# *Quantifying and Understanding Cloud Feedbacks, Rapid Adjustments, and Biases Using Cloud Radiative Kernels*

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**Lawrence Livermore National Laboratory**

PCMDI
Program for Climate Model Diagnosis and Intercomparison

CAPT
Cloud-Associated Parameterizations Testbed

ESGF
Earth System Grid Federation

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

# The Big Picture

- Climate sensitivity – the equilibrium warming from a doubling of $CO_2$ – is likely in the range of ***2 - 4.5 K*** (IPCC AR4)

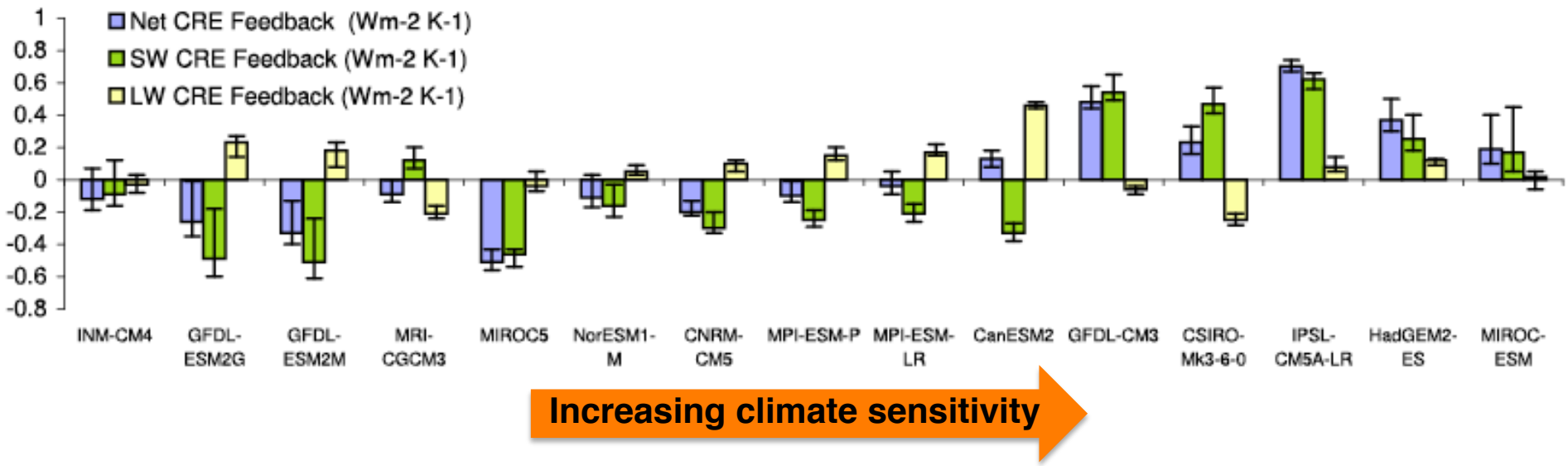
- This range has remained ***essentially unchanged*** since the Charney report of 1979

- Why?
  - Models have a wide range of ***radiative feedbacks*** – temperature-dependent processes that amplify or dampen the radiative forcing at the TOA

# Large inter-model spread persists in CMIP5

CMIP5 range of equilibrium climate sensitivity: **2.1-4.7 K**

Biggest contributor to this range: **cloud feedbacks**




Andrews, Gregory, Webb, **Taylor** (2012) *Geophys. Res. Lett.*

# Focus Areas of this Talk

1. **Diagnosing and partitioning cloud feedbacks in climate models**
   - Introduce new technique to compute the feedback: cloud radiative kernels
   - Partition the cloud feedback by individual cloud types & by nature of cloud changes

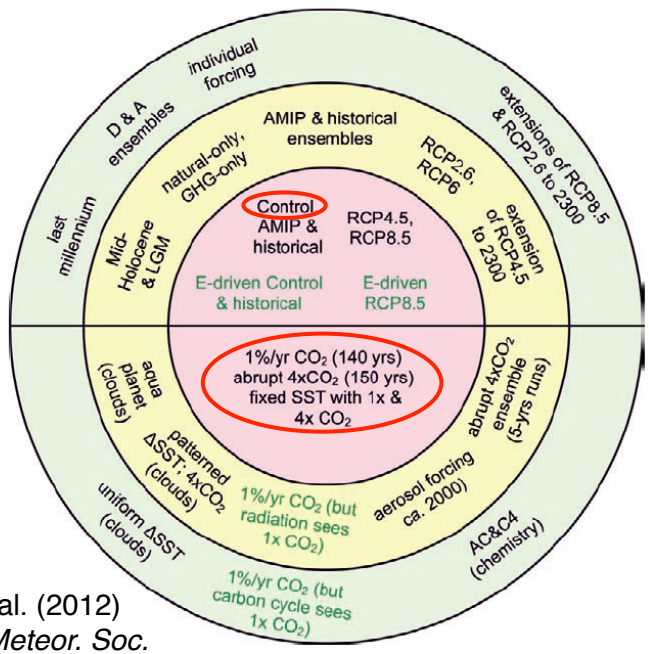
2. **Separating cloud feedbacks from rapid adjustments in CMIP5 models**
   - Use Gregory framework

3. **Evaluate model simulations of clouds – progress from CMIP3 to CMIP5**
   - Use kernels to quantify radiatively-relevant cloud biases

4. **Applications of the kernels to other problems**

# CMIP3 and CMIP5 Data

- CMIP3: Control and 2xCO2 runs from 11 GCMs coupled to slab oceans
- CMIP5: piControl, abrupt4xCO2, & sstClim4xCO2, runs from 6 AOGCMs
- ISCCP simulator (**Klein** & Jakob 1999) run inline during integration
  - Produce distribution of cloud fraction (as function of CTP and $\tau$) that is consistent with how a satellite-borne passive sensor would "view" the model atmosphere
  - Simulated cloud fractions are defined consistently across models




**Taylor** et al. (2012)
*Bull. Amer. Meteor. Soc.*

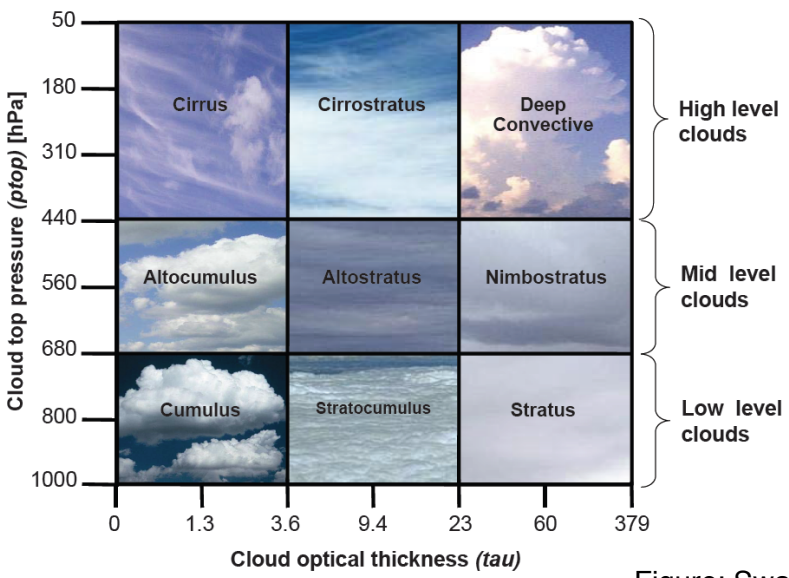


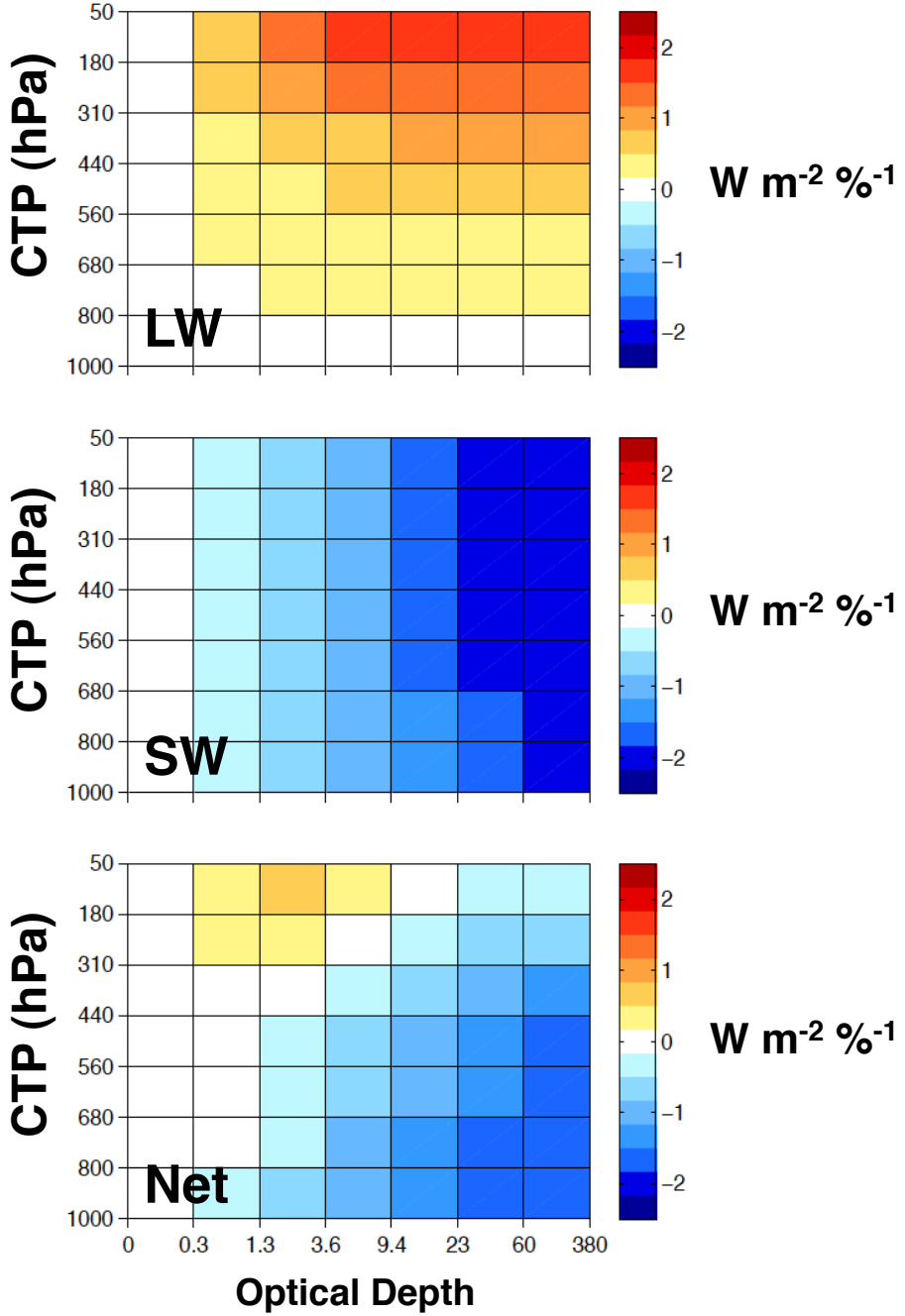

Figure: Swati Gehlot

# Methodology: Cloud Radiative Kernels

- Using Fu-Liou radiative transfer model, we compute cloud radiative kernels → sensitivity of TOA radiation to cloud fraction changes in each CTP-$\tau$ bin:

$$K_{p\tau} \equiv \frac{\partial R}{\partial C_{p\tau}}$$

# Global Annual Mean Cloud Kernels




**Zelinka**, **Klein**, & Hartmann (2012a) *J. Climate*

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- Cloud-induced radiative flux anomalies:

$$\Delta R_C = \sum_{p=1}^{P} \sum_{\tau=1}^{T} K_{p\tau} \times \Delta C_{p\tau}$$

$$\alpha_C = \frac{\Delta R_C}{\Delta T_S}$$

$\Delta$ = 2x$CO_2$ minus 1x$CO_2$ equilibrium climates
→ $\alpha_C$ = cloud feedback
**FOCUS AREA 1**

$$\Delta R_C = F_C + \alpha_C \Delta T_S$$

Plot $\Delta R_C$ against $\Delta T_S$
→ intercept ($F_C$) = adjustment
→ slope ($\alpha_C$) = feedback
**FOCUS AREA 2**

$\Delta$ = model minus observed
→ $\Delta R_C$ = radiative impacts of cloud biases
**FOCUS AREA 3**

# Focus Areas

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   - Introduce new technique to compute the feedback
   - Partition cloud feedback into individual cloud types and the nature of cloud changes

