Supporting Information for "A robust constraint on the response of convective mass fluxes to warming"

Andrew I.L. Williams[1] and Nadir Jeevanjee[2]

[1]Program in Atmospheric and Oceanic Sciences, Princeton University

[2]Geophysical Fluid Dynamics Lab, Princeton, NJ

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References

Chadwick, R., Boutle, I., & Martin, G. (2013). Spatial patterns of precipitation change in cmip5: Why the rich do not get richer in the tropics. *Journal of climate*, *26*(11), 3803–3822.

Liu, J., Yang, J., Ding, F., Chen, G., & Hu, Y. (2024). Hydrologic cycle weakening in hothouse climates. *Science Advances*, *10*(17), eado2515.

1. Text S1

We are not the first to notice that the classic form of the HS06 constraint is not particularly robust. As an alternative, some studies have suggested that perhaps the *vertically-averaged* M_c is better constrained by $P/q^*_{v,LCL}$ than the cloud-base M_c. This was first suggested by Chadwick, Boutle, and Martin (2013) in the context of CMIP5 GCMs and more recently by Liu, Yang, Ding, Chen, and Hu (2024) who vertically-averaged Eq. 3 of the main text to arrive at

$$P = \epsilon \langle M_c \rangle q^*_{v,LCL}, \tag{1}$$

where ϵ is a precipitation efficiency and $\langle . \rangle$ denotes a vertical integral over the free-troposphere. Their derivation assumes that $RH = 1$ and that vertical variations in M_c are small and that these variations are uncorrelated with moisture changes. They tested Eq. 1 over a wide range of climates using a single cloud-resolving model (`dam`) and showed that it did a reasonable job of emulating the simulated changes in $\langle M_c \rangle$.

Although RCEMIP outputs are not sufficient to calculate precipitation efficiency, we can test whether changes in $\langle M_c \rangle$ scale with $P/q^*_{v,LCL}$ in the RCEMIP simulations (note that Liu et al. found changes in ϵ were small in `dam`). This is shown in Supplemental Figure 7 for two different values of the vertical velocity threshold used in the M_c calculation. Changes in $\langle M_c \rangle$ with warming are consistently negative, as opposed to changes in cloud-base M_c, and cluster more strongly around the one-to-one line than in Fig. 5a of the main text. However, the correlation between changes in $\langle M_c \rangle$ and $P/q^*_{v,LCL}$ is weak and not statistically significant. We conclude while vertically-averaged M_c corresponds slightly better to the predictions of the HS06 scaling than cloud-base M_c, the HS06 scaling does not provide a quantitative constraint on $\langle M_c \rangle$. This is either because the assumptions made in Liu et al.'s derivation are too strong, or because one needs to account for changes in precipitation efficiency for the scaling to be quantitatively accurate.

