Do clouds contribute to polar amplification?

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Summary

Traditional climate feedback analysis, which assumes that individual feedback mechanisms are additive and act independently, suggests that clouds do not contribute to polar amplification. However, feedback locking experiments, where the cloud radiative feedback is disabled, suggest that clouds do contribute to polar amplification. Here, we reconcile these two perspectives by introducing a framework that accounts for feedback, forcing, and atmospheric heat transport interactions in a comprehensive climate model. We find that clouds do contribute to polar amplification by interacting with other climate feedbacks. A moist energy balance model (MEBM) with a locked cloud feedback supports these results and is used to further quantify the influence of clouds on polar amplification in a range of climate models under greenhouse-gas forcing. These results suggest that clouds do contribute to polar amplification and contribute significantly to the intermodel spread in polar amplification. These results highlight the need to better quantify the contributions of feedback and atmospheric heat transport interactions to polar amplification.

Background and motivation

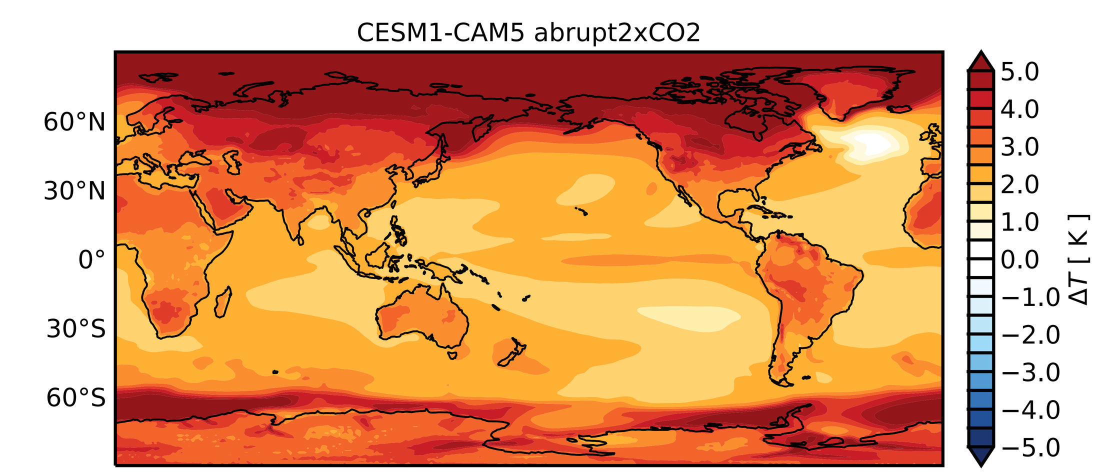

Figure 1. The change in surface temperature from CESM1-CAM5 averaged over years 100-150 after abrupt2xCO2.

- Under increased greenhouse-gas concentrations, climate models (e.g., CESM1-CAM5) exhibit polar-amplified warming (Fig. 1).

