Diagnosing Climate Feedbacks in CMIP5 Models

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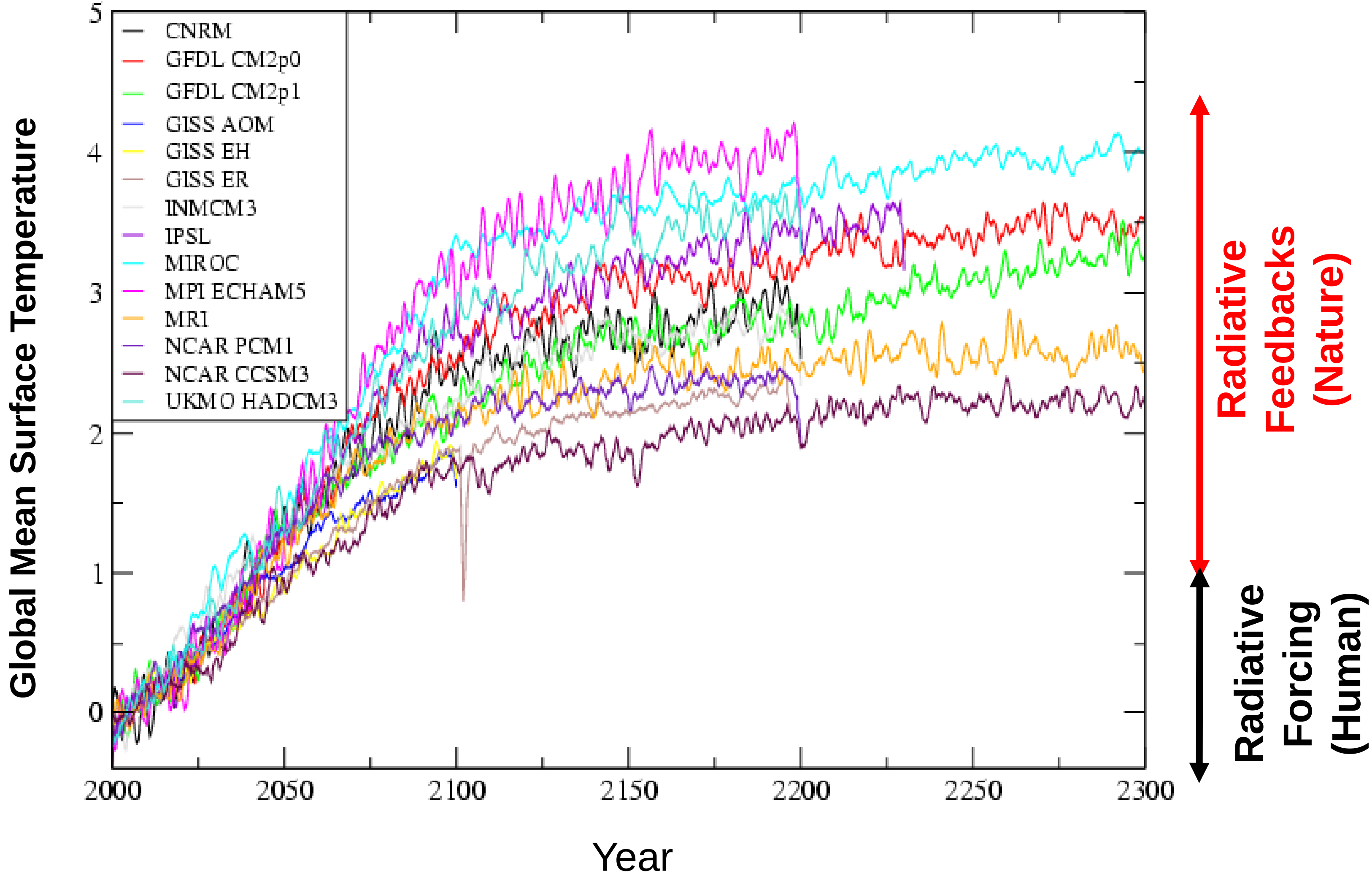
- Motivation
- Methodology: Radiative Kernels
- Climate Feedbacks in CMIP5 Models
- Radiative Forcings in CMIP5 Models

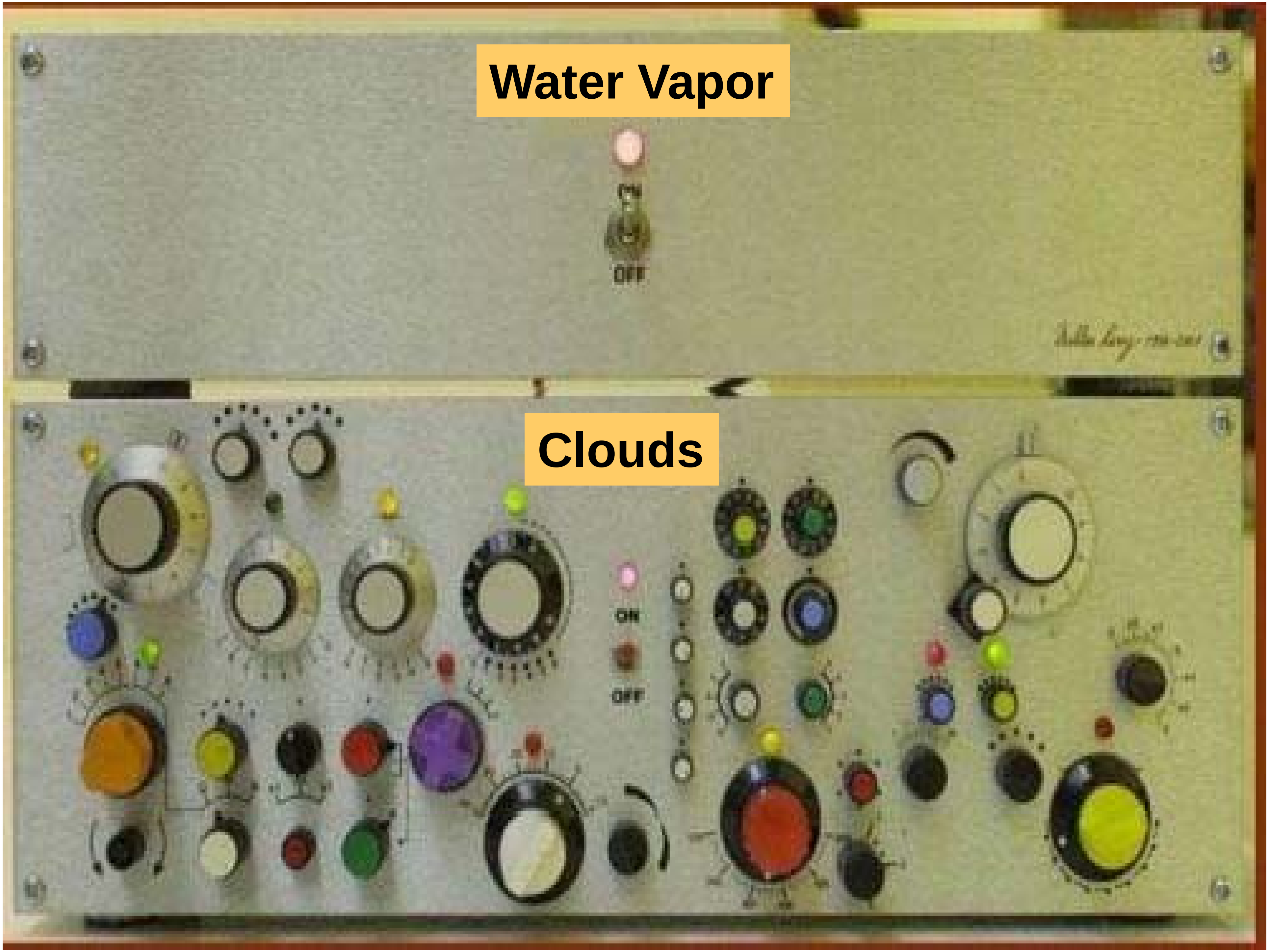
Motivation



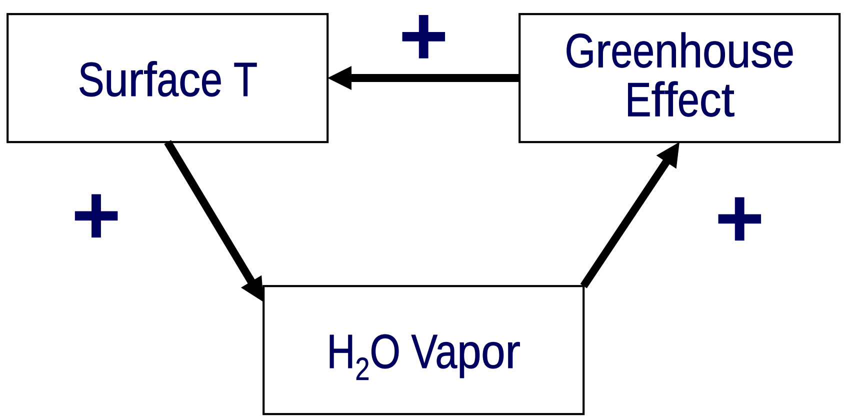
- **Feedbacks create uncertainty.**
- **Feedbacks cause roughly 2/3 of total warming.**

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

Water Vapor Feedback



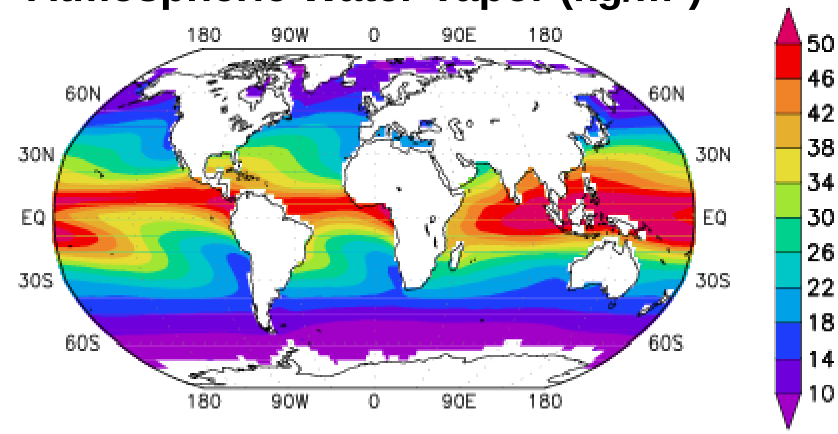
•All models predict a strong positive feedback from water vapor.

Water Vapor Feedback

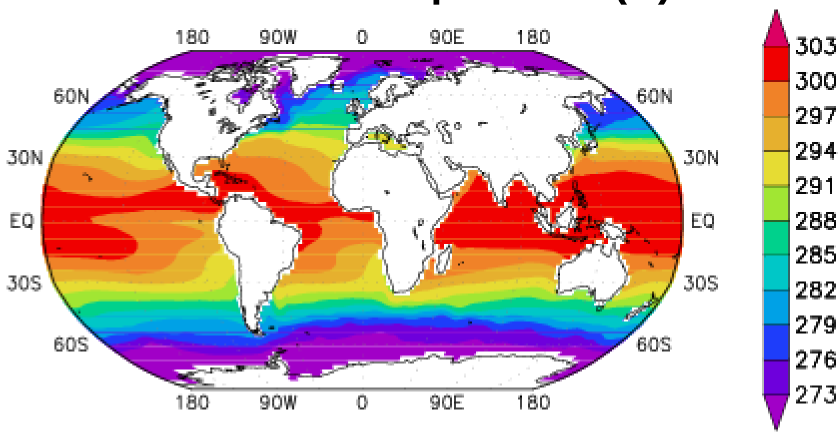
Satellite observations illustrate how water vapor enhances regional differences in ocean temperature.

1.

Atmospheric Water Vapor (kg/m^2)

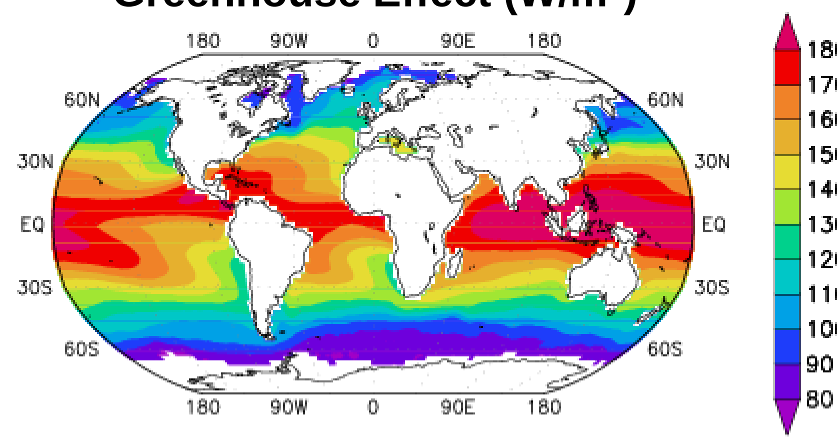


Ocean Surface Temperature (K)



2.

