Polar amplification is inevitable: using a moist energy balance model (MEBM) to teach about the mechanisms shaping the magnitude of polar amplification

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Summary

For the past ~8 years, I've been using a moist energy balance model (MEBM) to teach graduate and advanced undergraduate students about the causes of polar amplification. This tool elegantly demonstrates:

(1) the key role of moisture transport in driving polar amplification
(2) the relative contributions of individual radiative feedbacks to polar amplification
(3) how feedbacks together to shape the magnitude of polar amplification
(4) how the spatial pattern of CO_2 forcing shapes polar amplification and the key role of ocean heat uptake in driving the warming asymmetry between the poles

A key takeaway is that polar amplification is inevitable. It is driven by positive polar feedbacks, but even in their absence, atmospheric heat transport would still cause the poles to warm more than the tropics.

The moist energy balance model (MEBM)

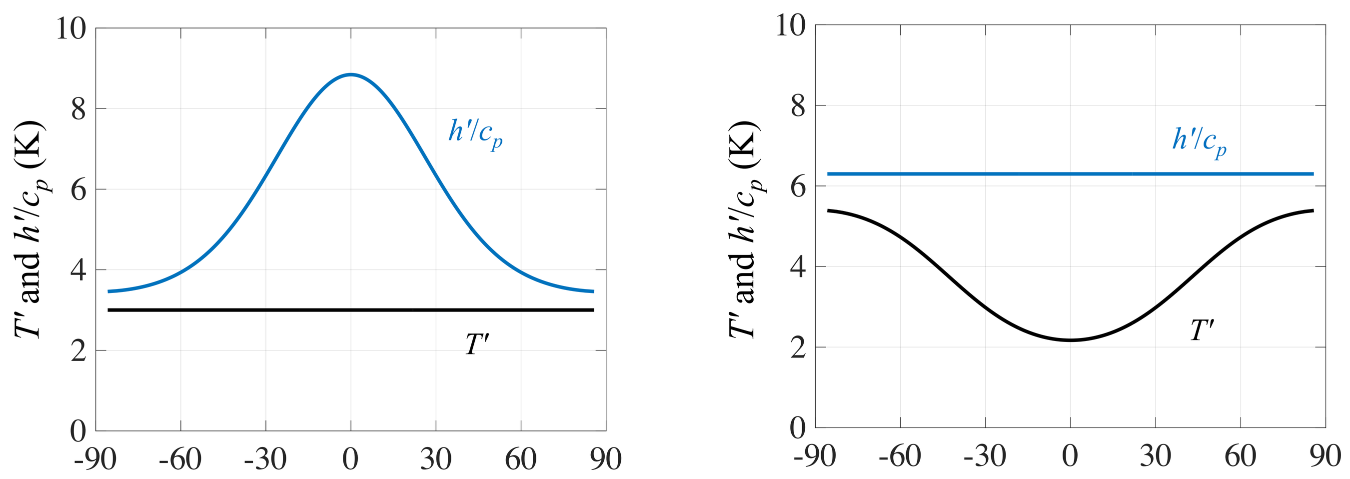
The MEBM is an idealized model for zonal-mean climate change that accurately reproduces the behavior of CMIP models[1-7]. The MEBM takes as inputs the zonal-mean radiative feedbacks (λ), radiative forcing (R_f), and ocean heat uptake (G') from CMIP models and predicts zonal-mean near-surface temperature anomaly (T'), near-surface moist static energy anomaly (MSE; h') assuming constant relative humidity, and atmospheric heat transport anomaly (right hand side); x is sine of latitude.

$$\lambda(x)T'(x) + R_f(x) + G'(x) = -\frac{p_s}{ga^2}D_m\frac{d}{dx}\left[(1-x^2)\frac{dh'}{dx}\right]$$