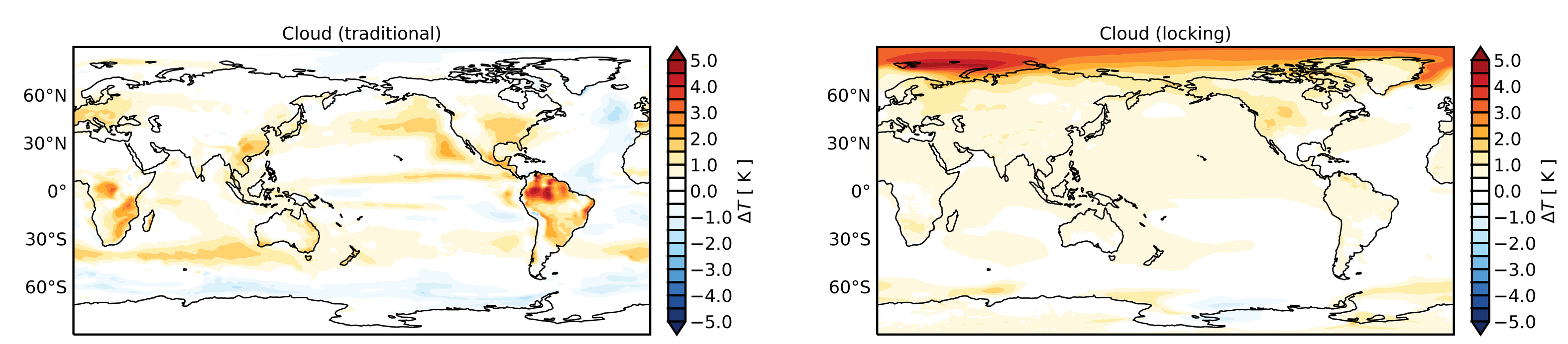

Figure 2. The change in surface temperature from CESM1-CAM5 that is associated with clouds (left) diagnosed using the traditional feedback framework and (right) estimated using cloud locking experiments.

- Traditional feedback analysis, which assumes the contribution of climate feedbacks to temperature change are additive and act indecently, suggests that clouds do not contribute to polar amplification (Fig. 2, left; Pithan and Mauritsen, 2014; Feldl et al., 2020, Hahn et al., 2021).
- Cloud locking experiments, however, where the cloud feedback is disabled, suggest that clouds do contribute to polar amplification (Fig. 2, right; Middlemas et al., 2020; Chalmers et al., 2022).
- How do we reconcile these two perspectives (Fig. 3)?

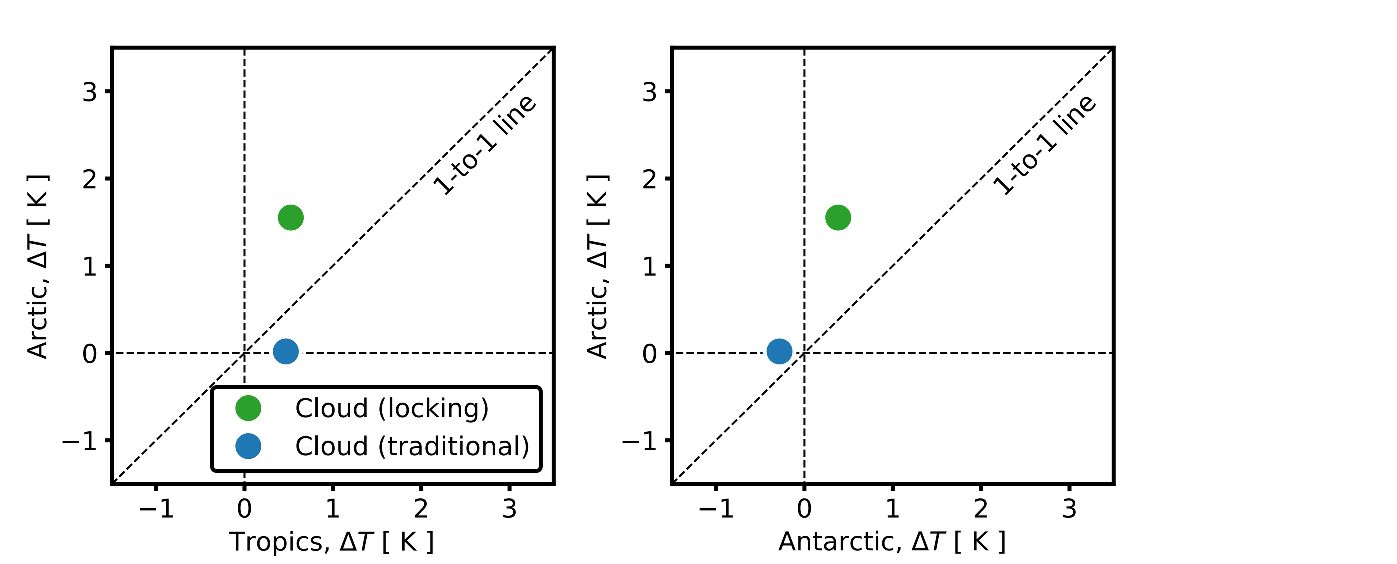

Figure 3. Scatter plot of cloud contribution to surface temperature change for the (left) Tropics versus Arctic and (right) Antarctic and Arctic. The green dot denotes the locking method. The blue dot denotes the traditional method.

