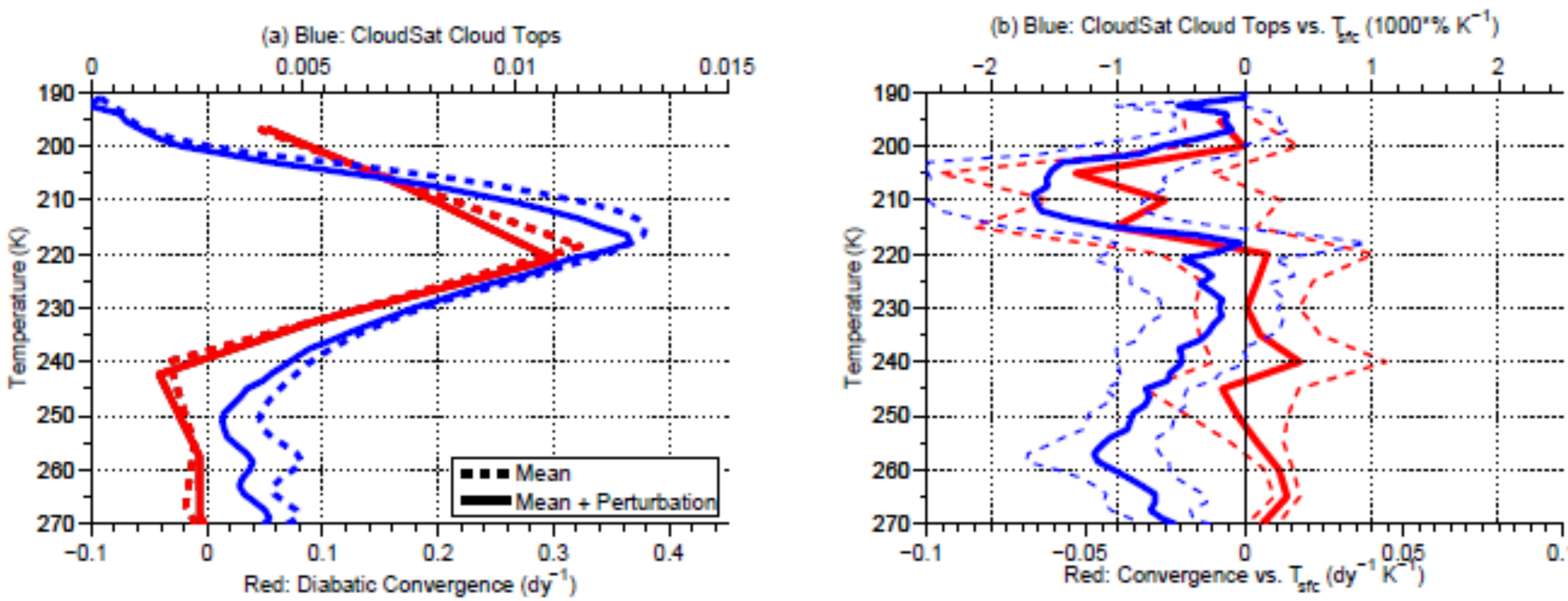
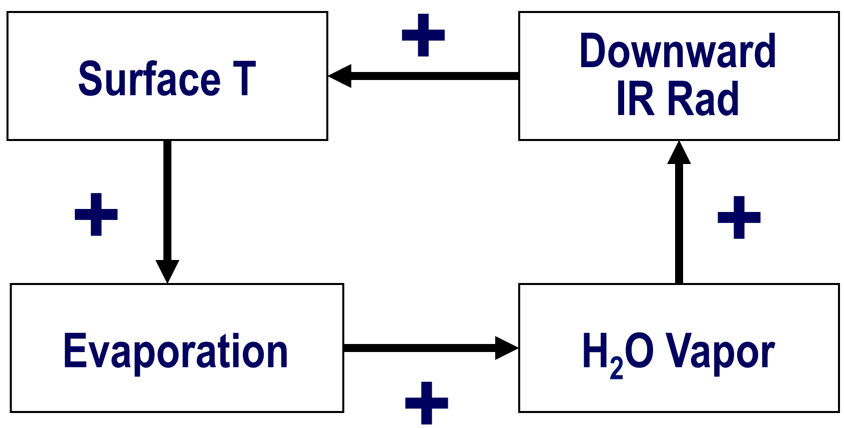


Figure 9. (a) Tropical mean (blue) CloudSat cloud top frequency of occurrence and (red) diabatic convergence. The dashed lines represent the mean profile and the solid lines represent the sum of the mean and perturbation profile shown in panel b. (b) Sensitivity of tropical mean (blue) CloudSat cloud top frequency of occurrence and (red) diabatic convergence to tropical mean surface temperature. The dashed lines represent the 2σ range on the regression coefficients computed using a bootstrapping method as described in the text.

Observed interannual changes in tropical high clouds follow FAT/PHAT.

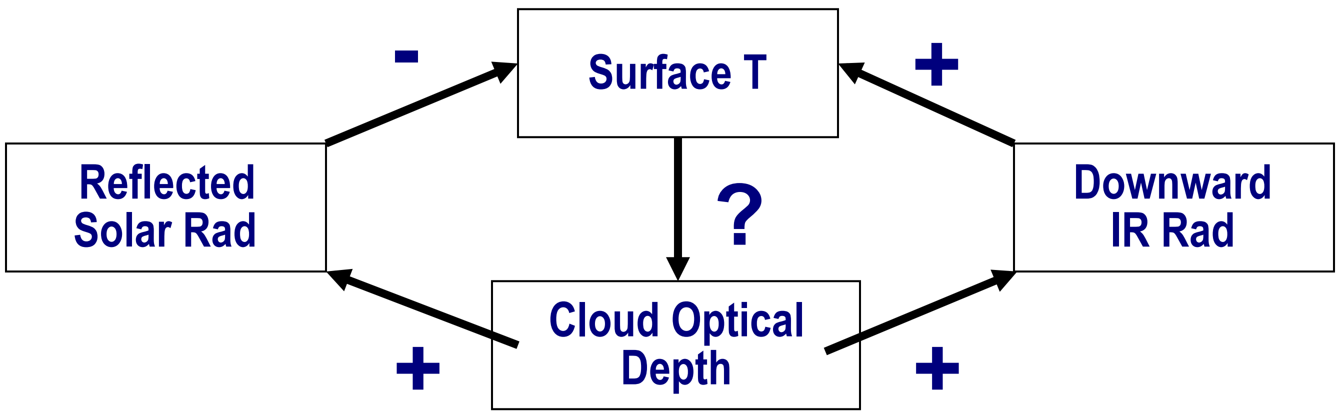
Zelinka and Hartmann (2011)

Water Vapor Feedback



•All models predict a strong positive feedback from water vapor.

Cloud Feedbacks



- Cloud feedbacks are uncertain in both magnitude and sign.