The role of the nonlinearity of the Stefan-Boltzmann law on the structure of radiatively forced temperature change

Matthew Henry (matthew.henry@mail.mcgill.ca) and Timothy Merlis

Atmospheric and Oceanic Sciences, McGill University

McGill

Objectives

Assess how Stefan-Boltzmann's σT^4 nonlinearity affects the horizontal and vertical structure of radiatively forced temperature change by:

- Comparing the structure of the Planck feedback and CO_2 forcing in comprehensive estimates for Earth.
- Linearizing σT^4 in an idealized GCM and assessing how this affects the horizontal and vertical structure of temperature change.
- Using pure radiative and radiative-convective model configurations to see how the effect of the linearization on the vertical structure of warming propagates through this hierarchy of models.

Introduction

A consequence of σT^4 is latitudinal structure of the Planck feedback, which is thought to contribute to polar amplification [1] because $\Delta T \approx F/4\sigma T^3$.

Using the same reasoning, nonlinearity of σT^4 may have an impact on the vertical structure of temperature change.

In contrast to [1] and [2], we find that combination of Planck feedback and forcing gives rise to *tropically*-amplified warming : the weaker forcing in high latitudes from more isothermal atmosphere dominates over Planck feedback.

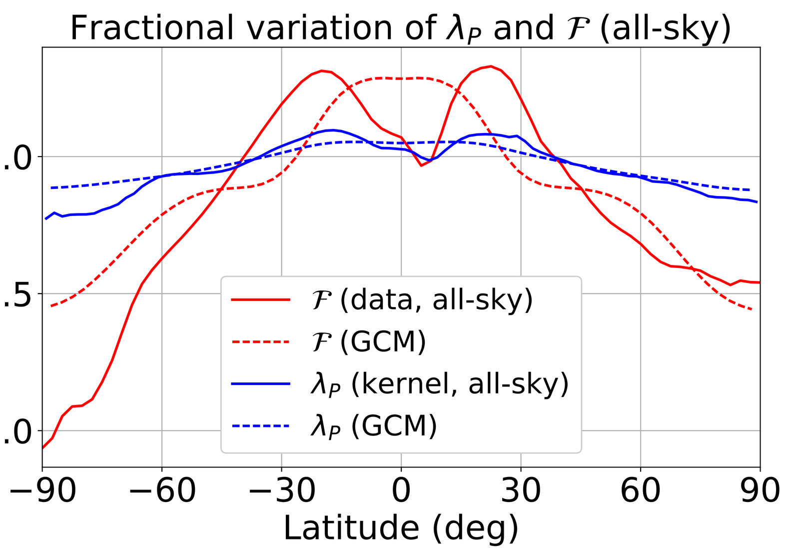

Figure 1: Percentage variation of forcing ($\mathcal{F}$) [3] and of the Planck feedback (λ_P) [4]

Idealized GCM

Moist idealized atmospheric GCM [5], with aquaplanet slab ocean surface boundary condition and interactive hydrological cycle.

Gray radiative transfer, no water vapor or cloud feedback. No representation of sea ice, yet the atmospheric warming comparable to comprehensive simulations (Fig. 2).

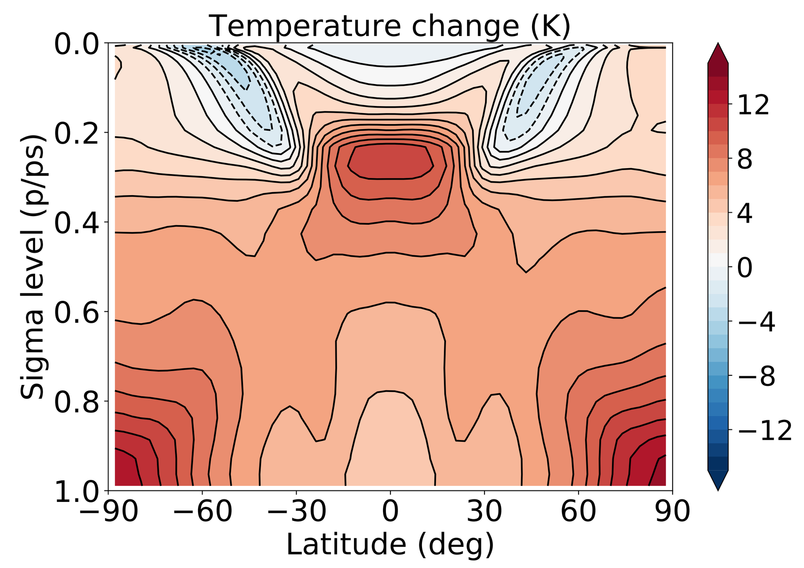

Figure 2: Temperature change in control experiment after increase in optical depth

Mechanism denial experiment

Radiation source function σT^4 is replaced by a linear approximation A + BT. Sensitivity to different values for A and B is tested.

No decrease in polar amplification of surface air warming with linearization. This mechanism denial experiment contradicts budget-based results [1], as other components also change [6].

