Climate Feedback Analysis of IPCC Global Warming Simulations

Christelle Castet and Ming Cai

Florida State University

Tallahassee, FL 32306

cai@met.fsu.edu

Ph.D thesis of Christelle Castet

Partial Radiative Perturbation Method

- **Forcing: a radiative flux perturbation at the TOA**
- **Response: surface temperature (or system temperature)**
- **Feedback: additional radiative flux perturbations at the TOA in response to surface temperature**

$$\Delta F^{TOA} = -(\Delta S_{TOA} - \Delta OLR_{TOA}) = -\frac{d(S_{TOA} - OLR_{TOA})}{dT_S}\Delta T_S$$
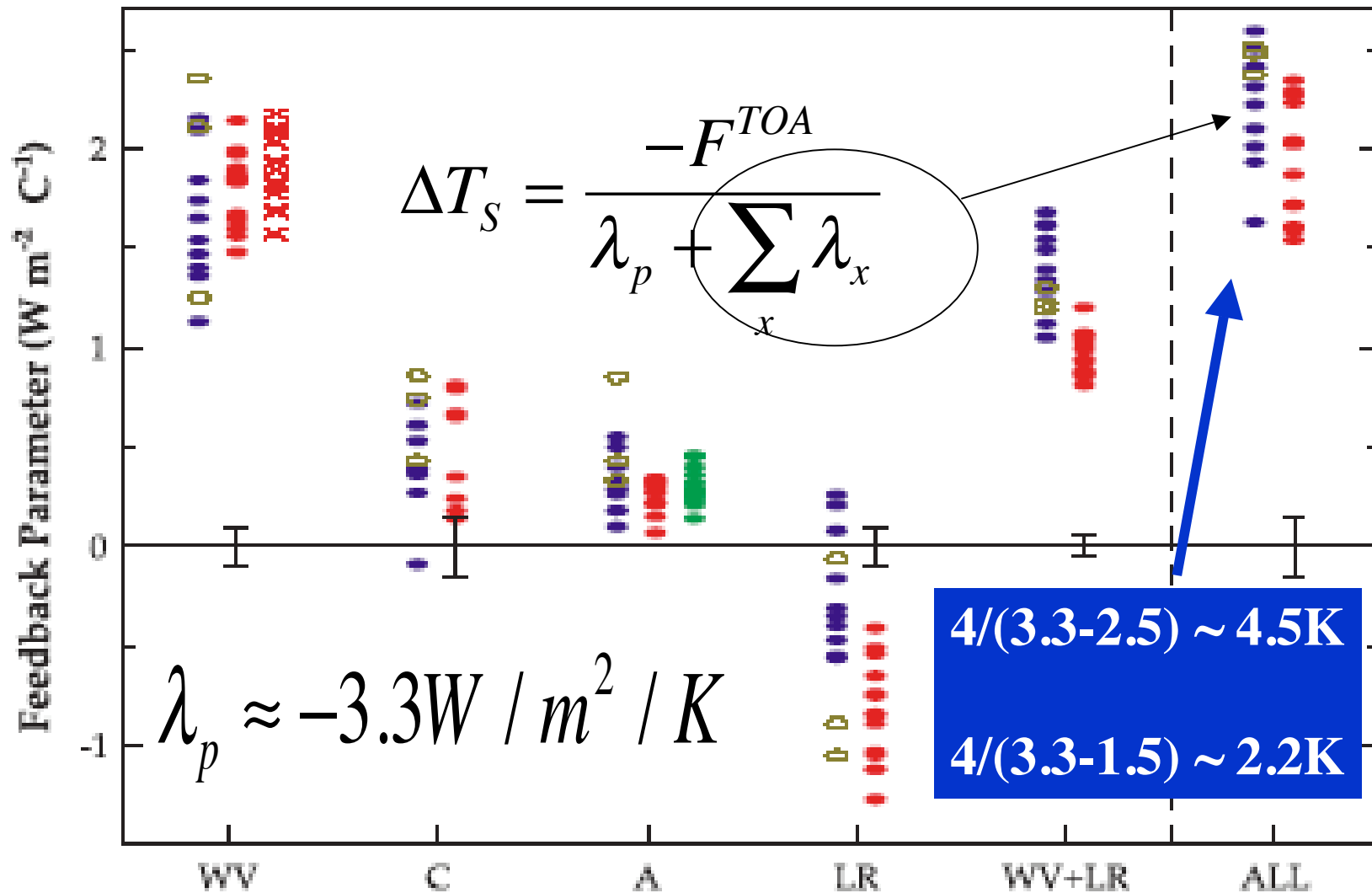
$$\lambda_{tot} = \frac{d(S_{TOA} - OLR_{TOA})}{dT_S}$$

$\lambda_{tot} < 0$: (Total) Feedback parameter

The warmer surface temp. is, the more energy outputs from the climate system

$$\Delta T_S = \frac{F^{TOA}}{-\lambda_{tot}} = \frac{G_0 F^{TOA}}{-(\lambda_P + \sum_x \lambda_x)}$$

Feedbacks are additive, but their effects are not!!

Application of PRP: Climate sensitivity and global warming projection uncertainties of IPCC AR4 models

$$\Delta T_S = \frac{-F^{TOA}}{\lambda_p + \sum_x \lambda_x}$$

$$\lambda_p \approx -3.3 \, W/m^2/K$$

$$4/(3.3-2.5) \sim 4.5K$$

$$4/(3.3-1.5) \sim 2.2K$$

Feedback Parameter (W m⁻² C⁻¹)

WV   C   A   LR   WV+LR   ALL

Feedback Type

Soden and Held (2006)

Main Limitations of PRP method

• Only radiative energy perturbations are considered => mainly applicable for the global mean temperature change.

• TOA-based analysis: does not **explicitly** include the thermodynamic/dynamic processes, such as evaporation and surface sensible heat fluxes.

