Quantifying Contributions to Global Warming Pattern in NCAR CCSM4 Climate Model

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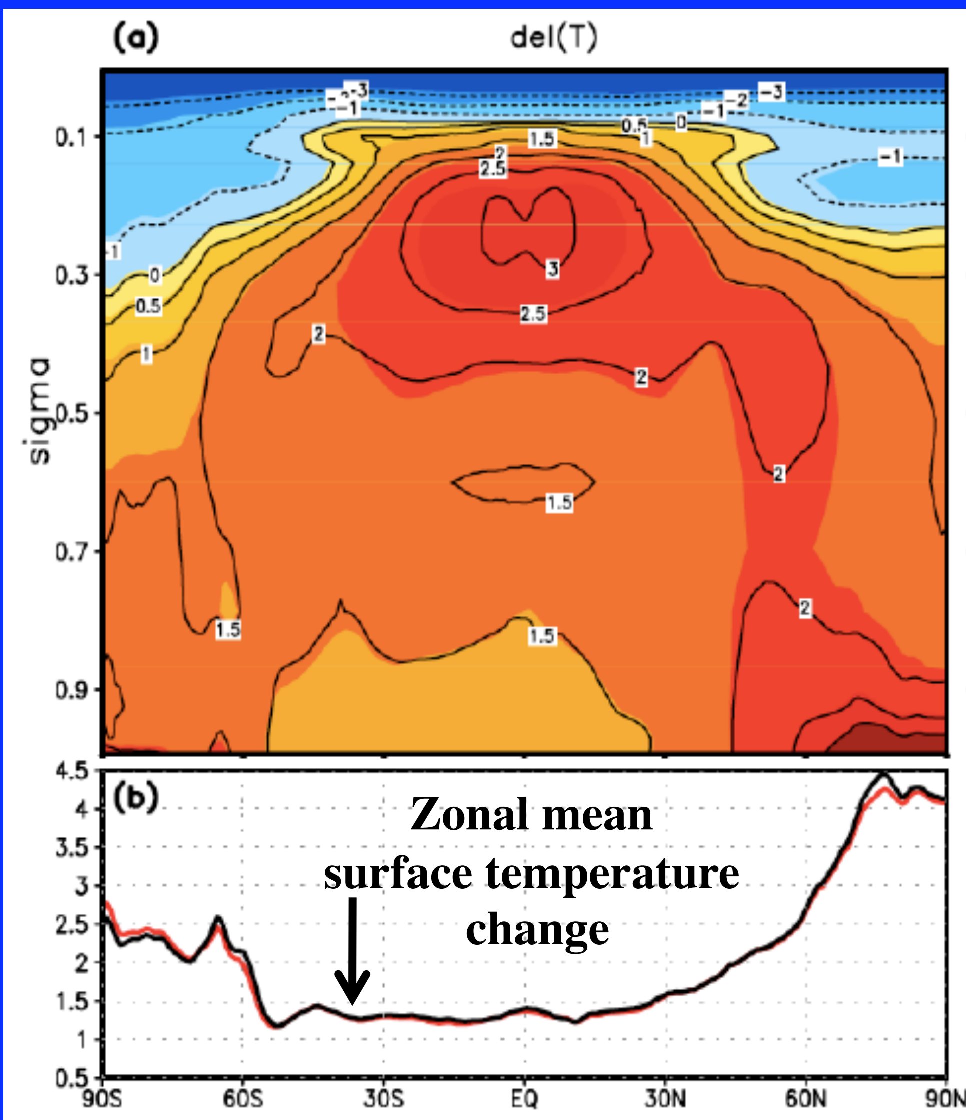
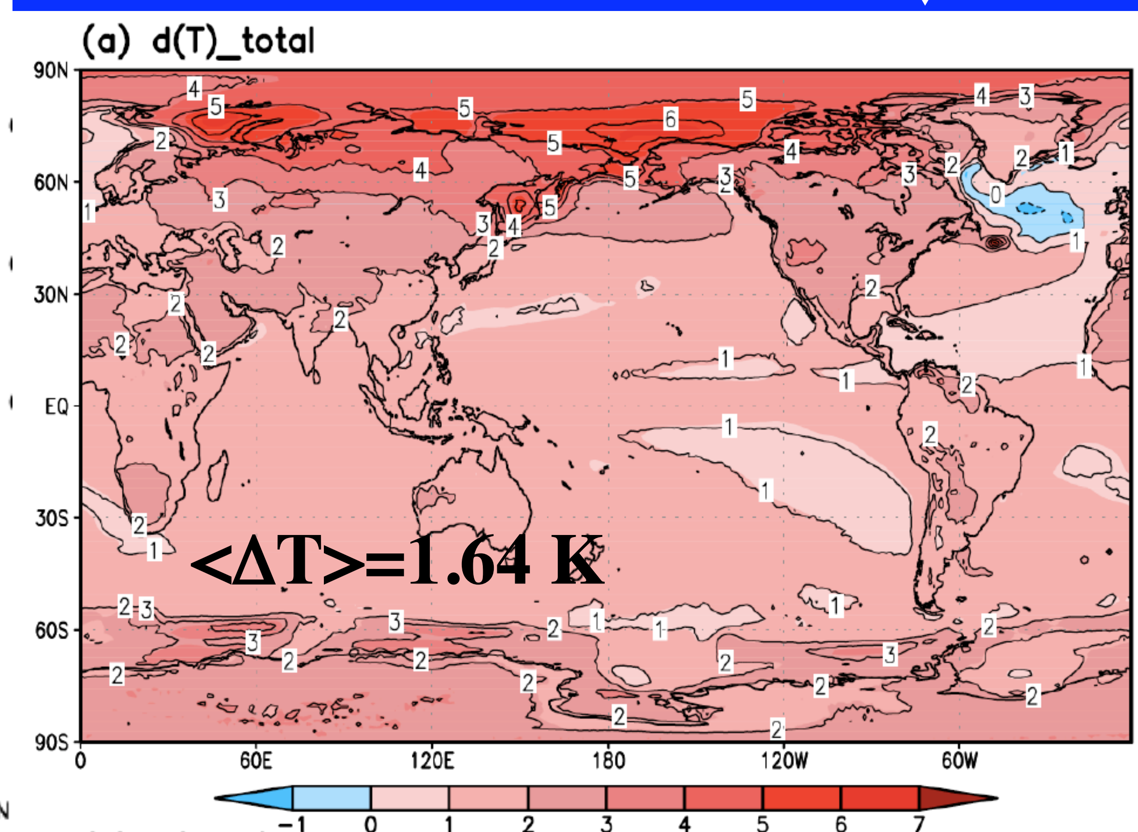
Temperature Response to $2xCO_2$ Forcing in NCAR CCSM4 Climate Simulations

(at the time of doubling of CO_2 from its pre-industry level 284.7 PPM)



Zonal mean air temperature change ←

surface ↓



Questions

- **How much warming is just due to the doubling of CO_2 alone?**
- **What are the additional temperature changes due to various radiative and non-radiative feedback processes?**
- **What are their contributions to the final warming pattern?**

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

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

Unperturbed climate state

$$\underbrace{(\vec{\mathbf{S}} - \vec{\mathbf{R}})}_{\textit{net}\ \text{rad. cooling/heating}} + \underbrace{\vec{\mathbf{Q}}}_{\textit{non-radiative}\ \text{dyn. heating/cooling}} = \frac{\partial \vec{E}}{\partial t}$$

Perturbation in response an external forcing

$$\underbrace{\Delta(\vec{\mathbf{S}} - \vec{\mathbf{R}})}_{\textit{change}\ \text{in}\ \textit{net}\ \text{rad. cooling/heating}\ (\text{F}^{2CO_2}\ \text{included})} + \underbrace{\Delta\vec{\mathbf{Q}}}_{\textit{change}\ \text{in}\ \textit{non-radiative}\ \text{dyn. heating/cooling}} = \underbrace{\Delta\vec{E}}_{\textit{Heat Storage}}$$