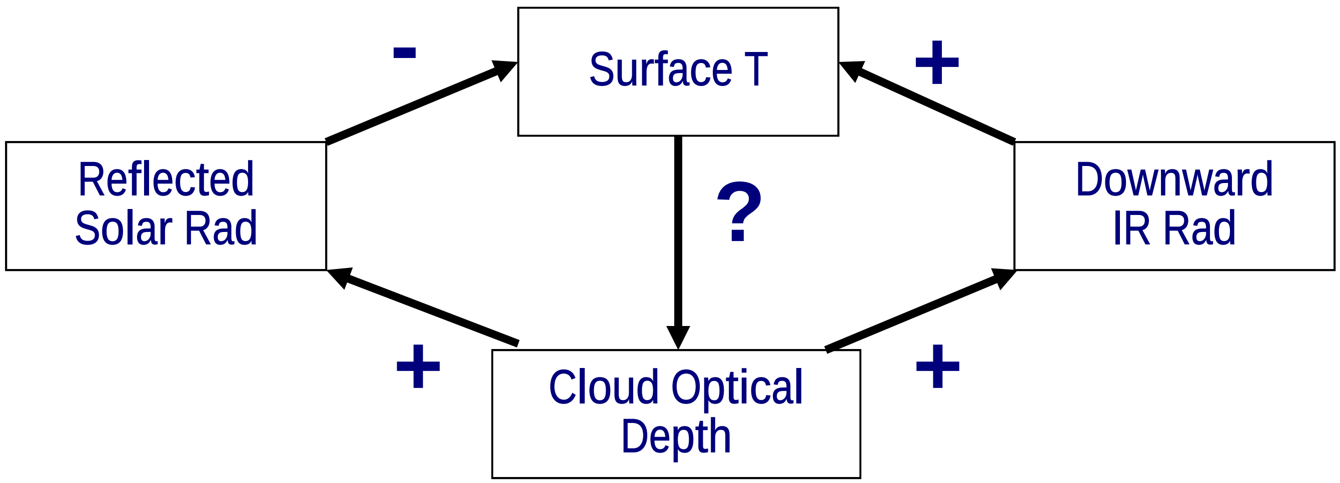
Greenhouse Effect (W/m^2)



3.

1. Warmer oceans → more water vapor.
2. More water vapor → larger Greenhouse Effect.
3. Larger GHE → warmer oceans.

Cloud Feedbacks



- Cloud feedbacks are uncertain in both magnitude and sign.

Methodology: “Radiative Kernels”

- Quantify the partial radiative response that results from changes in each feedback variable.
- Allows for consistent intermodel comparisons

Climate Feedbacks: Kernel Method

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

G = radiative forcing
R = net radiation at TOA
λ= climate sensitivity parameter
(rate of radiative damping)

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

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

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

Radiative Transfer — Climate Response

Climate Feedbacks: Kernel Method

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

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

Climate Feedback = $\delta R/\delta X$ X $dX/d\mathbf{T}_s$

Radiative Transfer | Climate Response

Method 1: $dX/d\mathbf{T}_s$

$dX = X_{2\ldots}$ … $_{2000\text{-}2020}$

FALSE?

Assume all change is feedback

Climate Feedbacks: Kernel Method

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

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

$dX/d\mathbf{T_s}$

Climate Response

Method 1:
$dX/d\mathbf{T_s}$

$dX=X_{2080-2100}-X_{2000-2020}$

Assume all change is feedback

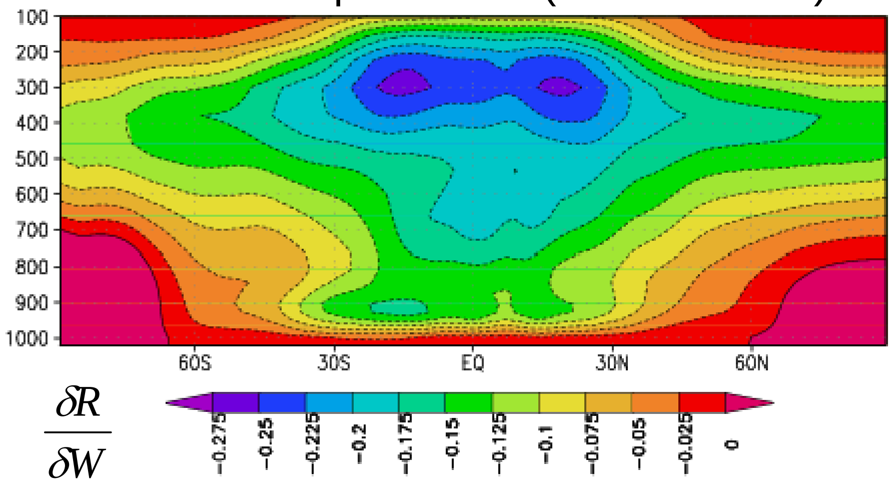
Method 2:
dX/dT_s

$X=a + b\ \mathbf{Ts}$
$dX/d\mathbf{Ts} = b$

Only use component correlated to dTs

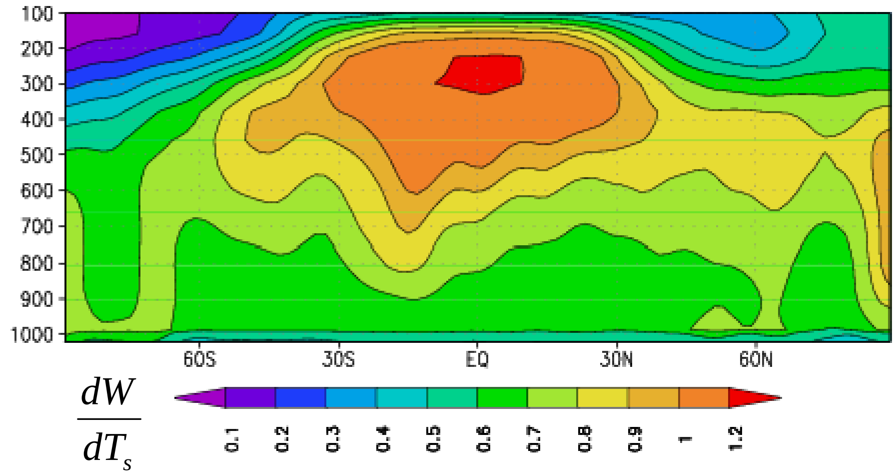
Water Vapor Feedback Kernels

Water Vapor Kernel (from RT code)



x

Water Vapor Response to 2xCO2 (from GCM)

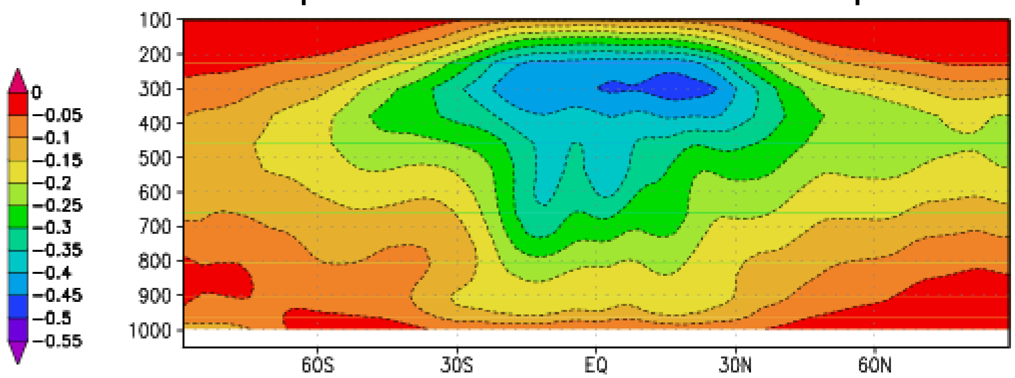


Radiation is most sensitive to upper troposphere because clouds mask contributions from lower levels

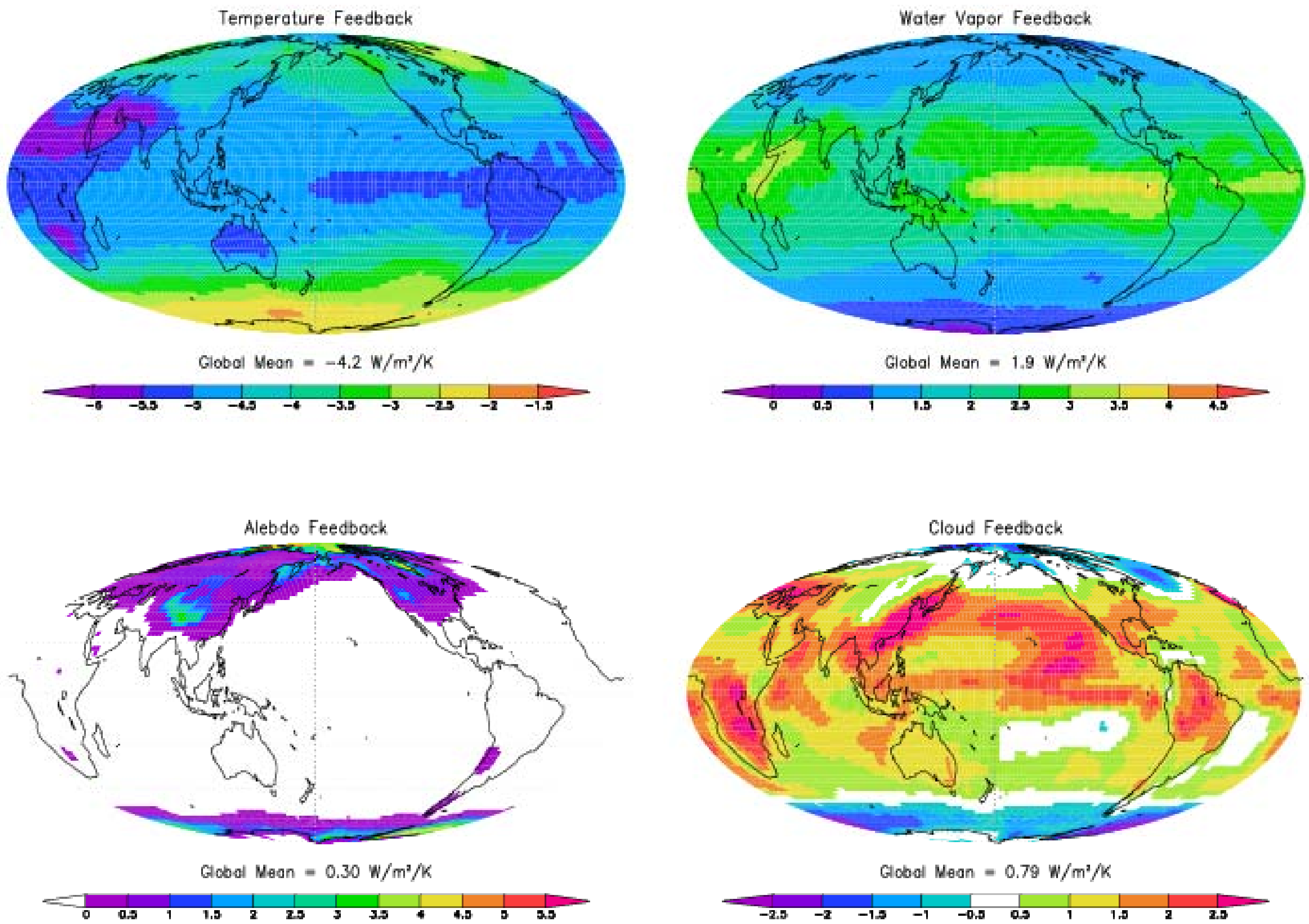
Fractional changes in water vapor are also largest in upper troposphere due to C-C.