• At regional scales, both radiative and <u>non-radiative energy</u> (due to changes in circulations) perturbations influence temperature changes. 4

Coupled Atmosphere-Surface Climate Feedback-Response Analysis Method (CFRAM) for CGCM feedback analysis

(Lu and Cai 2008; Cai and Lu (2008)

Unperturbed climate state

$$\underbrace{(\vec{S} - \vec{R})}_{net \text{ rad. cooling/heating}} +$$

$$\underbrace{\overline{\mathbf{Q}}^{conv} + \overline{\mathbf{Q}}^{turb} - \overline{\mathbf{D}}^{v} - \overline{\mathbf{D}}^{h} + \overline{\mathbf{W}}^{fric}}_{non-radiative \text{ dyn. heating/cooling}} = 0$$

Perturbation in response an external forcing

$$\underbrace{\Delta(\vec{S} - \vec{R})}_{change \text{ in } net \text{ rad. cooling/heating (F}^{ext} \text{ included)}}$$

$$+ \underbrace{\Delta\overline{\mathbf{Q}}^{conv} + \Delta\overline{\mathbf{Q}}^{turb} - \Delta\overline{\mathbf{D}}^{v} - \Delta\overline{\mathbf{D}}^{h} + \Delta\overline{\mathbf{W}}^{fric}}_{change \text{ in } non-radiative \text{ dyn. heating/cooling}} = 0$$

Mathematical formulation of CFRAM

$$\left(\frac{\partial \vec{R}}{\partial \vec{T}}\right) \Delta \vec{T}^{tot} = \{\Delta \vec{F}^{ext} + \underbrace{\Delta^{(\alpha)} \vec{S} + \Delta^{(c)}(\vec{S} - \vec{R}) + \Delta^{(w)}(\vec{S} - \vec{R})}_{non\_temp\_induced\_radiative\_energy}$$

$$+ \underbrace{\Delta \vec{Q}^{conv} + \Delta \vec{Q}^{turb} - \Delta \vec{D}^{v} - \Delta \vec{D}^{h} + \Delta \vec{W}^{fric}}_{non-radiative\_energy}\}$$

The radiation flux change only due to a change in the atmosphere-surface column temperature

=

Radiative energy input due to the external forcing

+

$$\left(\frac{\partial \vec{R}}{\partial \vec{T}}\right)$$ **Planck feedback matrix**

(**radiative** and **non-radiative**) **Energy flux perturbations that are not due to the radiation change associated with temperature changes and external forcing**

Mathematical formulation of CFRAM

$$\Delta \vec{\mathbf{T}}^{tot} = \left(\frac{\partial \overline{\mathbf{R}}}{\partial \overline{\mathbf{T}}}\right)^{-1} \{\Delta \vec{\mathbf{F}}^{ext} + \Delta^{(\alpha)}\vec{\mathbf{S}} + \Delta^{(c)}(\vec{\mathbf{S}} - \overline{\mathbf{R}}) + \Delta^{(w)}(\vec{\mathbf{S}} - \overline{\mathbf{R}})$$

$$+\Delta\overline{\mathbf{Q}}^{conv} + \Delta\overline{\mathbf{Q}}^{turb} - \Delta\overline{\mathbf{D}}^{v} - \Delta\overline{\mathbf{D}}^{h} + \Delta\overline{\mathbf{W}}^{fric}\}$$

RHS: external forcing plus energy flux perturbations due to each of (thermodynamic, local, and non-local dyn. feedbacks

$$\Delta \vec{\mathbf{T}}^{(n)} = \left(\frac{\partial \overline{\mathbf{R}}}{\partial \overline{\mathbf{T}}}\right)^{-1} \Delta \vec{\mathbf{F}}^{(n)}$$

$$\Delta \vec{\mathbf{T}}^{tot} = \sum_{n} \Delta \vec{\mathbf{T}}^{(n)}$$

Both feedbacks and their effects are are additive!

Application of CFRAM for feedback analysis of the GFDL-CM2.0 (slab-ocean model) global warming simulation.

$$\underbrace{\left(\frac{\partial \vec{R}}{\partial \vec{T}}\right)\Delta \vec{T} = \Delta^{(CO_2)}(\vec{S}-\vec{R}) + \Delta^{(h2o)}(\vec{S}-\vec{R}) + \underline{\Delta^{(\alpha)}\vec{S}}}_{Linearization\ of\ radiation\ transfer\ model} + \underline{\underline{\Delta(\vec{C}f+\vec{D}^{atmos-dyn})}} + (\Delta \vec{F}^{SH} + \Delta \vec{F}^{LH})$$

Linearization of radiation transfer model

$$\underline{\Delta^{(\alpha)}\vec{S}} = \vec{S}\Big|_{T_{1co_2},q_{1co_2},\textcolor{red}{\alpha_{2co_2}},1CO_2} - \vec{S}\Big|_{T_{1co_2},q_{1co_2},\textcolor{blue}{\alpha_{1co_2}},1CO_2} + \begin{pmatrix} 0 \\ \underbrace{-\Delta a(S^{\downarrow,cld}-S^{\downarrow})_{surf}} \end{pmatrix}$$

cloud forcing due to *surface* albedo change

$$\underline{\underline{\Delta(\vec{C}f+\vec{D}^{atmos-dyn})}} = -\left(\underbrace{(\vec{S}-\vec{R})\Big|_{T_{2CO_2},q_{2CO_2},\alpha_{2CO_2},2CO_2} - (\vec{S}-\vec{R})\Big|_{T_{1CO_2},q_{1CO_2},\alpha_{1CO_2},1CO_2}}_{\text{changes in total clear-sky radiation energy absorbed in each layer}} \right)$$

changes in total clear-sky radiation energy absorbed in each layer

$$+ \begin{pmatrix} 0 \\ \Delta a(S^{\downarrow,cld}-S^{\downarrow})_{surf} \end{pmatrix} - (\Delta \vec{F}^{(SH)} + \Delta \vec{F}^{(LH)})$$

# Errors in our offline clear-sky radiation calculations

- **sources of errors:**
  - **We use Fu-Liou 's radiation transfer model**
  - **Longtime averaging profiles of temperature and water vapors**
  - **Pressure level data (instead of native sigma-level)**

Table 1: Globally averaged CLEAR-SKY longwave (LW) and shortwave (SW) radiation flux at the surface and the TOA (unit: W/m^2).