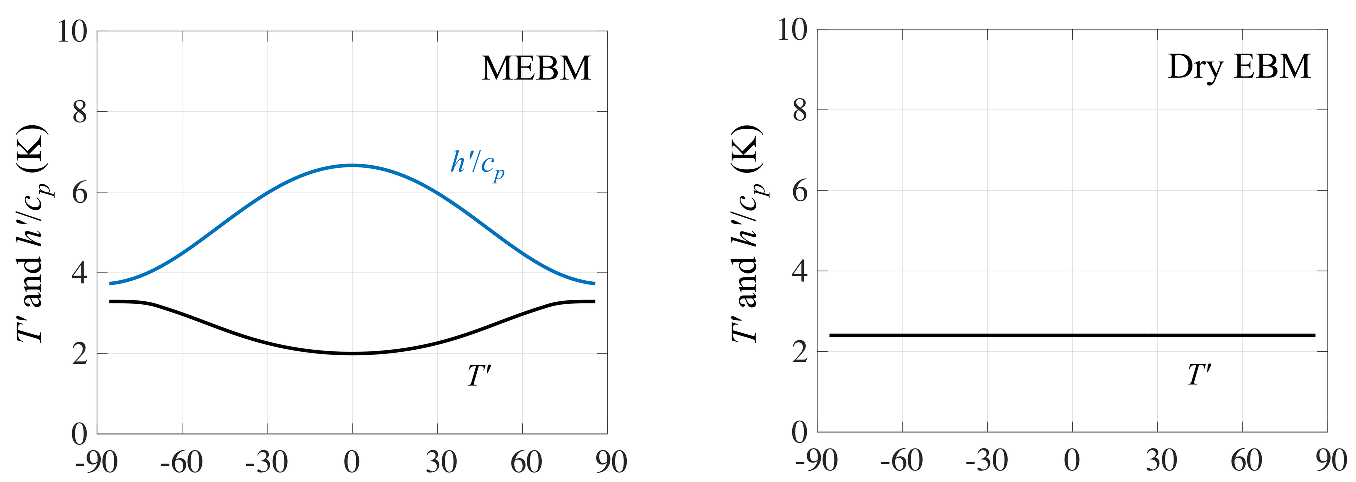
$$h'(x) \;=\; c_pT'(x) \;+\; L_v q'(x)$$

(1) Moisture is key to polar amplification

A uniform temperature increase comes with a larger increase in MSE in the tropics, while a uniform MSE increase comes with a larger increase in temperature at the poles. To the extent that atmospheric circulation acts to transport heat down the MSE gradient (heat transport ~ dh'/dx), surface warming will be polar amplified.