Water Vapor Feedback = Kernel x Response

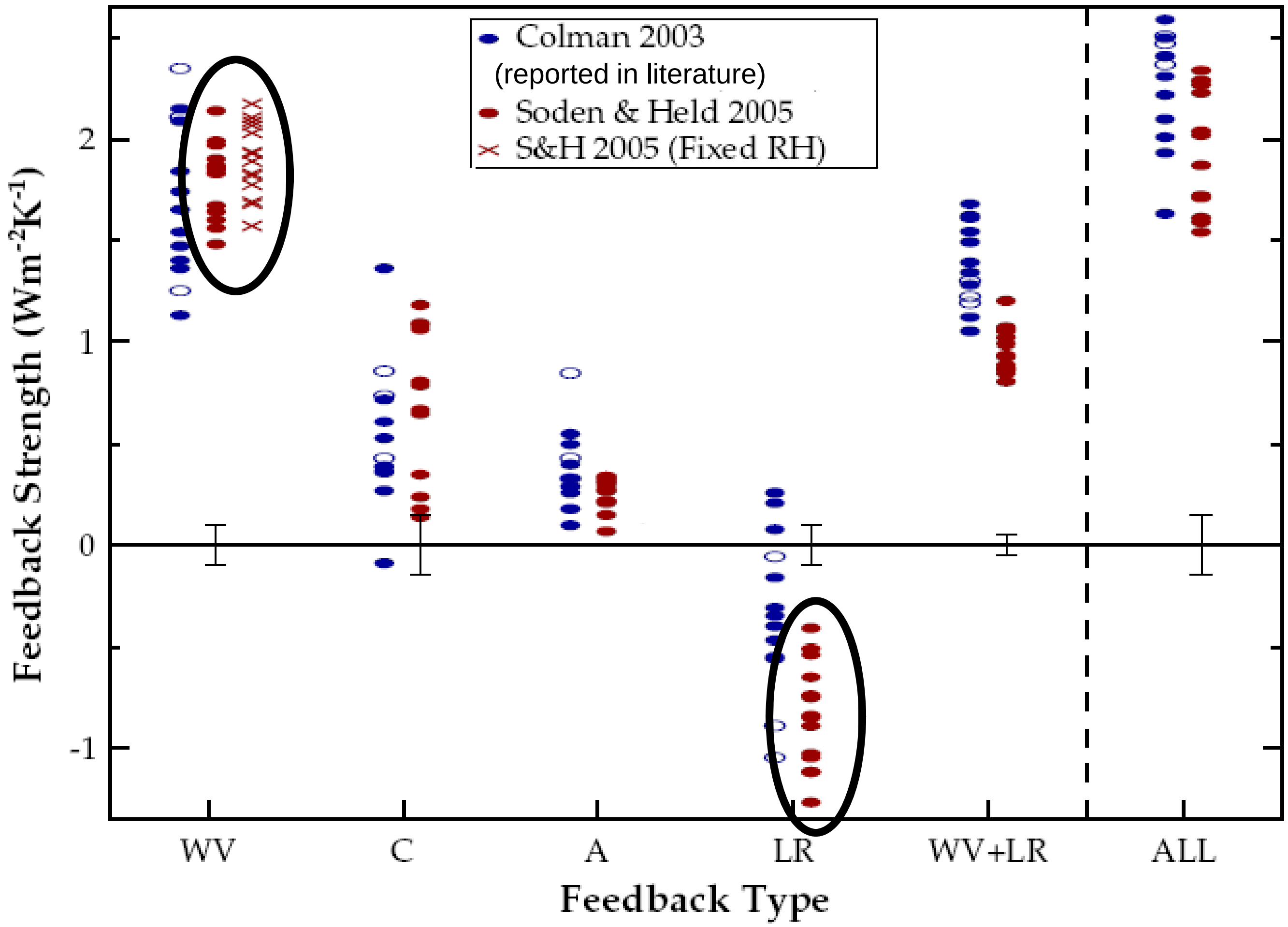
=



Ensemble Mean Feedbacks: IPCC AR4



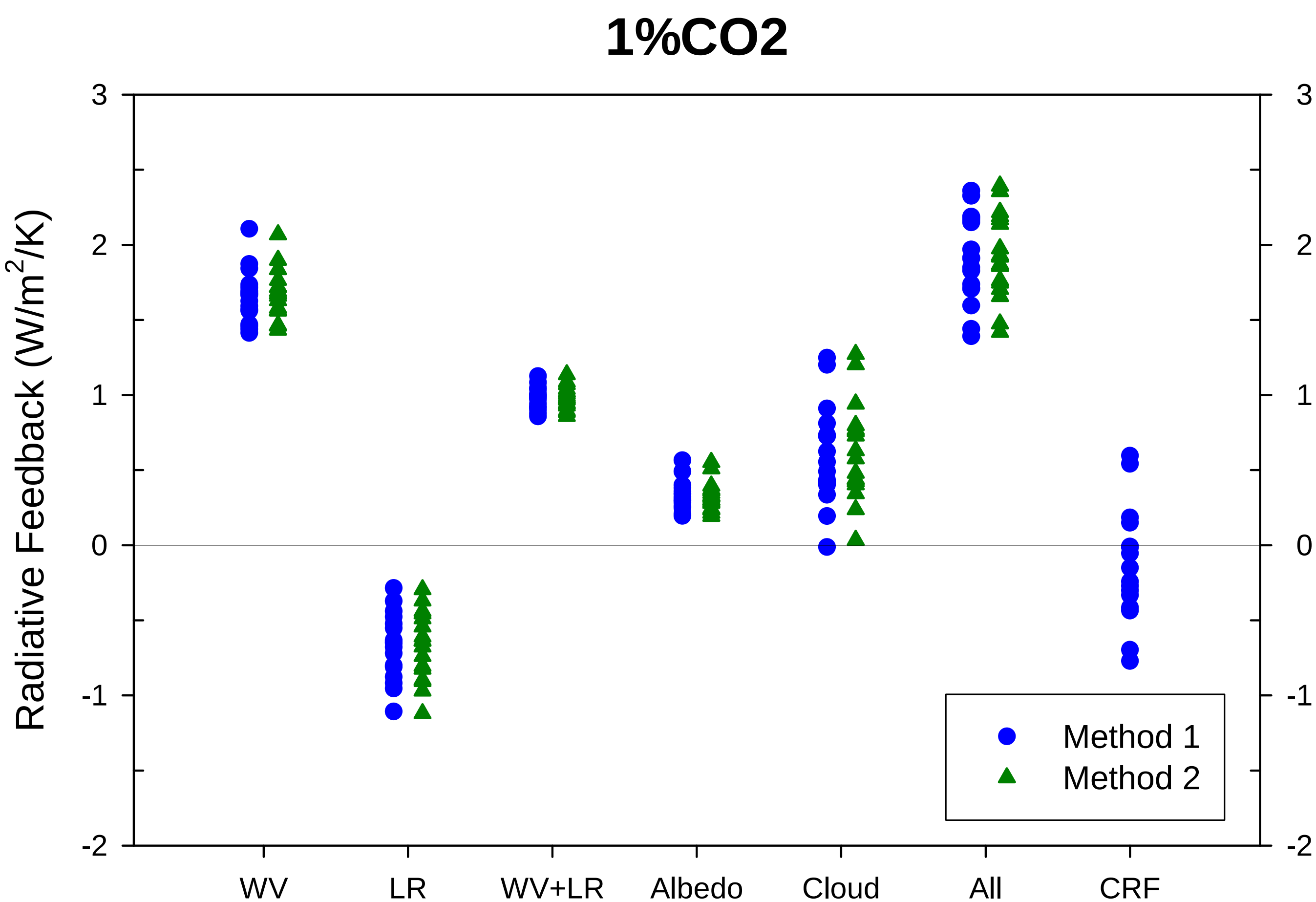
Climate Feedbacks in IPCC AR4 Models



Bony et al. 2006

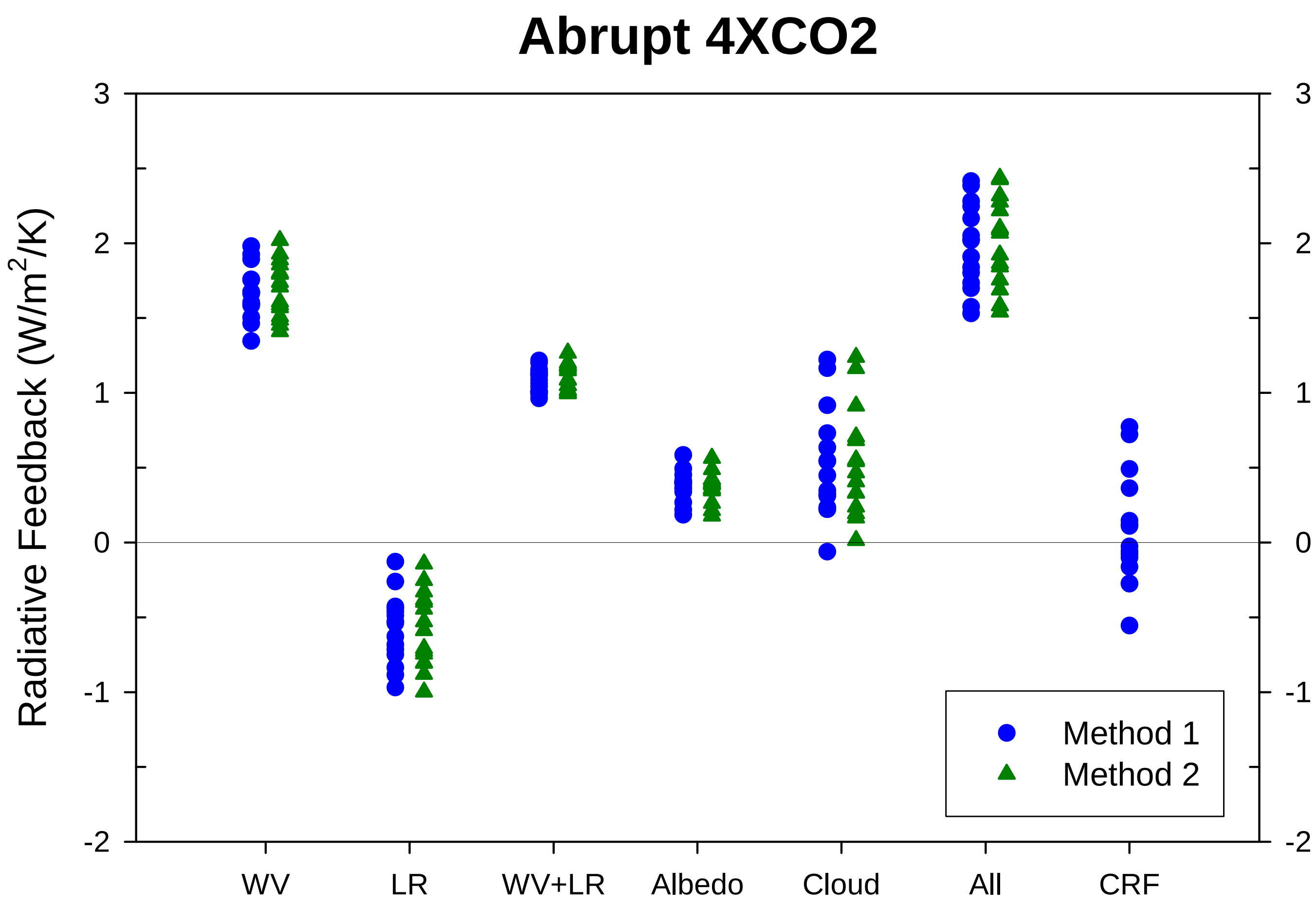
- Water vapor provides the strongest positive feedback in GCMs.
- Water vapor and lapse-rate are strongly correlated.
- There is no model with a negative cloud feedback.

Climate Feedbacks in IPCC AR5 Models



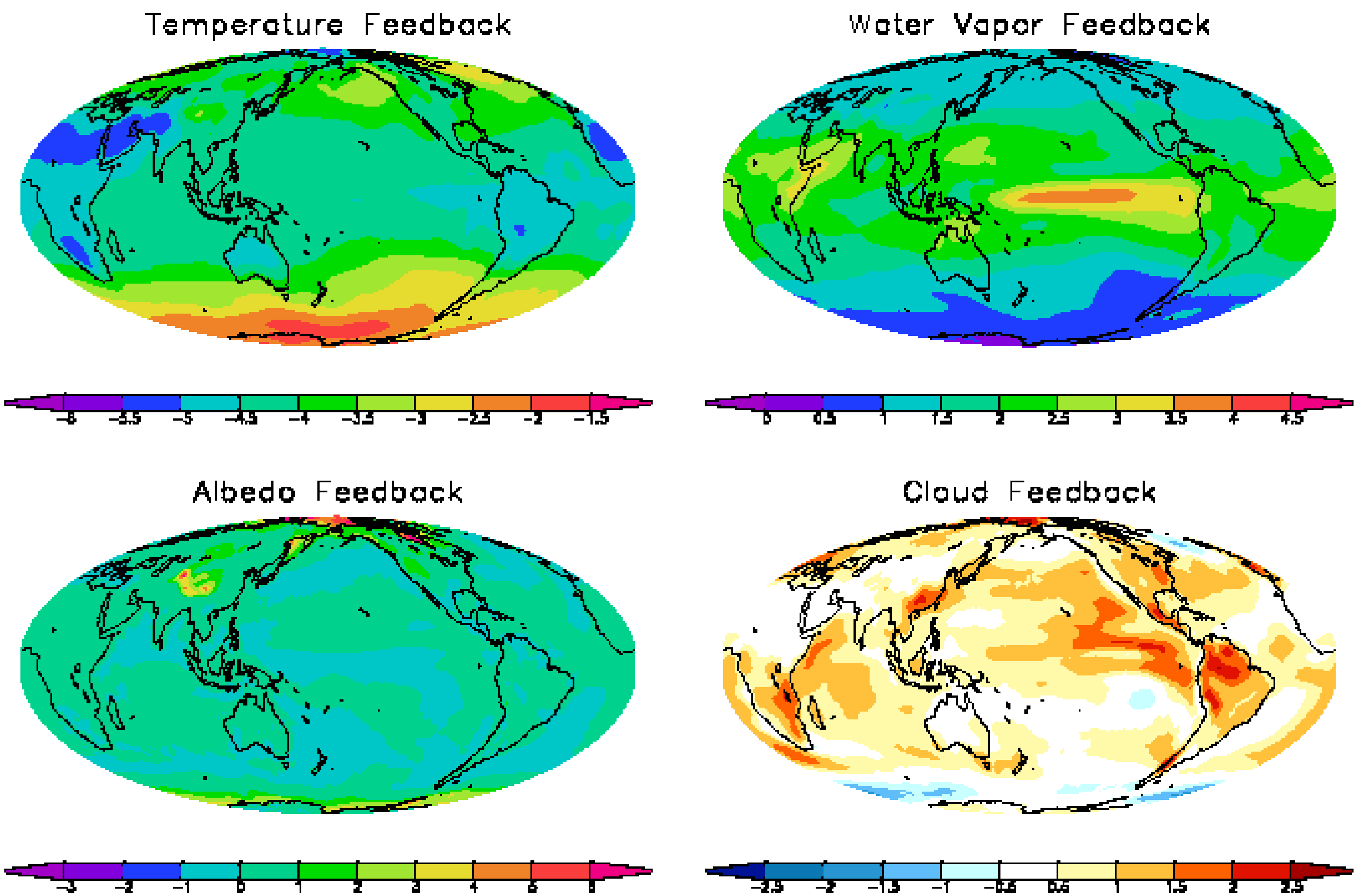
- **Similar to AR4 :**
  Water vapor +lapse-rate uncertainty is small.
  Cloud feedback is uncertain, but not negative.
- **Method 1 and Method 2 are consistent.**