	TOA	**TOA**	SURFACE	SURFACE	SURFACE
	Upward SW	Upward LW	Downward SW	Upward SW	Downward LW
GFDL_CM2.0	53.55	259.98	246.23	31.07	314.45
FL_RAD	61.77	272.75	238.59	30.57	301.05

- **Underestimates of water vapor greenhouse effects by less than 10%, consistent with Soden and Held (2006)'s findings**
- **The errors might not affect numerical accuracy of our feedback analysis but may lead to uncertainties in physical interpretations**

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"Accuracy" of linearization of radiation model

a)

b)
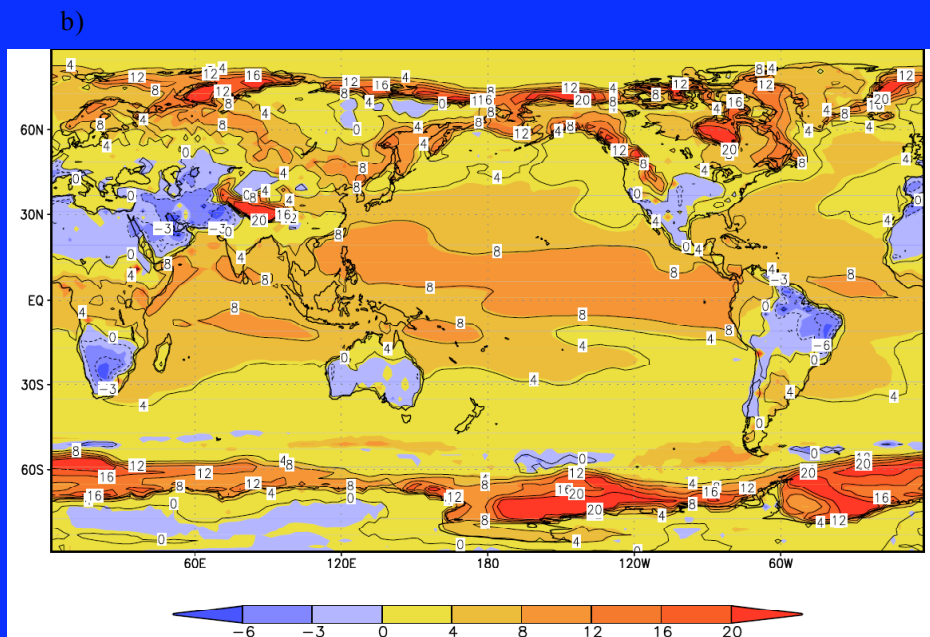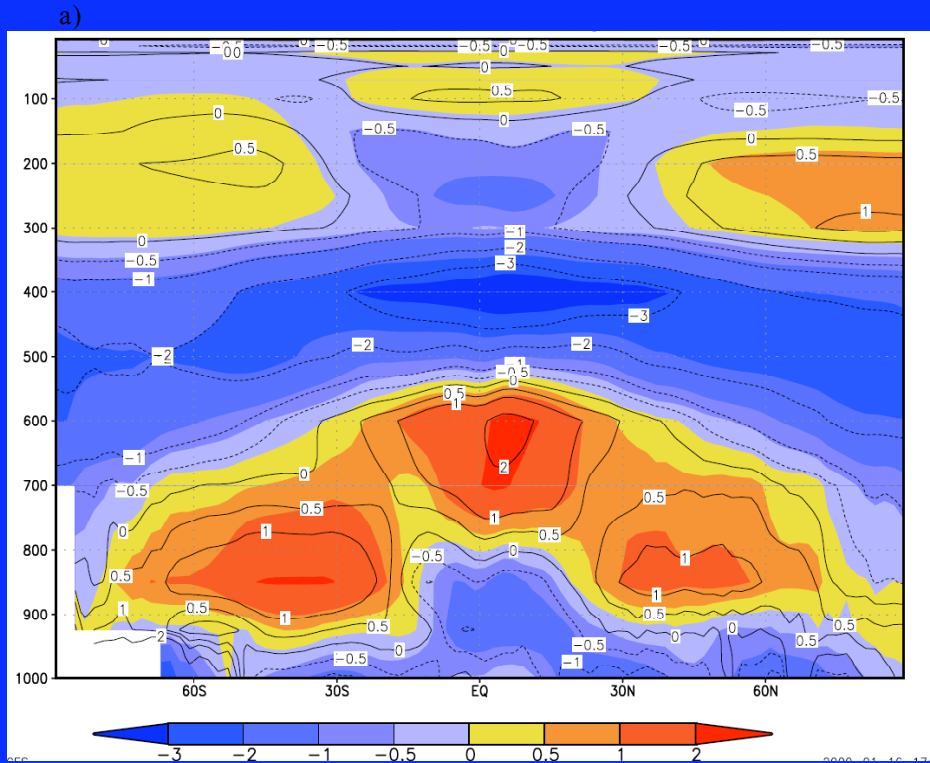
$$\Delta^{(total)}(\vec{S} - \vec{R})$$
$$(shadings)$$

$$versus$$

$$\Delta^{(CO_2)}(\vec{S} - \vec{R}) + \Delta^{(h2o)}(\vec{S} - \vec{R})$$

$$+\underline{\Delta^{(\alpha)}\vec{S}} - \left(\frac{\partial \vec{R}}{\partial \vec{T}}\right)\Delta \vec{T}$$