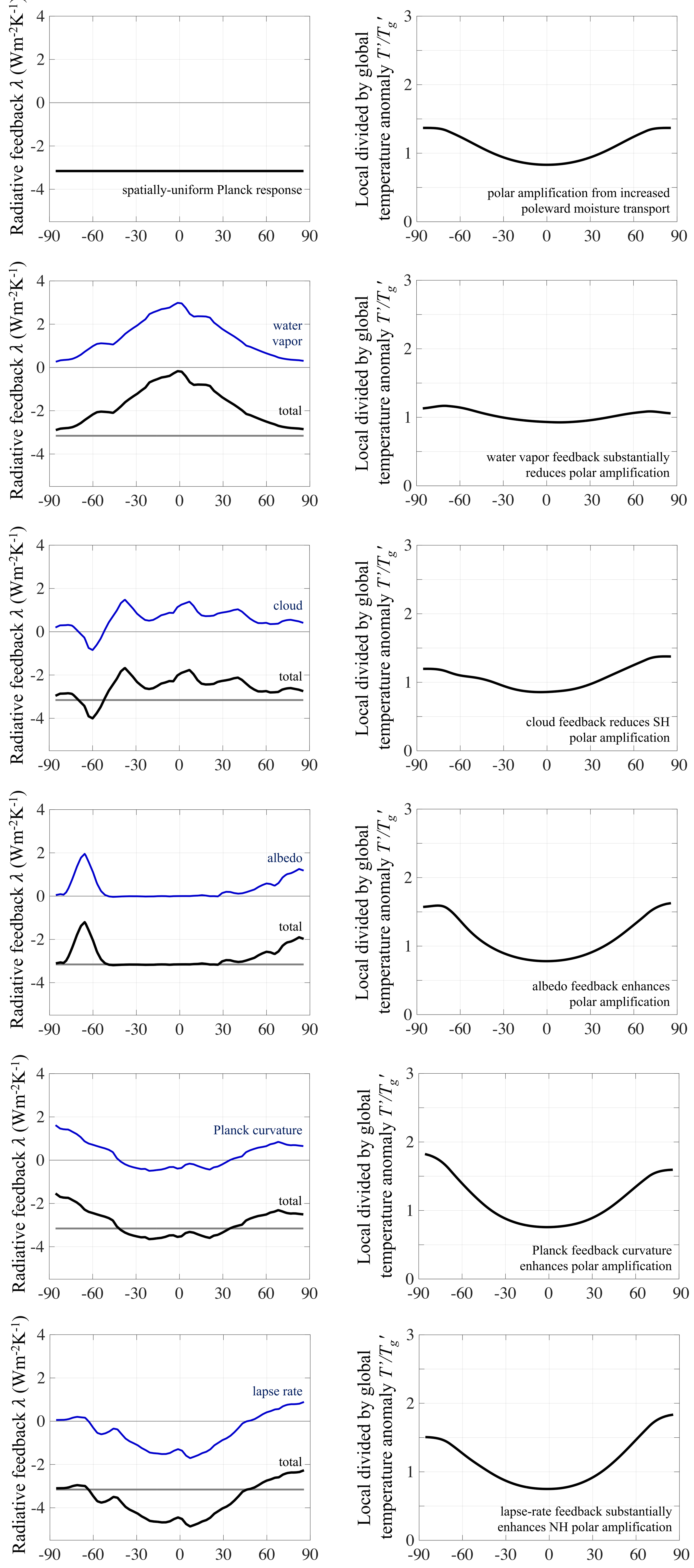


Running the MEBM with spatially uniform R_f and λ produces polar amplified surface warming, but only when moisture is included; a dry EBM produces spatially uniform warming.

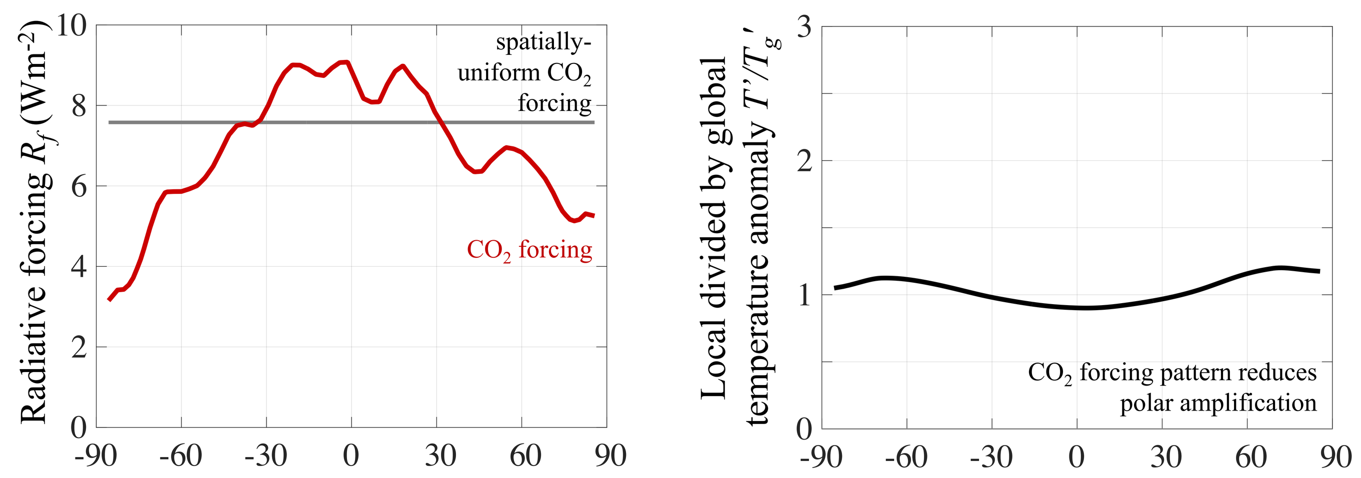


(2) Contributions of individual feedbacks to polar amplification

Starting with spatially uniform CO_2 forcing and spatially uniform Planck feedback, you can use the MEBM to illustrate how each individual feedback shapes the magnitude of polar amplification:

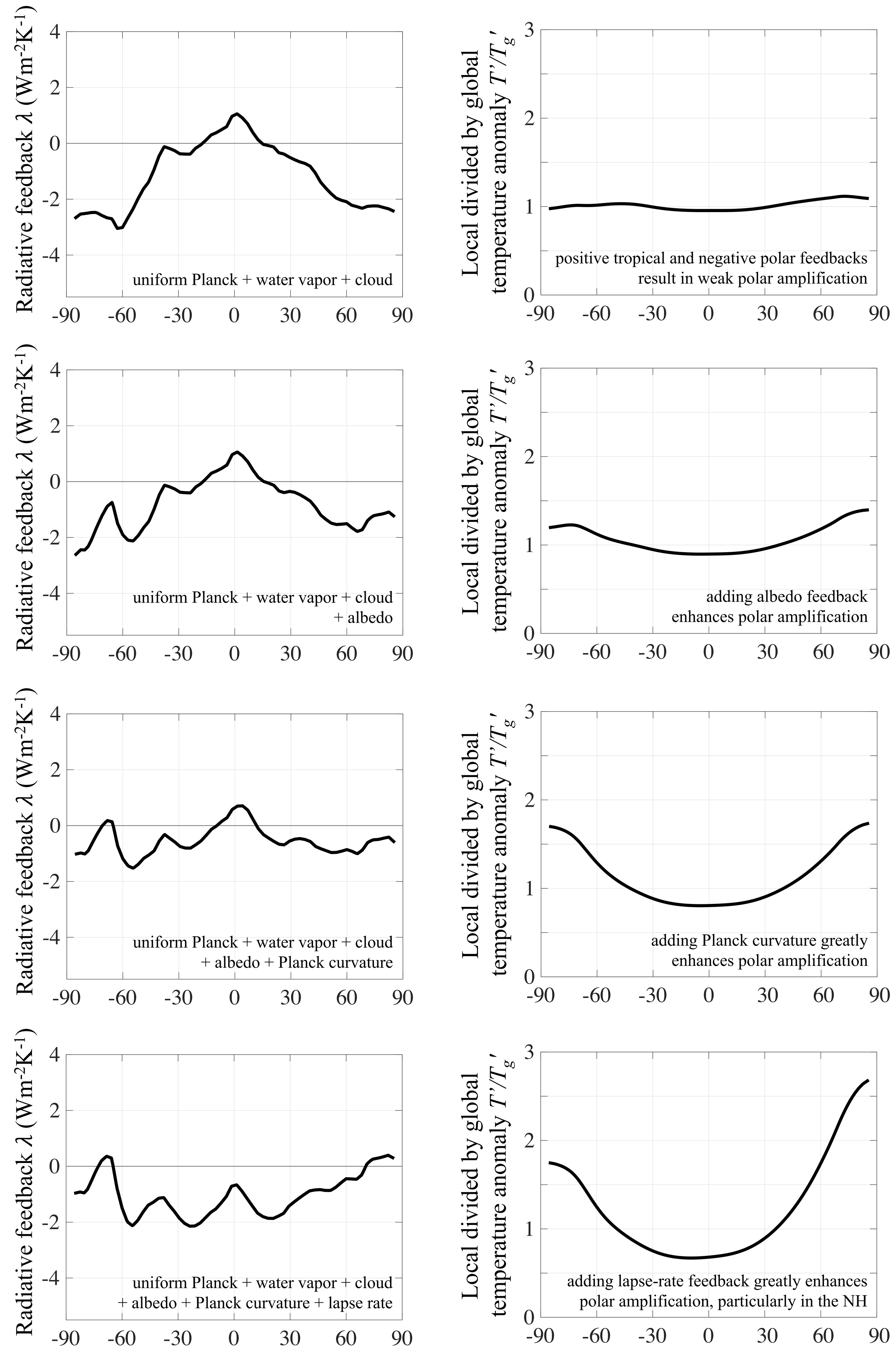


Starting with a spatially uniform Planck feedback, you can use the MEBM to illustrate how the pattern of CO_2 forcing shapes the pattern of warming:



(3) How feedbacks together shape polar amplification

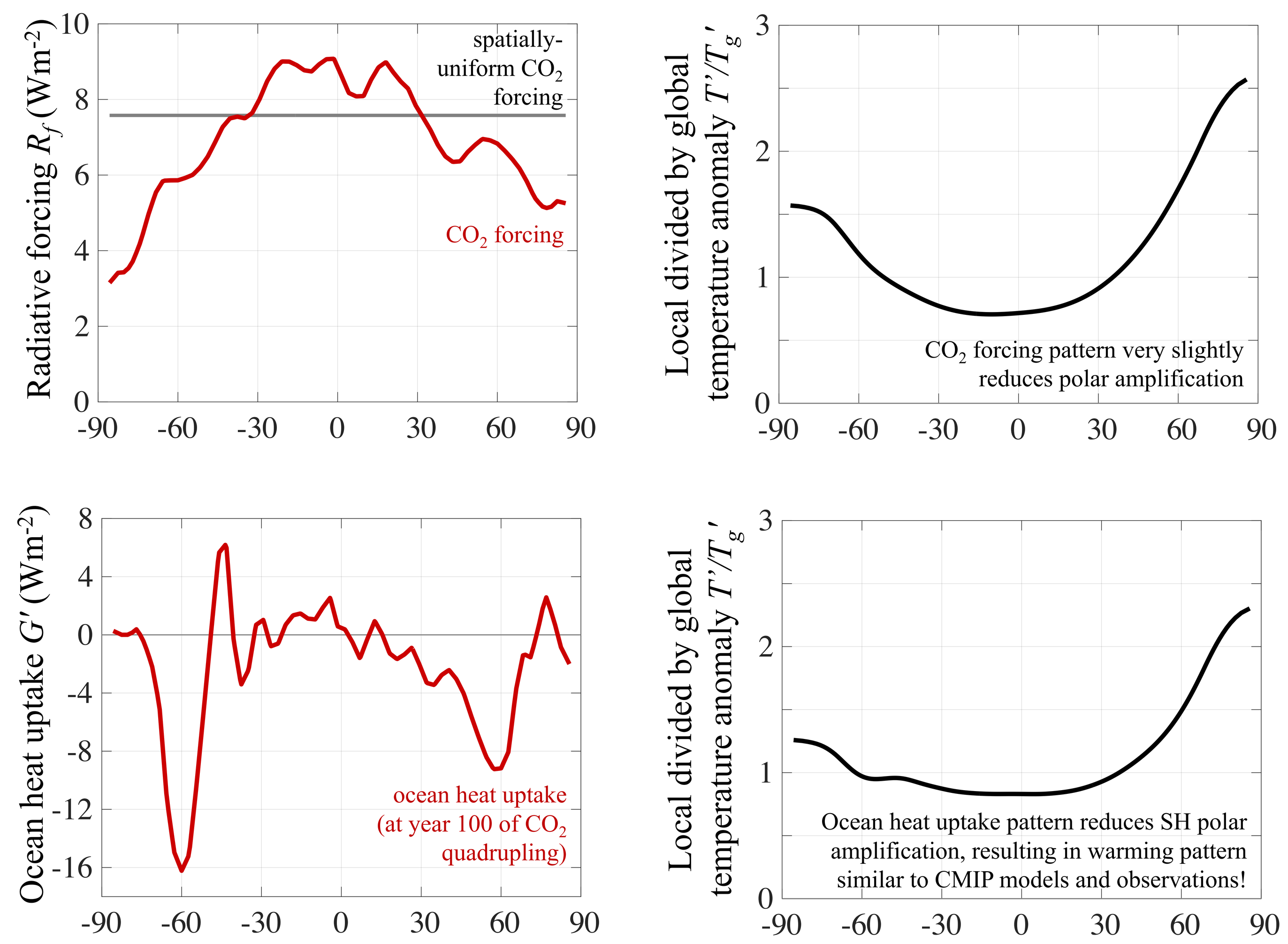
Starting with spatially uniform CO_2 forcing and spatially uniform Planck feedback, you can use the MEBM to illustrate how feedbacks together shape the magnitude of polar amplification by adding them one at a time:



Not shown, but also interesting, is that when feedbacks are positive in the tropics and negative in polar regions, polar amplification is maintained by increased poleward atmospheric heat transport (top figures); but when polar feedbacks are positive (bottom figure), polar amplification is maintained by those feedbacks and damped by reduced poleward atmospheric heat transport

(4) How the patterns of CO_2 forcing and ocean heat uptake shape polar amplification

Starting with spatially uniform CO_2 forcing but including all feedbacks, you can use the MEBM to illustrate how the spatial patterns of CO_2 forcing and ocean heat uptake shape the magnitude of polar amplification:



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