# A Decomposition of Feedback Contributions to Polar Warming Amplification: The Role of Clouds

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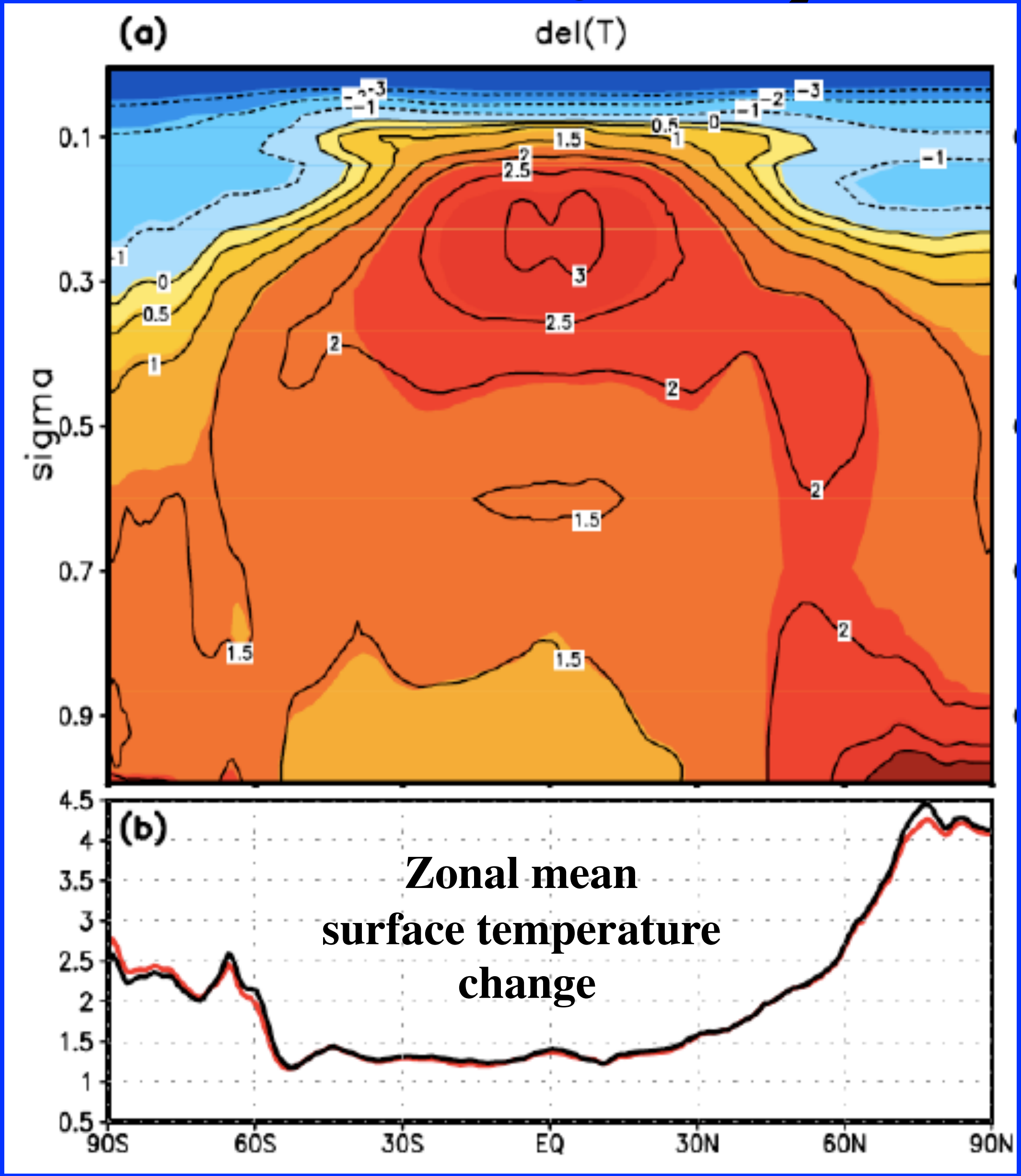
# Temperature Response to 2x$CO_2$ Forcing in NCAR CCSM4 Climate Simulations

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




**Zonal mean air temperature change**

**<DT>=1.64 K**

# Questions

- **How much warming is just due to the doubling of $CO_2$ alone?**
- **What are the additional temperature changes due to various radiative (e.g., clouds, water vapor, ice-albedo) and non-radiative (turbulence, convective, large-scale dynamic) feedback processes?**
- **What are their contributions to the final warming pattern?**
- **What are the main processes contributing the polar warming amplification?**

# General definition of feedback

- Forcing: an energy input to the system
- Response: an output of the system
- A feedback: an "induced input from the the output"

### 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**

# Coupled Atmosphere-Surface Climate Feedback-Response Analysis Method (CFRAM)

(Lu & Cai 2009; Cai & Lu 2009)