A framework for understanding feedback locking

- Following Pithan and Mauritsen, (2014), local surface temperature change ΔT can be partitioned into contributions from radiative forcing R_f, climate feedbacks λ, changes in the atmospheric heat flux convergence $\Delta(\nabla \cdot F)$ and ocean heat uptake ΔG via:

$$\Delta T = \frac{1}{\lambda_0}\left(-R_f - \sum_i \lambda_i \Delta T + \Delta(\nabla \cdot F) + \Delta G - \epsilon\right)$$

- Each term in the above expression can be diagnosed from the abrupt2xCO2 simulation or abrupt2xCO2 simulation with locked cloud feedbacks.
- The difference between the abrupt2xCO2 simulation and abrupt2xCO2 simulation with locked cloud feedbacks can be interpreted as the effect of clouds on surface temperature change under greenhouse-gas forcing.
- The above expression allows us to isolate specific mechanisms related to the effect of an inactive cloud feedback.

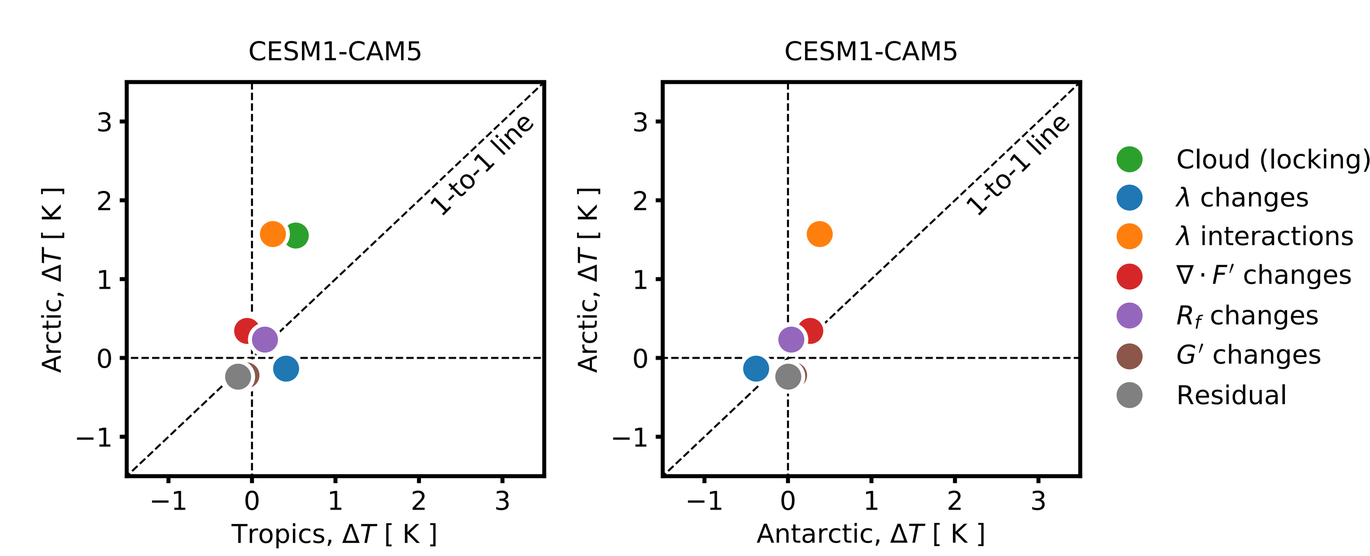

Figure 4. Scatter plot of the cloud contribution to surface temperature change for the (left) Tropics versus Arctic and (right) Antarctic and Arctic in CESM1-CAM5. The green dot denotes the cloud contribution. The blue dot denotes the change in the total feedback, the orange dot denotes the interactions of other feedbacks with the change in temperature from clouds, the red dot denotes changes in atmospheric heat transport from clouds, the purple dot denotes the change in surface temperature from cloud-induced radiative forcing, and the brown dot denotes the change in surface temperature from cloud-induced ocean heat uptake. The grey dot is a residual.