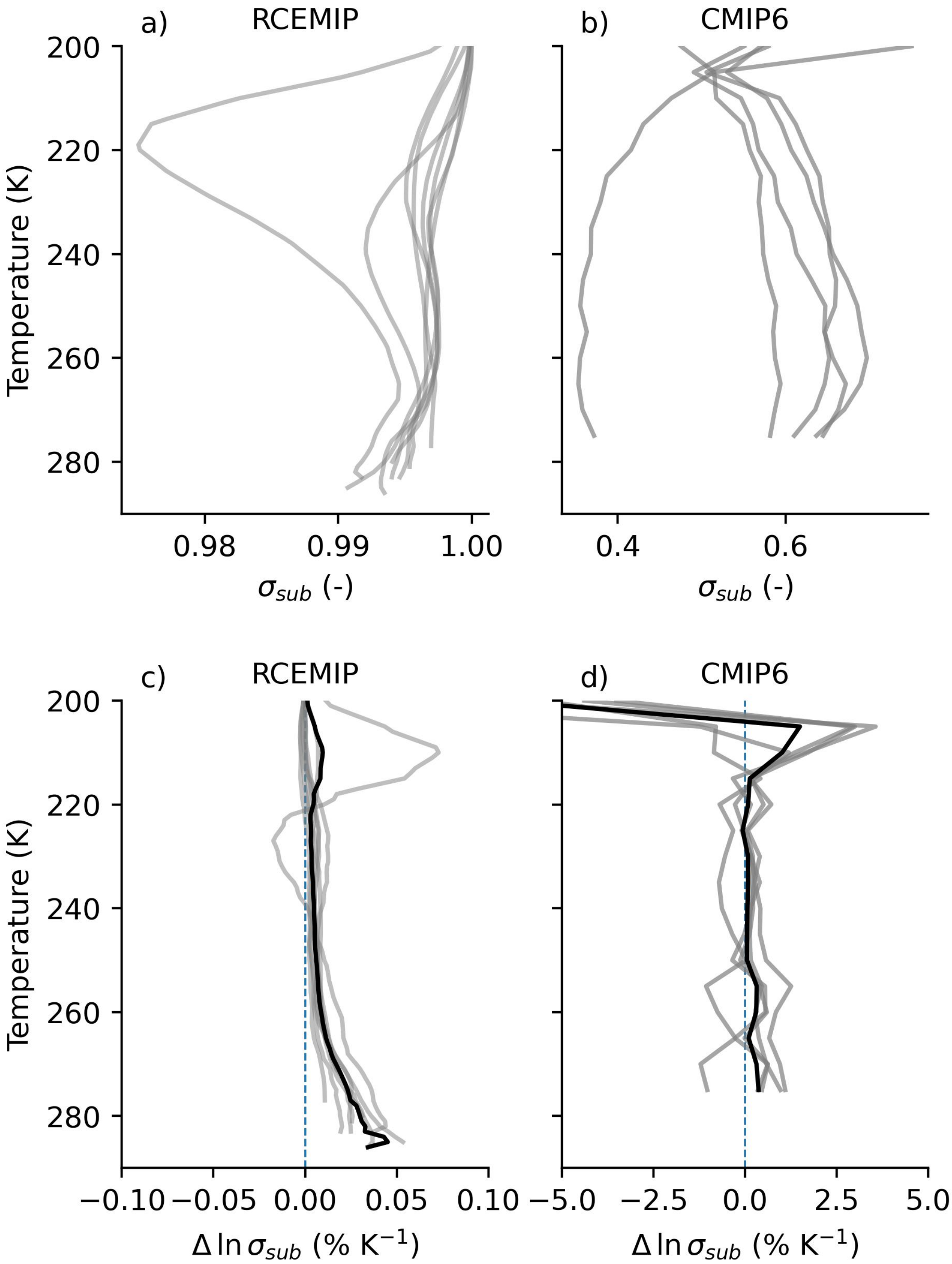

Figure S1. $\sigma_{sub} \approx 1$ *in RCEMIP, but not in GCMs. However,* σ_{sub} *changes very little with warming in either case.* Panels (a-b) show σ_{sub} profiles in $T-$coordinates in the control run, and panels (c-d) show fraction $\Delta\sigma_{sub}$ changes with warming, also in $T-$coordinates (cut off below cloud base and above the cold-point tropopause). The ensemble mean is shown in black for panels (c) and (d).