Mathematical formulation of CFRAM

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

$$+ \underbrace{\Delta\vec{\mathbf{Q}}}_{non-radiative\_energy} - \underbrace{\Delta\vec{E}}_{Heat\ \ Storage}\}$$

The radiation flux change only due to a change in the atmosphere-surface column temperature = **Radiative energy input due to the external forcing** +

Radiative and non-radiative energy flux perturbations that are not due to the radiation change associated with temperature changes and external forcing

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

Mathematical formulation of CFRAM

$$\Delta \vec{\overline{\mathbf{T}}}^{tot} = \left(\frac{\partial \vec{\overline{\mathbf{R}}}}{\partial \vec{\overline{\mathbf{T}}}} \right)^{-1} \{ \vec{\overline{\mathbf{F}}}^{2CO_2} + \Delta^{(\alpha)} \vec{\overline{\mathbf{S}}} + \Delta^{(c)} (\vec{\overline{\mathbf{S}}} - \vec{\overline{\mathbf{R}}}) + \Delta^{(w)} (\vec{\overline{\mathbf{S}}} - \vec{\overline{\mathbf{R}}}) + \Delta \vec{\overline{\mathbf{Q}}} - \Delta \vec{E} \}$$

$$-\Delta^{total} (\vec{S} - \vec{R}) = \Delta \vec{\overline{\mathbf{Q}}} - \Delta \vec{E} = \Delta \vec{\overline{\mathbf{Q}}}^{evaporation} + \Delta \vec{\overline{\mathbf{Q}}}^{surface\_sensibl\_heat+flux} + (\Delta \vec{\overline{\mathbf{Q}}}^{convection} + \Delta \vec{\overline{\mathbf{Q}}}^{ATM\_\lg\_dyn}) + \Delta \vec{\overline{\mathbf{Q}}}^{OCN\_dyn+storage}$$

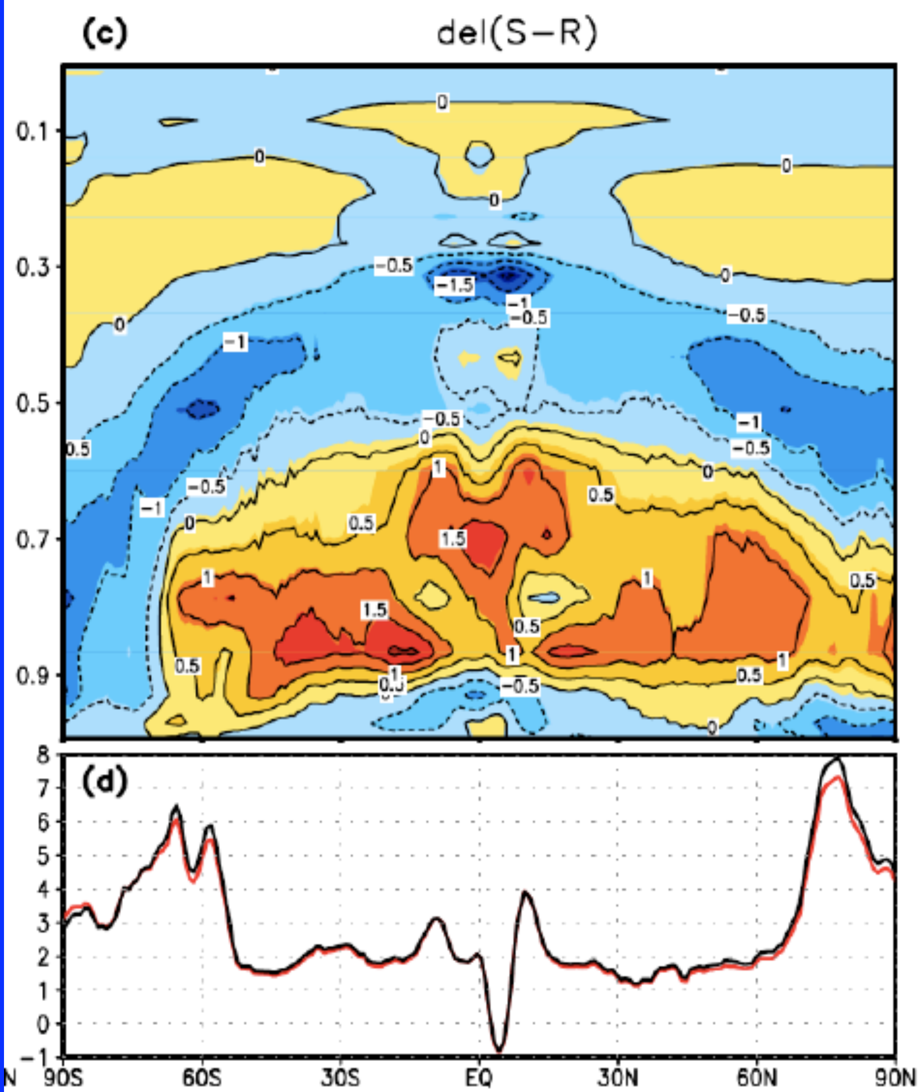
$$\Delta \vec{\overline{\mathbf{T}}}^{(n)} = \left(\frac{\partial \vec{\overline{\mathbf{R}}}}{\partial \vec{\overline{\mathbf{T}}}} \right)^{-1} \Delta \vec{\overline{\mathbf{F}}}^{(n)}$$

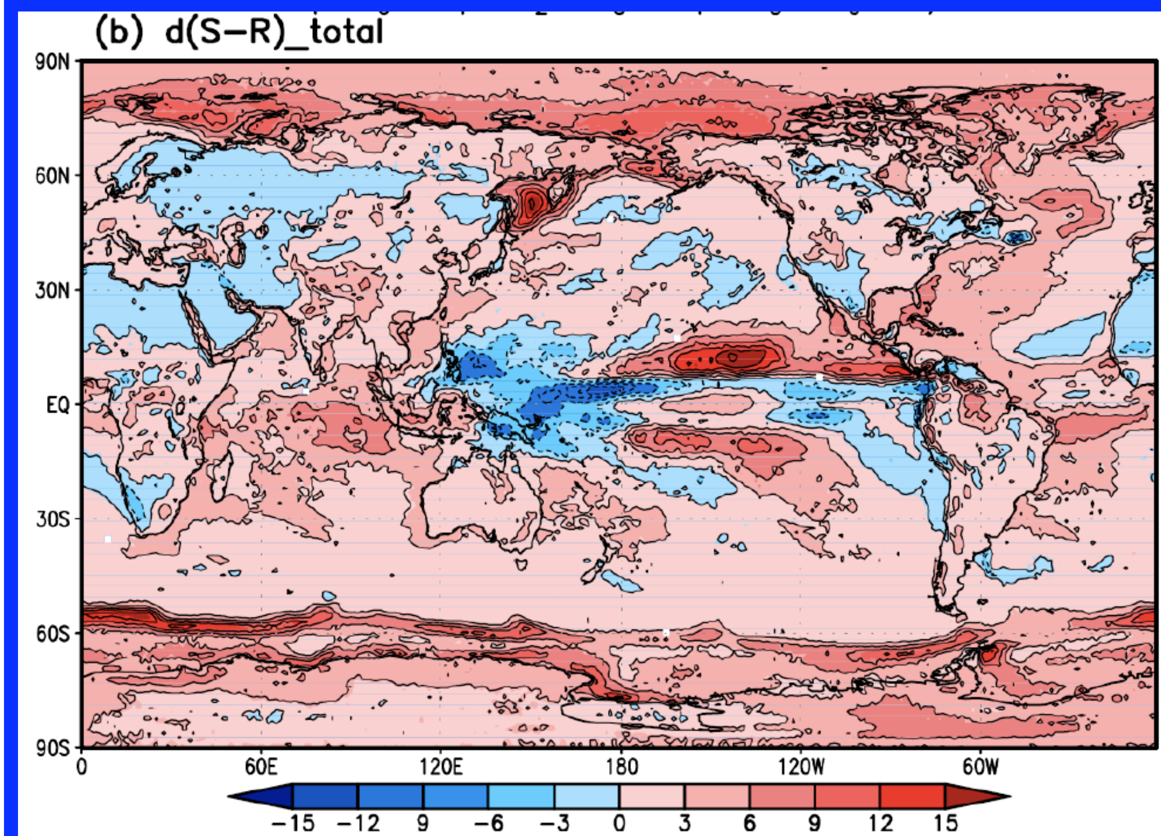
$$\Delta \vec{\overline{\mathbf{T}}}^{tot} = \sum_n \Delta \vec{\overline{\mathbf{T}}}^{(n)}$$

Both feedbacks and their effects are additive!