Climate Feedbacks in IPCC AR5 Models

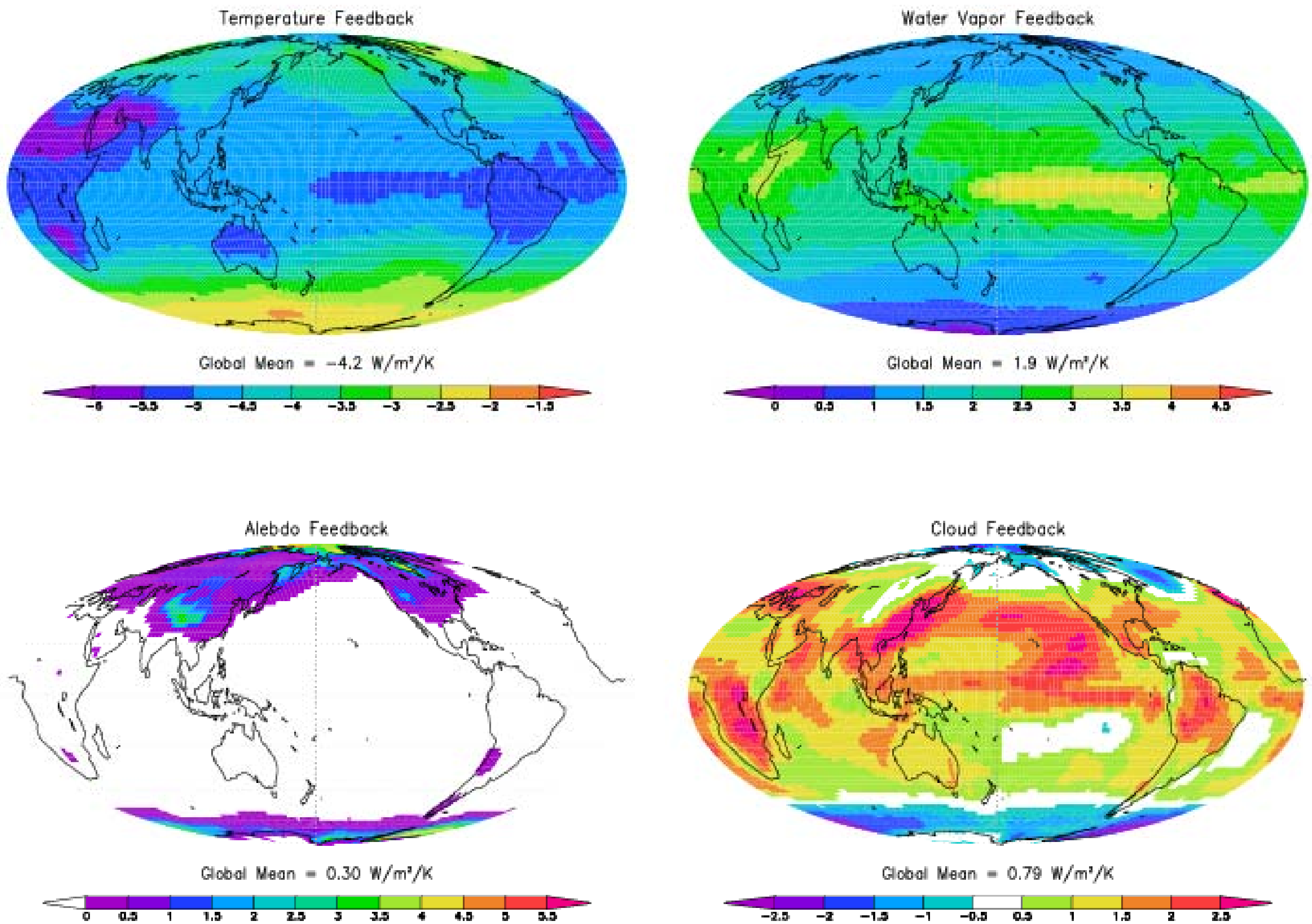


- No evidence of a significant indirect forcing from CO_2.
- Climate feedbacks are robust across CO_2 scenarios.

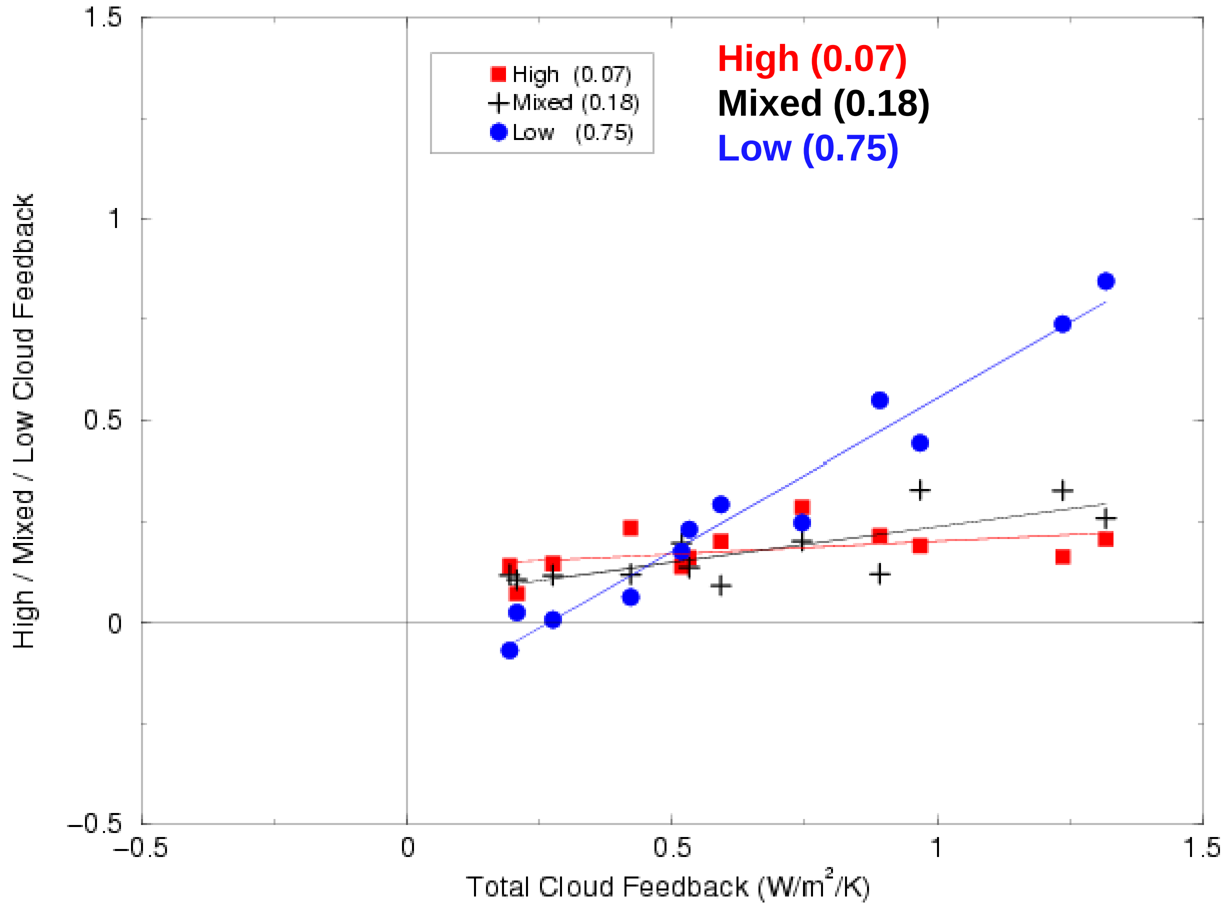
Ensemble Mean Feedbacks: IPCC AR5



Ensemble Mean Feedbacks: IPCC AR4



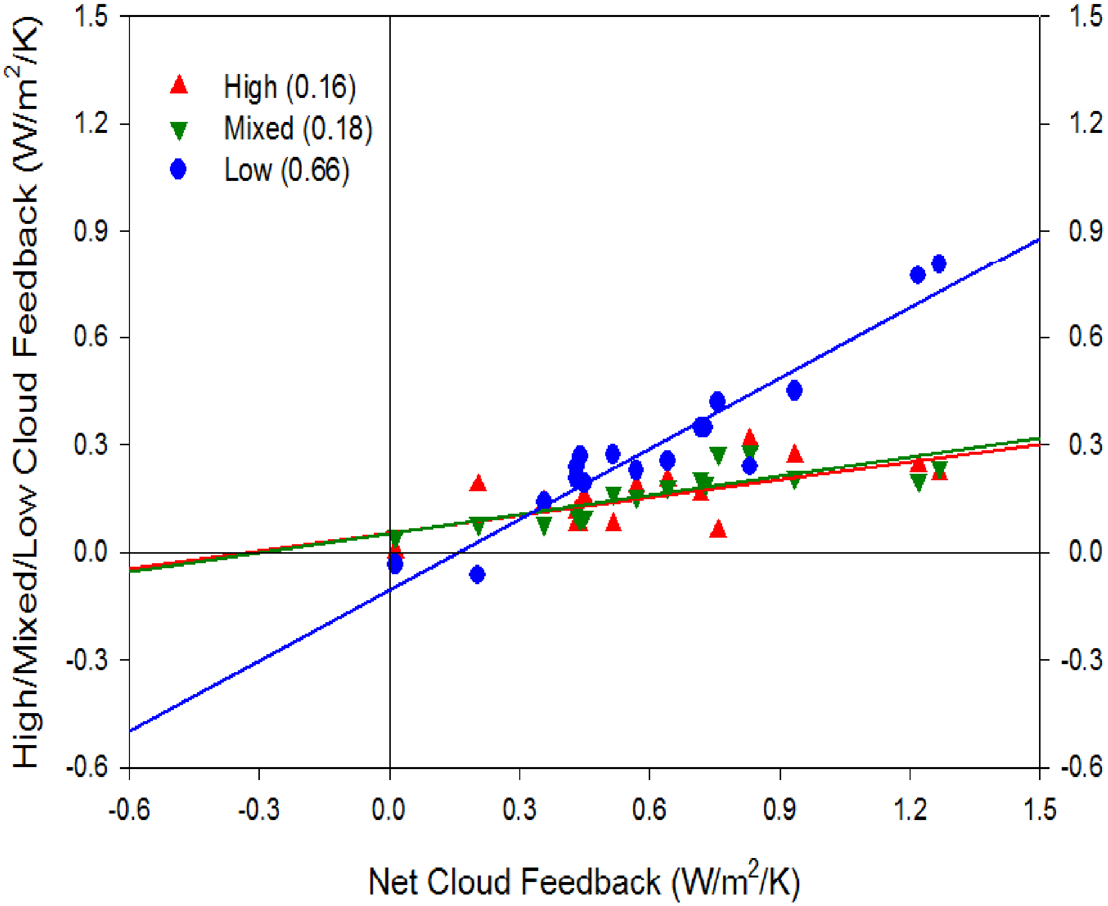
Vertical Distribution of Cloud Feedback: AR4 1% CO2



- High cloud feedback is positive and robust
- Low cloud feedback is highly variable

Soden and Vecchi (2011)

