Lapse-Rate Feedback: The Key to Reconciling TOA and Surface Attributions of Surface Warming

Sergio A. Sejas[1,2] and Ming Cai[3]

[1]ADNET Systems Inc., [2]NASA Langley Research Center, [3]Florida State University Contact: *sergio.sejas@nasa.gov*

1. Background

- Top-of-atmosphere (TOA) and surface energy budget decompositions are used in climate studies to evaluate process contributions to surface warming forced by increasing greenhouse gases.
- The TOA energy budget change is proportional to surface warming, as moist convection in the Tropics leads to a vertical temperature profile that follows the moist adiabatic lapse-rate.
- The applicability of the TOA framework in polar regions is questionable as strong static stability there decouples the surface from the atmosphere.
- Surface warming is directly connected to surface energy fluxes, making the surface energy budget a compelling alternative, especially in polar regions.
- Previous studies indicate the two perspectives provide a differing understanding of process contributions to surface warming (e.g., Previdi & Liepert 2012; Pithan & Mauritsen 2014)

2. Data and Methodology

50-yr CMIP5 historical (1951-2000) and RCP8.5 (2051-2100) data are used.

TOA Decomposition

$$\sum_{j=1}^{M+1} \frac{\partial R_{TOA}}{\partial T_j} \Delta T_s = \begin{bmatrix} \Delta(S_{TOA}^{ext} - R_{TOA}^{ext}) + \Delta(S_{TOA}^{wv} - R_{TOA}^{wv}) + \Delta(S_{TOA}^{cld} - R_{TOA}^{cld}) + \\ \Delta S_{TOA}^{alb} - \sum_{j=1}^{M} \frac{\partial R_{TOA}}{\partial T_j}(\Delta T_j - \Delta T_s) + \Delta Dyn\_trans - \Delta \frac{\partial E_{TOA}}{\partial t} \end{bmatrix} \quad (1)$$

Surface Decomposition

$$\frac{\partial R_s}{\partial T_s} \Delta T_s = \begin{bmatrix} \Delta\left(S_s^{ext} - R_s^{ext}\right) + \Delta\left(S_s^{wv} - R_s^{wv}\right) + \Delta\left(S_s^{cld} - R_s^{cld}\right) + \Delta S_s^{alb} \\ -\sum_{j=1}^{M} \frac{\partial R_s}{\partial T_j} \Delta T_j + \Delta Q_s^{non\_rad} - \Delta\left(\frac{\partial E_s}{\partial t}\right) \end{bmatrix} \quad (2)$$

Atmosphere Decomposition

$$\Delta\left(\frac{\partial E_{atm}}{\partial t}\right) \approx \begin{bmatrix} \Delta(S_{atm}^{ext} - R_{atm}^{ext}) + \Delta(S_{atm}^{wv} - R_{atm}^{wv}) + \Delta(S_{atm}^{cld} - R_{atm}^{cld}) \\ +\Delta S_{atm}^{alb} - \sum_{j=1}^{M} \frac{\partial R_{atm}}{\partial T_j} \Delta T_j - \frac{\partial R_{atm}}{\partial T_s} \Delta T_s + \Delta Q_{atm}^{non\_rad} \end{bmatrix} \quad (3)$$

The TOA energy budget is equal to the sum of the surface and atmospheric energy budgets: (2) + (3) = (1)

Lapse-Rate Feedback Decomposition:

$$-\sum_{j=1}^{M} \frac{\partial R_{TOA}}{\partial T_j}(\Delta T_j - \Delta T_s) = -\sum_x \left[\sum_{j=1}^{M} \frac{\partial R_{TOA}}{\partial T_j}(\Delta T_j^x - \Delta T_s^x)\right] \quad (4)$$

Atmospheric Temperature Feedback Decomposition:

$$-\sum_{j=1}^{M} \frac{\partial R_s}{\partial T_j} \Delta T_j = -\sum_x \sum_{j=1}^{M} \frac{\partial R_s}{\partial T_j} \Delta T_j^x \quad (5)$$