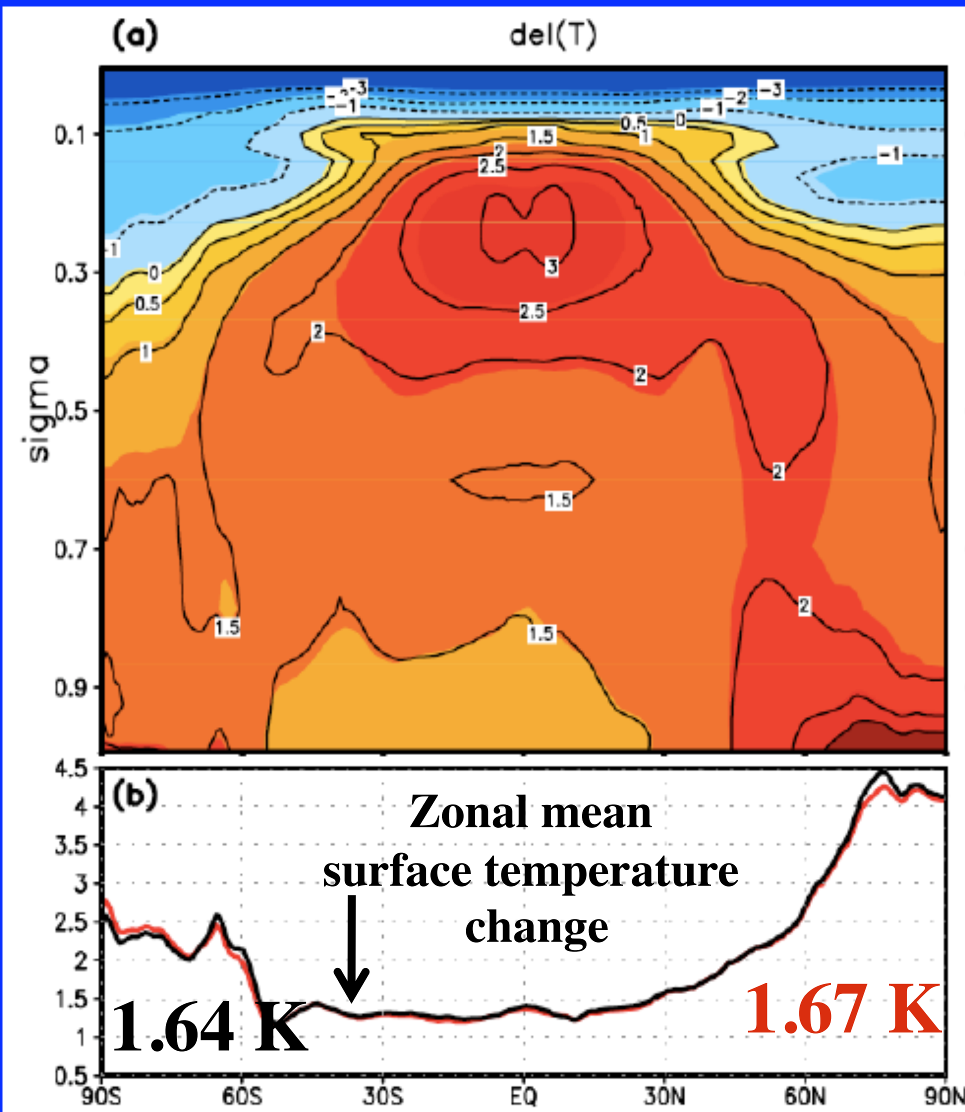
Validation of Linearization

$$\underbrace{\Delta^{(tot)}(\vec{\mathbf{S}}-\vec{\mathbf{R}})}_{\textit{Shadings}} \simeq \underbrace{\vec{\mathbf{F}}^{2CO_2} + \Delta^{(\alpha)}\vec{\mathbf{S}} + \Delta^{(c)}(\vec{\mathbf{S}}-\vec{\mathbf{R}}) + \Delta^{(w)}(\vec{\mathbf{S}}-\vec{\mathbf{R}}) - \left(\frac{\partial \vec{\mathbf{R}}}{\partial \vec{\mathbf{T}}}\right)\Delta\vec{\mathbf{T}}^{tot}}_{\textit{contours}}$$