- **Forcing: an external energy perturbation profile in the atmosphere-surface column at each grid point**
- **Response: a vertically varying atmosphere-surface temperature profile at each grid point.**
- **Feedback: any energy flux perturbations that are not caused by the the longwave radiation change due to temperature changes.**

- **Changes in feedback agents are regarded as parallel to temperature changes, rather than as the response to changes in surface temperature as in PRP method.**
- **CFRAM calculate the effect of changes in each feedback agent on the temperature.**

# Formulation of CFRAM

**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**

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

# 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**

# Formulation of CFRAM

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

**Feedbacks are additive!**

$$\Delta\overrightarrow{\mathbf{Q}}=\Delta\overrightarrow{\mathbf{Q}}^{LH\_flux}+\Delta\overrightarrow{\mathbf{Q}}^{SH\_flux}+(\Delta\overrightarrow{\mathbf{Q}}^{convection}+\Delta\overrightarrow{\mathbf{Q}}^{ATM\_lg\_dyn})+\Delta\overrightarrow{\mathbf{Q}}^{OCN\_dyn}$$

**How much does atmosphere-surface temperature have to change in order to balance out the energy perturbation due to external forcing, due to each feedback via thermal radiation?**

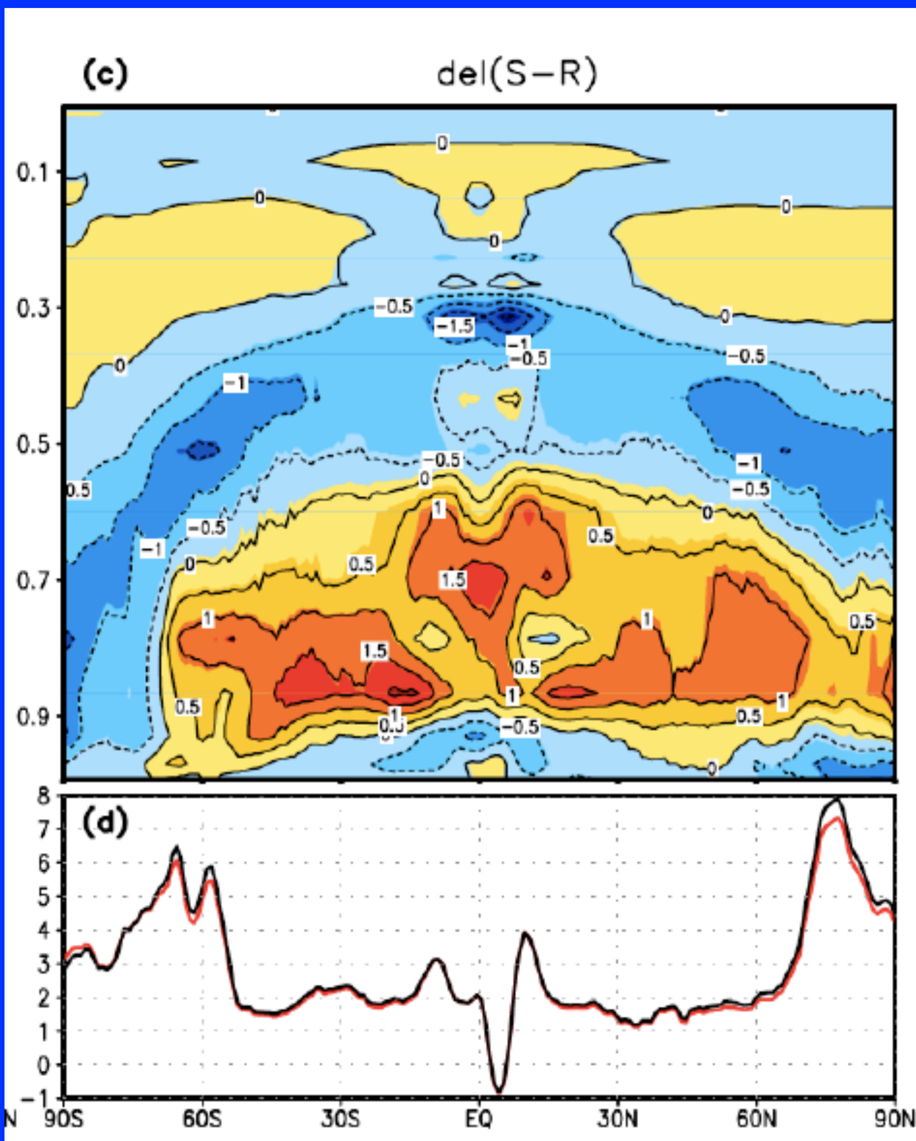
$$\Delta\overrightarrow{\mathbf{T}}^{(n)}=\left(\frac{\partial\overrightarrow{\mathbf{R}}}{\partial\overrightarrow{\mathbf{T}}}\right)^{-1}\Delta\overrightarrow{\mathbf{F}}^{(n)}$$