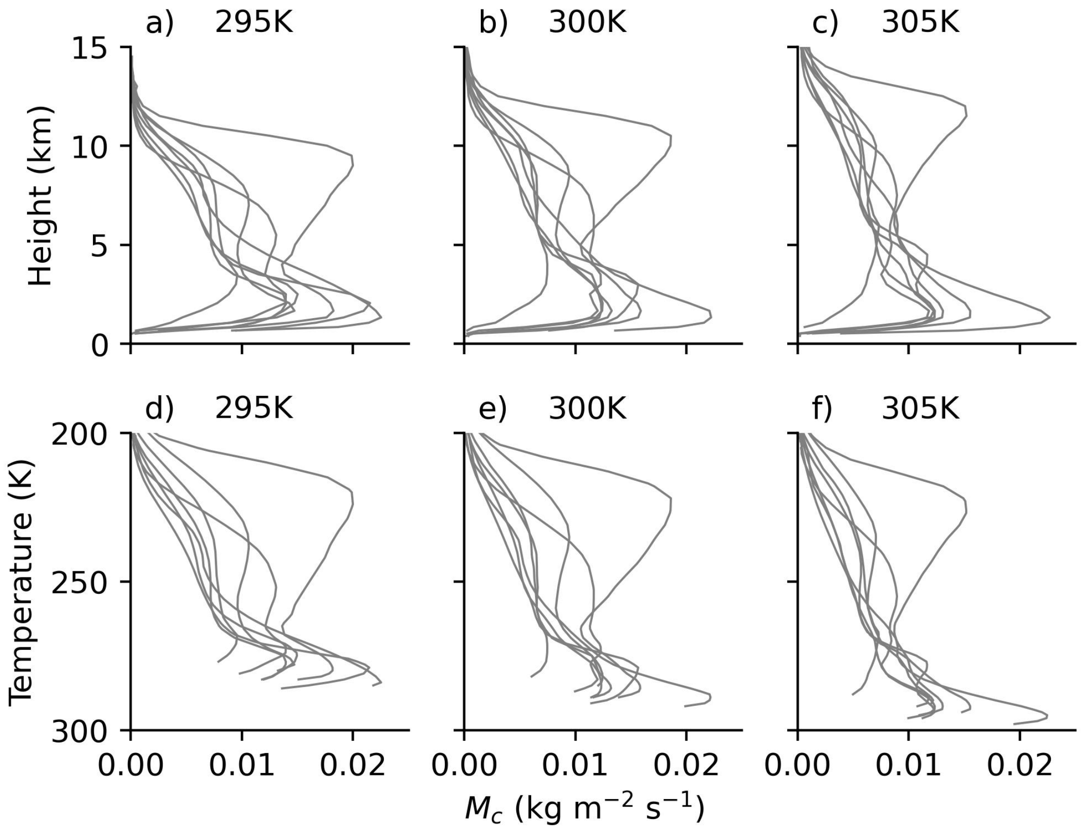

Figure S2. *There is a large spread in M_c profiles across RCEMIP models.* Panels (a-c) show M_c profiles in $z-$coordinates, and panels (d-f) show M_c profiles in $T-$coordinates (cut off below cloud base and above the cold-point tropopause).

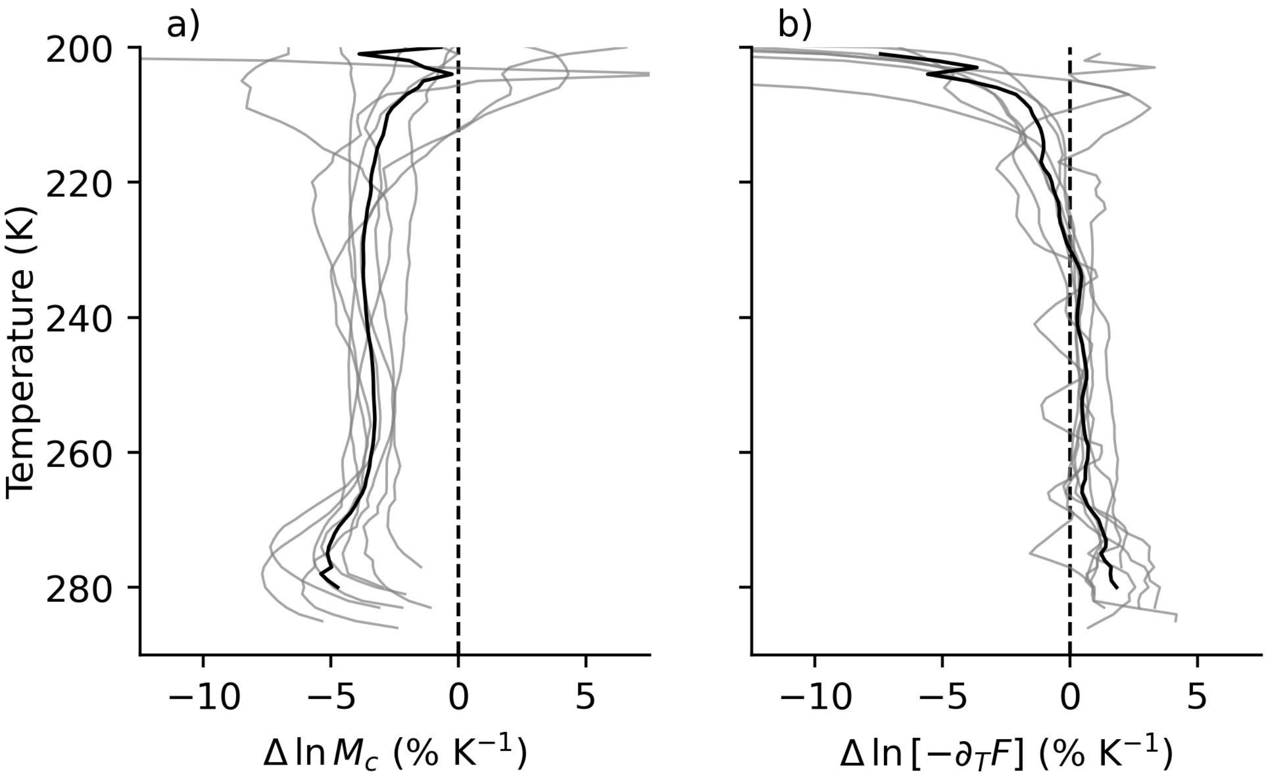

Figure S3. *Changes in $-\partial_T F$ (along isotherms) are small, and uncertain, compared to changes in M_c.*