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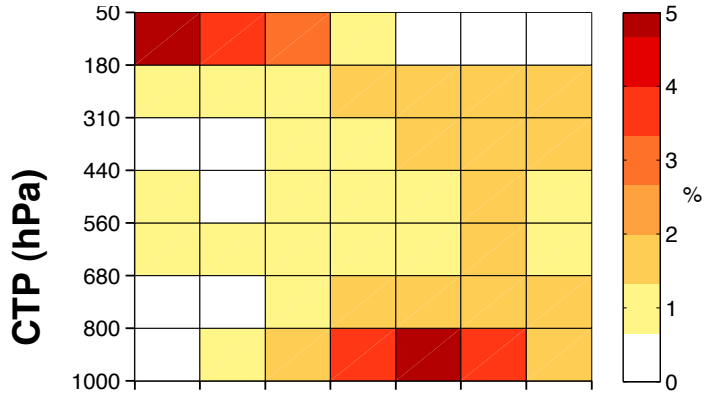
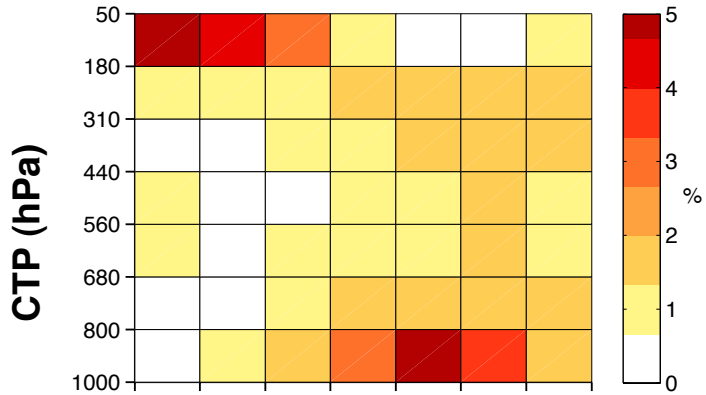
**FOCUS AREA 1**

# Cloud Fraction

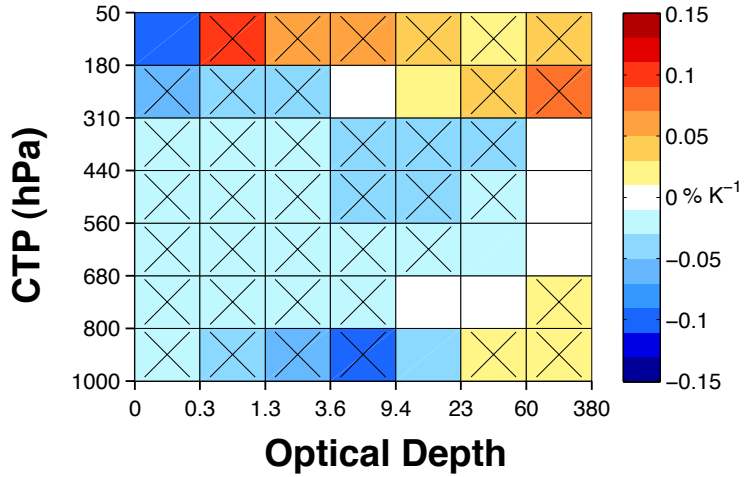
**1x$CO_2$**
**58.1 %**




**2x$CO_2$**
**56.8 %**

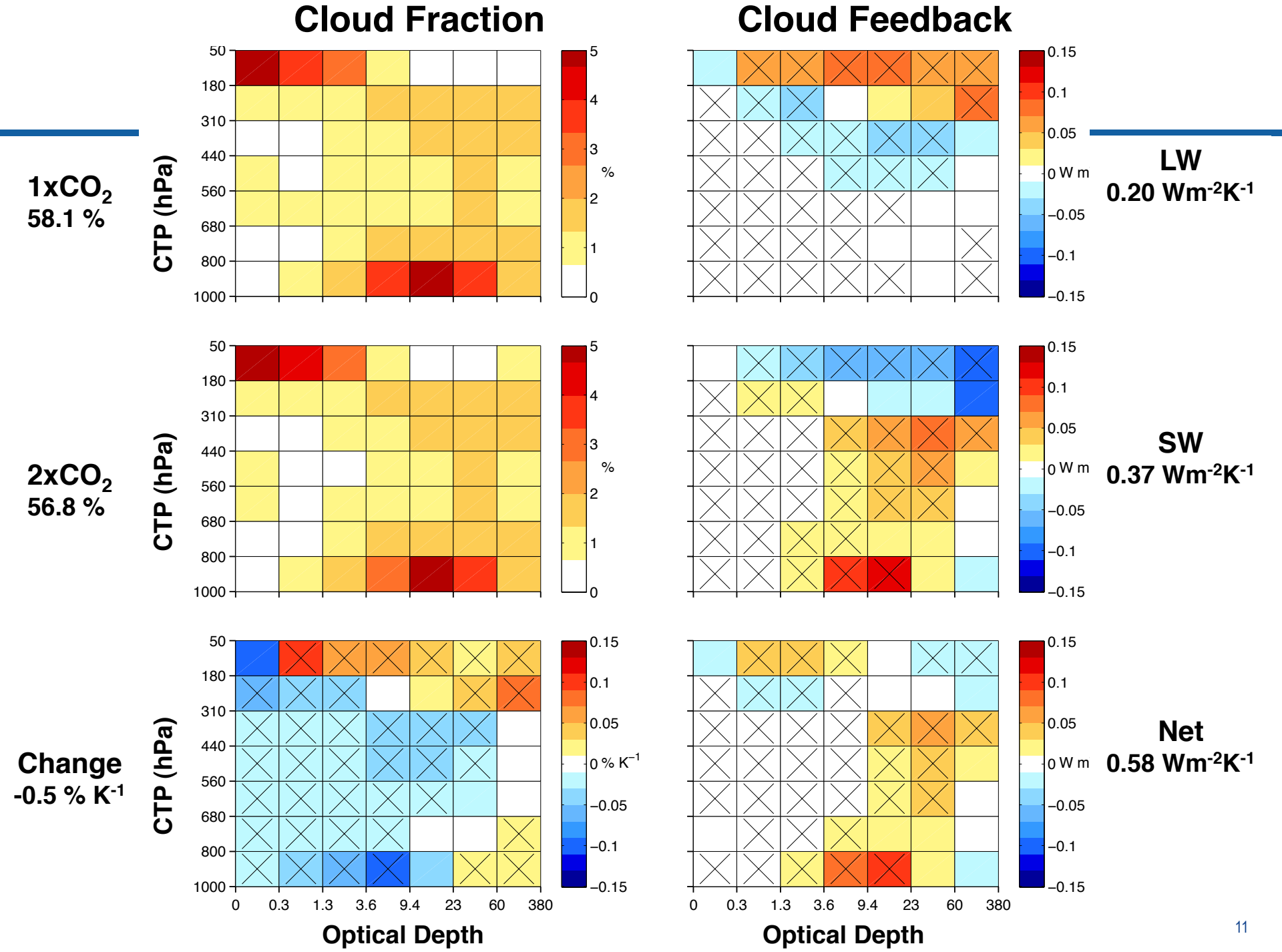



**Change**
**-0.5 % $K^{-1}$**

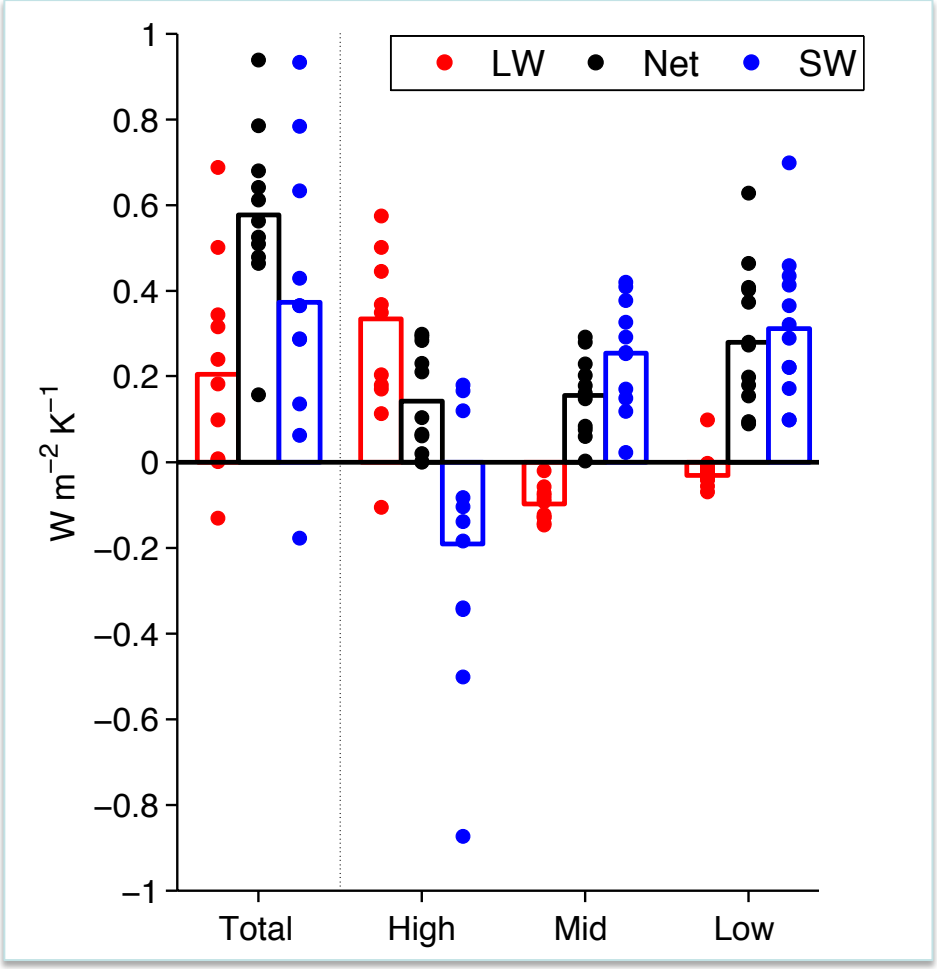



Each cloud fraction shown is "visible" from space (i.e., the non-overlapped cloud fraction)

x Cloud Radiative Kernels at each location and month, then averaged annually, globally, and across models…


Cloud Fraction
Cloud Feedback
1xCO2
58.1 %
2xCO2
56.8 %
Change
-0.5 % K-1
LW
0.20 Wm-2K-1
SW
0.37 Wm-2K-1
Net
0.58 Wm-2K-1
CTP (hPa)
50
180
310
440
560
680
800
1000
0
0.3
1.3
3.6
9.4
23
60
380
Optical Depth
%
% K−1
W m
5
4
3
2
1
0
0.15
0.1
0.05
0
−0.05
−0.1
−0.15

# Global mean cloud feedbacks, segregated by cloud top altitude

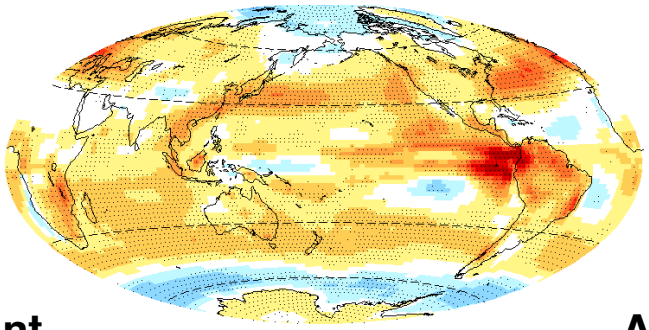



**dots = models**
**bar = model mean**

**Zelinka**, **Klein**, & Hartmann (2012a) *J. Climate*

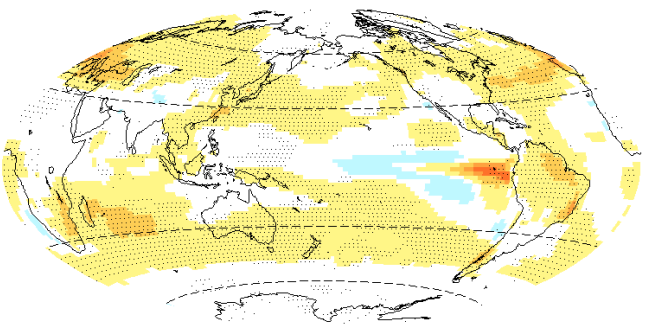
## Net Cloud Feedback

**0.57 W m$^{-2}$ K$^{-1}$**



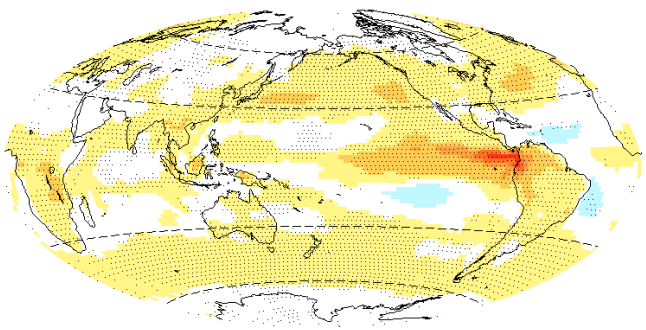
## Amount

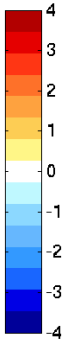
**0.27 W m$^{-2}$ K$^{-1}$**



## Altitude

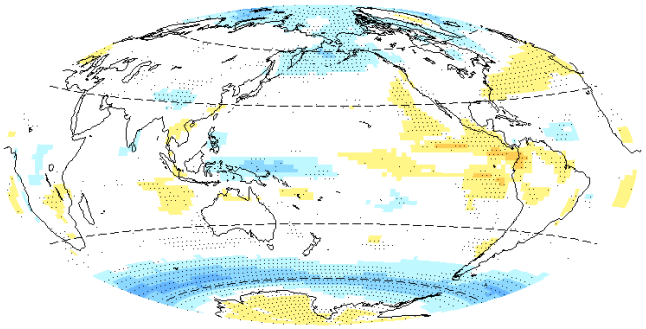
**0.34 W m$^{-2}$ K$^{-1}$**





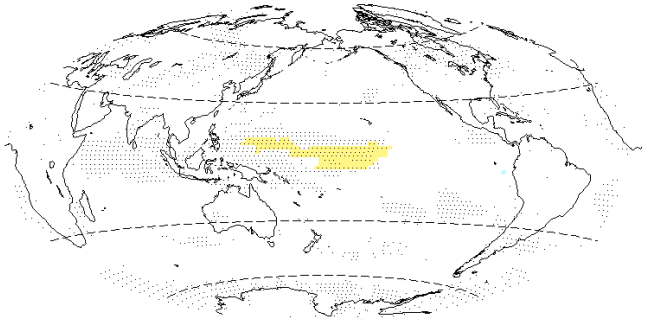

## Optical Depth

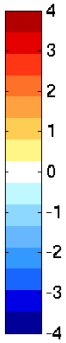
**-0.06 W m$^{-2}$ K$^{-1}$**



## Residual

**0.02 W m$^{-2}$ K$^{-1}$**






**Zelinka**, **Klein**, & Hartmann (2012b) *J. Climate*

# Focus Areas

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   - Introduce new technique to compute the feedback
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   - Use Gregory framework