$$(contours)$$

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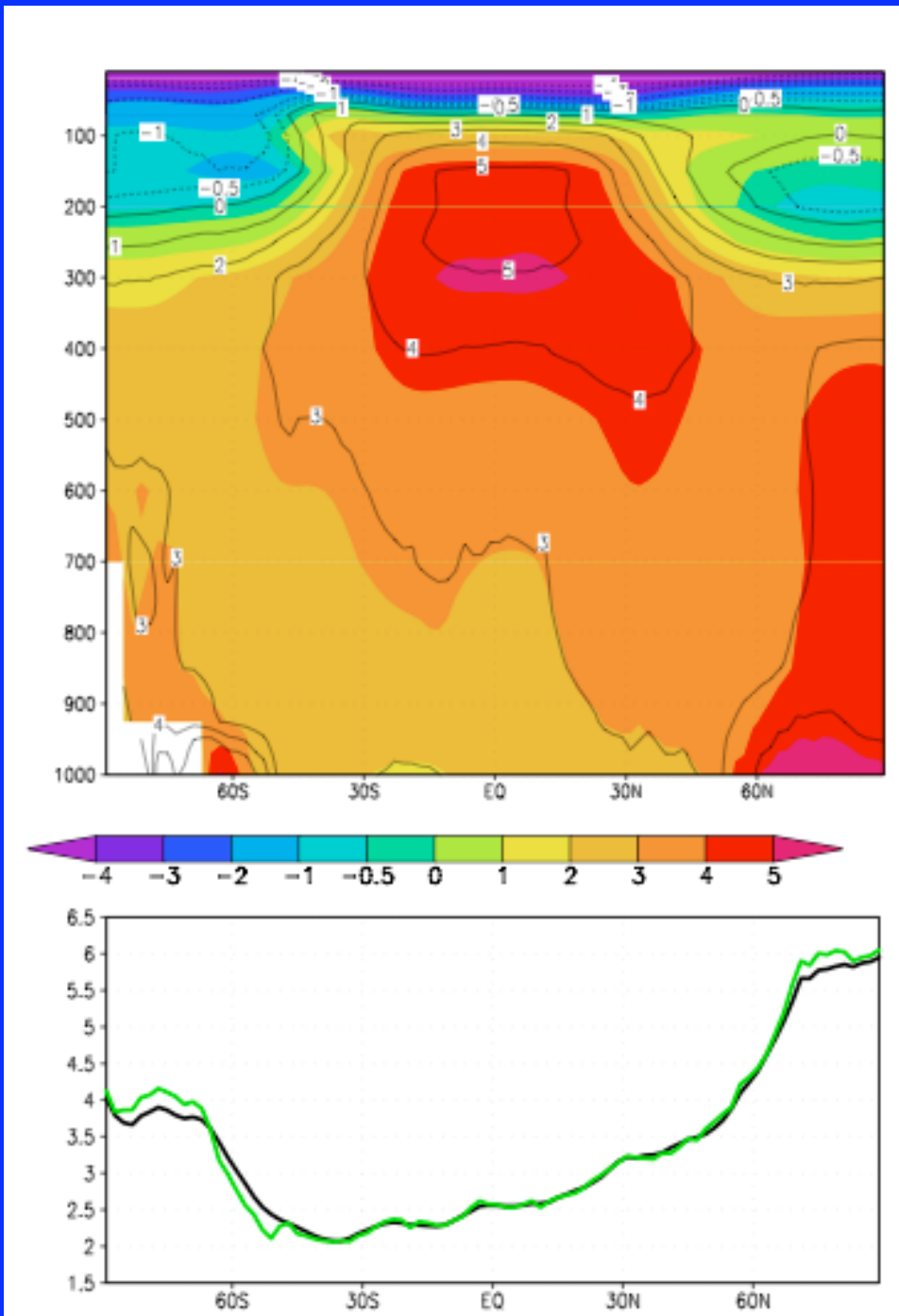Changes in cloud forcing at surface inferred from clear-sky radiation
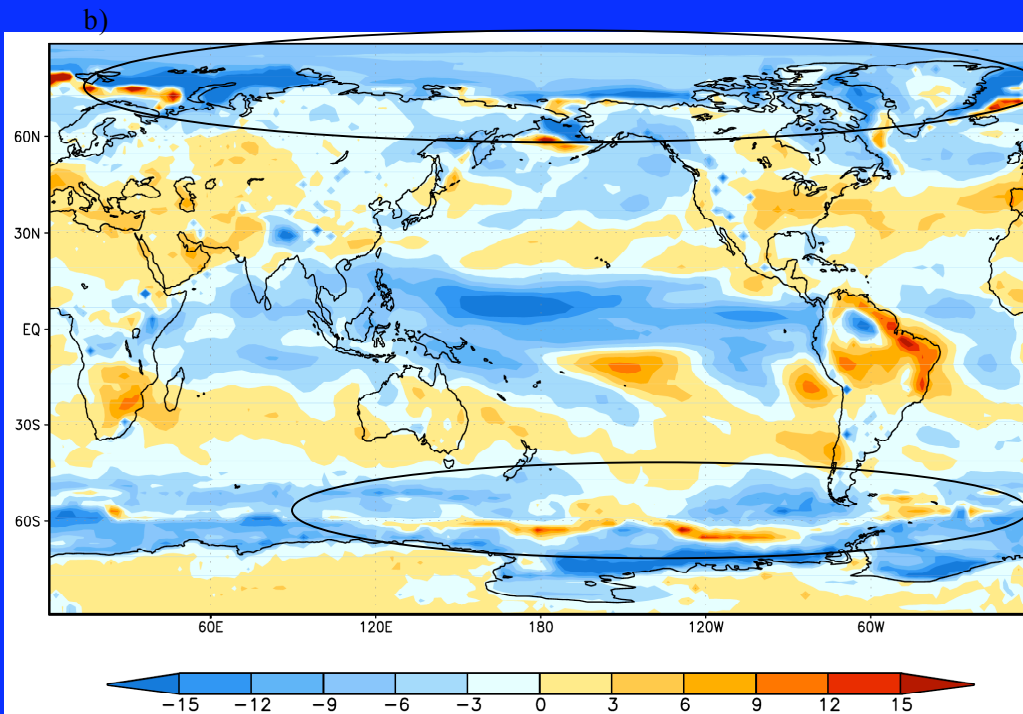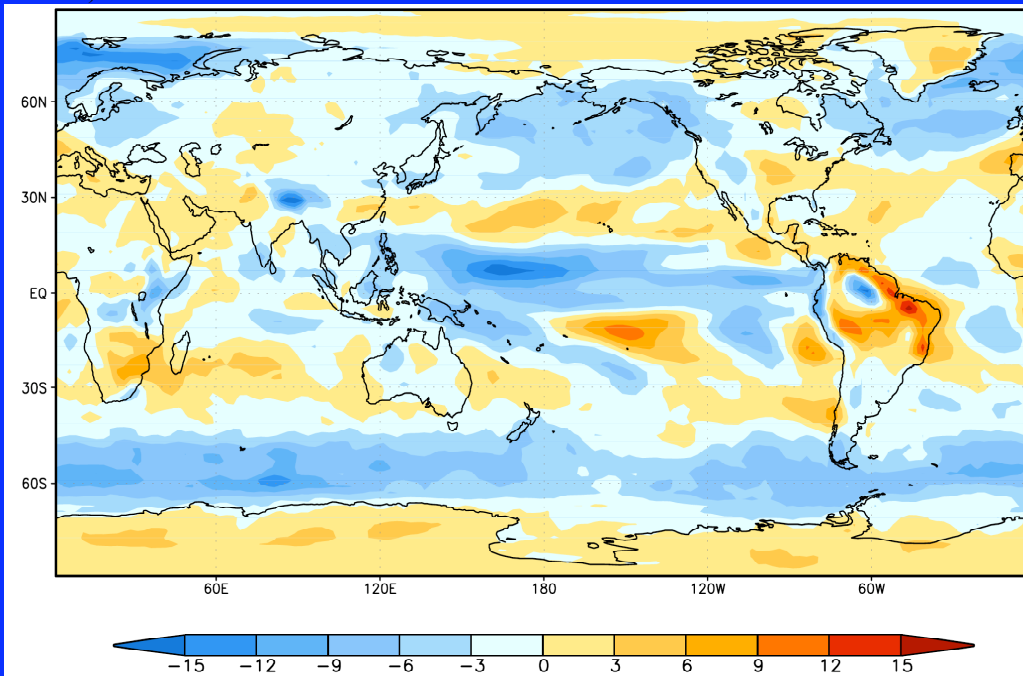
Change in cloud forcing at surface inferred from our clear-sky radiation calculations