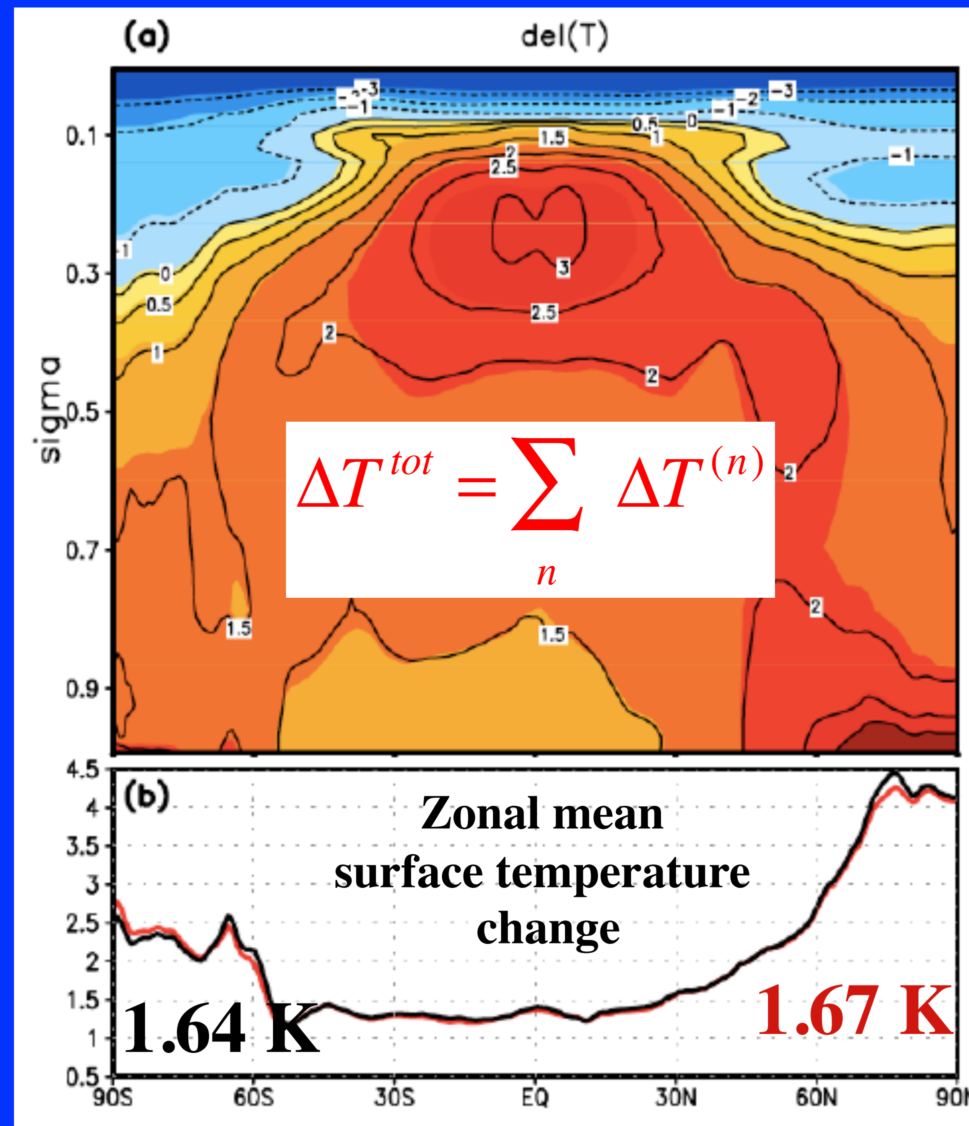
$$\Delta\overrightarrow{\mathbf{T}}^{tot}=\sum_n\Delta\overrightarrow{\mathbf{T}}^{(n)}$$