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Plot $\Delta R_C$ against $\Delta T_S$
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**FOCUS AREA 2**

# Cloud-Induced Net Radiation Anomalies

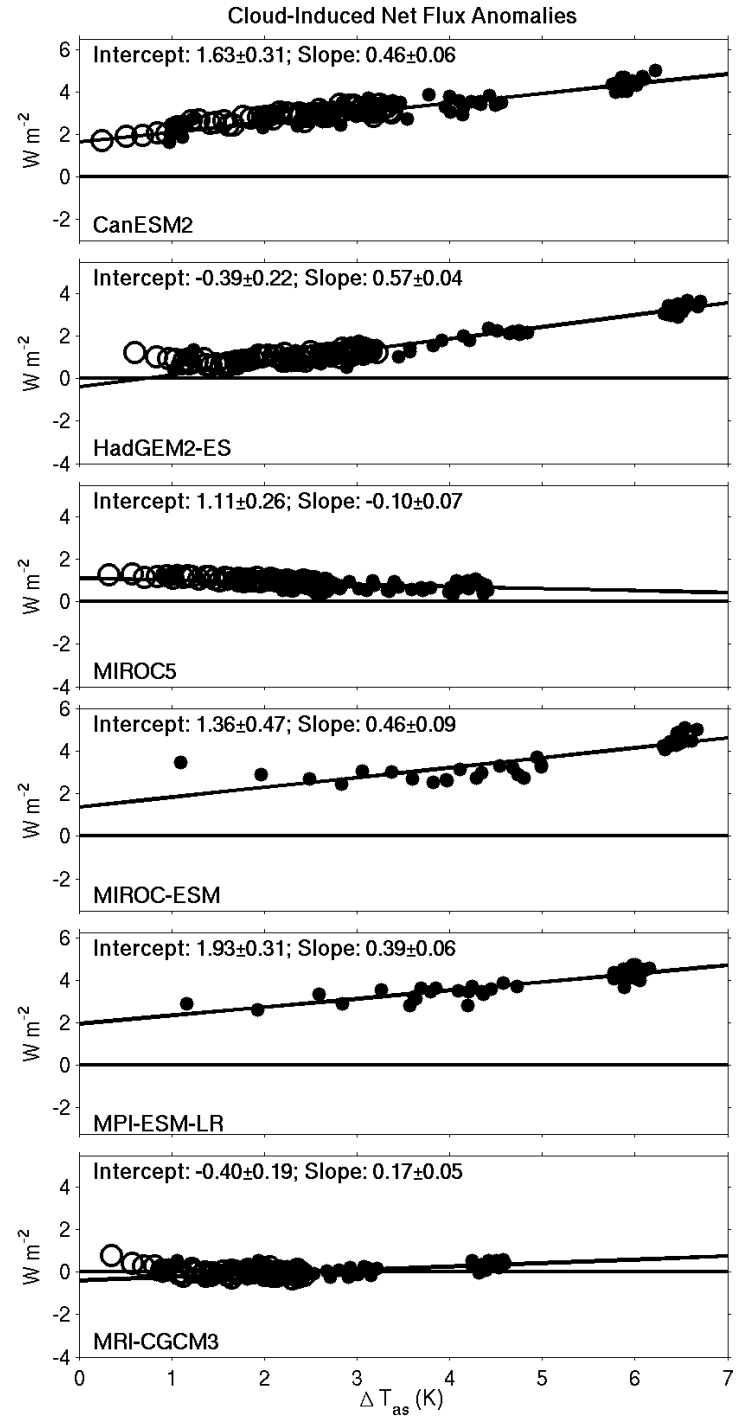
(Positive = heating)

$$\Delta R_C = F + \alpha_C \Delta T_S$$

→ intercept ($F_C$) = adjustment
→ slope ($\alpha_C$) = feedback

-Robust positive cloud adjustments
-Positive cloud feedbacks in 5 out of 6 models
-Some early departures from linearity

**These feedback estimates will be included in AR5**



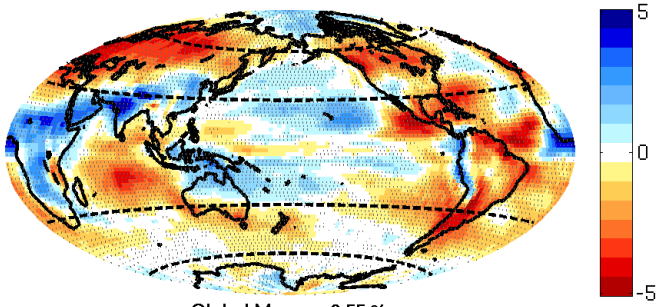

**Zelinka**, **Klein**, **Taylor**, Andrews, Webb, Gregory, & Forster, subm., *J. Climate*

# Comparing Cloud Responses

**Zelinka**, **Klein**, **Taylor**, Andrews, Webb, Gregory, & Forster, subm., *J. Climate*

**Rapid Adjustment**

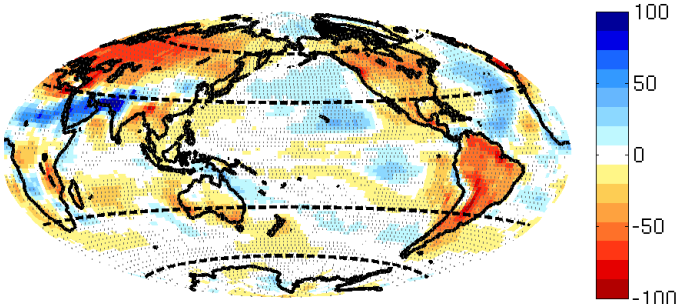
$\Delta C_{tot}$




Global Mean = -0.55 %

Upon $CO_2$ quadrupling, clouds become fewer, higher, & thinner

$\Delta CTP$

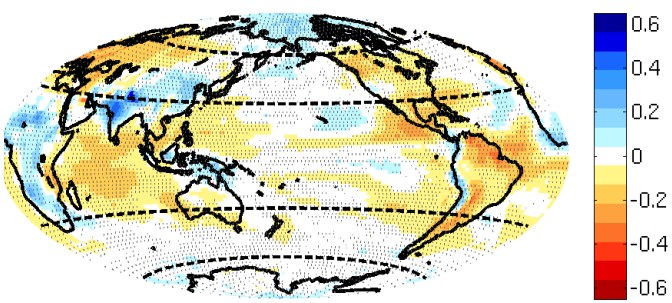



Global Mean = -7.80 hPa

Fewer / thinner oppose higher → small negative LW adjustment

Thinner + fewer → big positive SW adjustment

$\Delta \ln(\tau)$




Global Mean = -0.03

Net positive cloud adjustment comes from roughly equal contributions from clouds becoming fewer, higher, and thinner

# Comparing Cloud Responses

**Zelinka**, **Klein**, **Taylor**, Andrews, Webb, Gregory, & Forster, subm., *J. Climate*

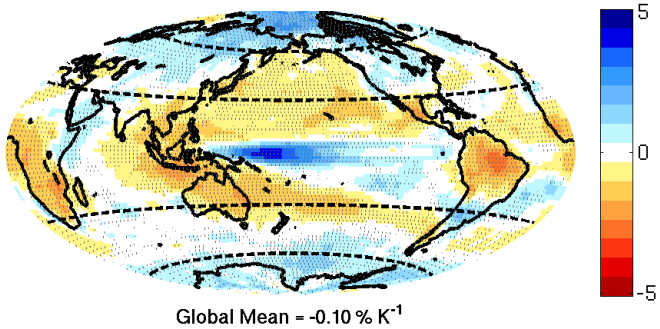
As the planet warms, cloud fraction continues to decrease → SW cloud amount feedback is robustly positive

Cloud top altitude increases rather uniformly → LW cloud altitude feedback is robustly positive

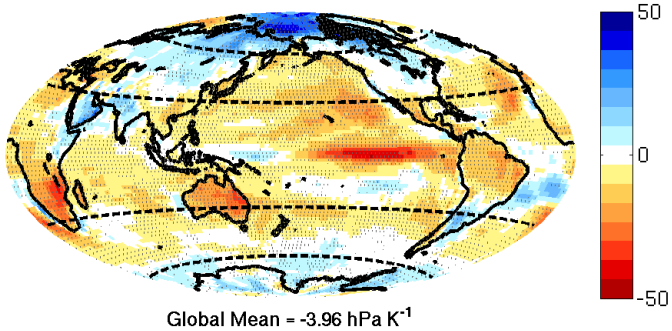
Optical depth of cold clouds increases dramatically →
SW cloud optical depth feedback is robustly negative & is the only negative contributor to net cloud feedback in ensemble mean

**Temperature-Mediated**

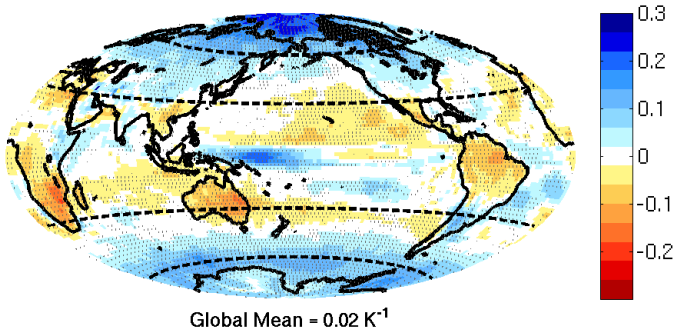
$\Delta C_{tot}$




$\Delta CTP$




$\Delta \ln(\tau)$



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2. **Separating cloud feedbacks from rapid adjustments in CMIP5 models**
   - Use Gregory framework
3. **Evaluate model simulations of clouds – progress from CMIP3 to CMIP5**
   - Use kernels to quantify radiatively-relevant cloud biases

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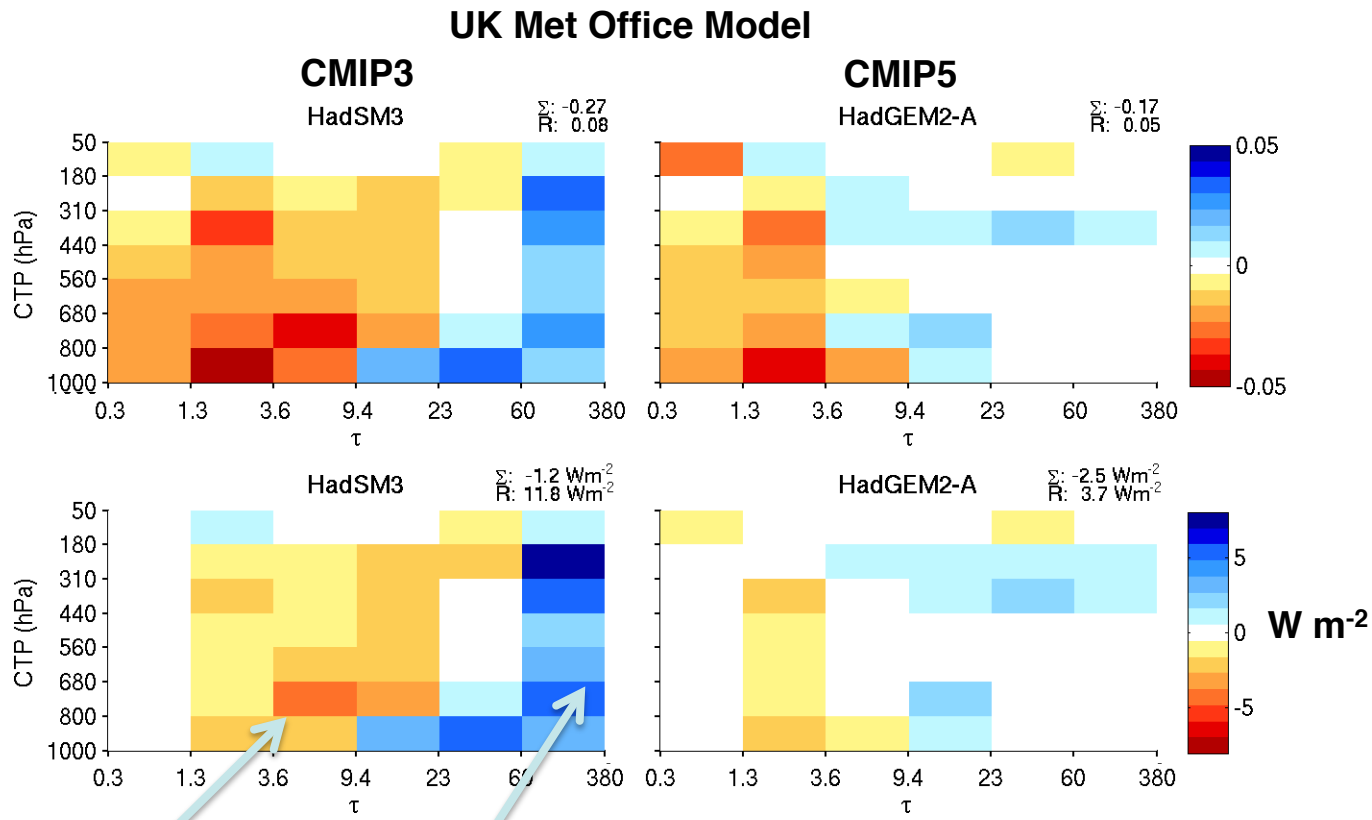
**FOCUS AREA 2**