$$-\Delta^{total}(S-R)_{surface}$$

$$+\Delta\alpha(S^{\downarrow,cld} - S^{\downarrow})^{1CO_2}_{surface}$$

$$-\Delta SH - \Delta LH$$

Change in cloud forcing at surface derived from original GFDL model outputs

$$(1 - a_{1co2})\Delta(S^{\downarrow,cld} - S^{\downarrow})$$

$$+\Delta(R^{\downarrow,cld} - R^{\downarrow})_{surface}$$

Validation of the accuracy of CFRAM feedback analysis

Shadings for the atmosphere and black curve for surface are obtained from the original GFDL model outputs

Contours for the atmosphere and green curve for surface are derived from the sum of the partial temperature changes calculated with CFRAM
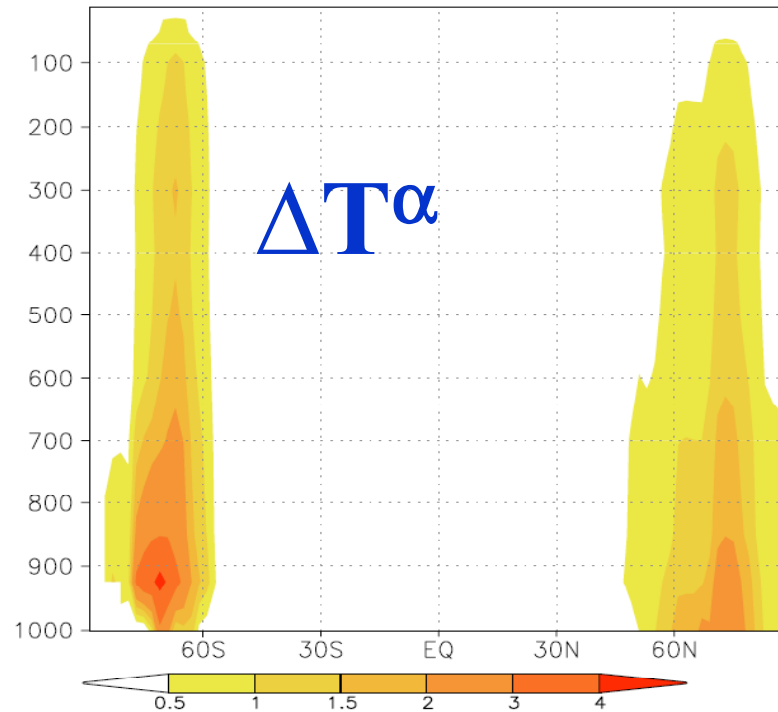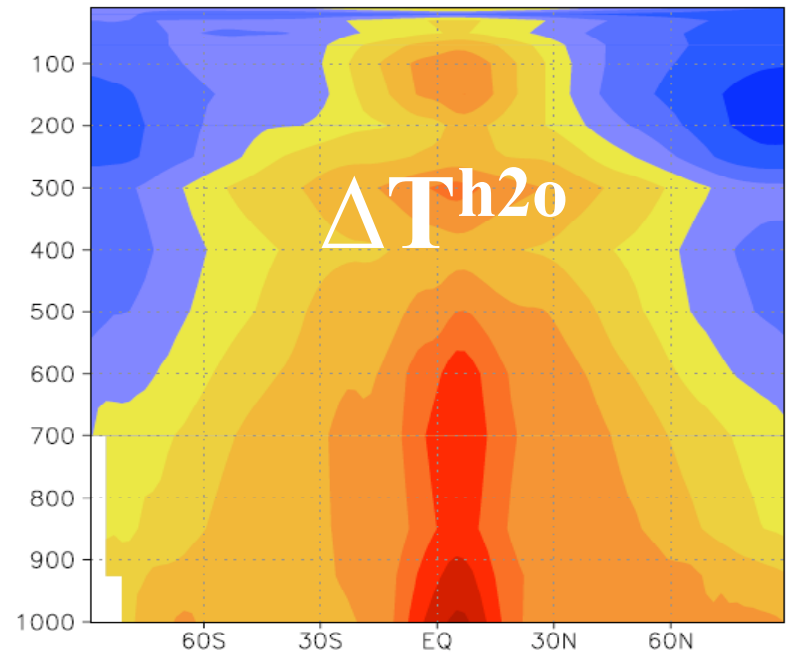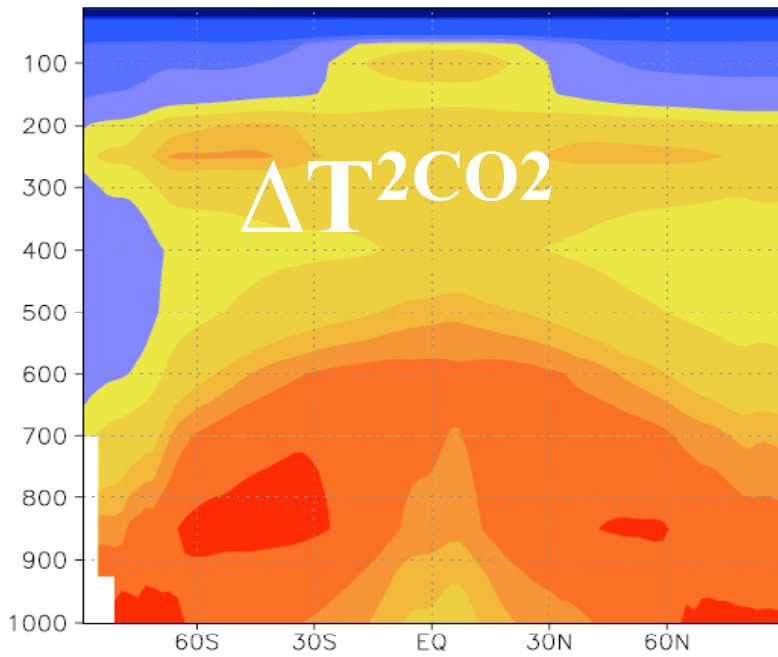
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Validation of the accuracy of CFRAM feedback analysis