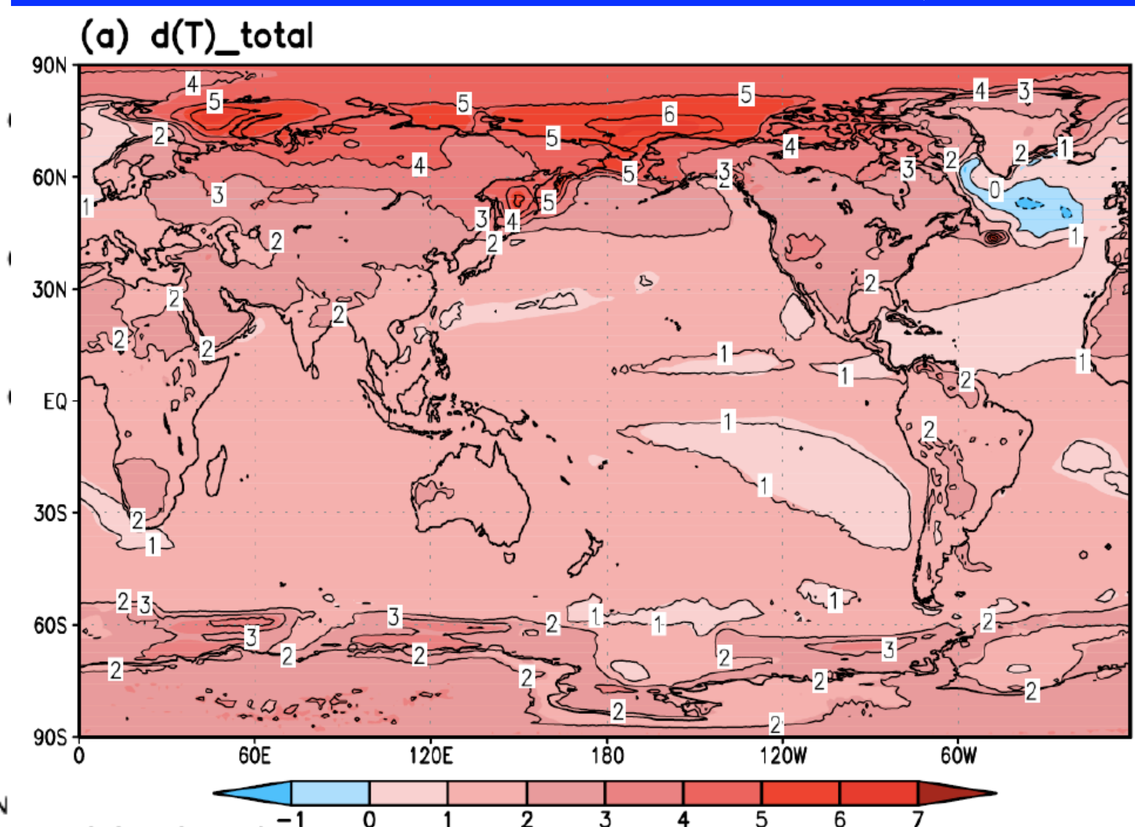


Validation of CFRAM: $\Delta T^{tot} = \sum_{n} \Delta T^{(n)}$

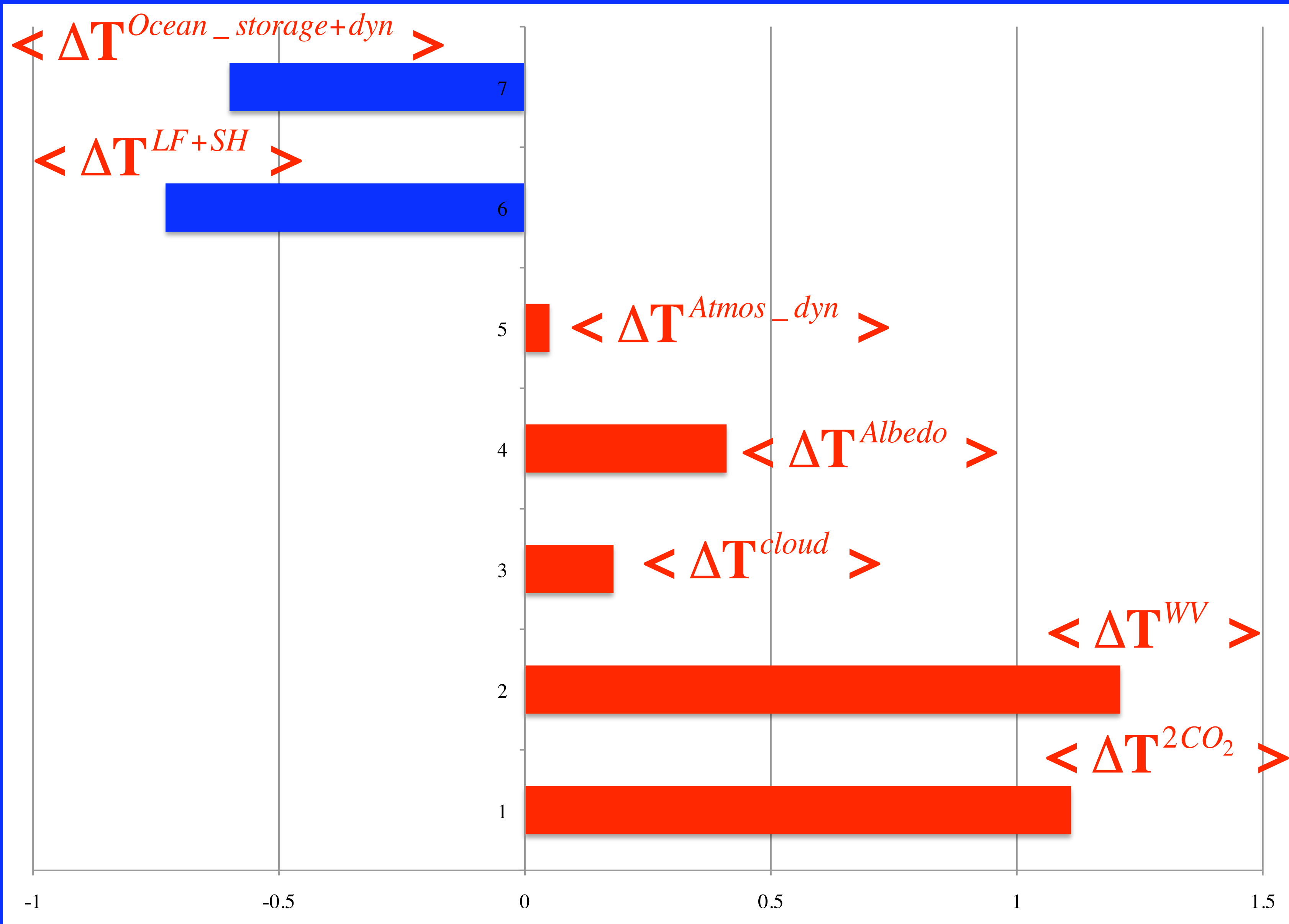


Zonal mean
air temperature
change

surface



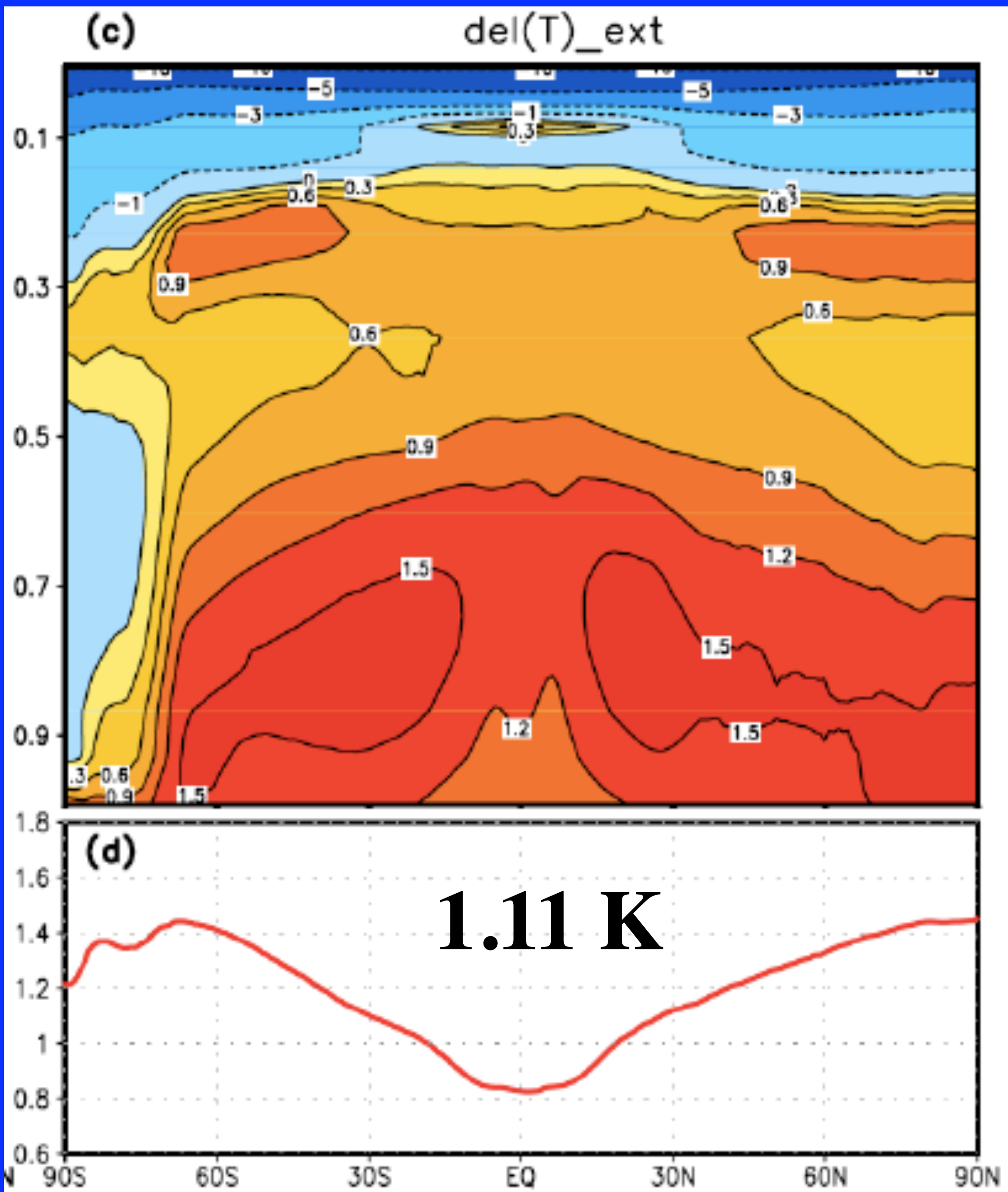
Global Mean Surf. Temp. Changes

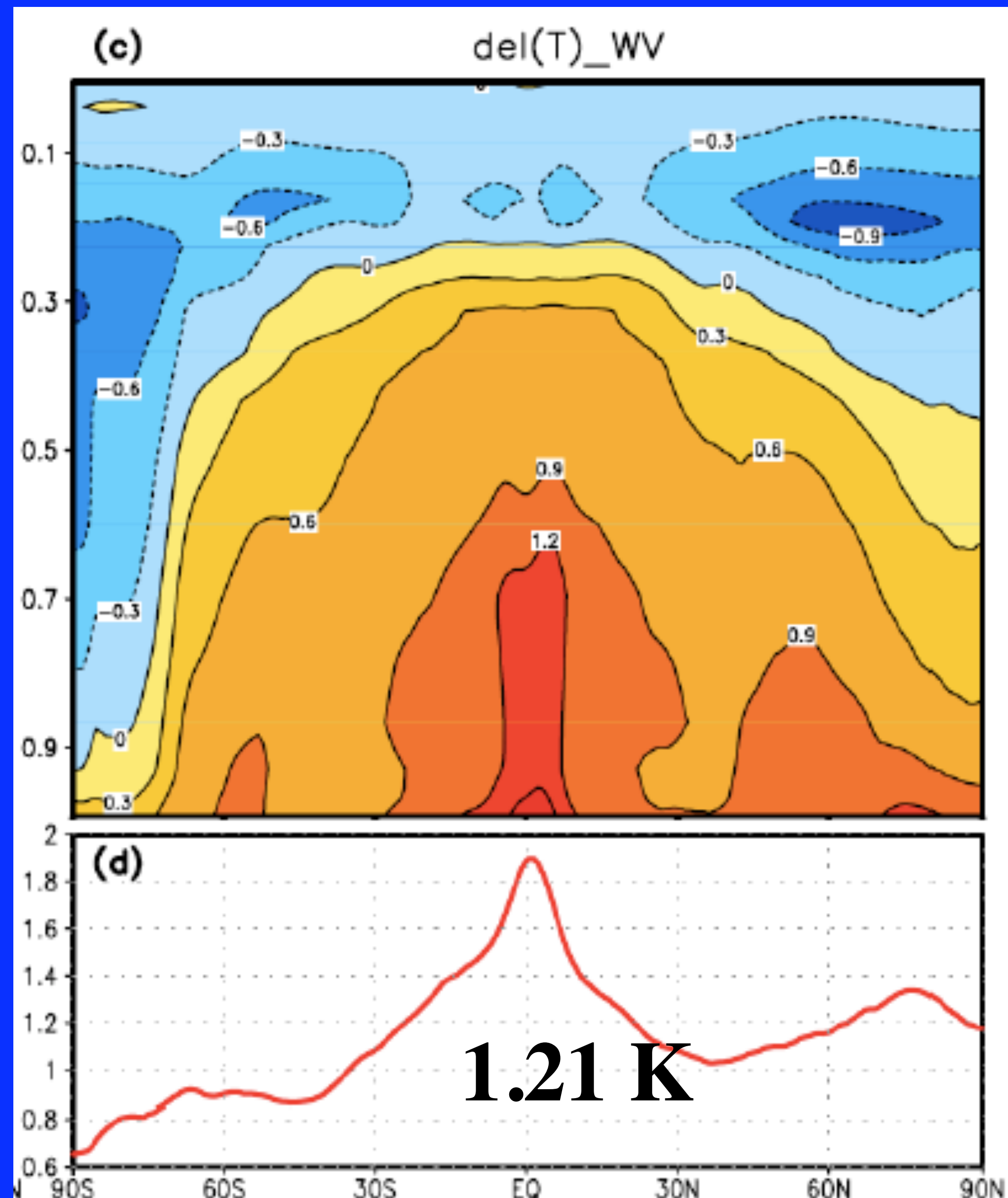


Global mean equilibrium response should be somewhat larger than 2.2K