Δ = model minus observed
→ $\Delta R_C$ = radiative impacts of cloud biases
**FOCUS AREA 3**

# Quantifying the Radiative Impact of Cloud Biases in Models

**Cloud fraction biases: Model minus ISCCP**

**Reflected SW biases: Model minus ISCCP**



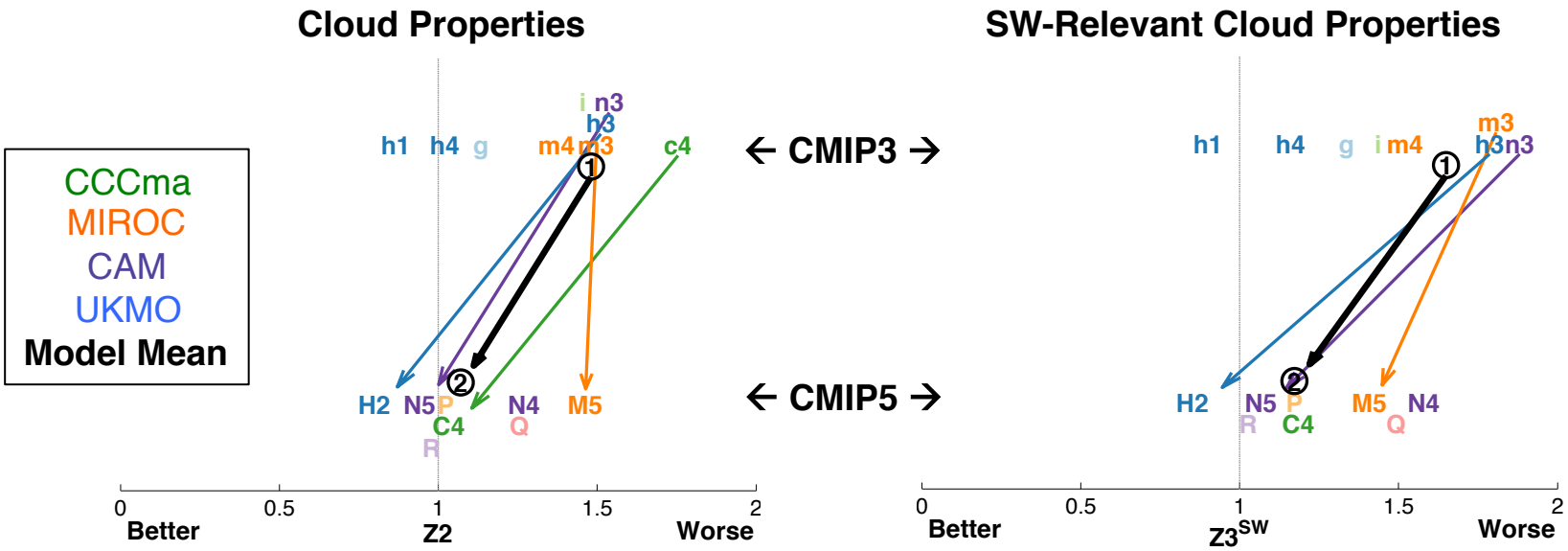

**Big improvement in CMIP5**

**Not enough thin clouds**
**→ Too little SW reflection**

**Too many thick clouds**
**→ Too much SW reflection**

**Klein**, **Zhang**, **Zelinka**, Pincus, **Boyle**, **Gleckler**, subm., *J. Geophys. Res.*

# Metrics of model performance




**Individual modeling centers show big improvement between CMIP3 and CMIP5**

**See Glecker Poster**

**Klein**, **Zhang**, **Zelinka**, Pincus, **Boyle**, **Gleckler**, subm., *J. Geophys. Res.*

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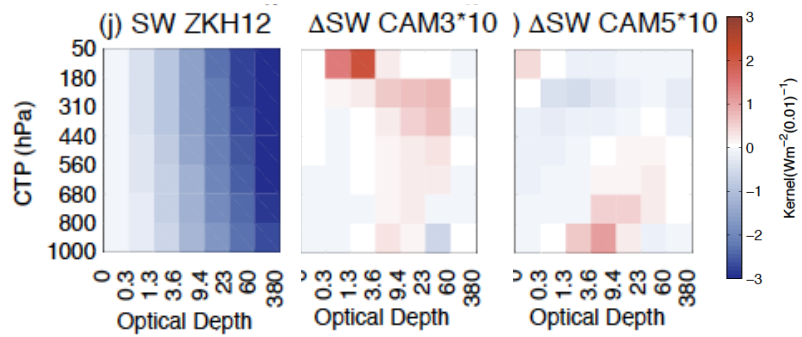
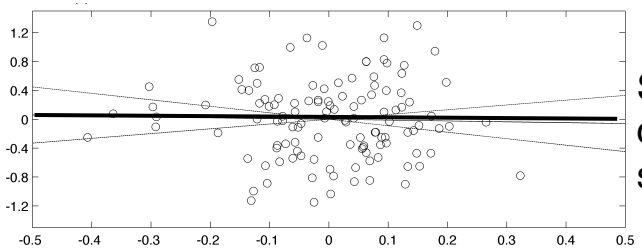
# Kernel-Facilitated Research



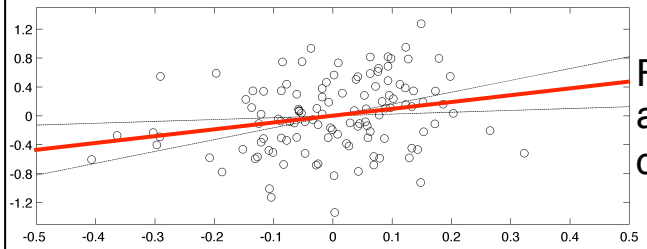

Modified from Sanderson and Shell, in press, *J. Climate*

All Clouds



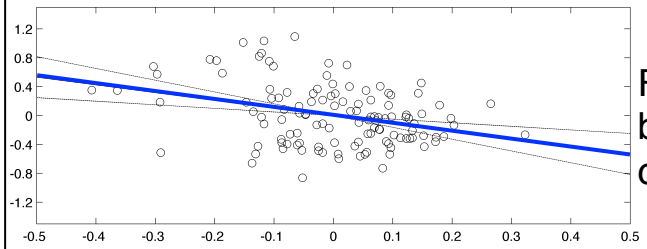
Short-term net cloud feedback: sign **unconstrained**

800-50 hPa Clouds



Feedback from clouds above 800 hPa level: clearly **positive**

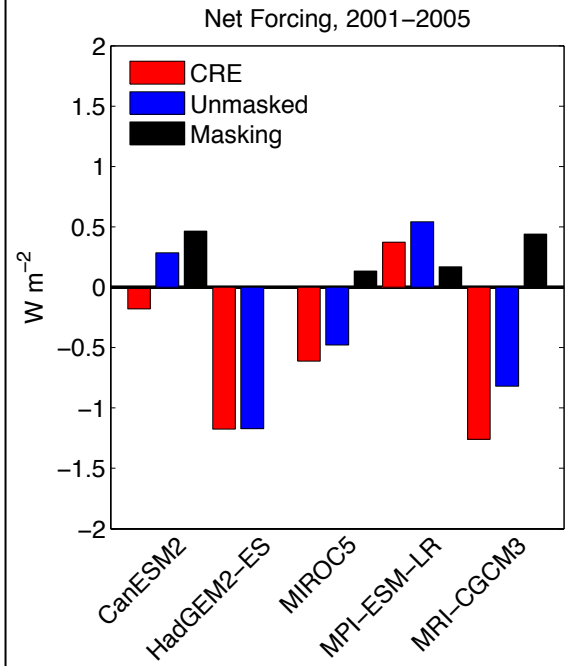
1000-800 hPa Clouds



Feedback from clouds below 800 hPa level: clearly **negative**

$\Delta T_S$

Zhou, **Zelinka**, Dessler, & Yang, subm. *J. Climate*

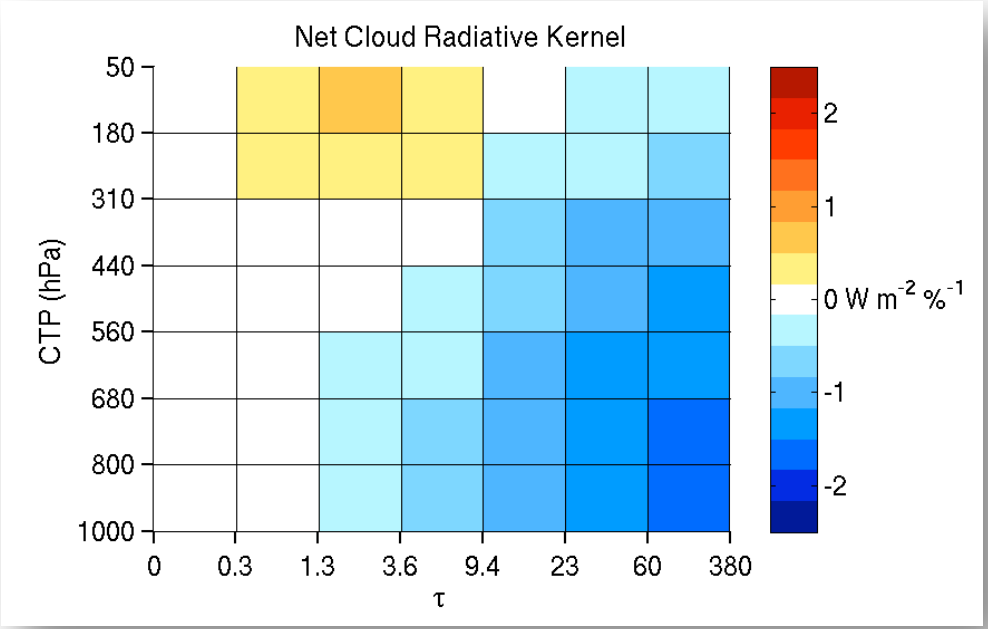



Forster, Andrews, Good, Gregory, Jackson, & **Zelinka**, subm. *J. Geophys. Res.*

# Summary of Results

- **Key Accomplishments**
  - Performed the most detailed / rigorous diagnosis of how different cloud types contribute to cloud feedbacks, adjustments, and radiative biases to date
  - Produced a useful, efficient, and informative tool: cloud radiative kernels
- **Key Findings**
  - Upon abrupt $CO_2$ quadrupling, clouds become ***fewer***, ***higher***, and ***thinner*** → each contributes roughly equally to the net positive adjustment
  - As the planet warms, the ***rise in high cloud altitude*** quantitatively produces the most ***positive*** cloud feedback – but still exhibits significant ***spread*** worthwhile of future exploration
  - ***High*** cloud changes induce ***wider range*** of LW and SW cloud feedbacks across models than do ***low*** cloud changes
  - The only significant ***negative*** cloud feedbacks robustly produced by models are due to the increases in ***cloud brightening*** at high latitudes
  - Models show ***big reduction in compensating errors*** ("too few but too bright") between CMIP3 and CMIP5
- Armed with these tools, we now set out to understand sources of inter-model spread in cloud feedbacks and to narrow their range using physical constraints