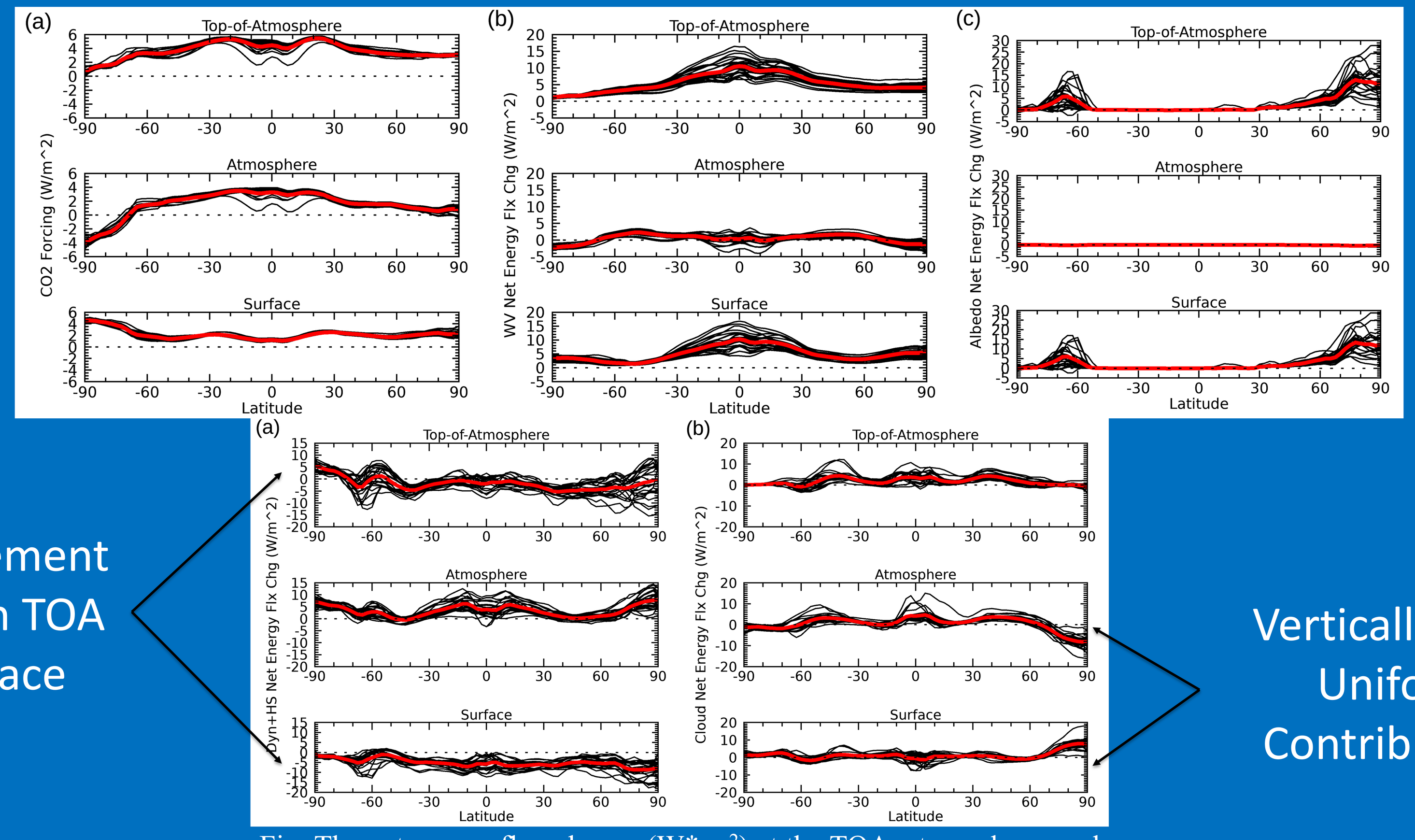
The climate feedback-response analysis method (CFRAM; Lu and Cai 2009) provides the 3-D partial temperature changes due to an individual process (*x*), which can be used for the decomposition in Eqs. (4) & (5).

$$\Delta\vec{T} = \left(\frac{\partial\vec{R}}{\partial\vec{T}}\right)^{-1} \left[\Delta(\vec{S}^{ext} - \vec{R}^{ext}) + \Delta(\vec{S}^{wv} - \vec{R}^{wv}) + \Delta(\vec{S}^{cld} - \vec{R}^{cld}) + \Delta\vec{S}^{alb} + \Delta\vec{Q}^{non\_rad}\right]$$

At a given grid point, the CFRAM considers the energy budget of its atmosphere-surface column to evaluate the local temperature change needed to balance the local energy flux perturbation.

The major discrepancies in the feedback attribution of surface warming given by a surface versus a TOA energy budget decomposition are due to the vertically non-uniform energy flux perturbations individual processes cause that naturally produce a vertically non-uniform warming response. The lapse-rate feedback is the result of the vertically non-uniform warming response caused by multiple processes. A decomposition of the lapse-rate feedback into individual process contributions allows us to reconcile the major differences.