**Effects are additive!**

# Validation of Linearization

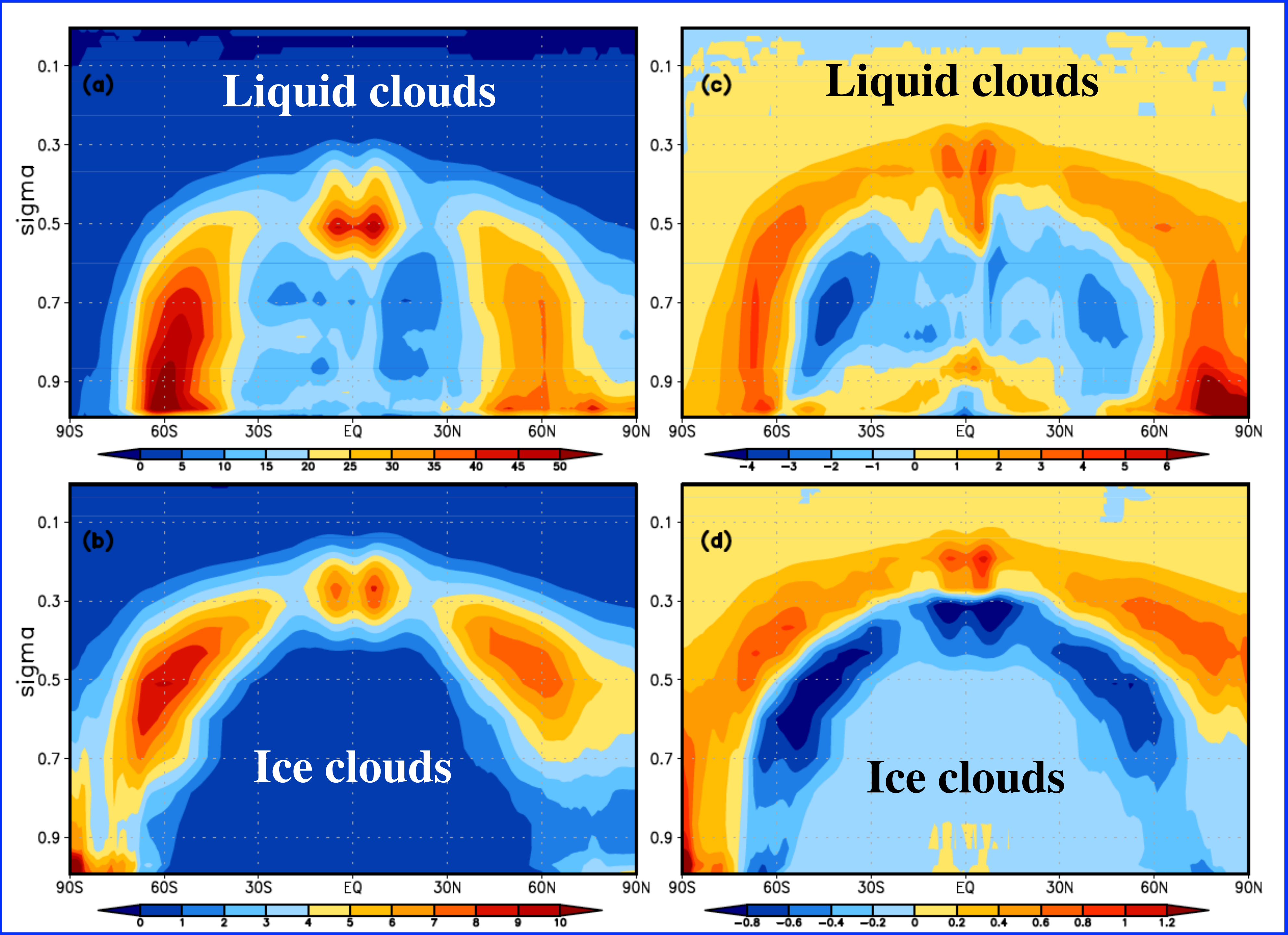
$$\underbrace{\Delta^{(tot)}(\vec{\mathbf{S}}-\vec{\mathbf{R}})}_{\textit{Shadings}} \simeq \underbrace{\vec{\mathbf{F}}^{2CO_2} + \Delta^{(\alpha)}\vec{\mathbf{S}} + \Delta^{(c)}(\vec{\mathbf{S}}-\vec{\mathbf{R}}) + \Delta^{(w)}(\vec{\mathbf{S}}-\vec{\mathbf{R}}) - \left(\frac{\partial\vec{\mathbf{R}}}{\partial\vec{\mathbf{T}}}\right)\Delta\vec{\mathbf{T}}^{tot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