# Thank you!

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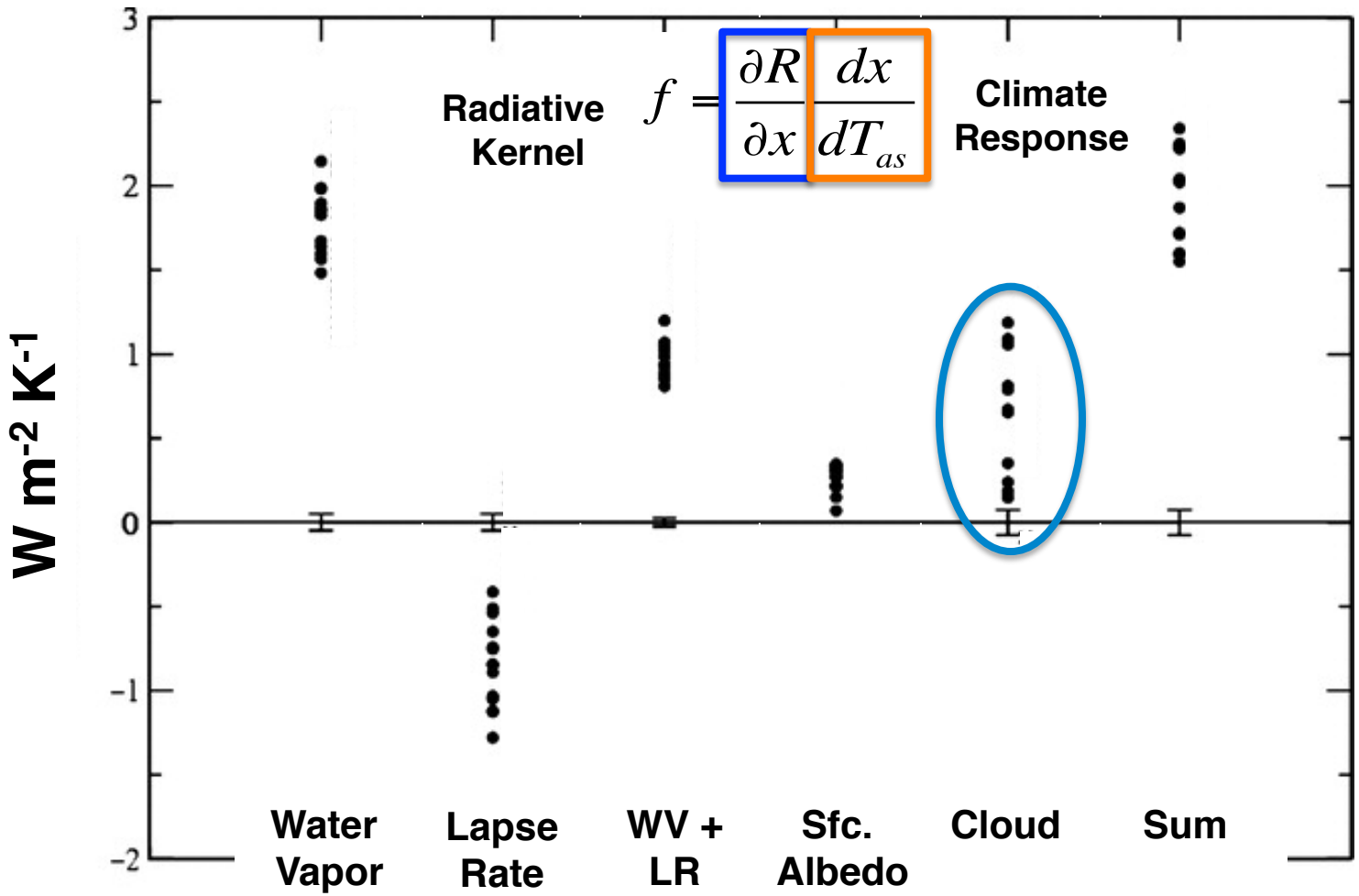
IM release #LLNL-PRES-576954

# Extra Slides

# Feedback Magnitudes: CMIP3 Models




Modified from Soden and Held (2006)

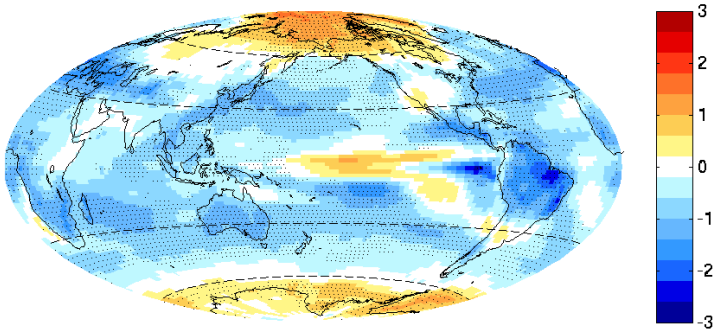
# New Technique: Cloud Radiative Kernels

- A ***clean*** and ***simple*** method of calculating cloud-induced TOA radiation anomalies that is highly ***informative***

- ***Clean***:
  - compute radiative anomalies directly from cloud changes (not inferred)
  - standard radiation code & definition of "cloud" across models
- ***Simple***:
  - no need to correct for non-cloud effects
  - can use monthly mean model output
- ***Informative***:
  - can quantify the contributions from…
    …changing amounts of individual cloud types (high, middle, low)
    …individual processes (Δaltitude, Δoptical depth, Δtotal amount)

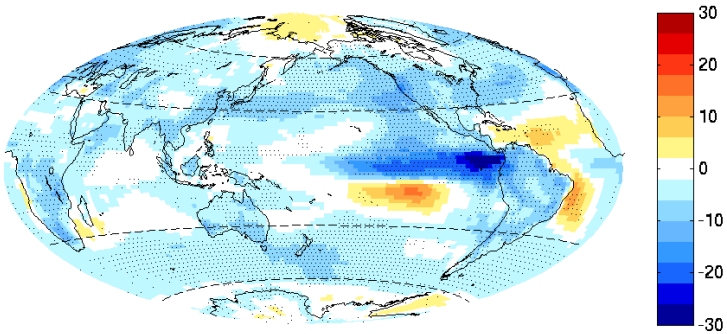
**Clouds go away**

**Δ Total Cloud Fraction: -0.44 % $K^{-1}$**



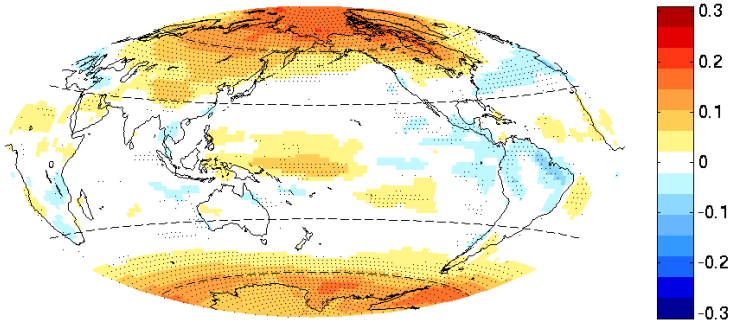

**Clouds rise**

**Δ CTP: -3.68 hPa $K^{-1}$**




**Cold clouds get thicker**

**Δ ln(τ): 0.03 $K^{-1}$**




**Next we will quantify the contributions to cloud feedback from changes in cloud amount, altitude, & optical depth…**

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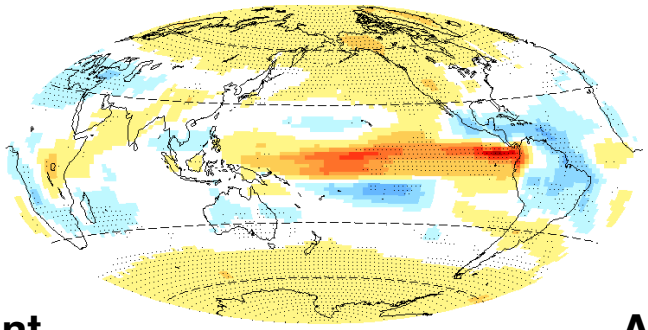
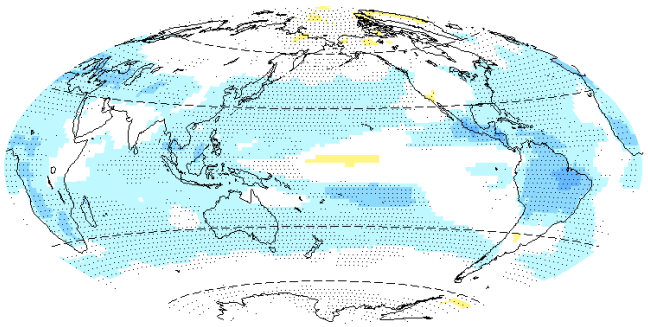
# LW Cloud Feedback

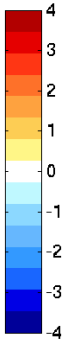
**0.21 W m$^{-2}$ K$^{-1}$**



## Amount

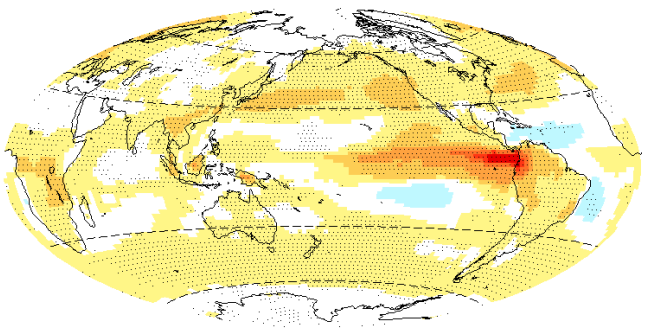
**-0.29 W m$^{-2}$ K$^{-1}$**





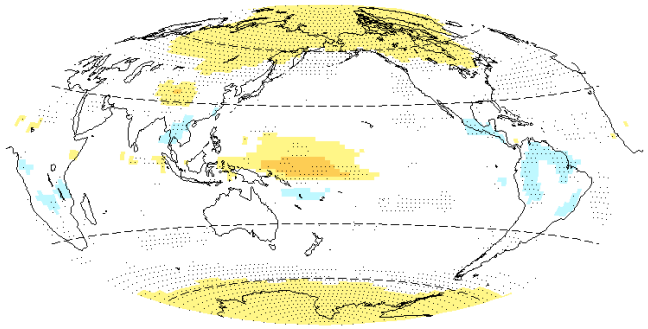

## Altitude

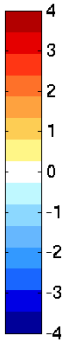
**0.39 W m$^{-2}$ K$^{-1}$**



## Optical Depth

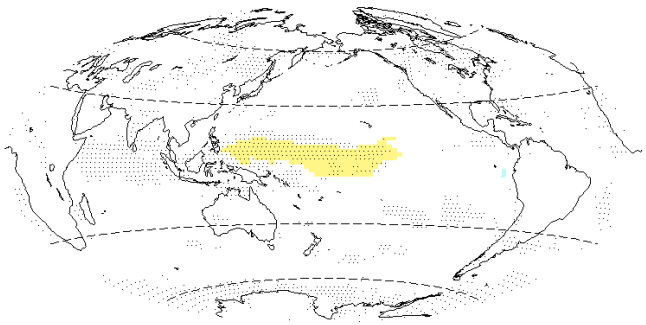
**0.09 W m$^{-2}$ K$^{-1}$**






## Residual

**0.02 W m$^{-2}$ K$^{-1}$**



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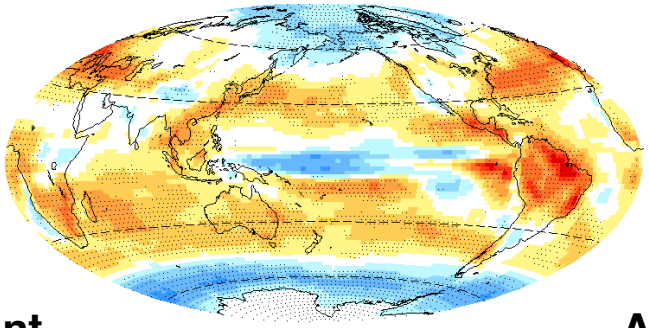
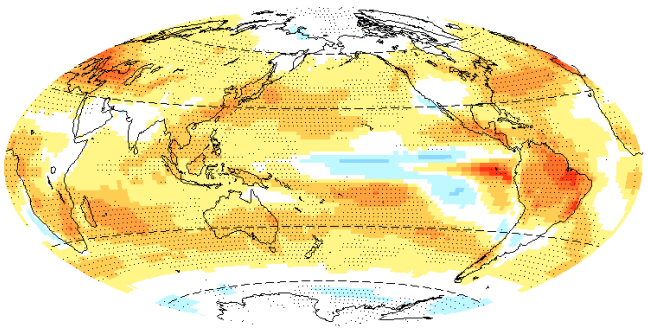
## SW Cloud Feedback