Before:

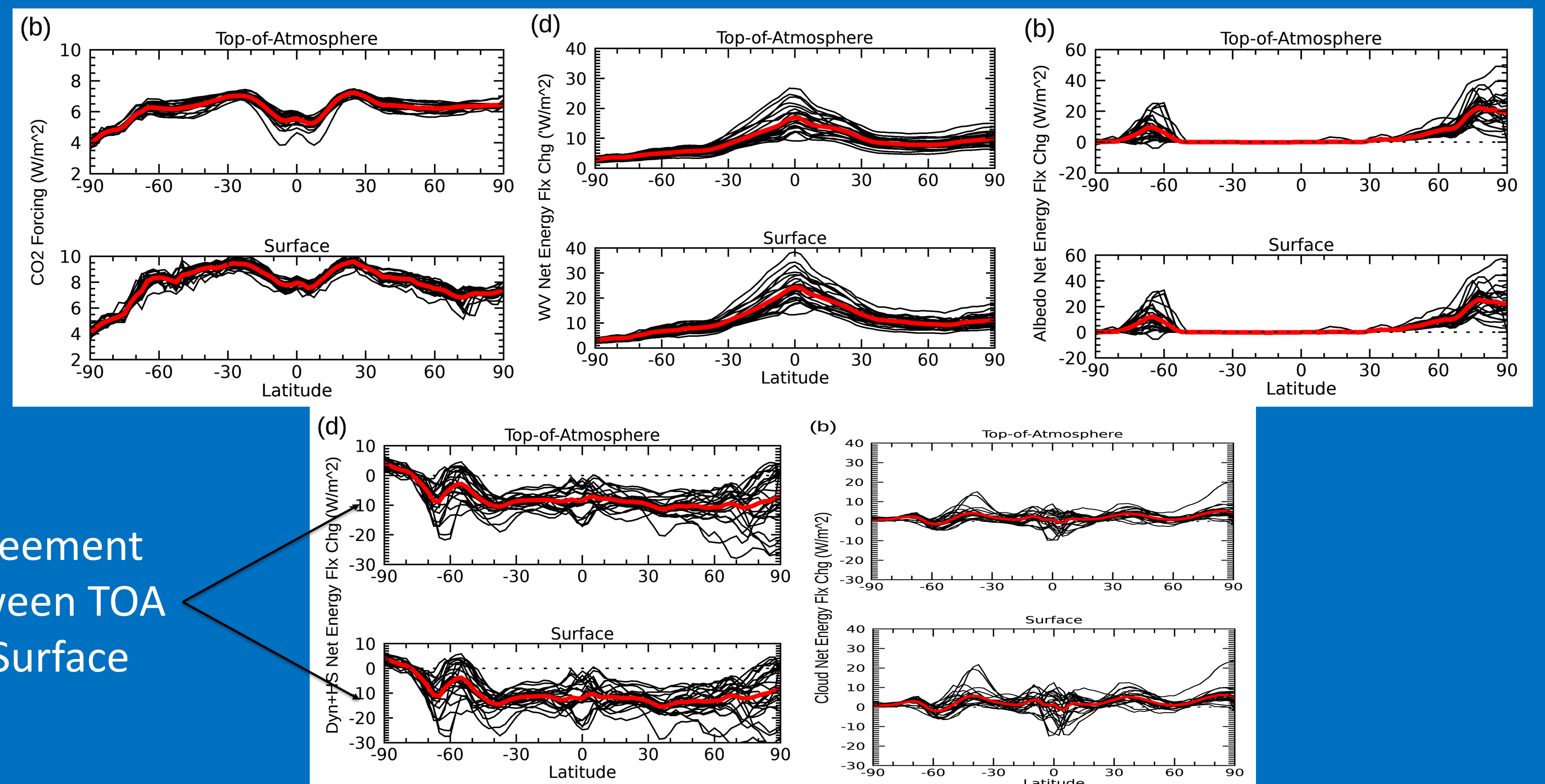


Disagreement between TOA & Surface

Vertically Non-Uniform Contributions

Fig. The net energy flux change (W*m^{-2}) at the TOA, atmosphere, and surface due exclusively to changes in CO_2, water vapor, surface albedo, dynamics plus heat storage, and clouds. The sum of the surface and atmosphere contributions equals their respective TOA contributions. Individual CMIP5 models (black lines); ensemble mean (red lines).

After:



Agreement between TOA & Surface

Fig. The net energy flux change (W*m^{-2}) at the TOA and surface due exclusively to changes in CO_2, water vapor, surface albedo, dynamics plus heat storage, and clouds. These total process contributions include their respective contributions to the lapse-rate and atmospheric temperature feedbacks. Individual CMIP5 models (black lines); ensemble mean (red lines).