- A decomposition of the cloud locking simulation shows that, at least in CESM1-CAM5, clouds contribute to polar amplification via interactions of the temperature change associated with clouds and other climate feedbacks (Fig. 4, orange dot).
- Most other terms contribute little to the surface temperature change.
- Interestingly, the change in the total feedback (Fig. 4, blue dot) is nearly identical to the local cloud feedback (Fig. 3, blue dot), suggesting other feedbacks do not change when the cloud feedback is locked.

Cloud locking in a moist energy balance model (MEBM)

- We further use a MEBM to investigate the influence of clouds on polar amplification. The MEBM can be described via:

$$R_f + \sum_i \lambda_i \Delta T - \Delta G = \Delta(\nabla \cdot F)$$

$$\Delta F = -\frac{2\pi p_s}{g} D(1-x^2)\frac{d\Delta h}{dx} \qquad h = c_p \Delta T + L_v \Delta q$$

Comparison to CESM1-CAM5

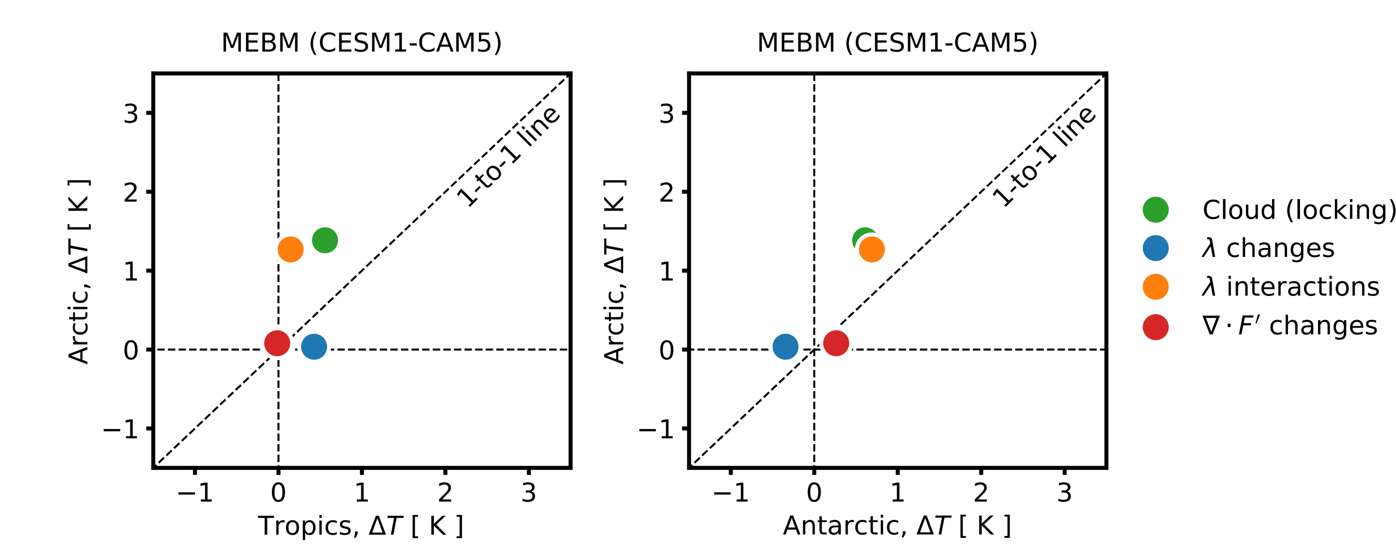

Figure 5. Scatter plot of the cloud contribution to surface temperature change for the (left) Tropics versus Arctic and (right) Antarctic and Arctic in a MEBM using CESM1-CAM5 output. The green dot denotes the cloud contribution. The blue dot denotes the change in the total feedback, the orange dot denotes the interactions of other feedbacks with the change in temperature from clouds, and the red dot denotes cloud-induced atmospheric heat transport.