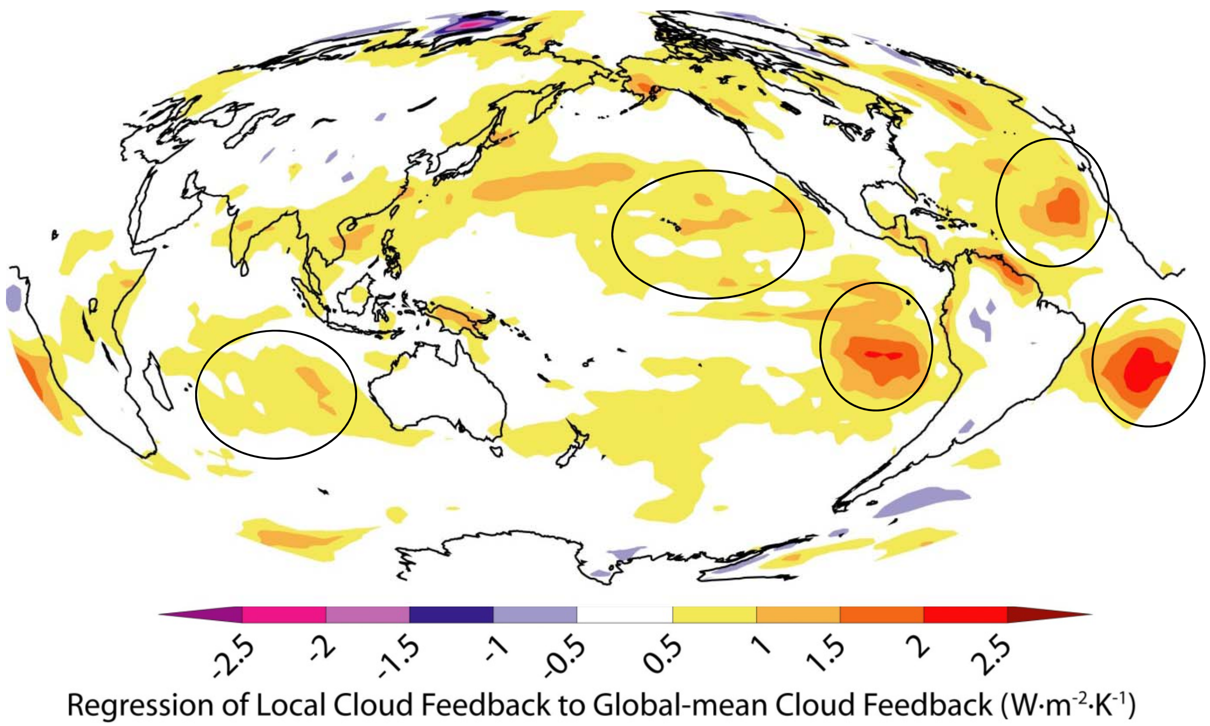
Vertical Distribution of Cloud Feedback: AR5 1% CO_2



- Very similar to AR4

- Slightly more contribution from high clouds.

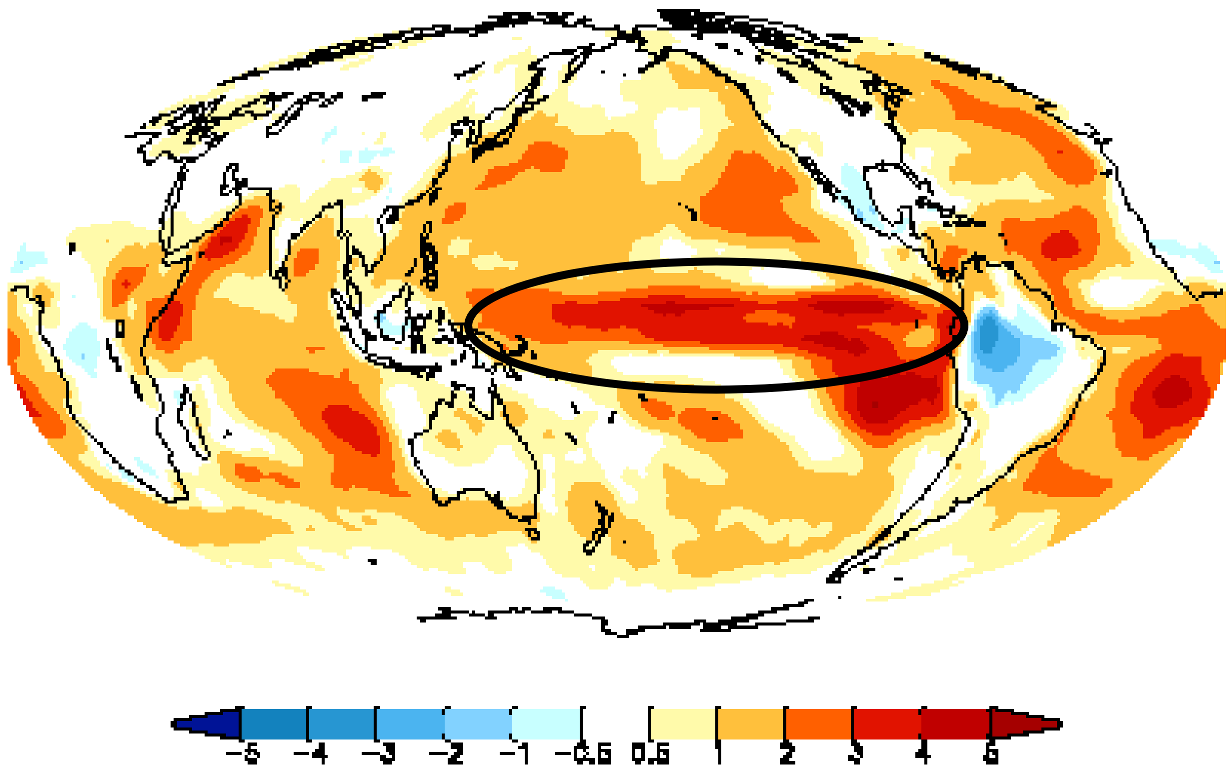
Local contribution to intermodel spread in cloud feedback: AR4



- **Most of intermodel spread arises from low stratocumulus/cumululs regions**

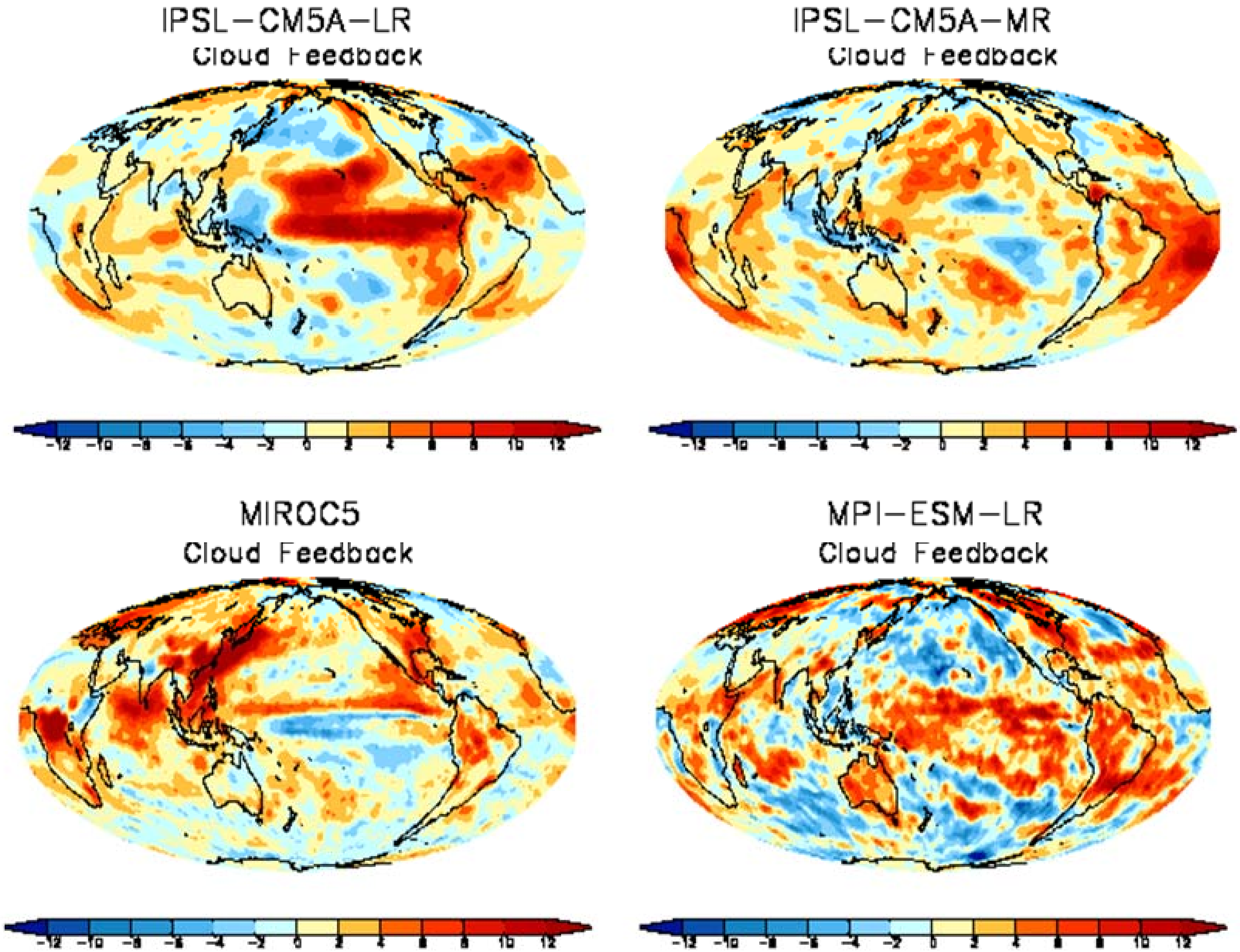
Soden and Vecchi (2011)

Local contribution to intermodel spread in cloud feedback: AR5

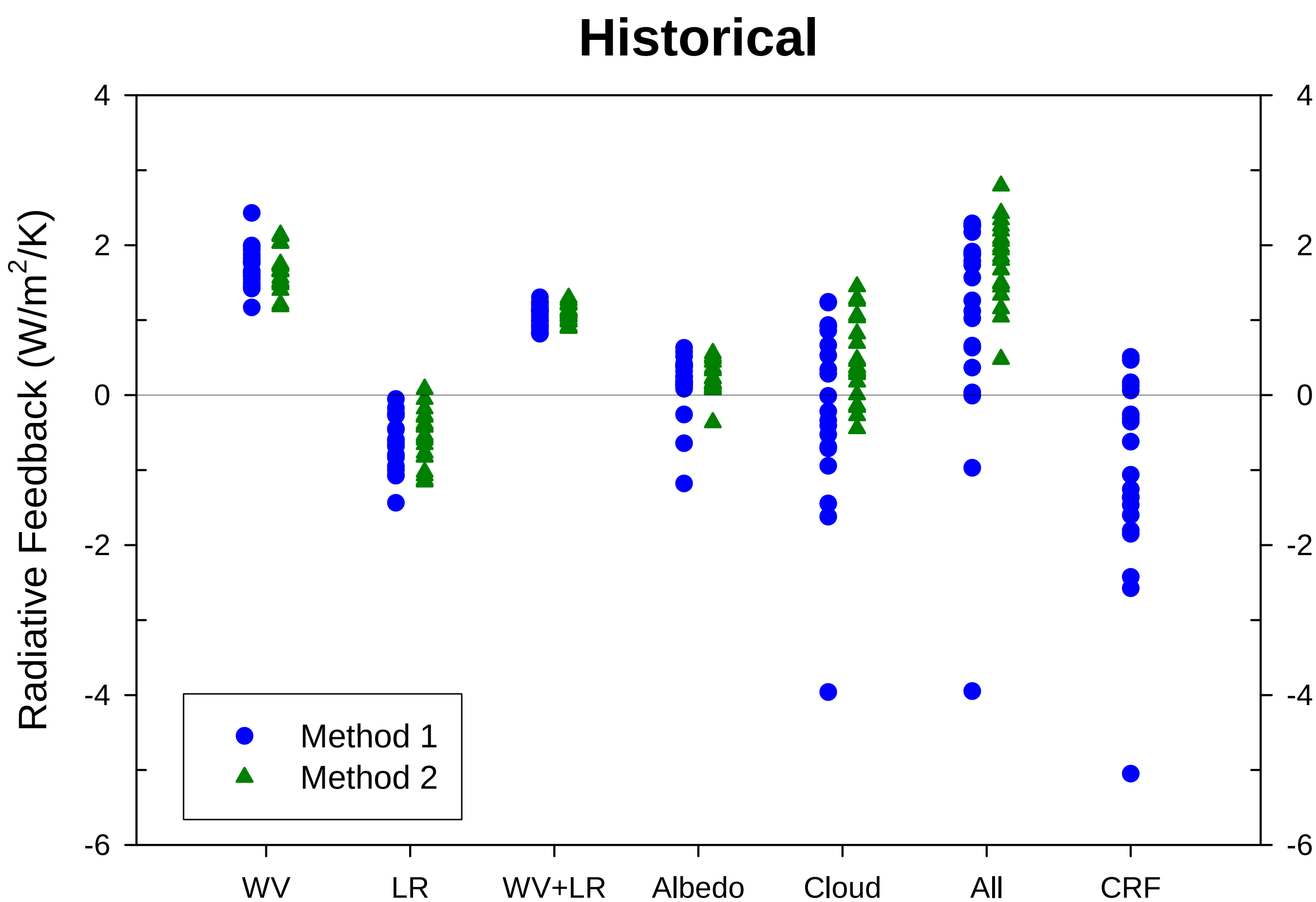


- Low subtropical clouds still uncertain.
- Large contribution from equatorial Pacific.