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3. Lapse-Rate Feedback Decomposition

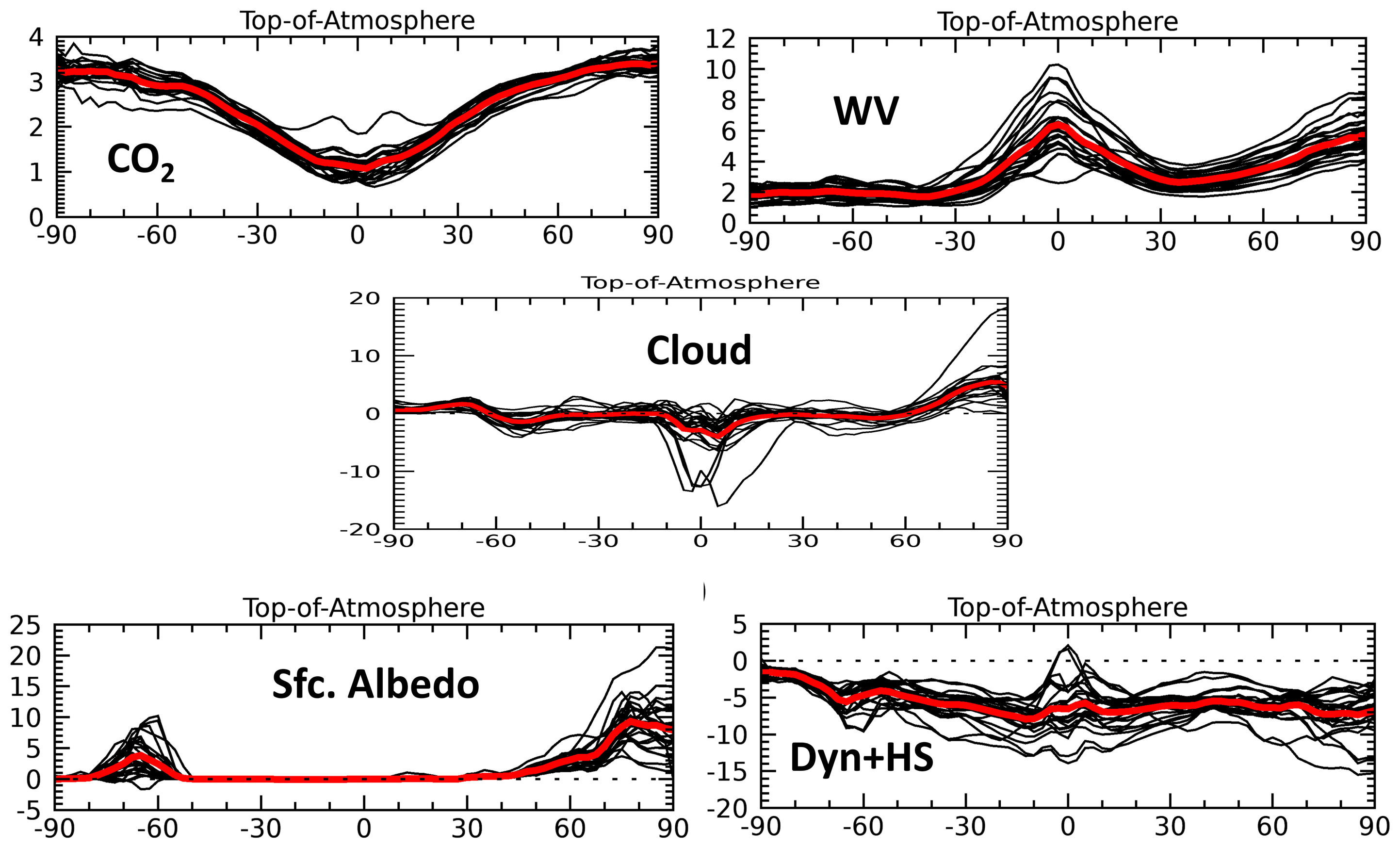

Fig. The contributions of the CO_2 forcing, water vapor, net cloud, surface albedo, and dynamics plus heat storage feedbacks to the net energy flux change (W*m^{-2}) associated with the lapse-rate feedback at the TOA. Individual CMIP5 models (black lines); CMIP5 ensemble mean (red lines).