- The MEBM tends to emulate CESM1-CAM5, with feedback interactions contributing to the contribution of clouds to polar amplification (Fig. 5).
- Feedback locking in the MEBM with CMIP5 output suggest clouds can contribute to polar amplification, however, there is a substantial amount of intermodel spread (Fig. 6).

Extrapolating to CMIP5

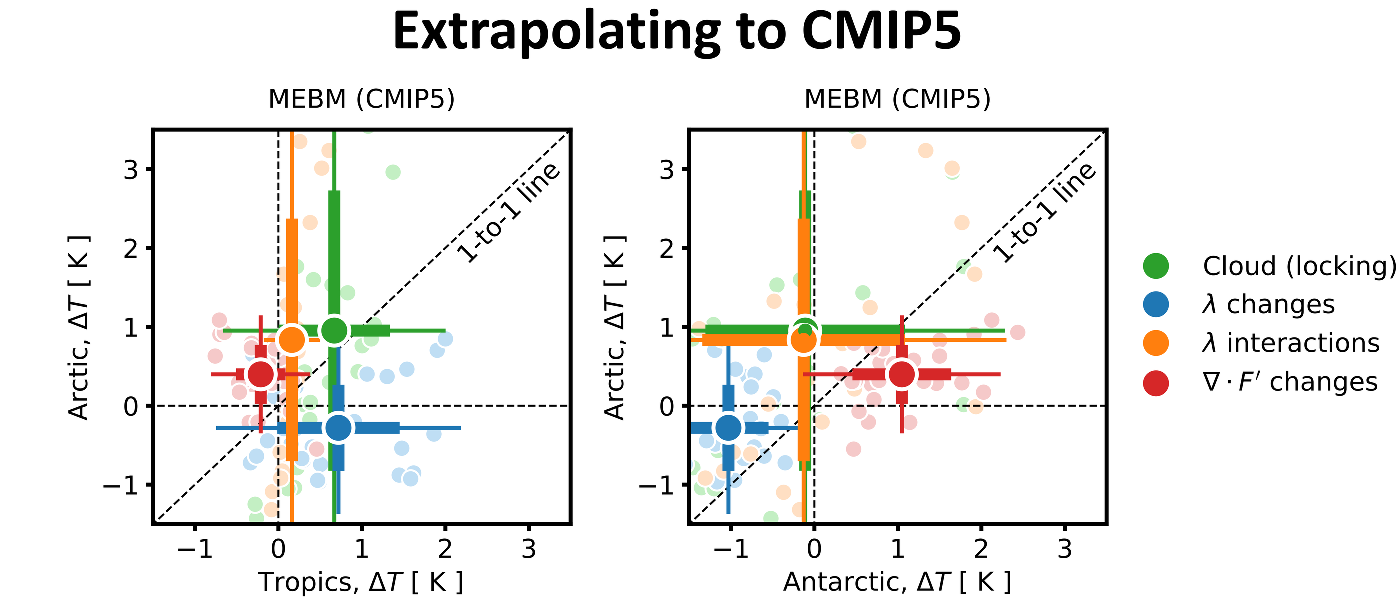

Figure 6. Scatter plot of the cloud contribution surface temperature change for the (left) Tropics versus Arctic and (right) Antarctic and Arctic in a MEBM using CMIP5 output. The green dot denotes the cloud contribution. The blue dot denotes the change in the total feedback, the orange dot denotes the interactions of other feedbacks with the change in temperature from clouds, and the red dot denotes cloud-induced atmospheric heat transport. The thick bars denote one standard deviation and the thin bars denote two standard deviations.