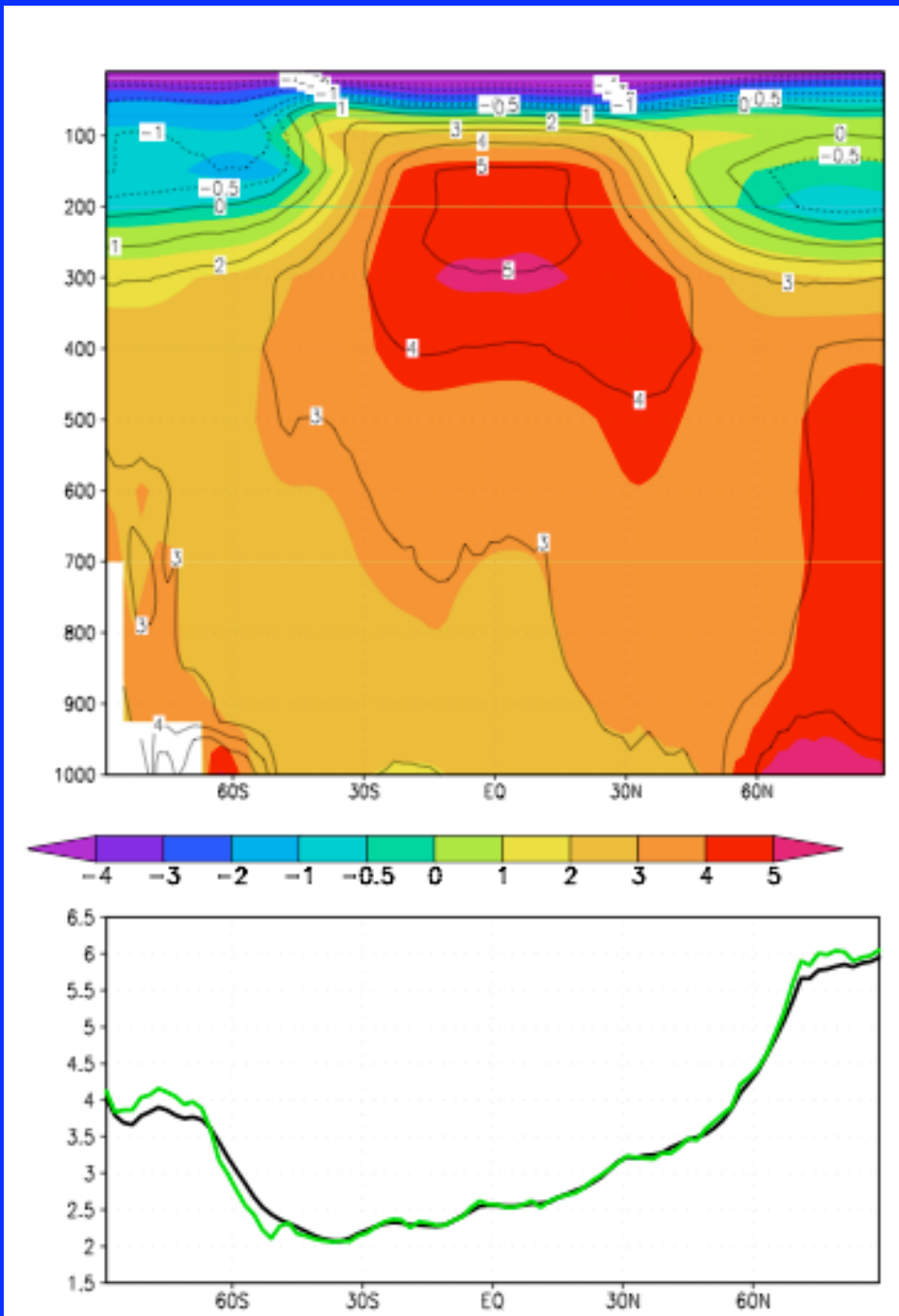$<\Delta T^{total}>=2.84K$

$<\Delta T^{sum}>=2.75K$

Surface temp. change obtained from the original GFDL model outputs

Surface temperature change derived from the sum of the partial temperature changes calculated with CFRAM 13

Atmospheric Warming Decomposition using CFRAM
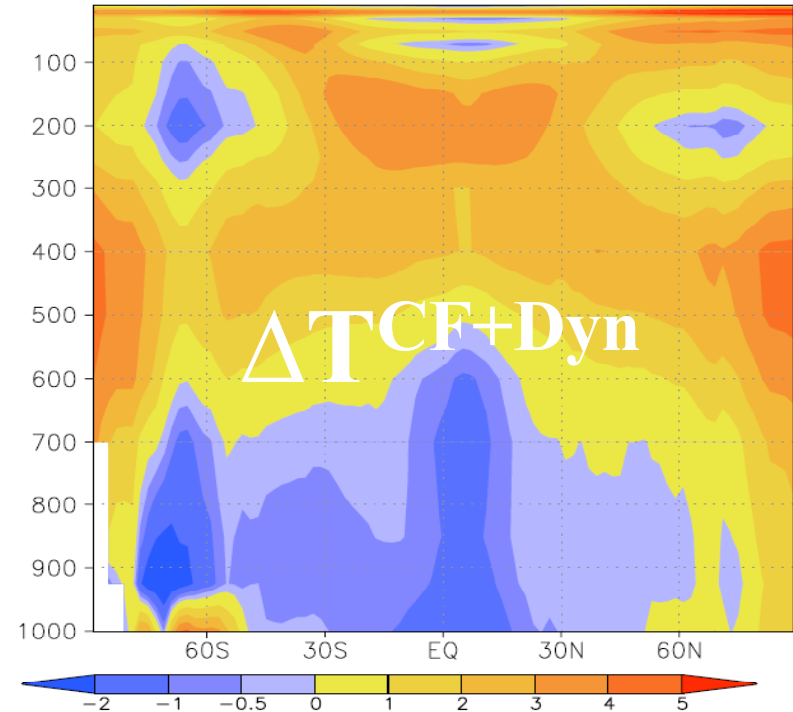
ΔT^{2CO2}