**0.37 W m$^{-2}$ K$^{-1}$**



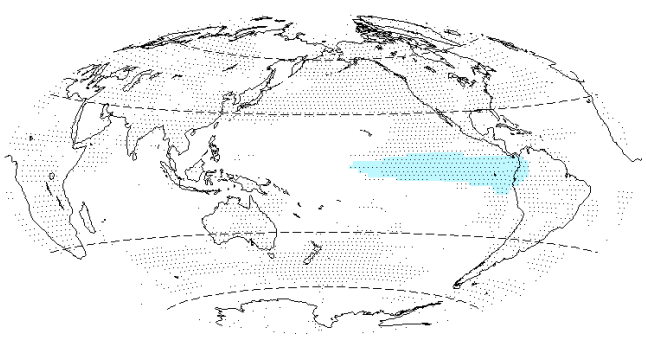
### Amount

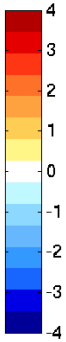
**0.57 W m$^{-2}$ K$^{-1}$**



### Altitude

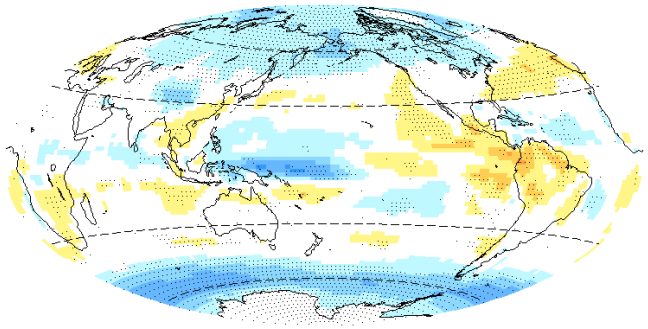
**-0.05 W m$^{-2}$ K$^{-1}$**





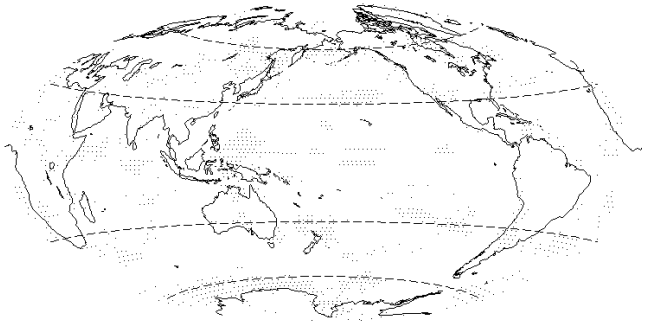

### Optical Depth

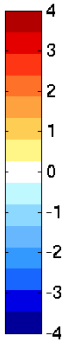
**-0.14 W m$^{-2}$ K$^{-1}$**



### Residual

**-0.00 W m$^{-2}$ K$^{-1}$**



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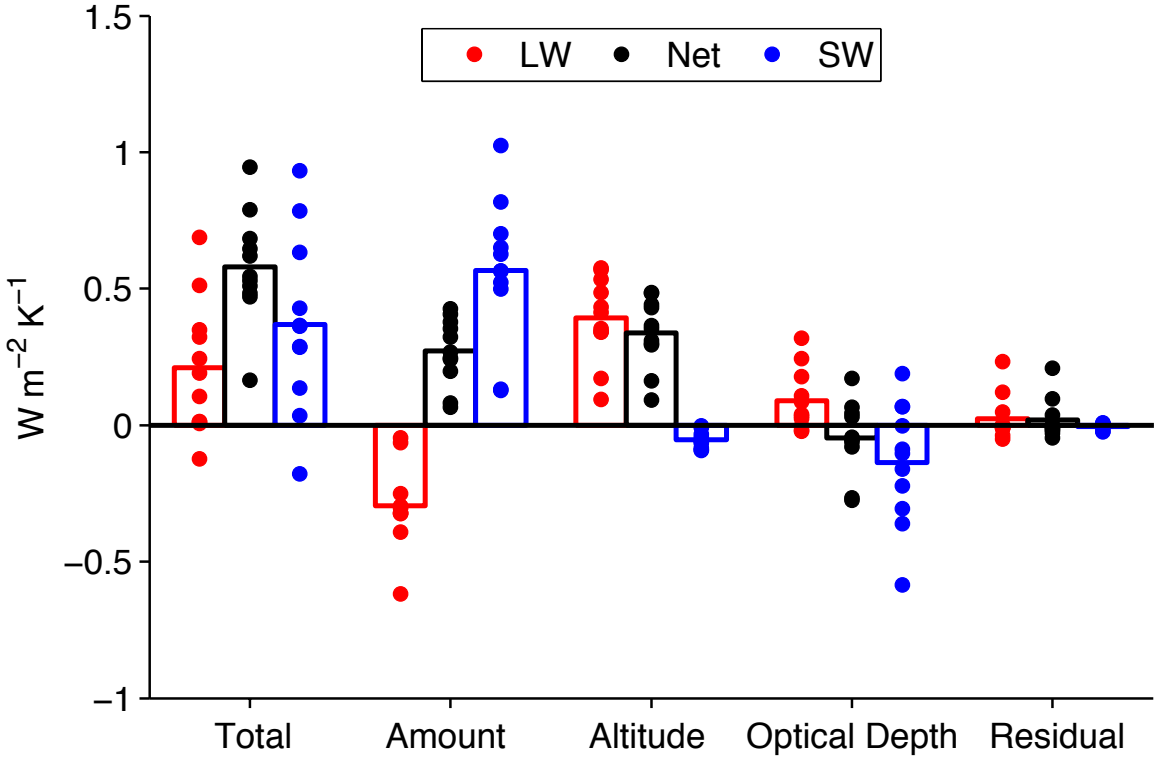
# Global mean cloud feedbacks, segregated by the *nature* of the cloud change




**Zelinka**, **Klein**, & Hartmann (2012b) *J. Climate*

GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L03205, doi:10.1029/2003GL018747, 2004

# A new method for diagnosing radiative forcing and climate sensitivity

J. M. Gregory,[1,2] W. J. Ingram,[2] M. A. Palmer,[3] G. S. Jones,[2] P. A. Stott,[2] R. B. Thorpe,[2] J. A. Lowe,[2] T. C. Johns,[2] and K. D. Williams[2]

Received 1 October 2003; revised 10 November 2003; accepted 28 November 2003; published 11 February 2004.

F = radiative forcing

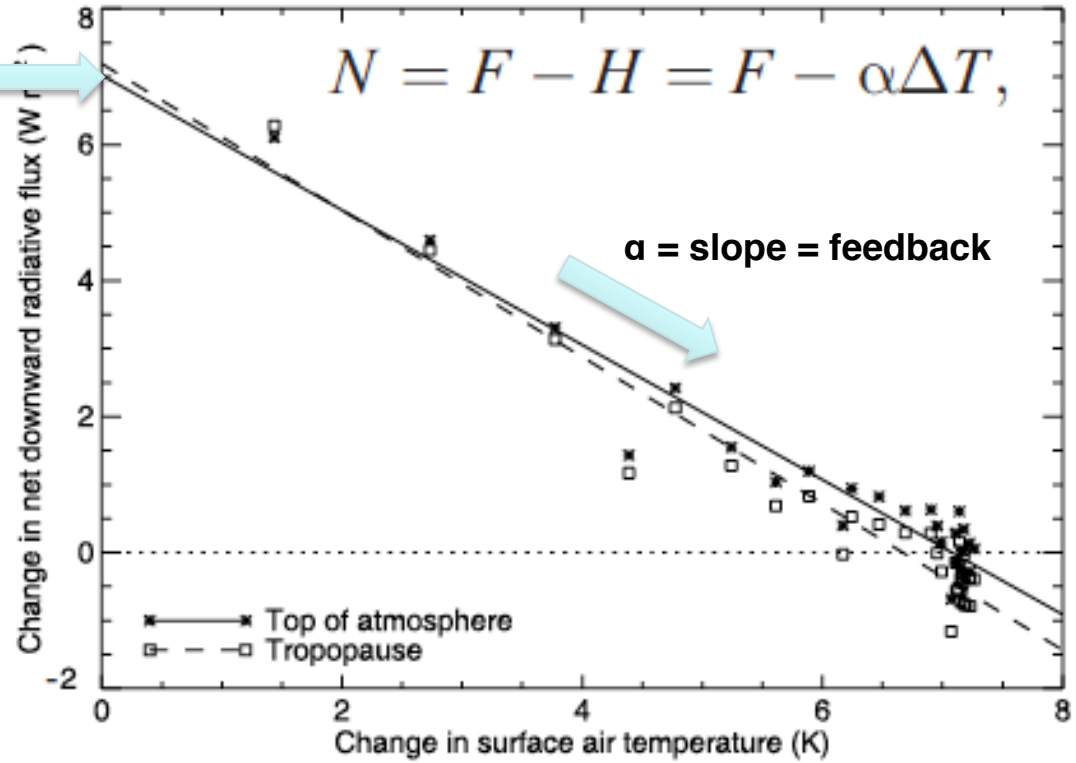



**Figure 1.** The evolution of global average net downward radiative flux with global average surface air (1.5 m height) temperature change in a HadSM3 experiment with constant $4 \times CO_2$. The dotted line is $N = 0$.

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# Tropospheric Adjustment Induces a Cloud Component in $CO_2$ Forcing

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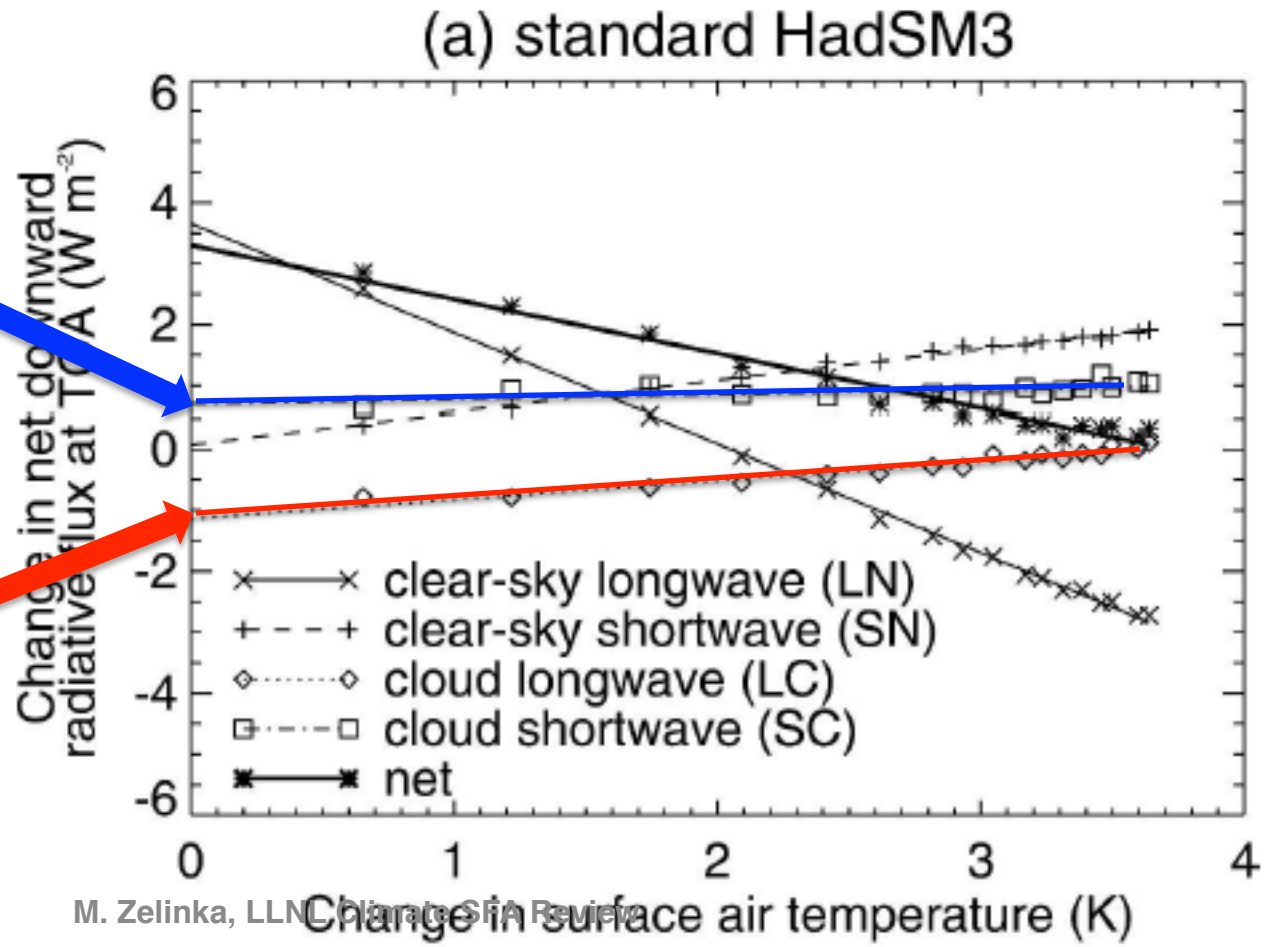
MARK WEBB

*Hadley Centre, Met Office, Exeter, United Kingdom*

(Manuscript received 22 December 2006, in final form 1 May 2007)

**Big positive SW cloud adjustment; subsequent small SW cloud feedback**

**Big negative LW cloud adjustment; subsequent positive LW cloud feedback**



LW: $\Delta R_C = F + \alpha_C \Delta T_S$

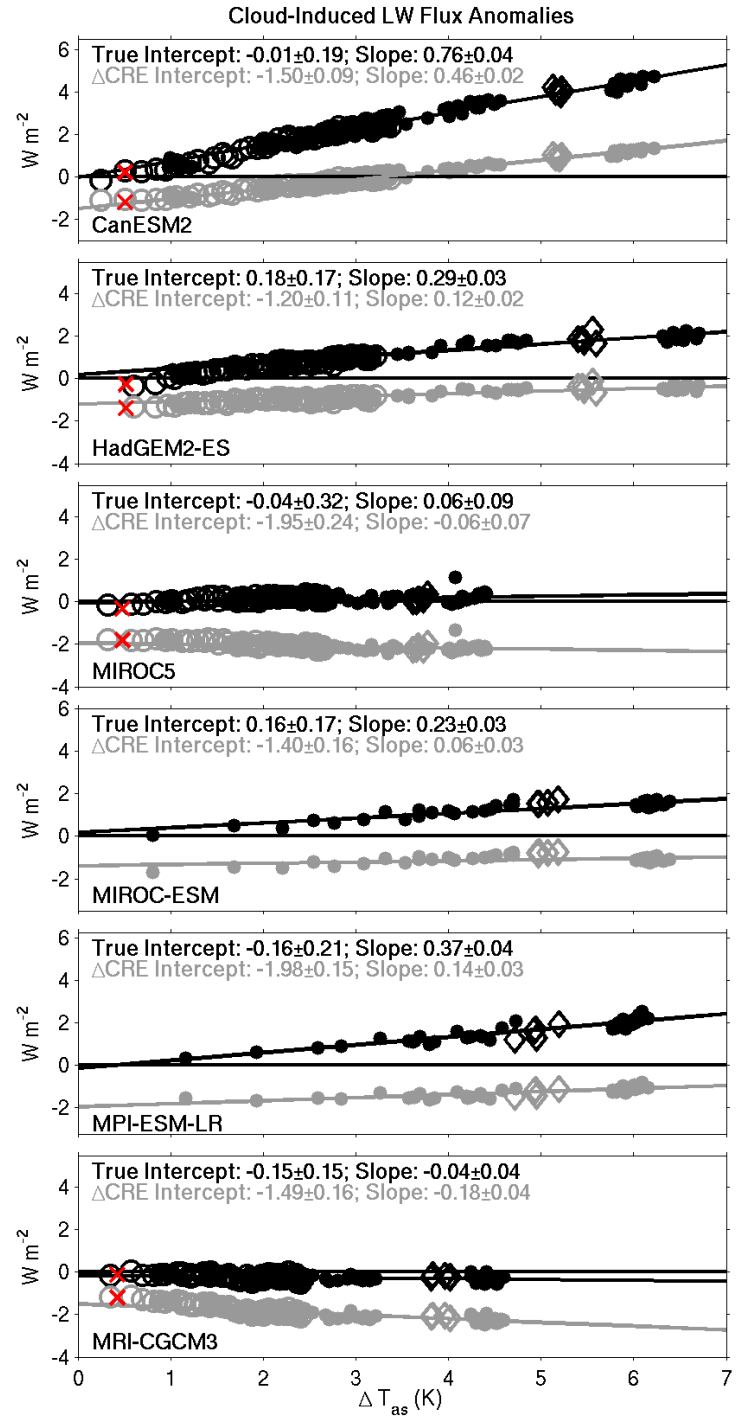
Black: Cloud-induced LW radiation anomalies ($\Delta R_C$)