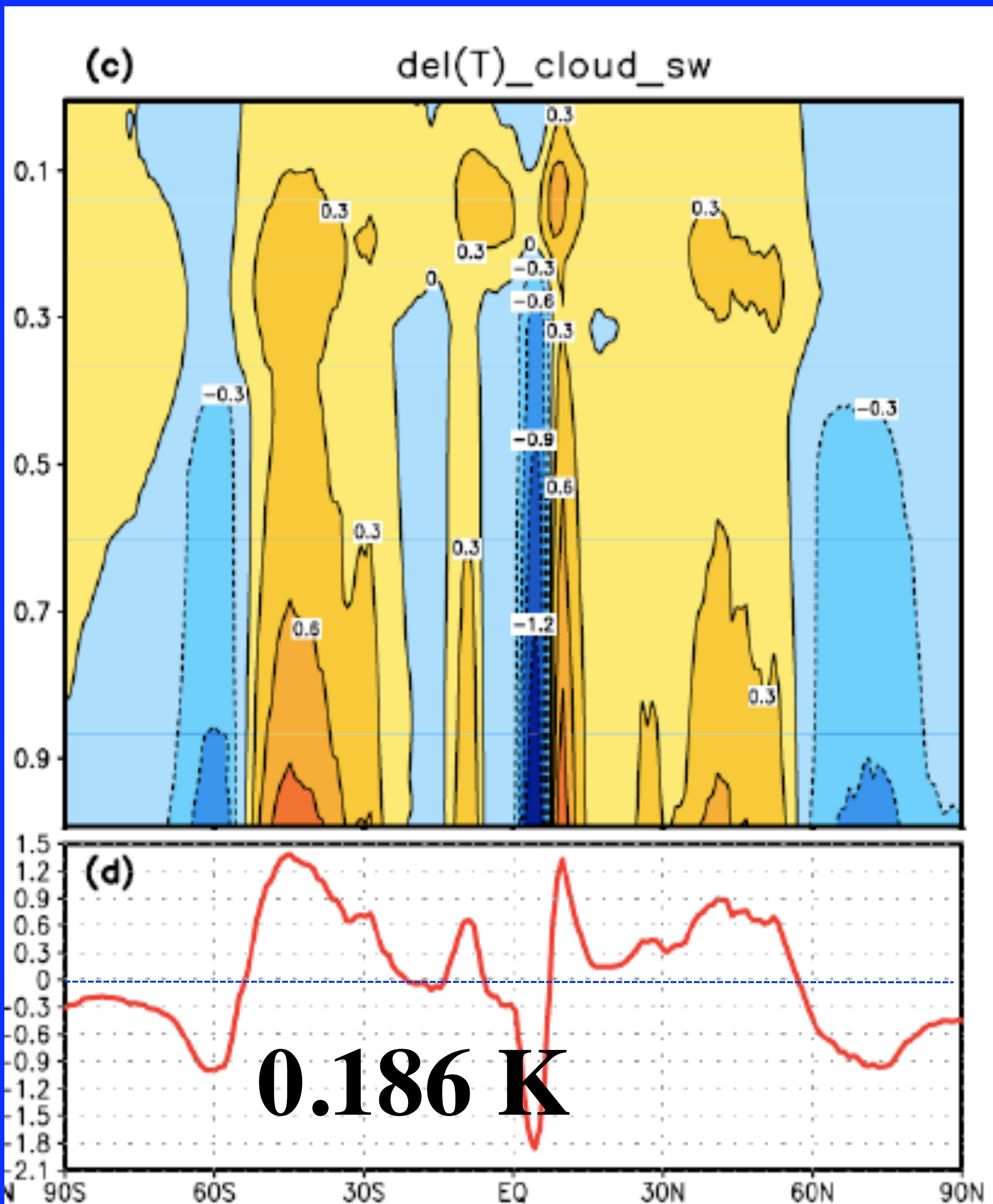
$$[\Delta T^{(EXT)}]$$

$$[\Delta T^{(WV)}]$$

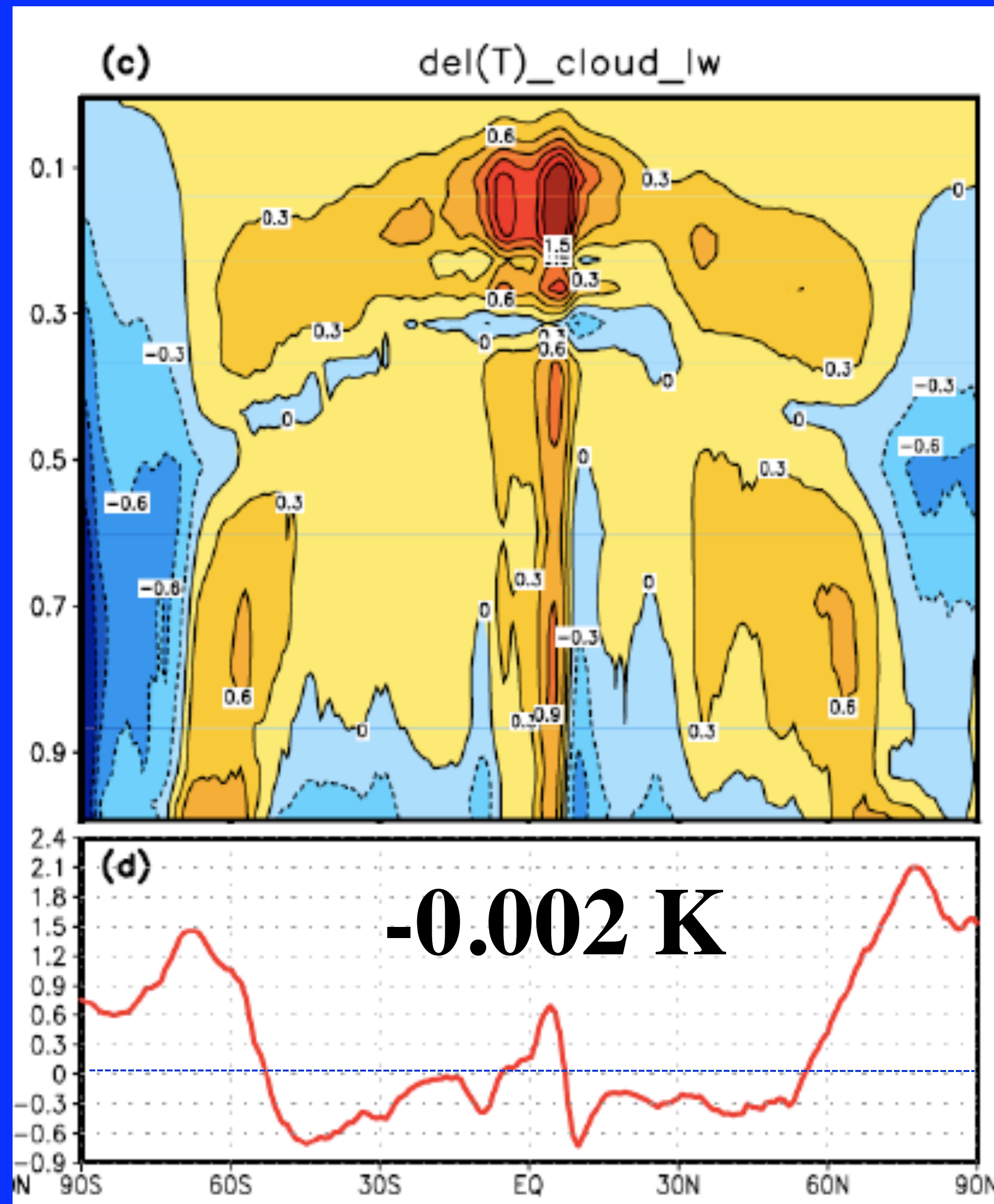




$$[\Delta T^{(Cloud\_SW)}]$$

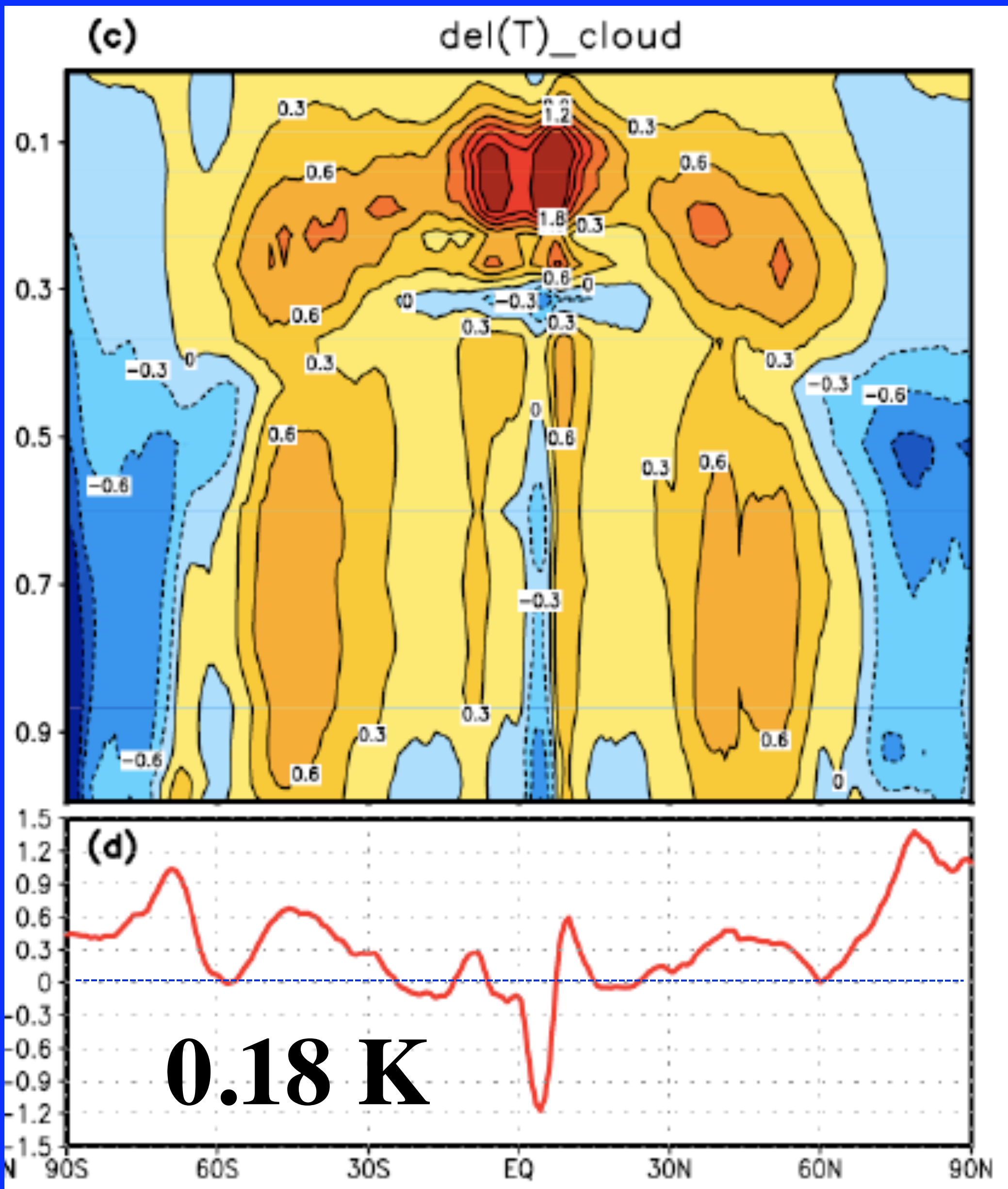


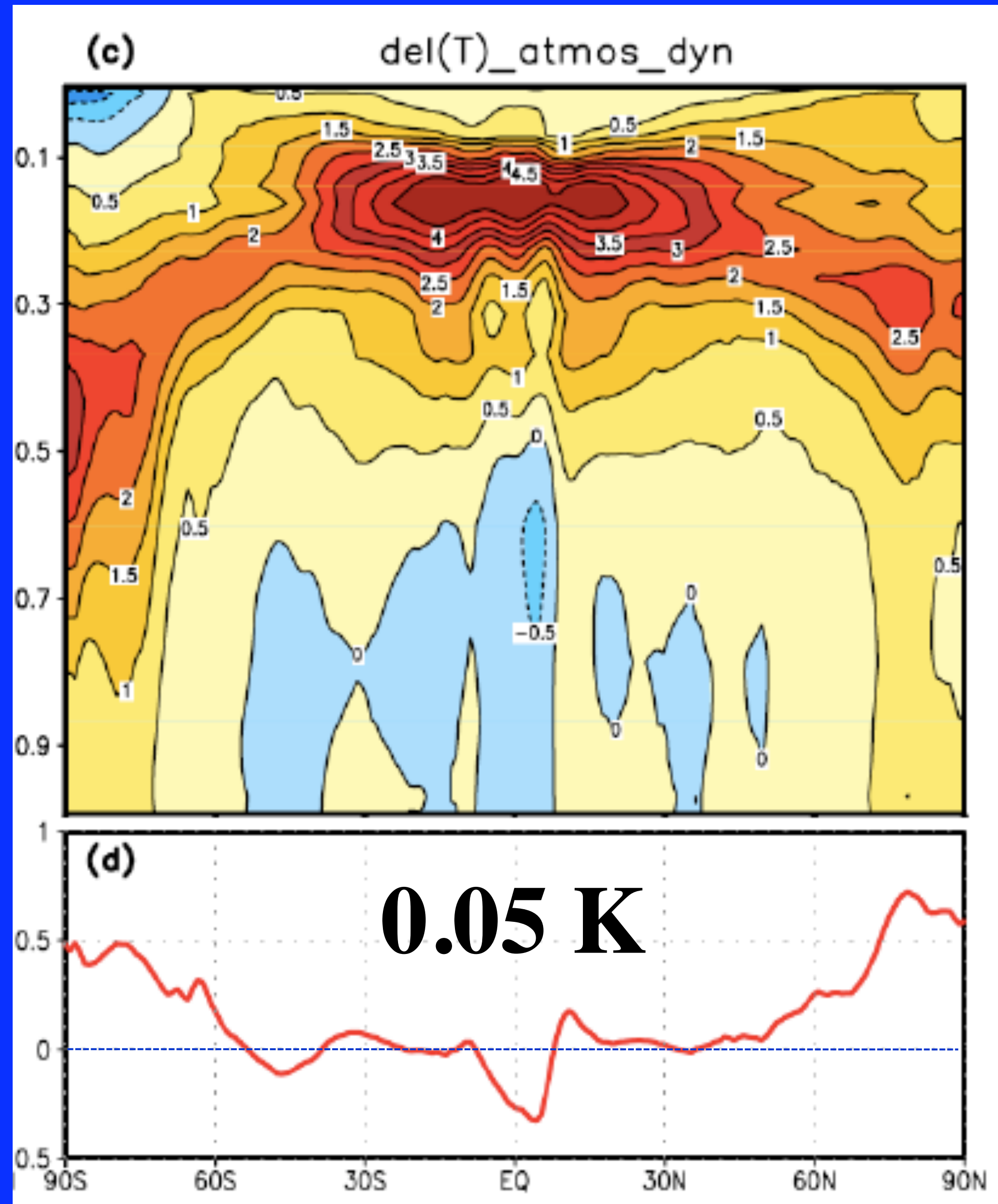
$$[\Delta T^{(Cloud\_LW)}]$$

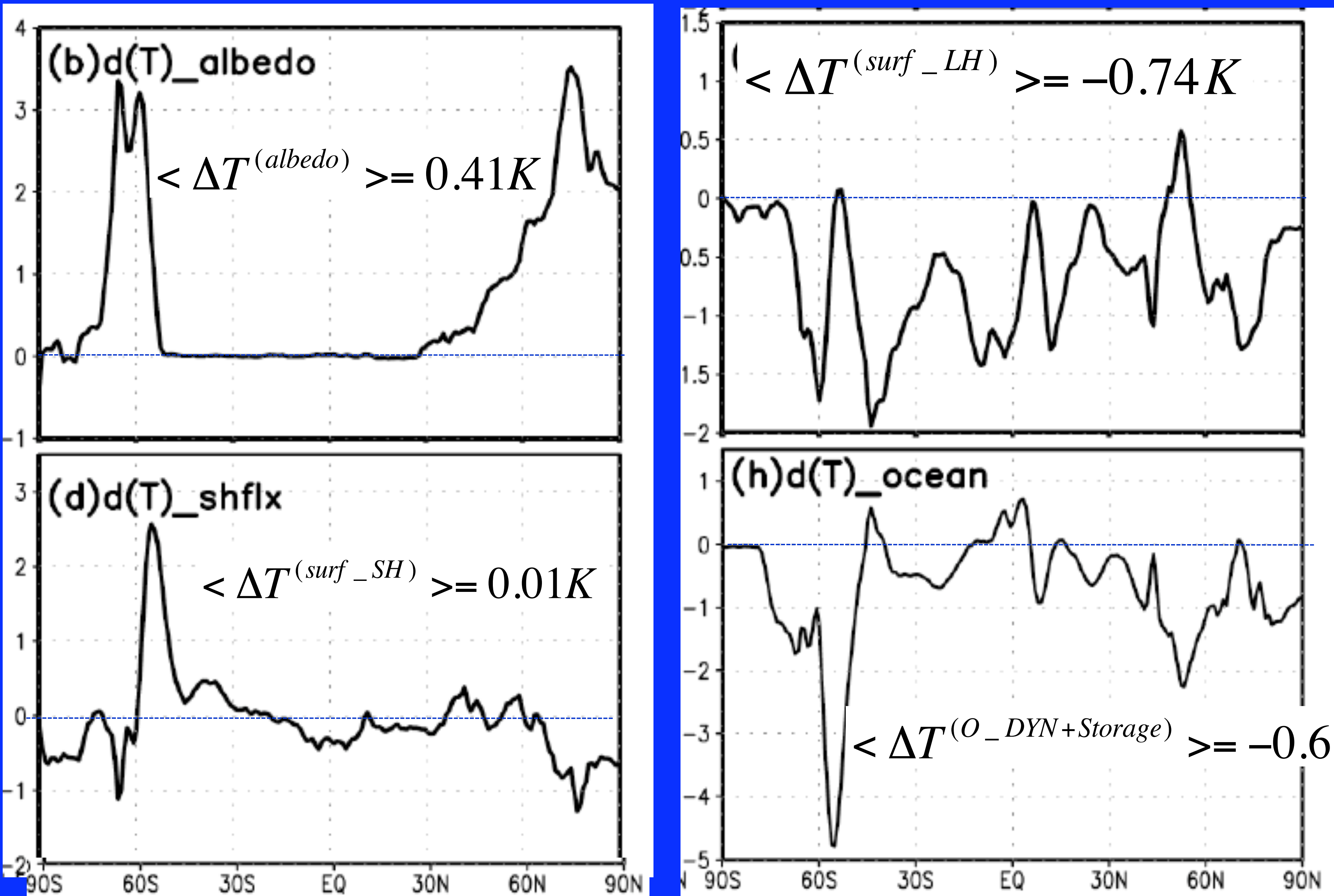


$$[\Delta T^{(Cloud\_NET)}]$$

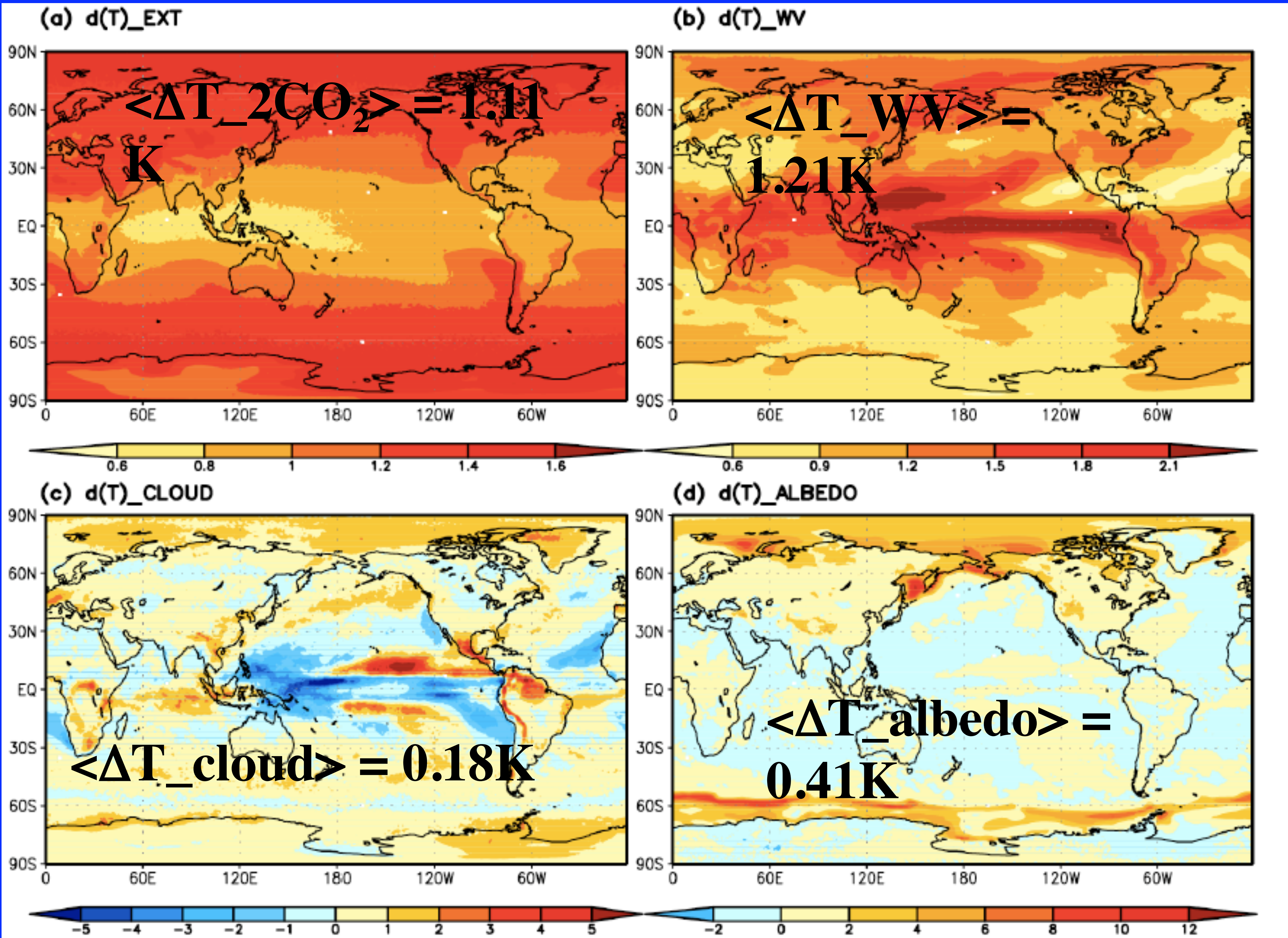
$$[\Delta T^{(Atmos\_DYN)}]$$