Intermodel spread in cloud feedback: AR5

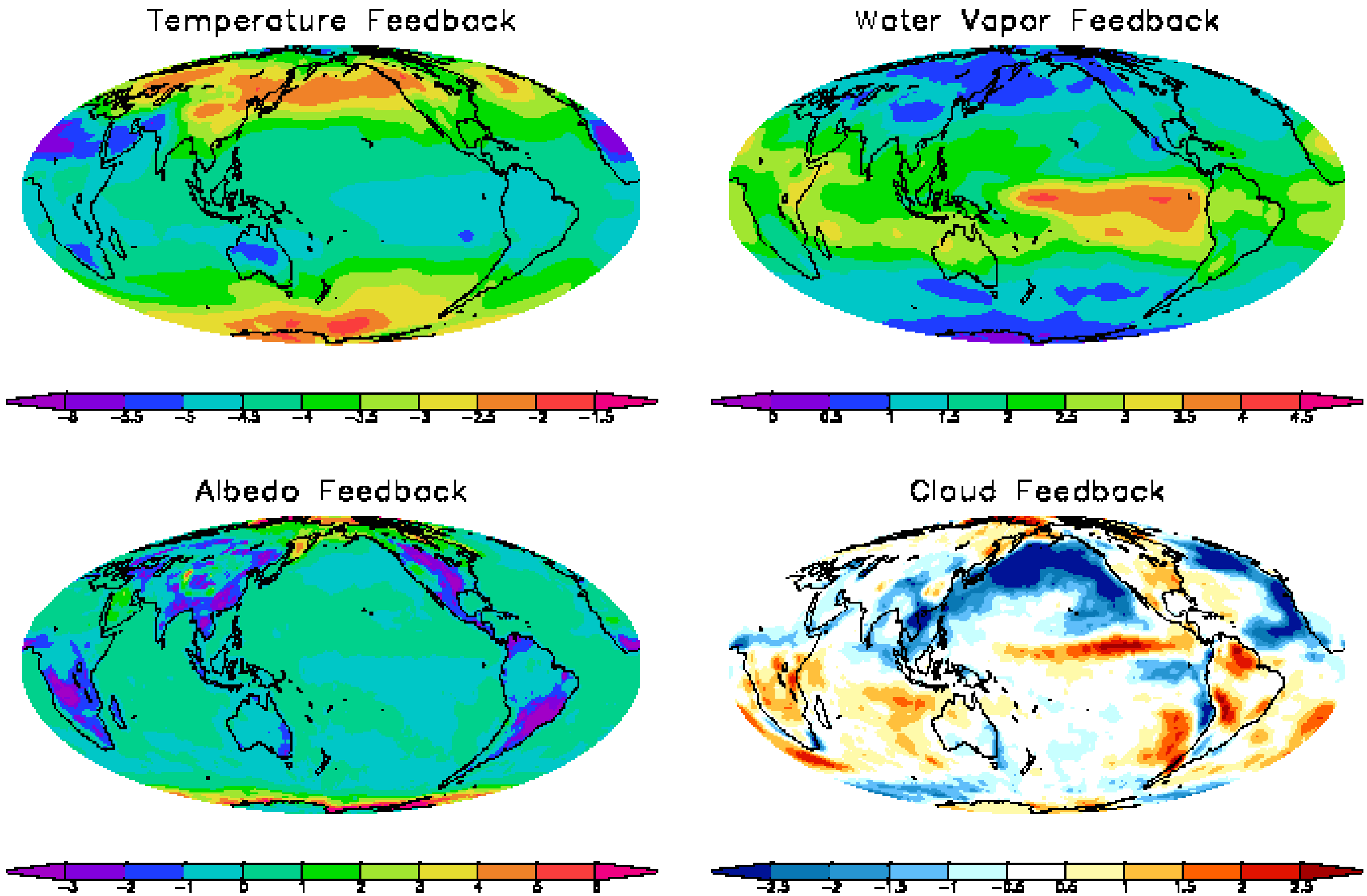


Climate Feedbacks in IPCC AR5 Models

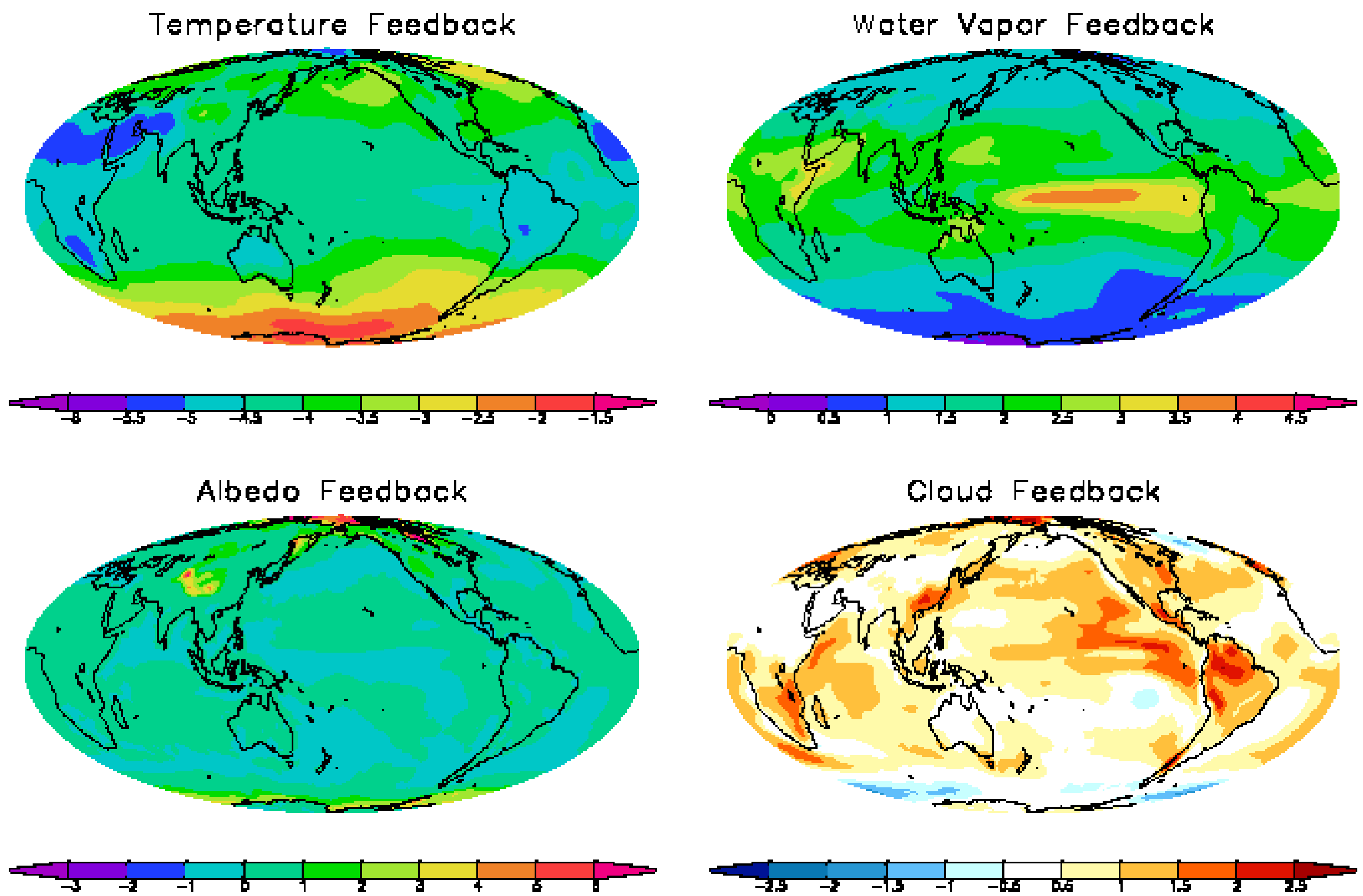


- **Some models indicate a negative cloud feedback …**
- **Cloud feedback differs between Method 1 (difference) & Method 2 (regression)**

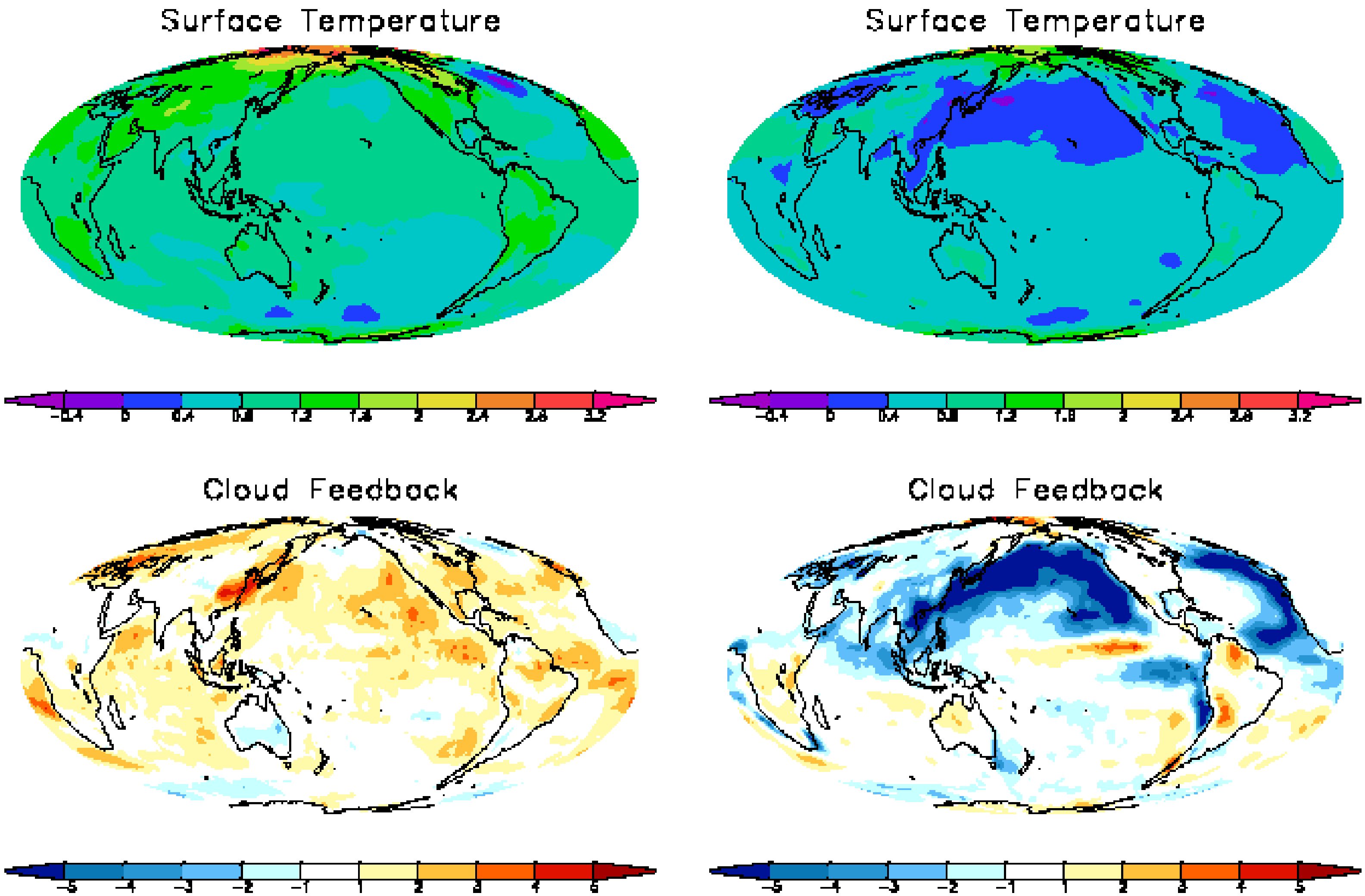
Ensemble Mean Feedbacks: IPCC AR5 Historical



Ensemble Mean Feedbacks: IPCC AR5 1%CO2



Ensemble Mean Cloud Feedback: IPCC AR5 Historical



Positive Cloud Feedback (9 GCMs)

Negative Cloud Feedback (11 GCMs)

Summary and Remaining Challenges

- Feedbacks in AR5 (CMIP5) models are very similar to those simulated in AR4 (CMIP3) era models … *but still no answer for why low cloud feedback is positive*.