Gray: LW cloud radiative effect (CRE) anomalies
(CRE = clear- minus all-sky upwelling TOA flux)

Red crosses: climatological SSTs but with 4x$CO_2$ imposed

Positive = heating

**These feedback estimates will be included in AR5**




**Zelinka**, **Klein**, **Taylor**, Andrews, Webb, Gregory, & Forster, subm., *J. Climate*

SW: $\Delta R_C = F + \alpha_C \Delta T_S$

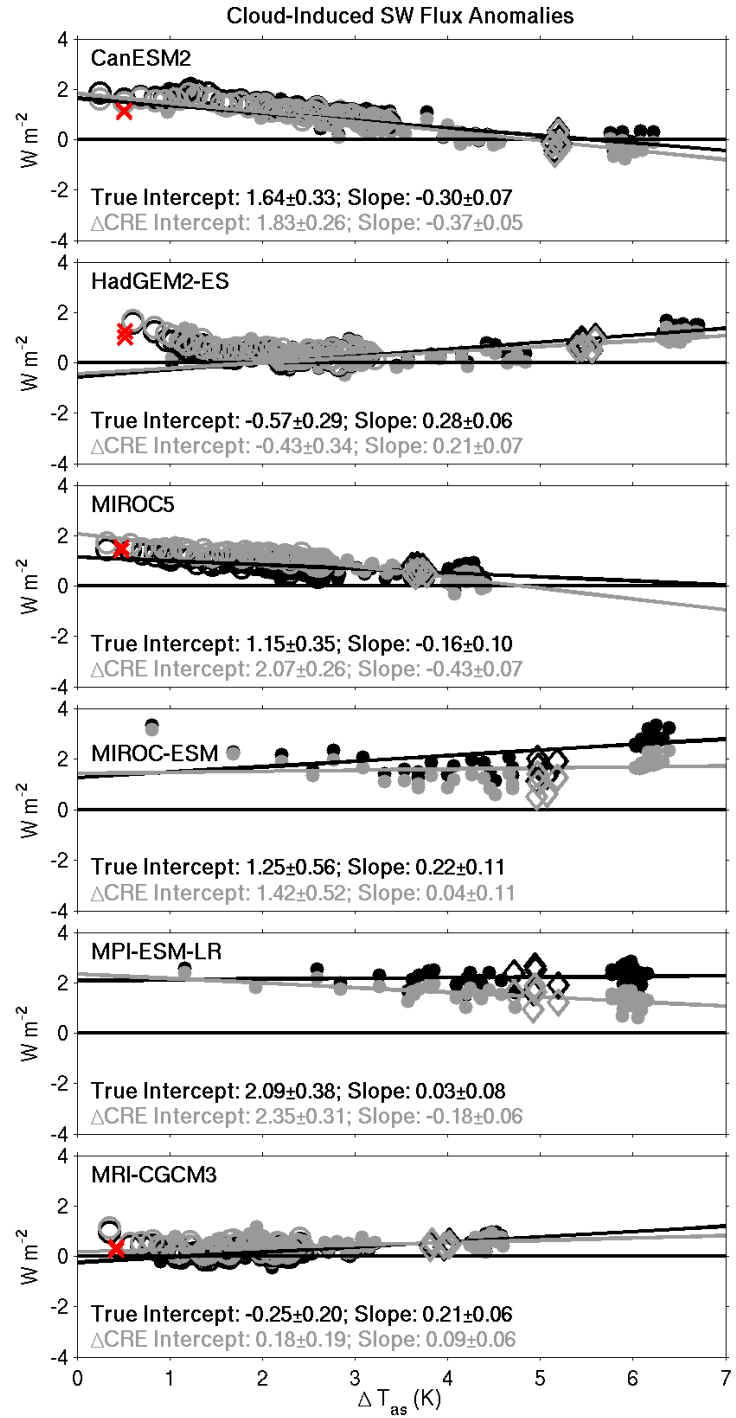
Black: Cloud-induced SW radiation anomalies ($\Delta R_C$)

Gray: SW cloud radiative effect (CRE) anomalies
(CRE = clear- minus all-sky upwelling TOA flux)

Red crosses: climatological SSTs but with 4x$CO_2$ imposed

Positive = heating

**These feedback estimates will be included in AR5**

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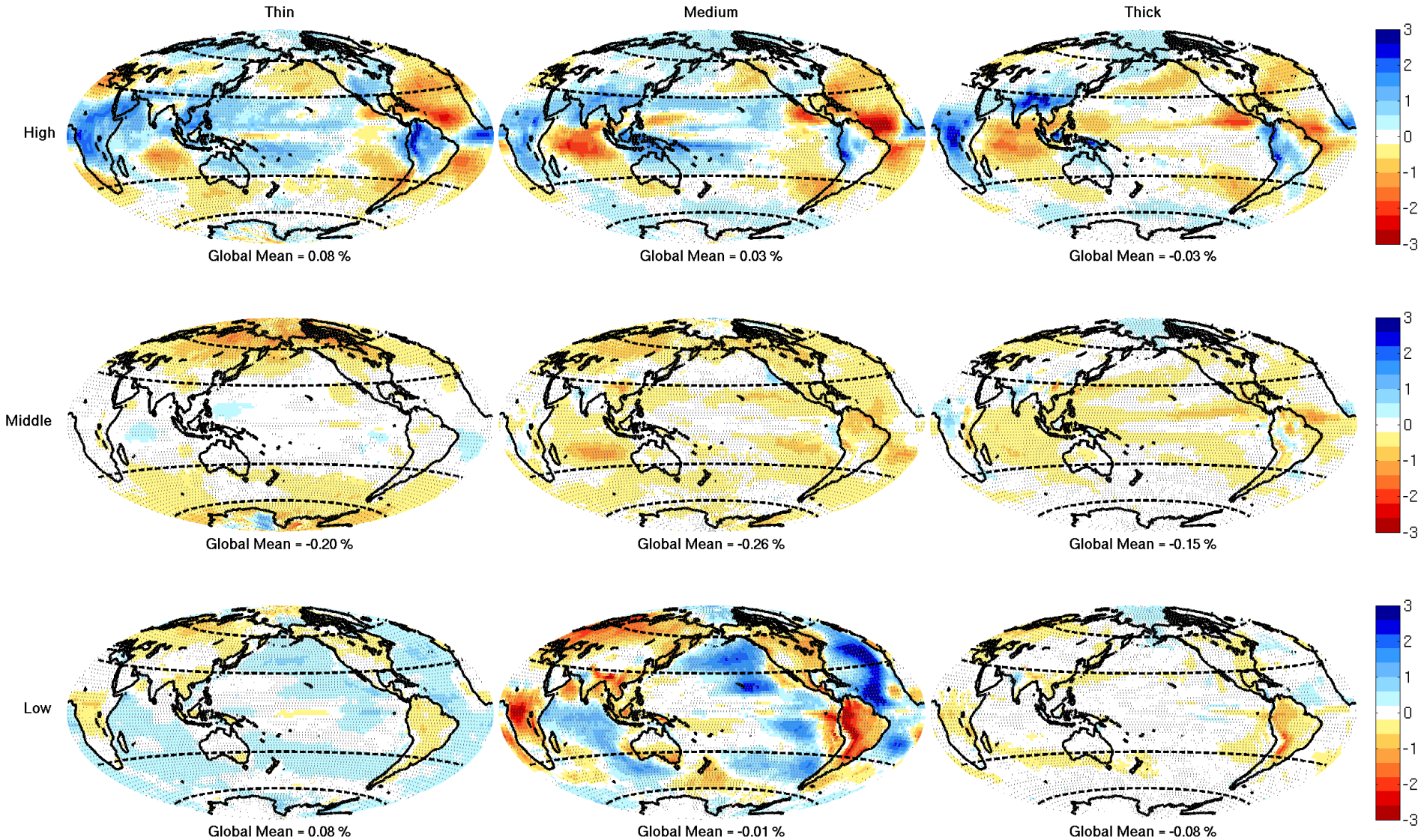
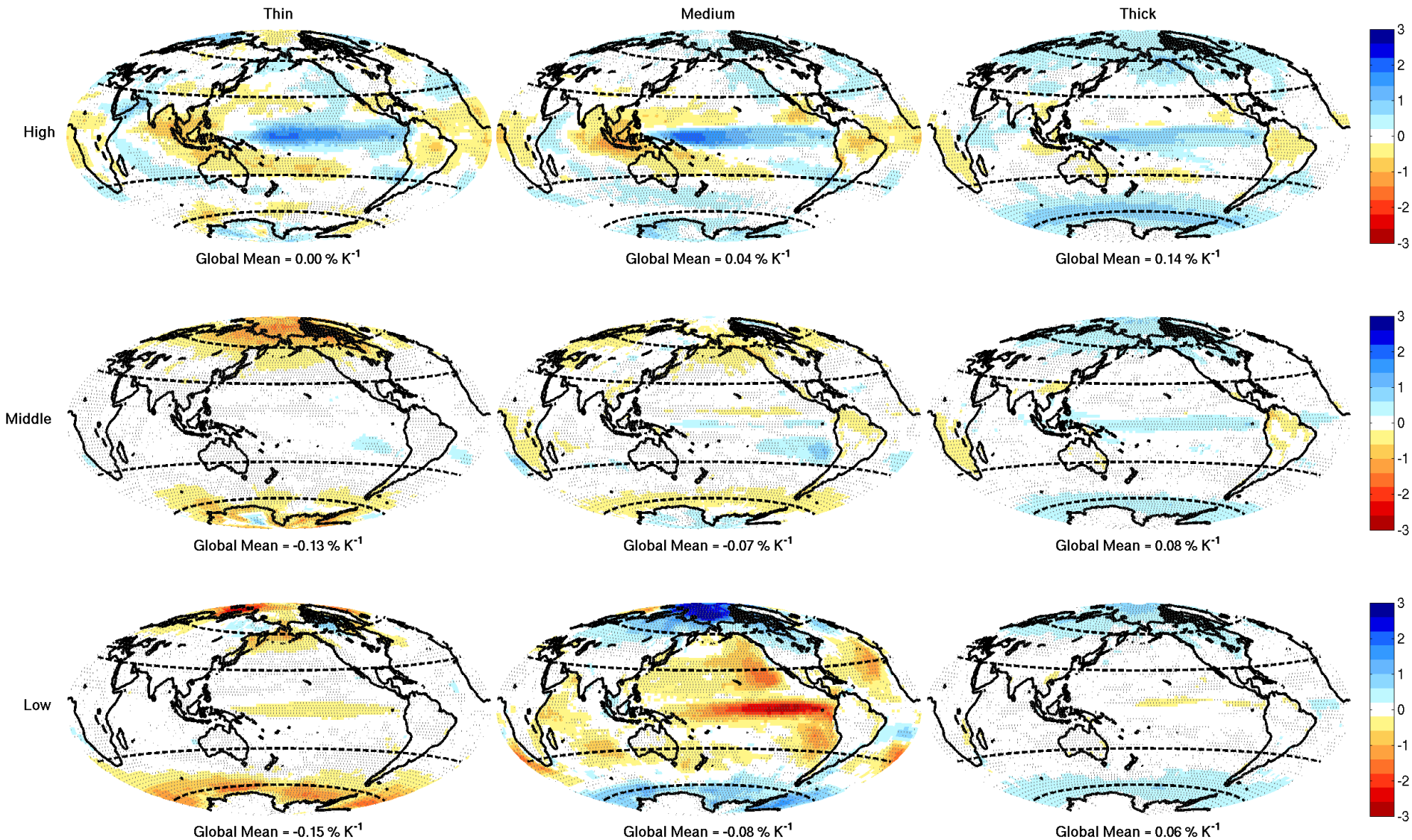
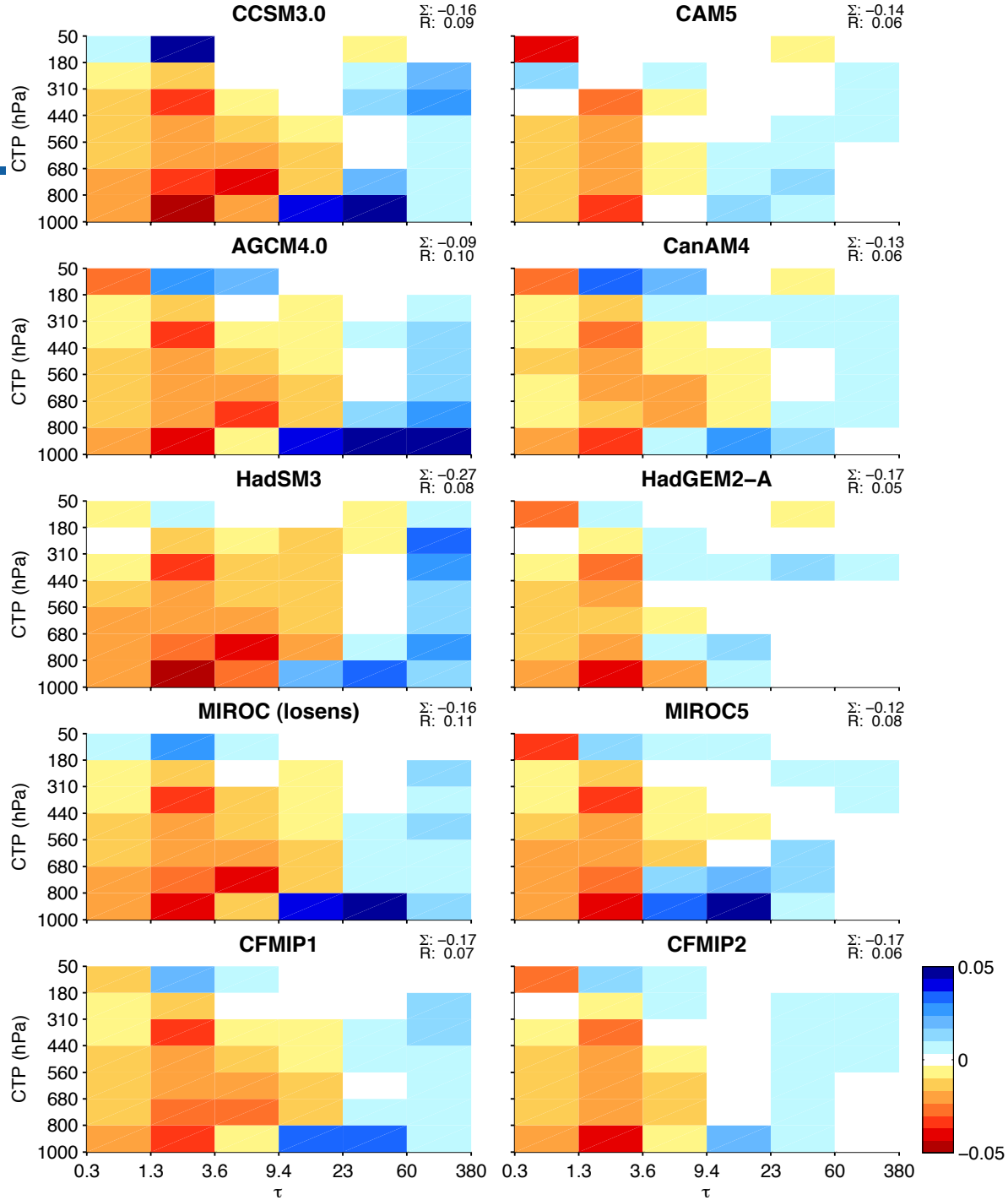
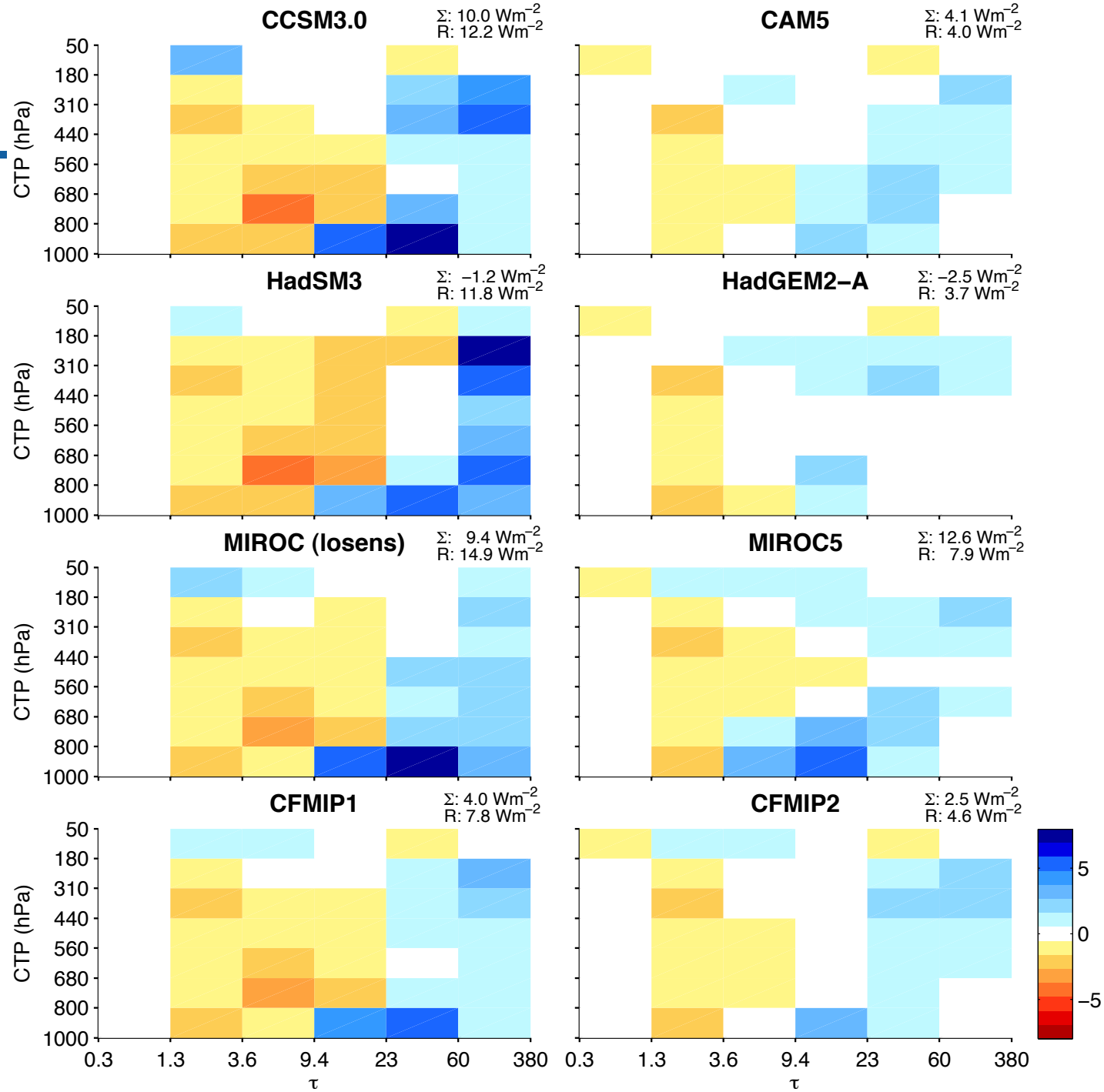
# Rapid Cloud Adjustments