ΔT^{h2o}

ΔT^{α}

ΔT^{CF+Dyn}

Validation of the accuracy of CFRAM feedback analysis

Shadings for the atmosphere and black curve for surface are obtained from the original GFDL model outputs

Contours for the atmosphere and green curve for surface are derived from the sum of the partial temperature changes calculated with CFRAM
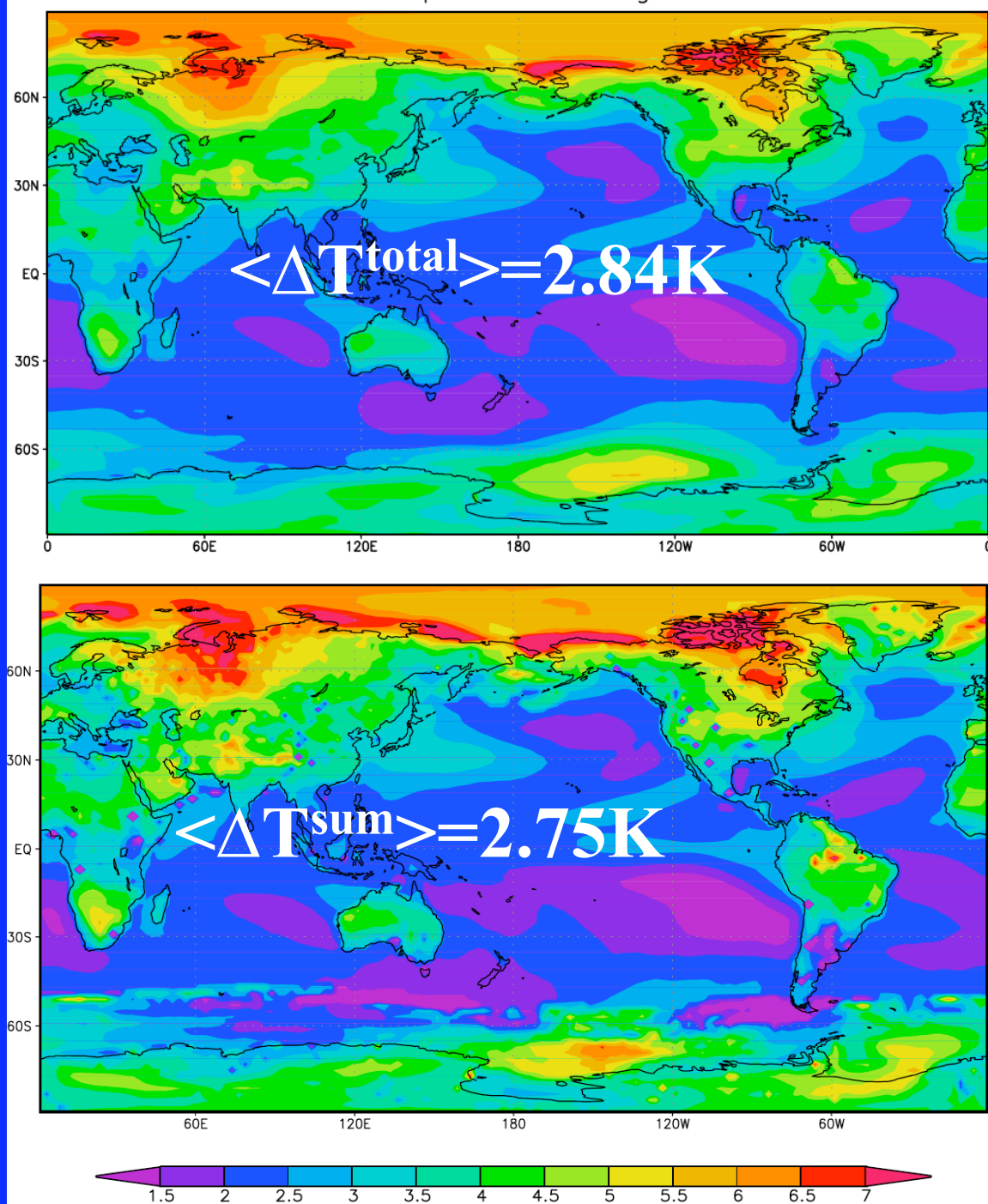
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Surface Warming Decomposition
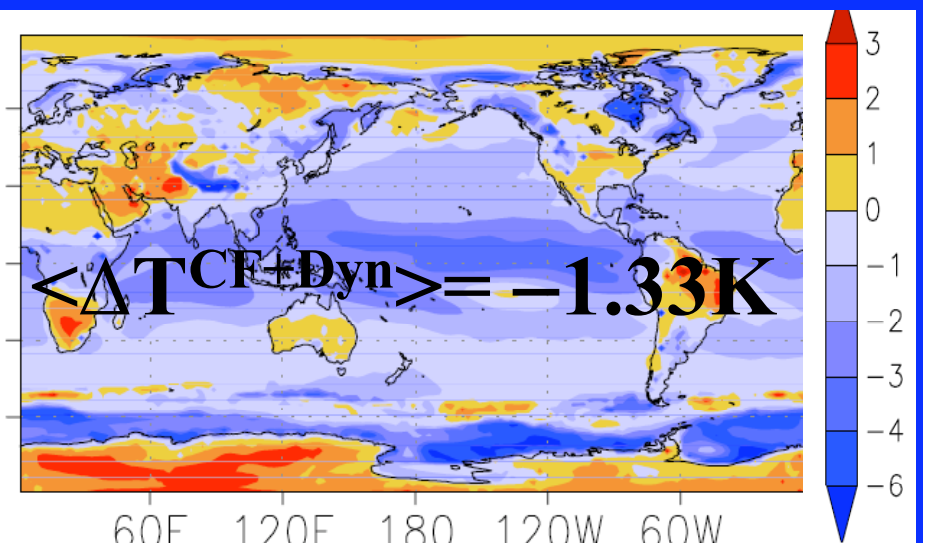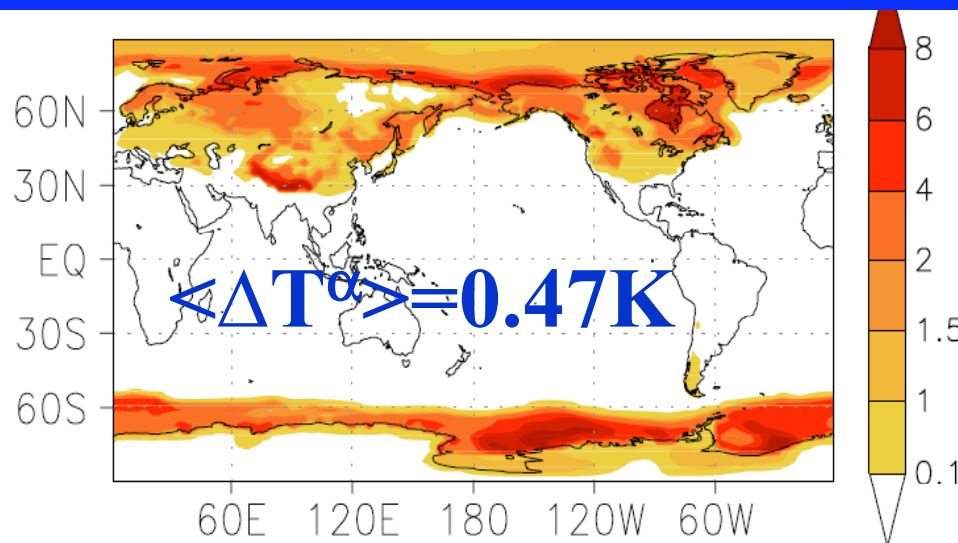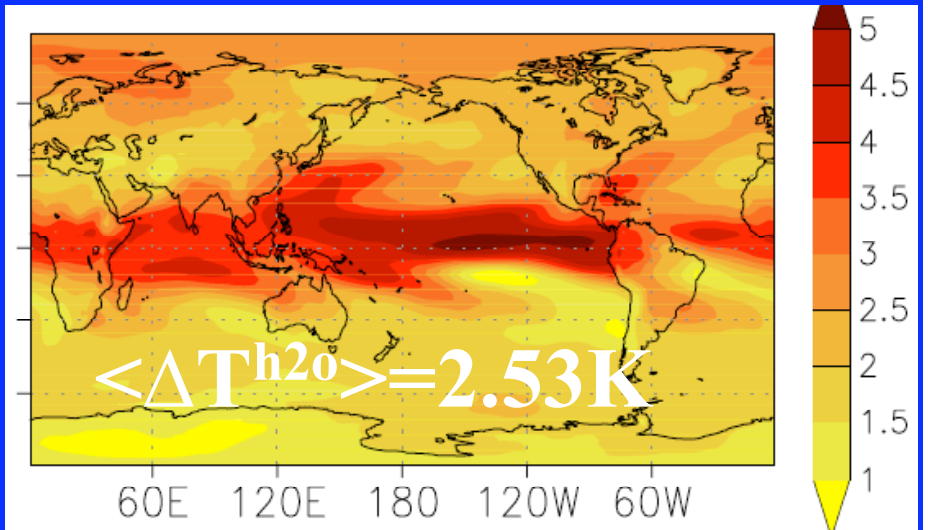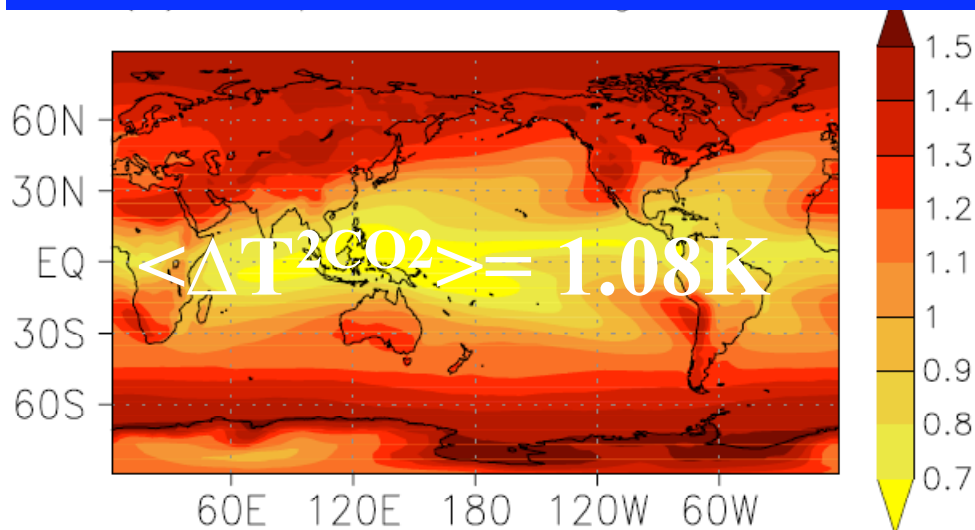
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Surface temperature change derived from the sum of the partial temperature changes calculated with CFRAM

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Summary

- **We applied CFRAM to calculate 3D warming patterns due to external forcing and due to feedbacks in GFDL model.**
- **Sum of partial temp. changes is very close to the total temp. change**
- **Change in cloud forcing can be estimated from changes in clear-sky radiation provided that the changes in non-radiative dynamical energy fluxes are diagnosed during model integrations.**
- **The linearization of radiation transfer model is a good approximation for global warming climate feedback analysis.**
- **In the upper troposphere, both external forcing and water vapor feedbacks are stronger in tropics.**
- **At surface, external forcing (water-vapor feedbacks) causes strong warming in high (low) latitudes**
- **Vertical convection feedbacks amplify warming in the upper troposphere in the tropics.**
- **Dynamical (and cloud forcing) feedbacks amplify warming in high latitudes both at surface and in the troposphere.**
- **Surface albedo feedback amplifies polar warming most strongly.**