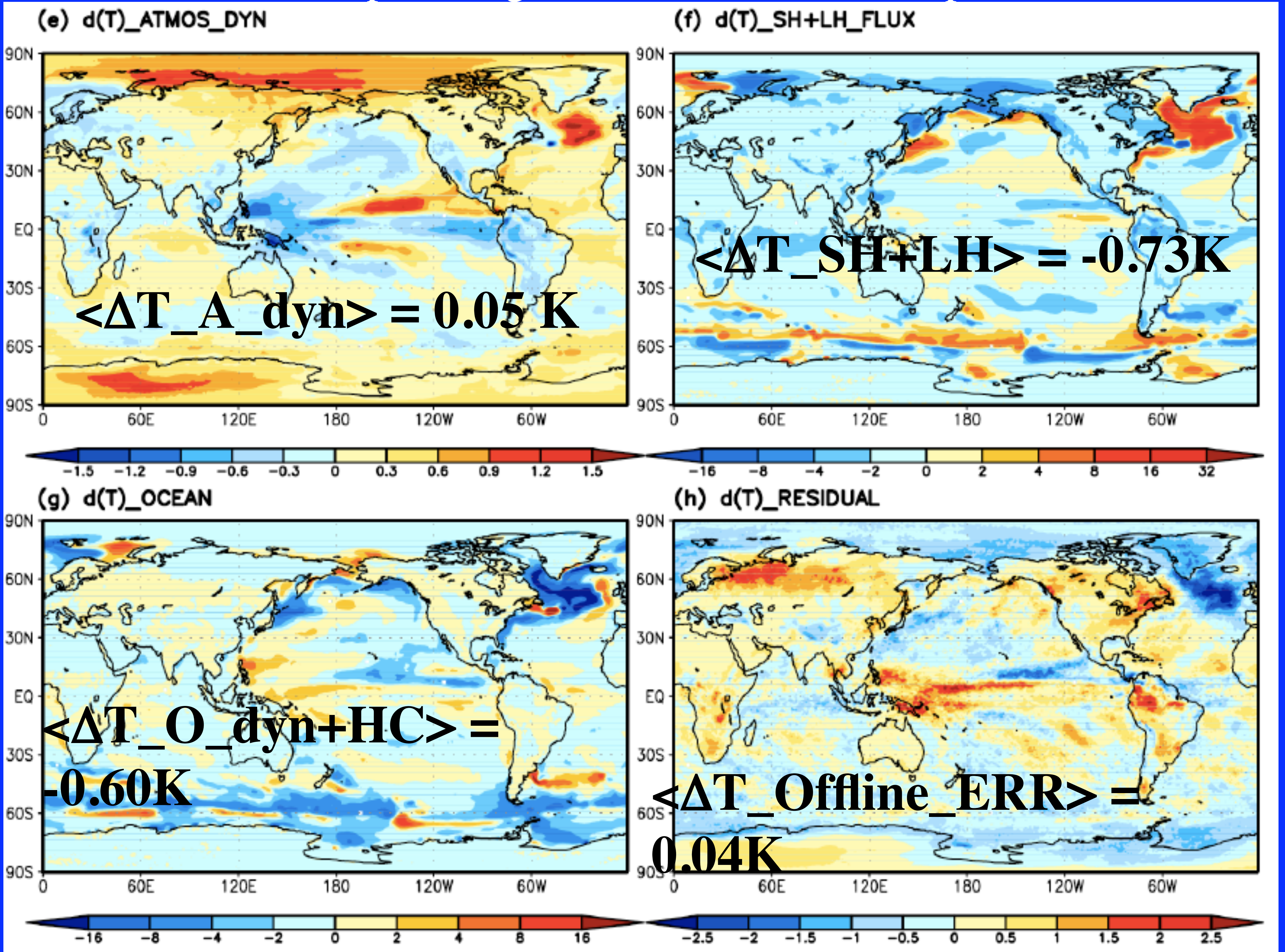



(b)d(T)_albedo
$< \Delta T^{(albedo)} >= 0.41K$
(d)d(T)_shflx
$< \Delta T^{(surf\_SH)} >= 0.01K$
$< \Delta T^{(surf\_LH)} >= -0.74K$
(h)d(T)_ocean
$< \Delta T^{(O\_DYN+Storage)} >= -0.6K$
90S
60S
30S
EQ
30N
60N
90N

Surface Temp. Change due to radiative processes



Surface Temp. Changes due to non-radiative processes



Summary

- **The linearization of radiation transfer model is a good approximation for global warming climate feedback analysis.**
- **Sum of partial temp. changes is very close to the total temp. change (validation of CFRAM).**

- **$2CO_2$ forcing and water vapor feedback tend to create largest warming at the lower troposphere and surface.**
- **Evaporation feedback acts to reduce warming over the vast global surface while cloud shortwave radiative feedback mainly reduces warming over the warm pool area.**
- **Cloud longwave radiative and atmospheric dynamical (non-radiative) feedbacks tend to place larger warming in upper troposphere.**
- **$2CO_2$ forcing, cloud longwave, and surface albedo radiative feedbacks and atmospheric dynamical feedbacks all contribute to stronger surface warming at high latitudes.**