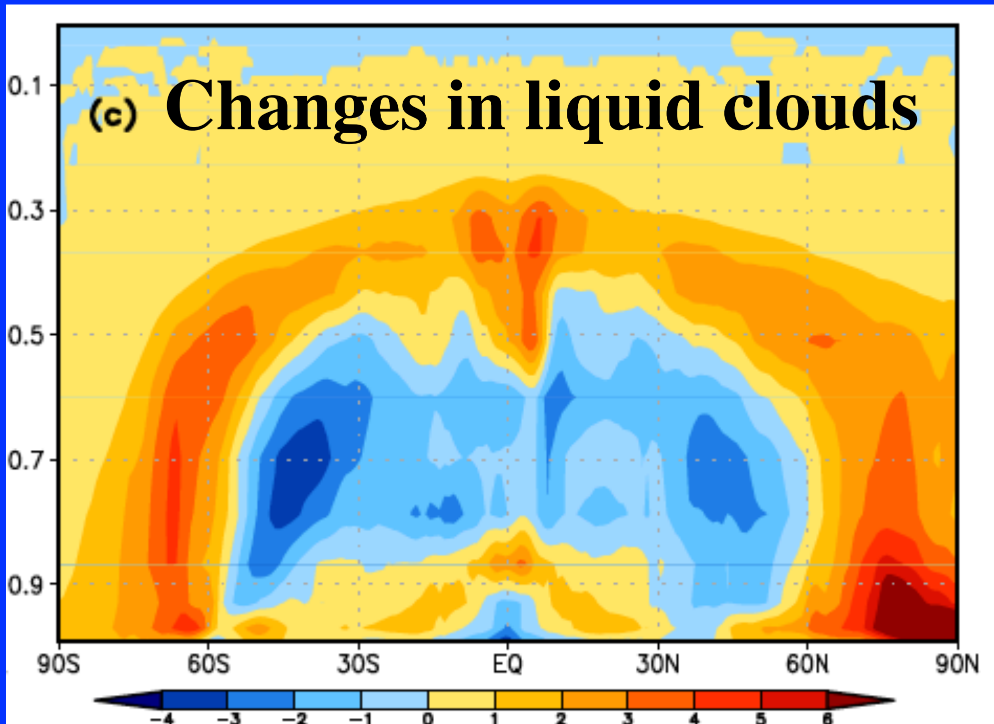



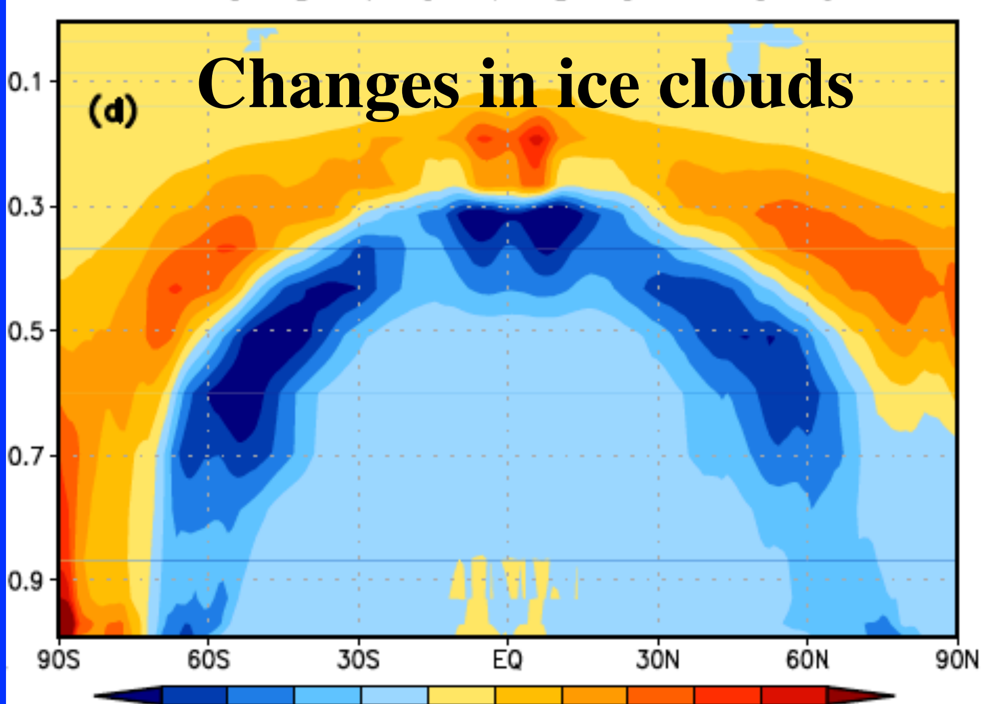
# Climatological Clouds

# Changes in Clouds

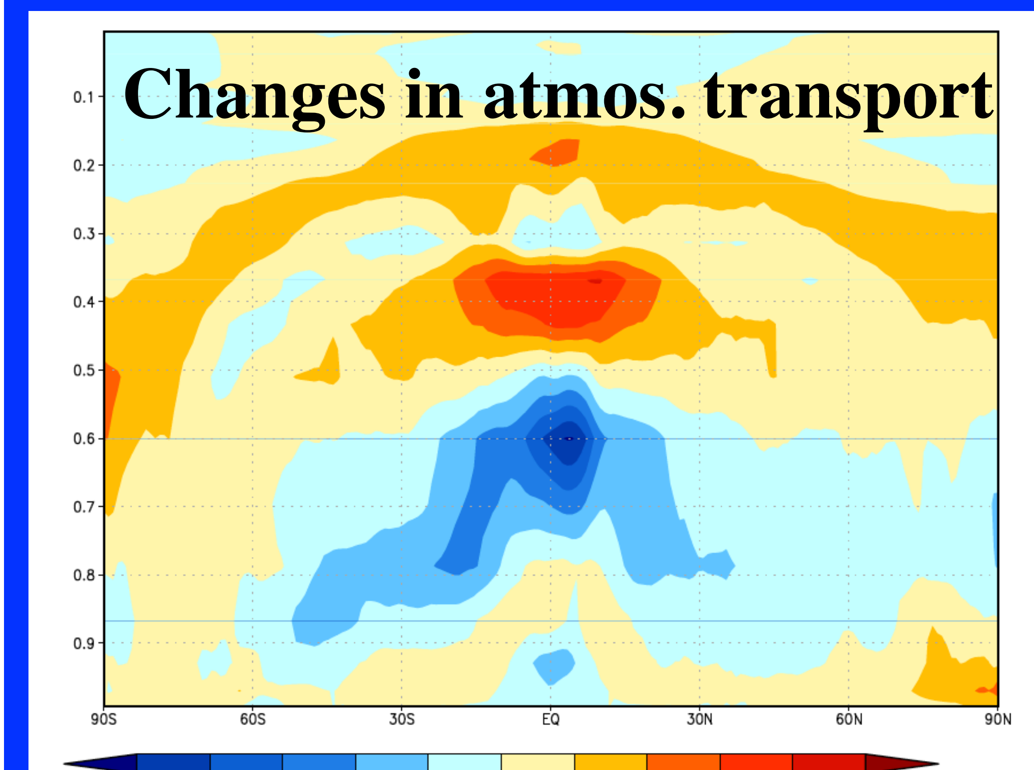


# Changes in clouds versus changes in circulations



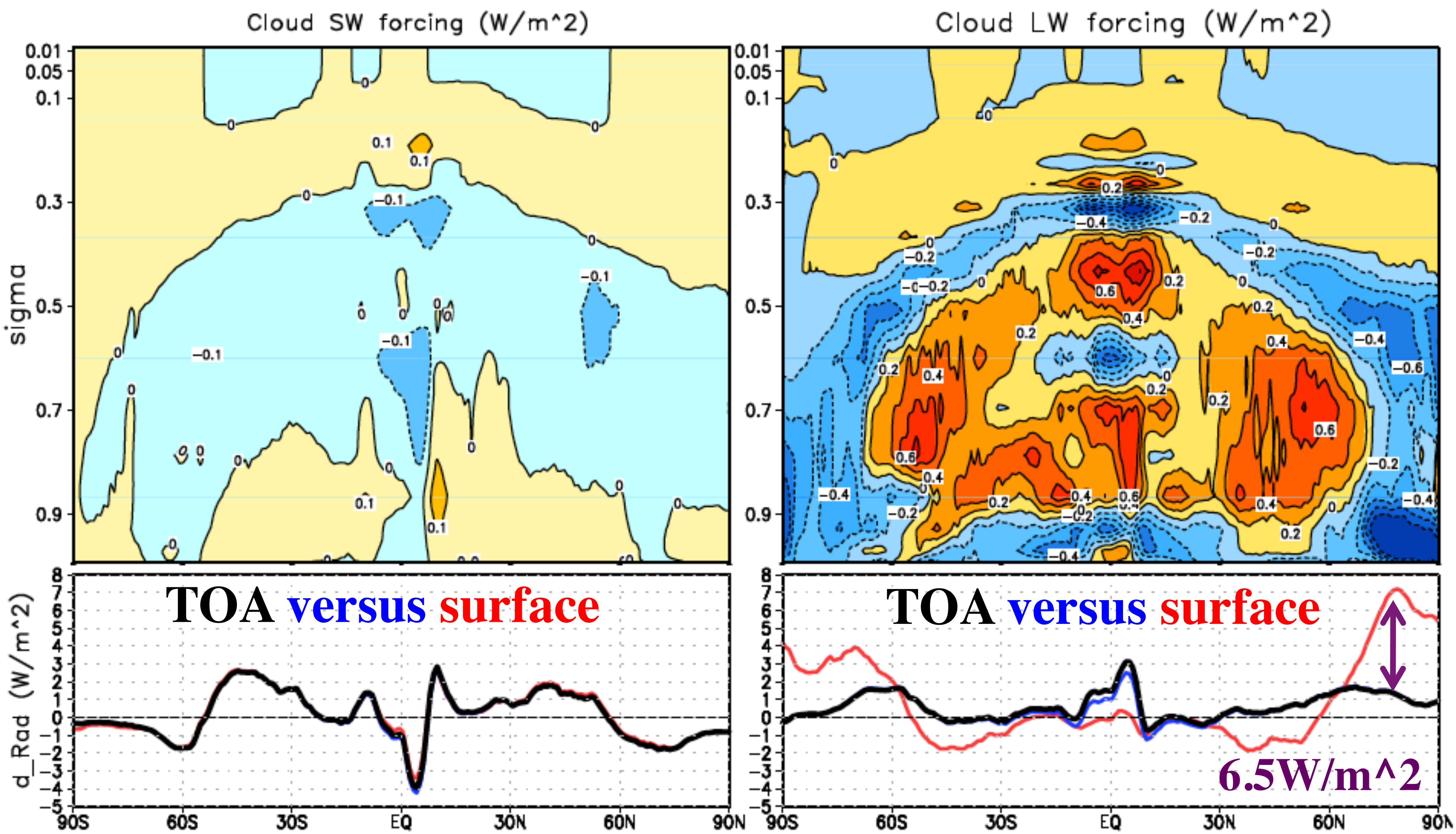




**Changes in clouds are coupled with changes in energy flux convergence associated with atmospheric circulation.**



# Cloud Feedbacks

$SW$ forcing: $\Delta^{(c)}(\bar{\mathbf{S}})$ | $LW$ forcing: $\Delta^{(c)}(-\overline{R})$