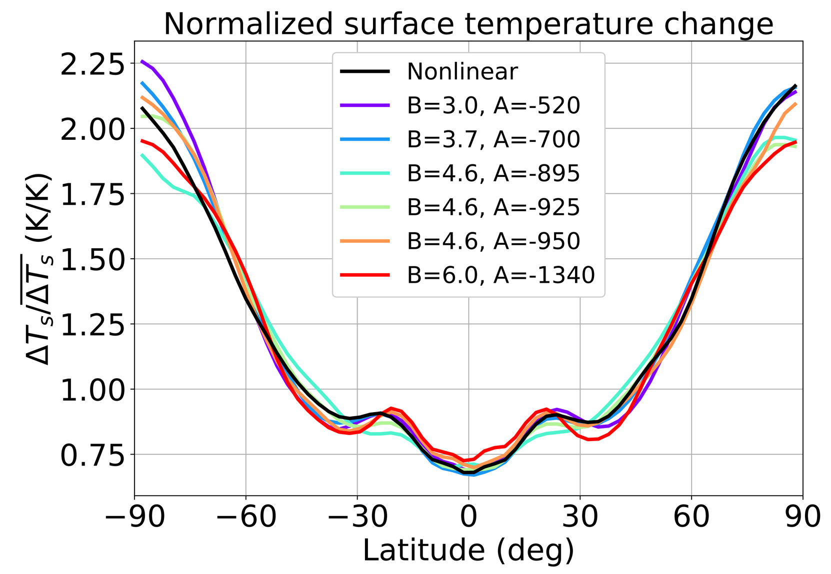

Figure 3: Normalized surface air temperature change for all configurations

Important Result

- **Nonlinearity of σT^4 does not affect horizontal structure of warming.**
- **But lowers the lapse rate feedback across all latitudes.**

Effect on lapse rate

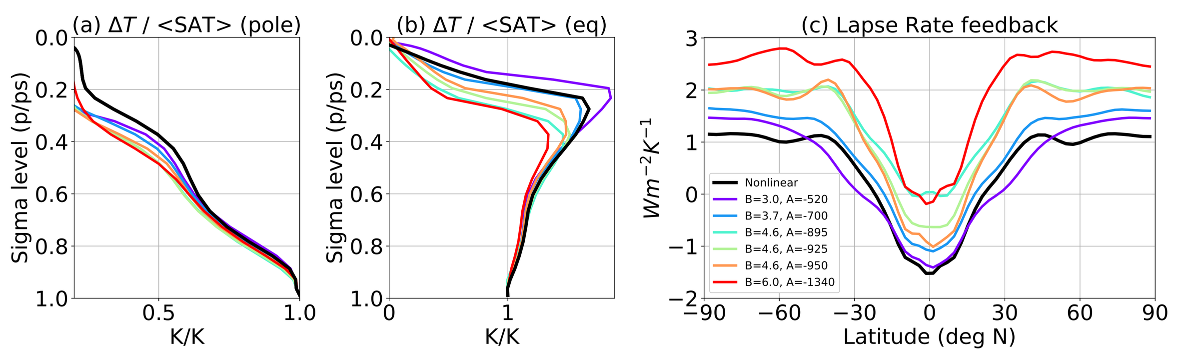

Figure 4: Effect on vertical structure of temperature change

Effect of nonlinearity on radiation is simple to understand, so we start with a pure radiative configuration, then a radiative-convective configuration, to see if they have a comparable ≈0.5 W m^{-2} feedback difference.

Model Hierarchy

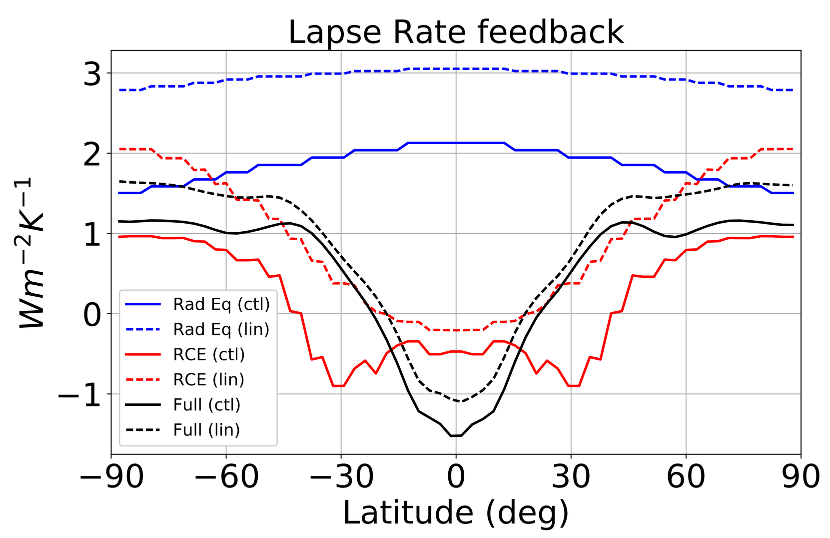

Figure 5: Lapse rate feedback for nonlinear and linear (A=-700, B=3.7) radiation simulations for three different configurations (pure radiative, radiative-convective and full GCM).

Conclusion

Climatological atmospheric temperature structure is responsible for latitudinal structure in radiative forcing, which leads to tropically-amplified forcing if only the forcing and Planck feedback are considered.

Contrary to expectations, nonlinearity of σT^4 does not affect horizontal structure of warming when it is eliminated in the prognostic radiative transfer calculation.

Nonlinear radiation simulation has a systematically lower (more stabilizing) lapse rate feedback across all latitudes compared to linear radiation simulations. Therefore, this nonlinearity results in cold upper layers warming more to reach the same increase in radiation.

Hierarchy of models shows how effect of nonlinearity on pure radiative configuration propagates to the full GCM. Changes in convective and advective tendencies bring linear radiation simulations closer to nonlinear radiation simulations, but are not sufficient to completely offset the cold-altitudes-warm-more effect of σT^4.

References

[1] Pithan and Mauritsen 2014

[2] Payne et al. 2015

[3] Huang et al. 2016

[4] Soden et al. 2008

[5] Frierson et al. 2006

[6] Henry and Merlis 2017