4. Atmospheric Temperature Feedback Decomposition

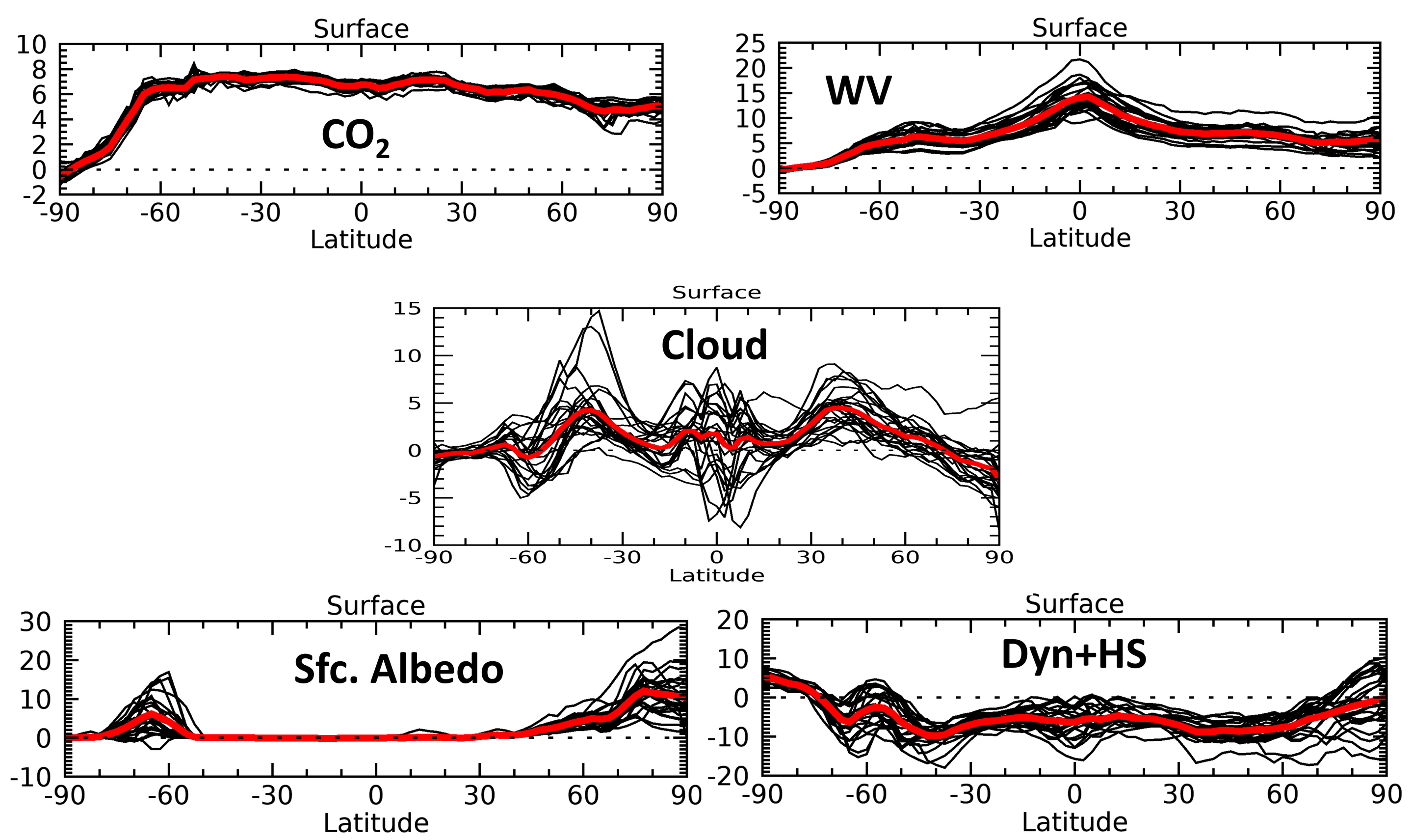

Fig. The contributions of the CO_2 forcing, water vapor, net cloud, surface albedo, and dynamics plus heat storage feedbacks to the net energy flux change (W*m^{-2}) associated with the atmospheric temperature feedback at the surface. Individual CMIP5 models (black lines); CMIP5 ensemble mean (red lines).

5. Conclusions

- The negative tropical lapse-rate feedback is predominantly due to the dynamics plus ocean heat storage.
- The positive lapse-rate feedback in polar regions is primarily due to surface albedo feedback.
- Water vapor and surface albedo feedbacks are the main contributors to surface warming in the tropics and poles, respectively.
- Dynamics plus heat storage changes are the primary suppressors of surface warming.
- Individual model contributions are qualitatively similar but there is substantial inter-model spread.
- Large inter-model uncertainty in the contributions of water vapor, clouds, surface albedo, and dynamics plus heat storage.
- The large uncertainty in the dynamics plus heat storage term represents a possible source of uncertainty often overlooked in the global mean TOA perspective as it is hidden within the lapse-rate feedback.