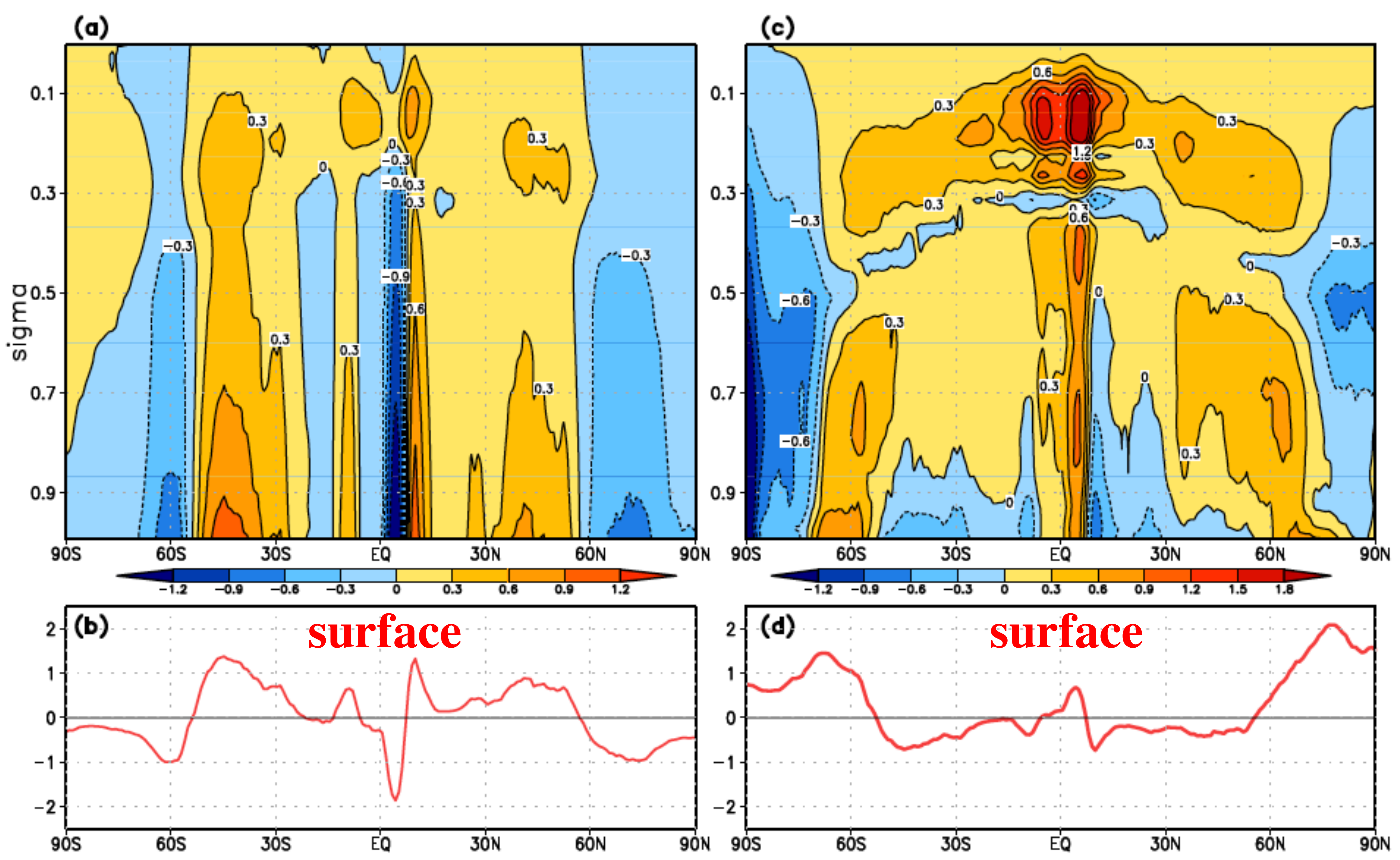



**At TOA, one only "see" a fractional part of cloud LW forcing applied to the surface over the polar area (over Arctic: 1.5/7)**