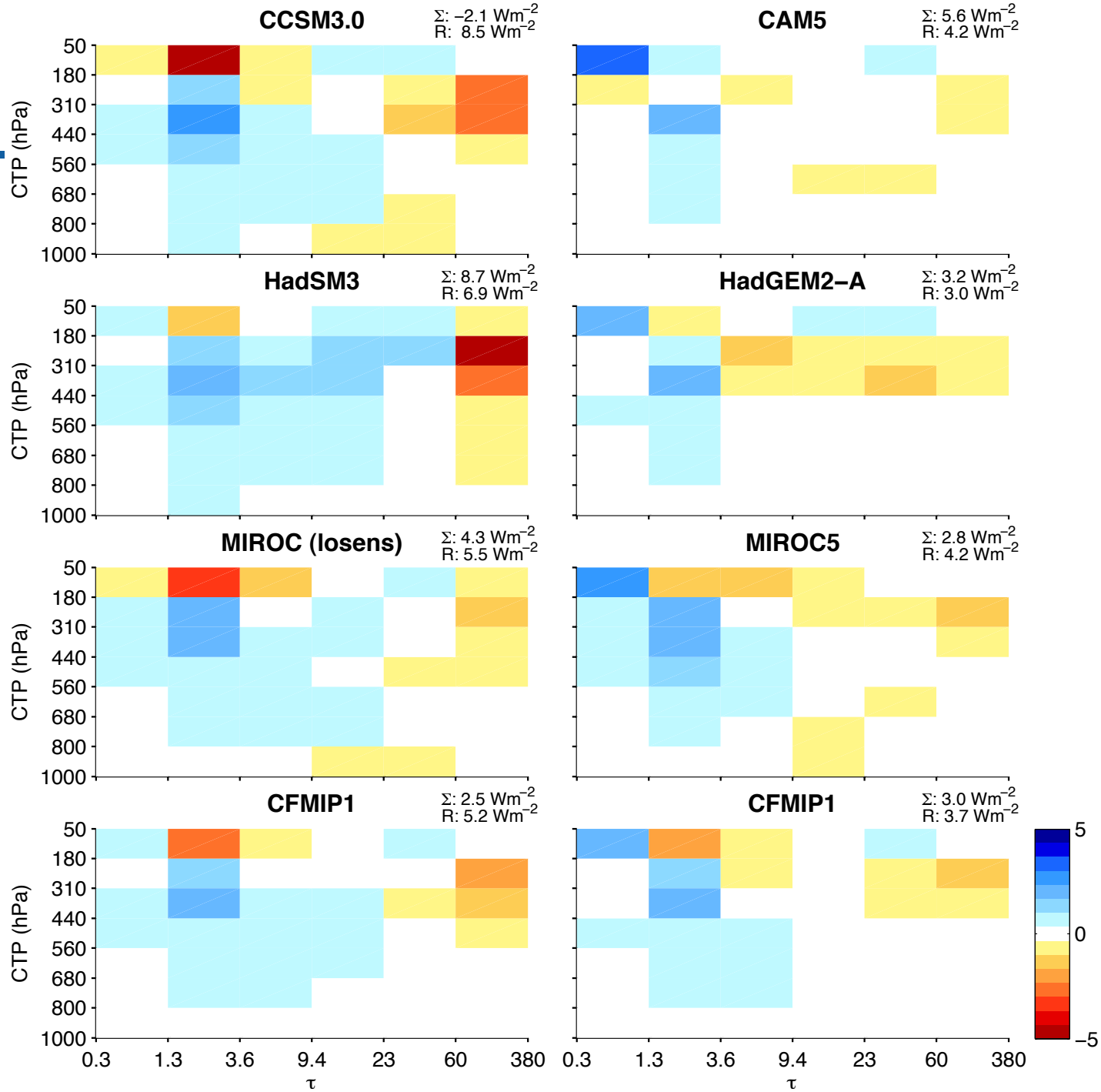


# $T_{sfc}$-Mediated Cloud Anomalies




CCSM3.0
Σ: −0.16
R: 0.09
CAM5
Σ: −0.14
R: 0.06
AGCM4.0
Σ: −0.09
R: 0.10
CanAM4
Σ: −0.13
R: 0.06
HadSM3
Σ: −0.27
R: 0.08
HadGEM2−A
Σ: −0.17
R: 0.05
MIROC (losens)
Σ: −0.16
R: 0.11
MIROC5
Σ: −0.12
R: 0.08
CFMIP1
Σ: −0.17
R: 0.07
CFMIP2
Σ: −0.17
R: 0.06
CTP (hPa)
50
180
310
440
560
680
800
1000
0.3
1.3
3.6
9.4
23
60
380
τ
0.05
0
−0.05


CCSM3.0
Σ: 10.0 Wm−2
R: 12.2 Wm−2
CAM5
Σ: 4.1 Wm−2
R: 4.0 Wm−2
HadSM3
Σ: −1.2 Wm−2
R: 11.8 Wm−2
HadGEM2−A
Σ: −2.5 Wm−2
R: 3.7 Wm−2
MIROC (losens)
Σ: 9.4 Wm−2
R: 14.9 Wm−2
MIROC5
Σ: 12.6 Wm−2
R: 7.9 Wm−2
CFMIP1
Σ: 4.0 Wm−2
R: 7.8 Wm−2
CFMIP2
Σ: 2.5 Wm−2
R: 4.6 Wm−2
CTP (hPa)
50
180
310
440
560
680
800
1000
0.3
1.3
3.6
9.4
23
60
380
τ
5
0
−5


CCSM3.0
Σ: −2.1 Wm−2
R: 8.5 Wm−2
CAM5
Σ: 5.6 Wm−2
R: 4.2 Wm−2
HadSM3
Σ: 8.7 Wm−2
R: 6.9 Wm−2
HadGEM2−A
Σ: 3.2 Wm−2
R: 3.0 Wm−2
MIROC (losens)
Σ: 4.3 Wm−2
R: 5.5 Wm−2
MIROC5
Σ: 2.8 Wm−2
R: 4.2 Wm−2
CFMIP1
Σ: 2.5 Wm−2
R: 5.2 Wm−2
CFMIP1
Σ: 3.0 Wm−2
R: 3.7 Wm−2
CTP (hPa)
50
180
310
440
560
680
800
1000
0.3
1.3
3.6
9.4
23
60
380
τ
5
0
−5