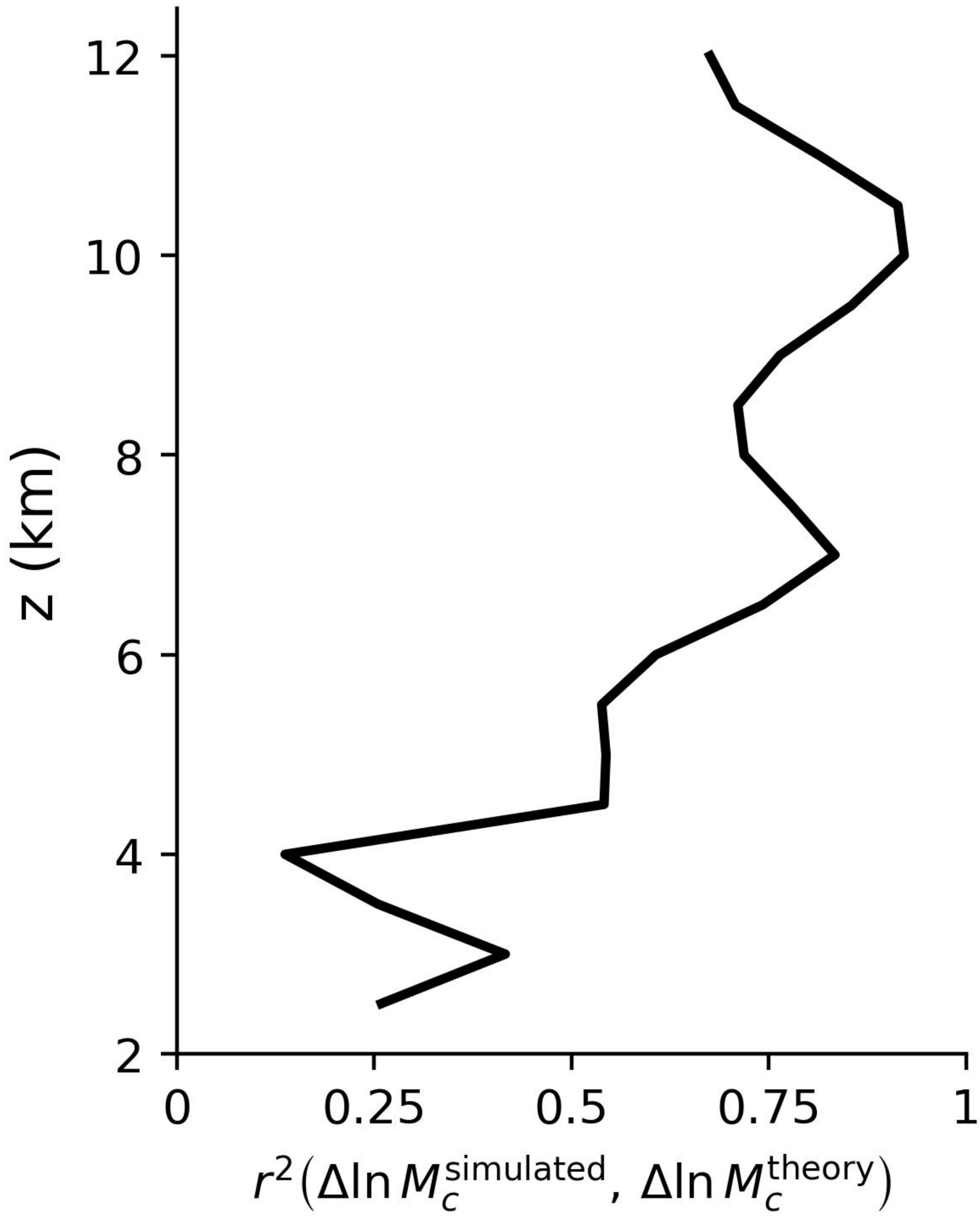

Figure S4. *Our theory captures inter-model spread in M_c changes in RCEMIP, throughout the troposphere.* The square of the Pearson correlation coefficient between predicted and simulated % K^{-1} changes in M_c across RCEMIP simulations. Result is plotted at every height where M_c is defined in all models, for every SST value.