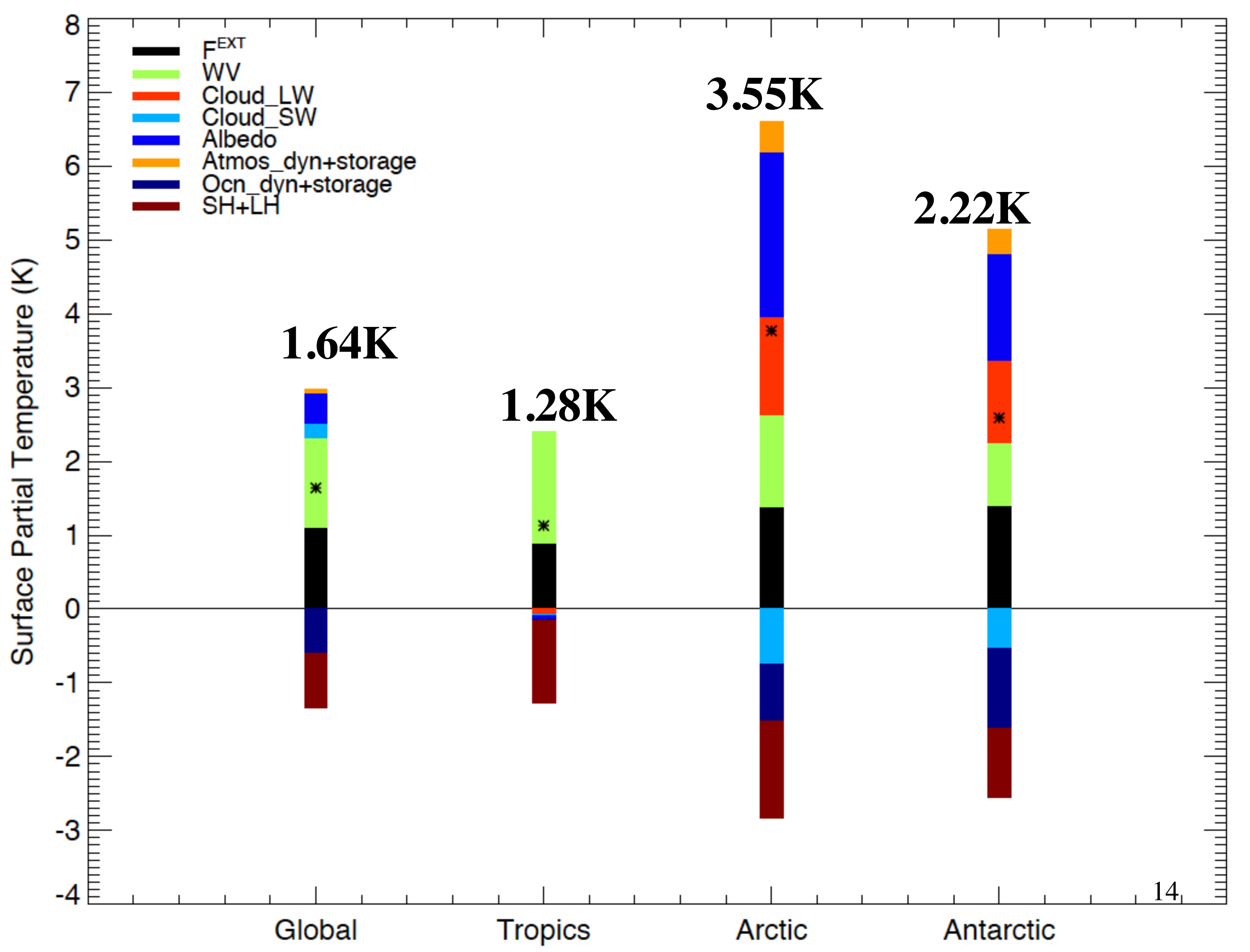
# Temperature changes due to changes in clouds

$$SW\ \text{effect: } \Delta\vec{\mathbf{T}}^{cloud\_sw} = \left(\frac{\partial\vec{\mathbf{R}}}{\partial\vec{\mathbf{T}}}\right)^{-1}\Delta^{(c)}(\vec{\mathbf{S}})$$

$$LW\ \text{effect: } \Delta\vec{\mathbf{T}}^{cloud\_sw} \simeq \left(\frac{\partial\vec{\mathbf{R}}}{\partial\vec{\mathbf{T}}}\right)^{-1}\Delta^{(c)}(-\vec{R})$$



# Attributions



# Summary

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

- **Cloud SW forcing at the TOA is almost same as at the Surface. However, only a fraction of cloud LW forcing at the surface can be seen at the TOA, particularly over the polar region.**

- **$2CO_2$ forcing, cloud longwave, surface albedo feedbacks, and atmospheric dynamical feedbacks all contribute to stronger surface warming at high latitudes.**

- **Cloud LW feedback is the dominant feedback for winter polar warming amplification while ice-albedo feedback indirectly contributes the winter polar warming amplification via ocean heat storage (Sejas et al. 2013)**