- No evidence for the indirect forcing of clouds by CO_2 … *but there is for aerosols?*

- Equatorial Pacific convective clouds and low marine subtropical clouds are biggest contributors to spread … *may depend on climatology/resolution of model?*

Extra Slides

Estimating Radiative Forcing

For Clear-sky Fluxes

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

Temperature Feedback

Water Vapor Feedback

Sfc Albedo FeedbacK

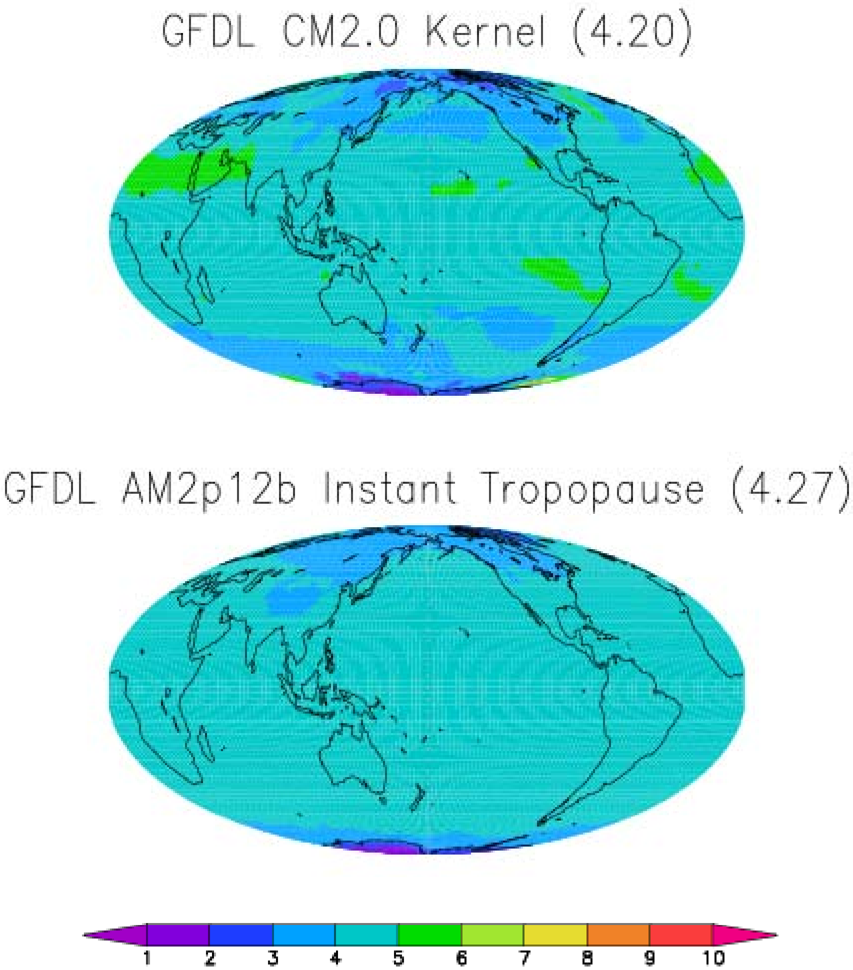
From GCM Output

From Kernels

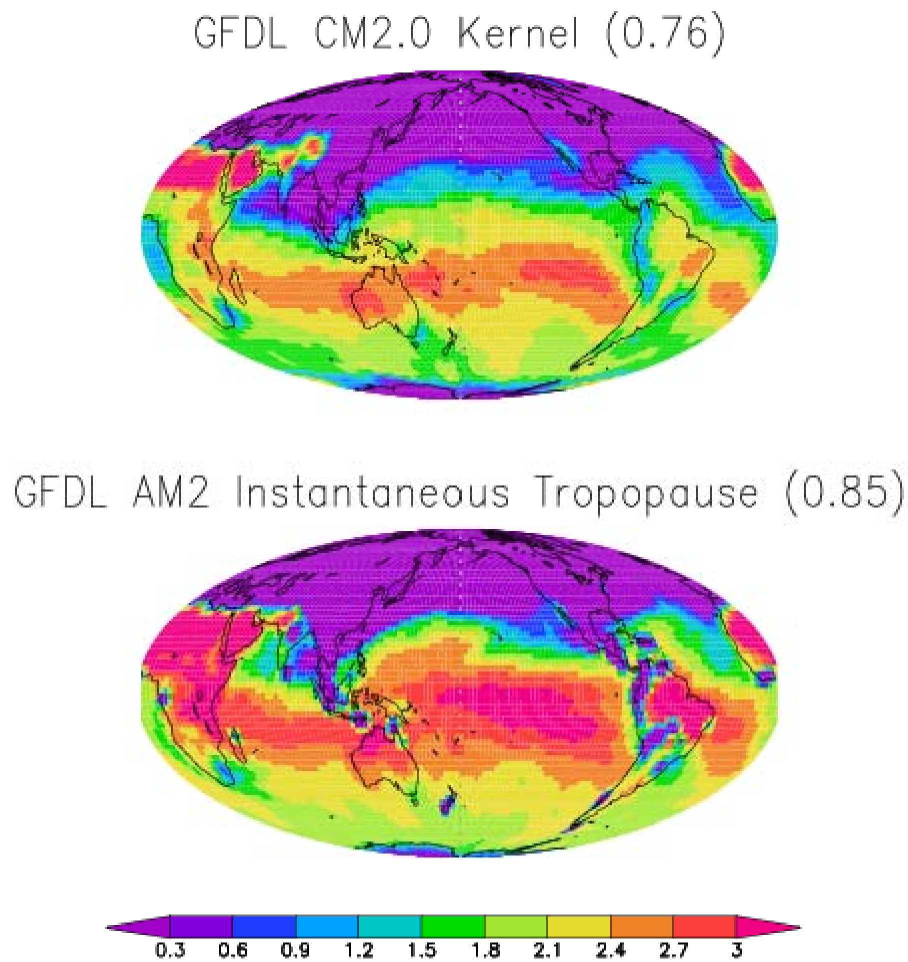
Clear-Sky Radiative Forcing as a Residual

Kernel vs. Direct Radiative Forcing

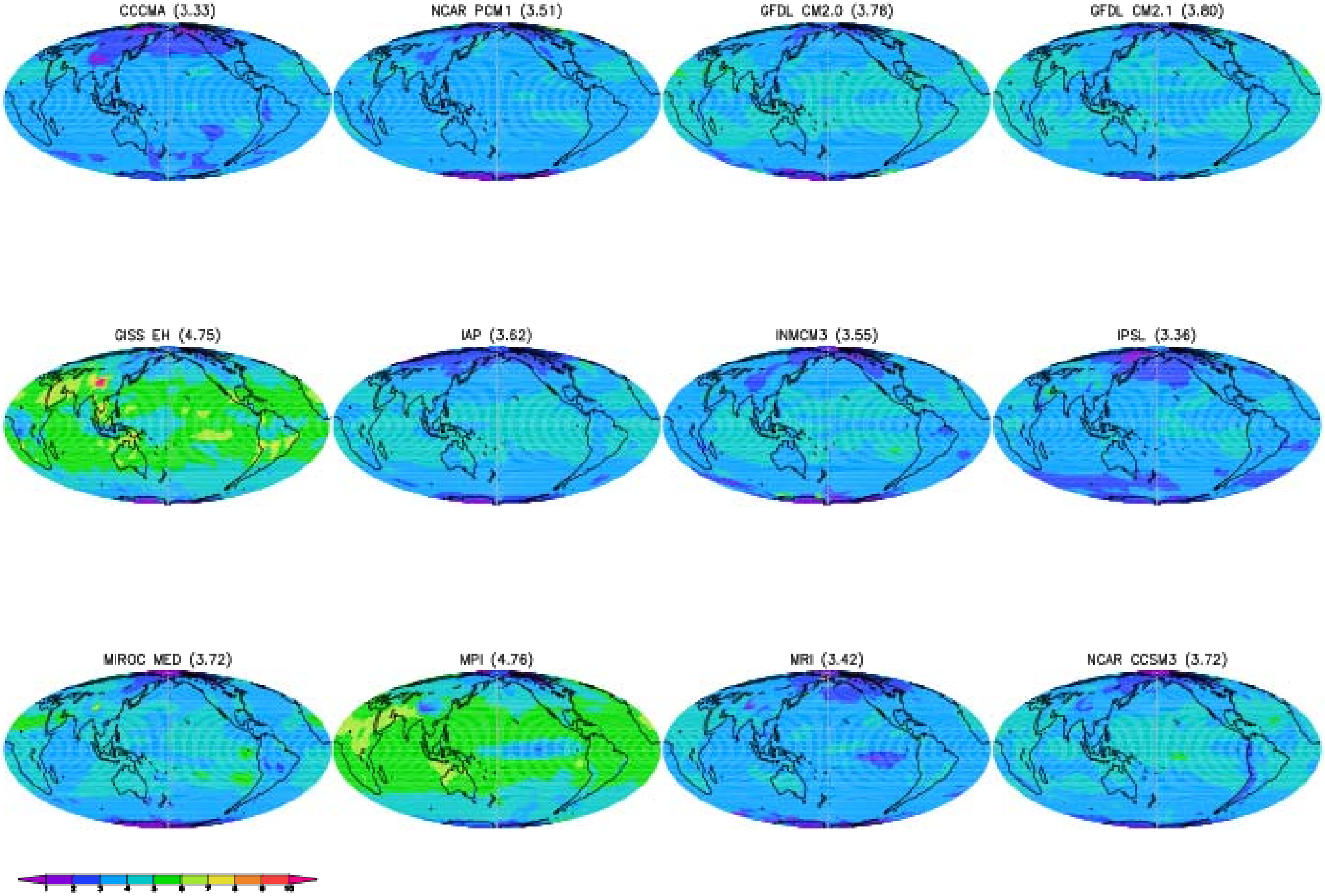
2x CO2



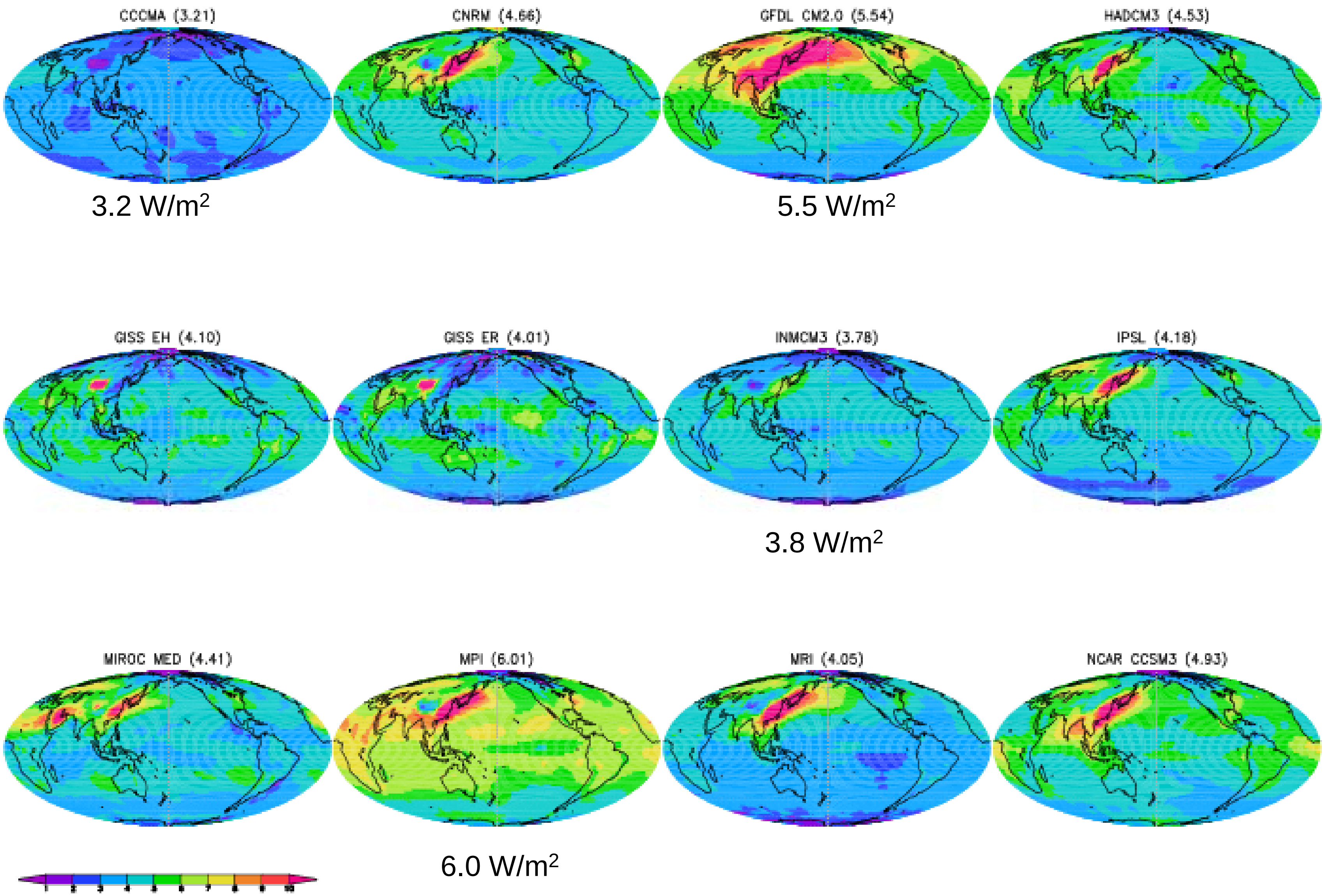
20C3M



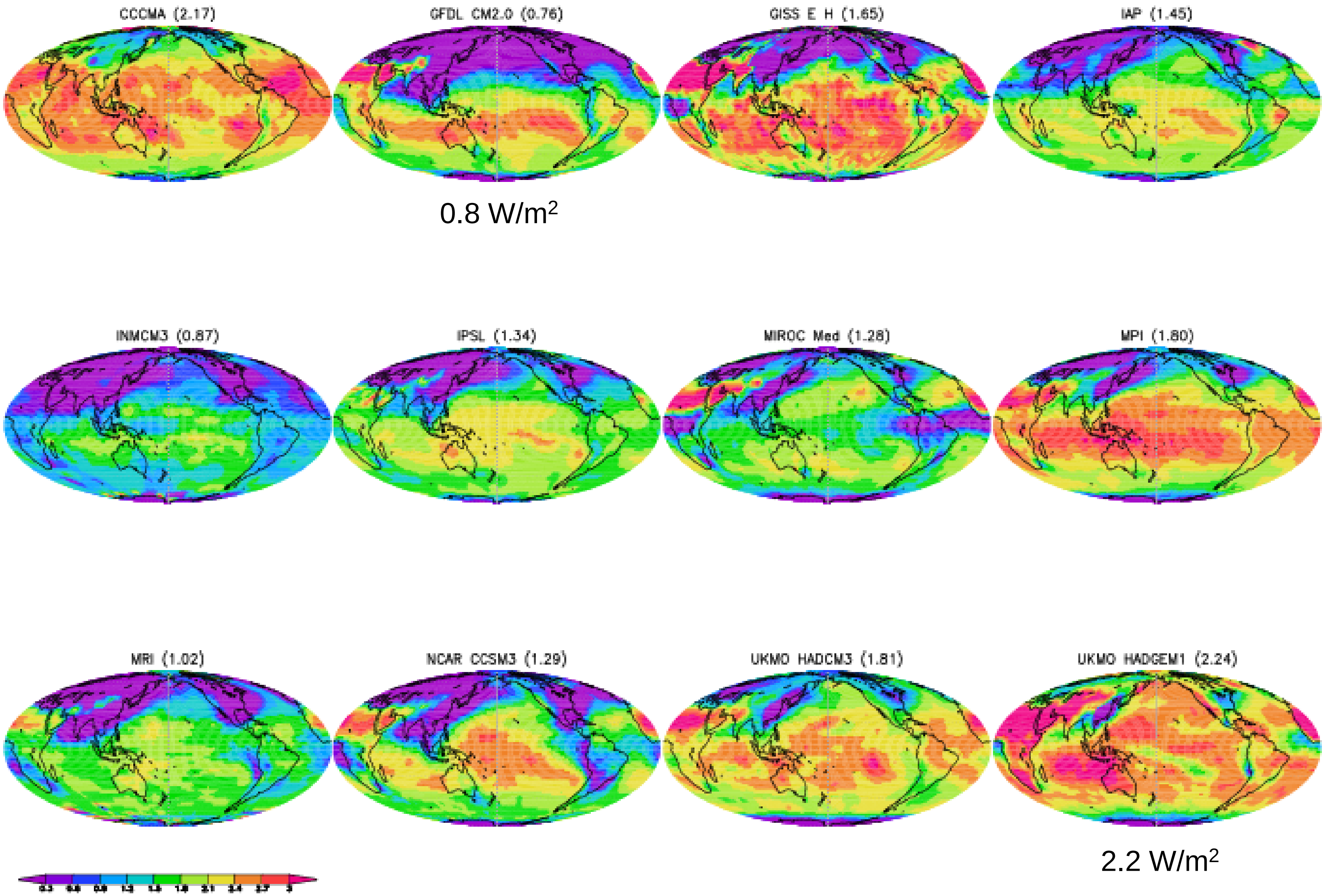
Kernel Estimates: IPCC AR4 2xCO2



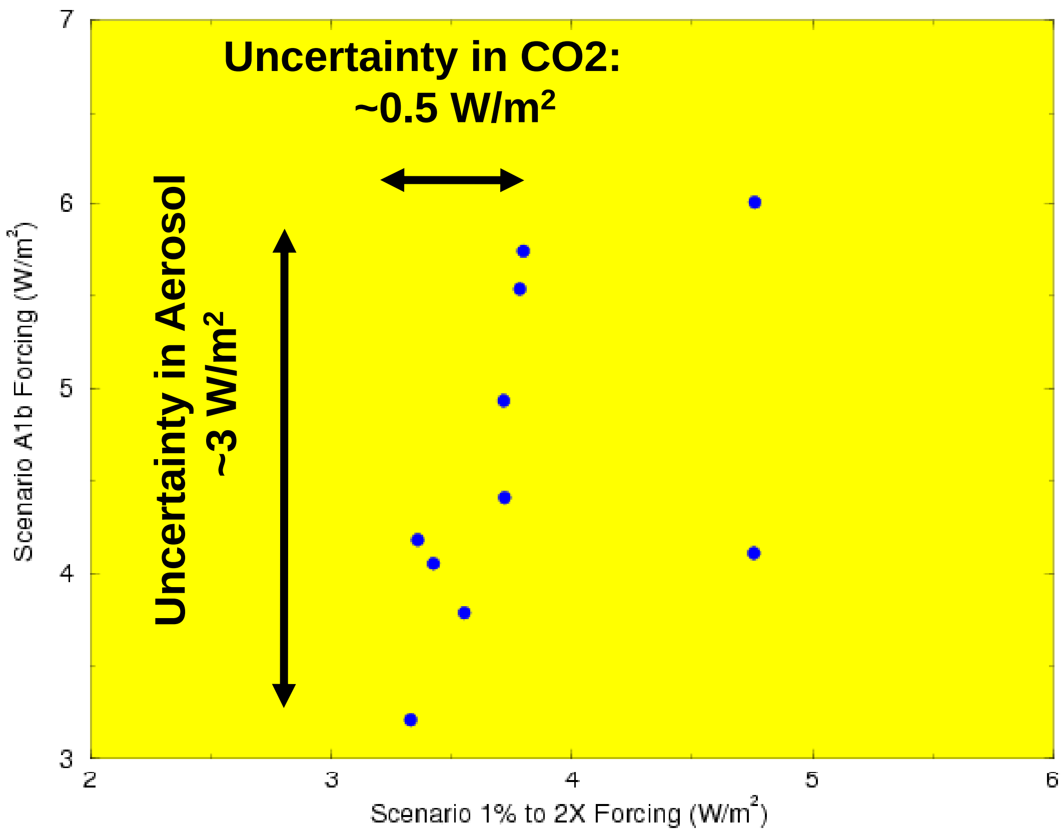
Kernel Estimates: IPCC AR4 A1b



Kernel Estimates: IPCC AR4 20C3M

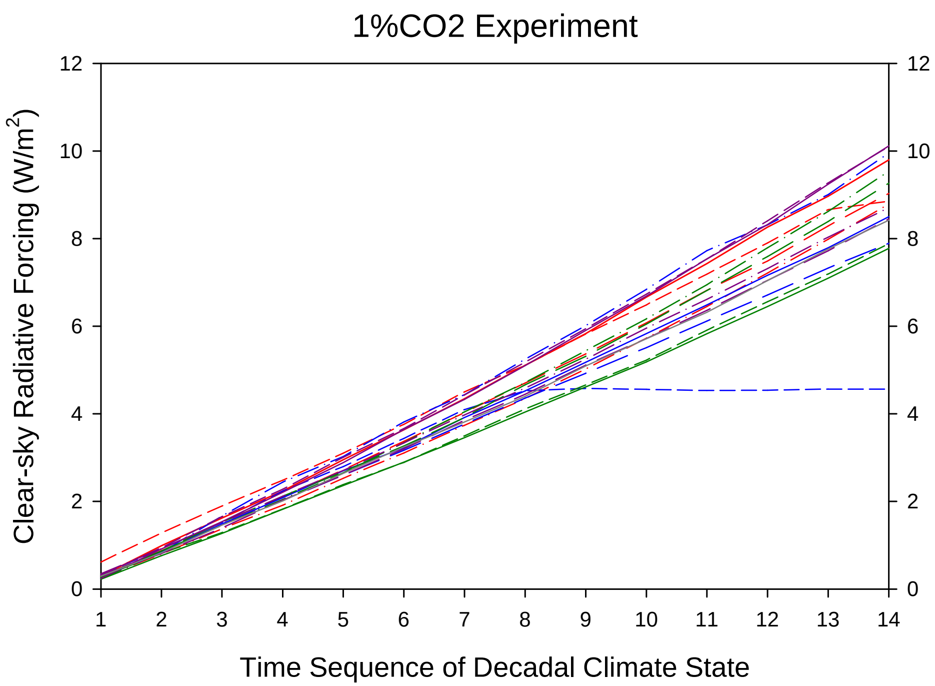


Radiative Forcing: 2xCO2 vs. A1b

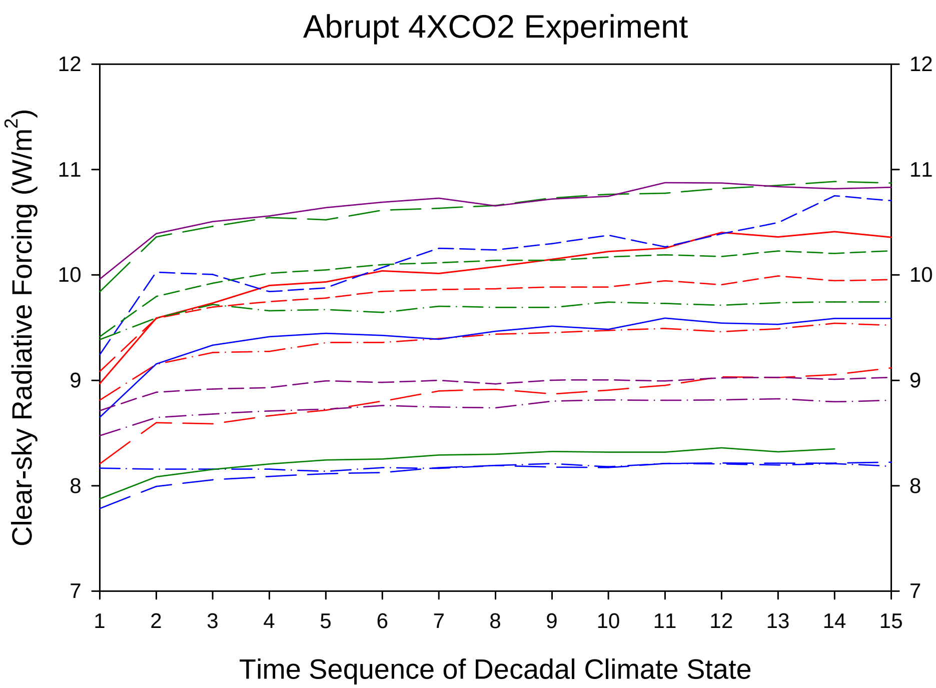


Climate Forcing in IPCC AR5 Models

Radiative Forcing

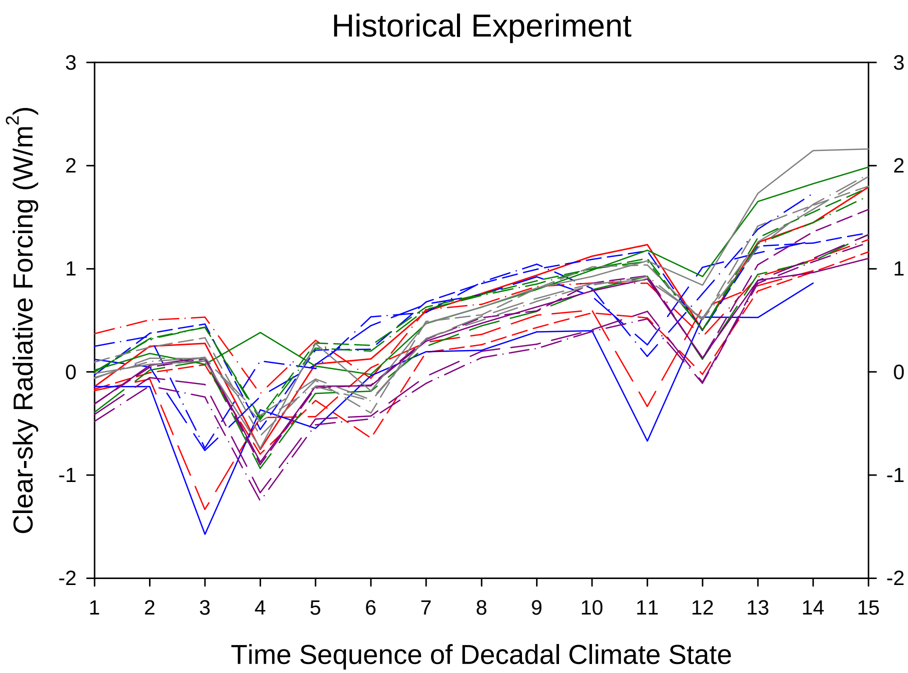


Radiative Forcing



Climate Forcing in IPCC AR5 Models

Radiative Forcing



Radiative Forcing