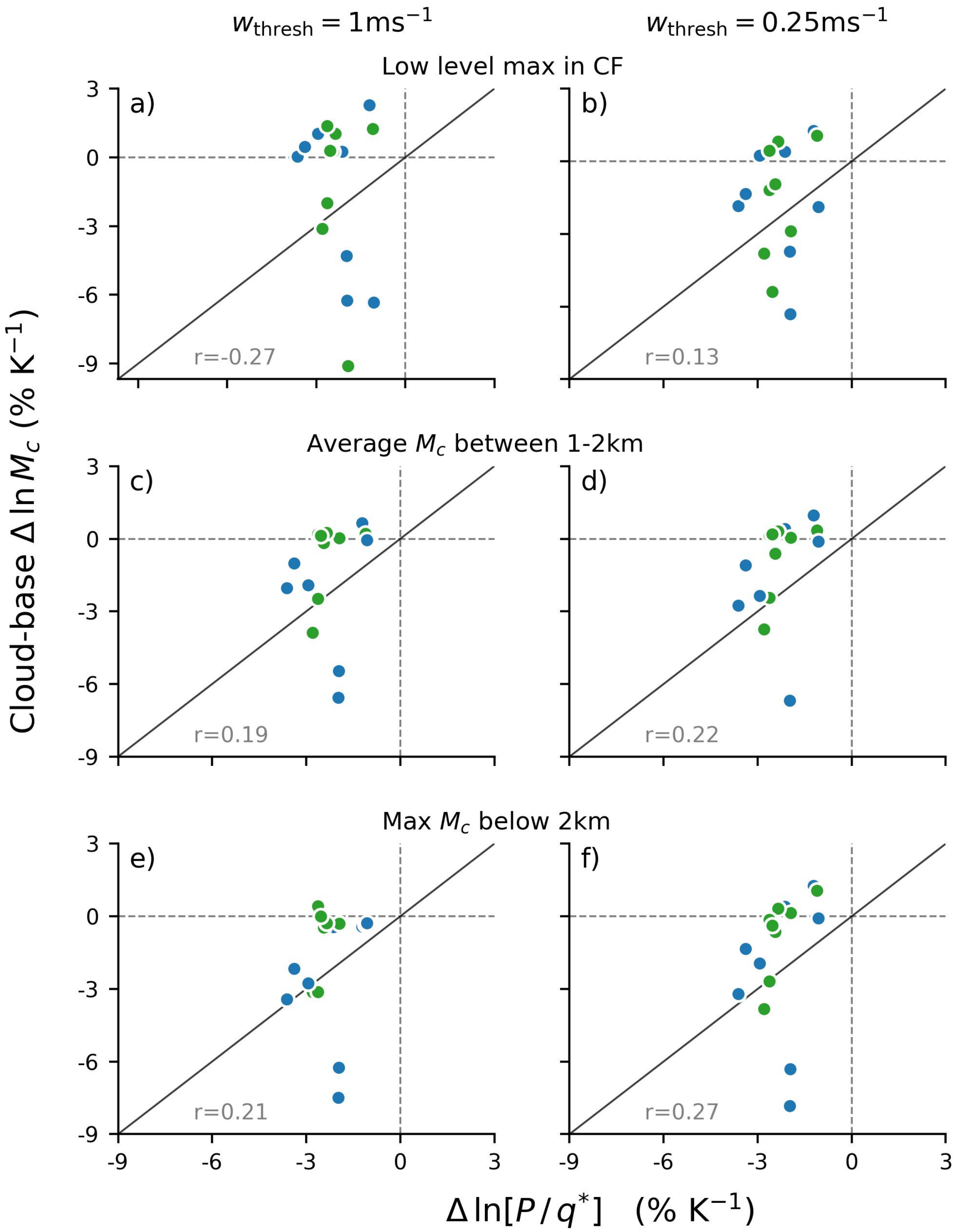

Figure S5. Assessing the sensitivity of Fig. 1 to different definitions of cloud base M_c. Panels (a-b) using M_c diagnosed at the level corresponding to the lower-level maximum in domain-average cloud fraction. Panels (c-d) using average M_c between 1-2km. Panels (e-f) using the maximum M_c below 2km. The left column shows the results when M_c is diagnosed using a threshold vertical velocity of $1\mathrm{ms}^{-1}$ (as in the main text), the right column shows the results when using a smaller threshold of $0.25\mathrm{ms}^{-1}$. Pearson correlation coefficients are shown in grey in each panel; none of the correlation coefficients are significant (i.e. $p > 0.05$).

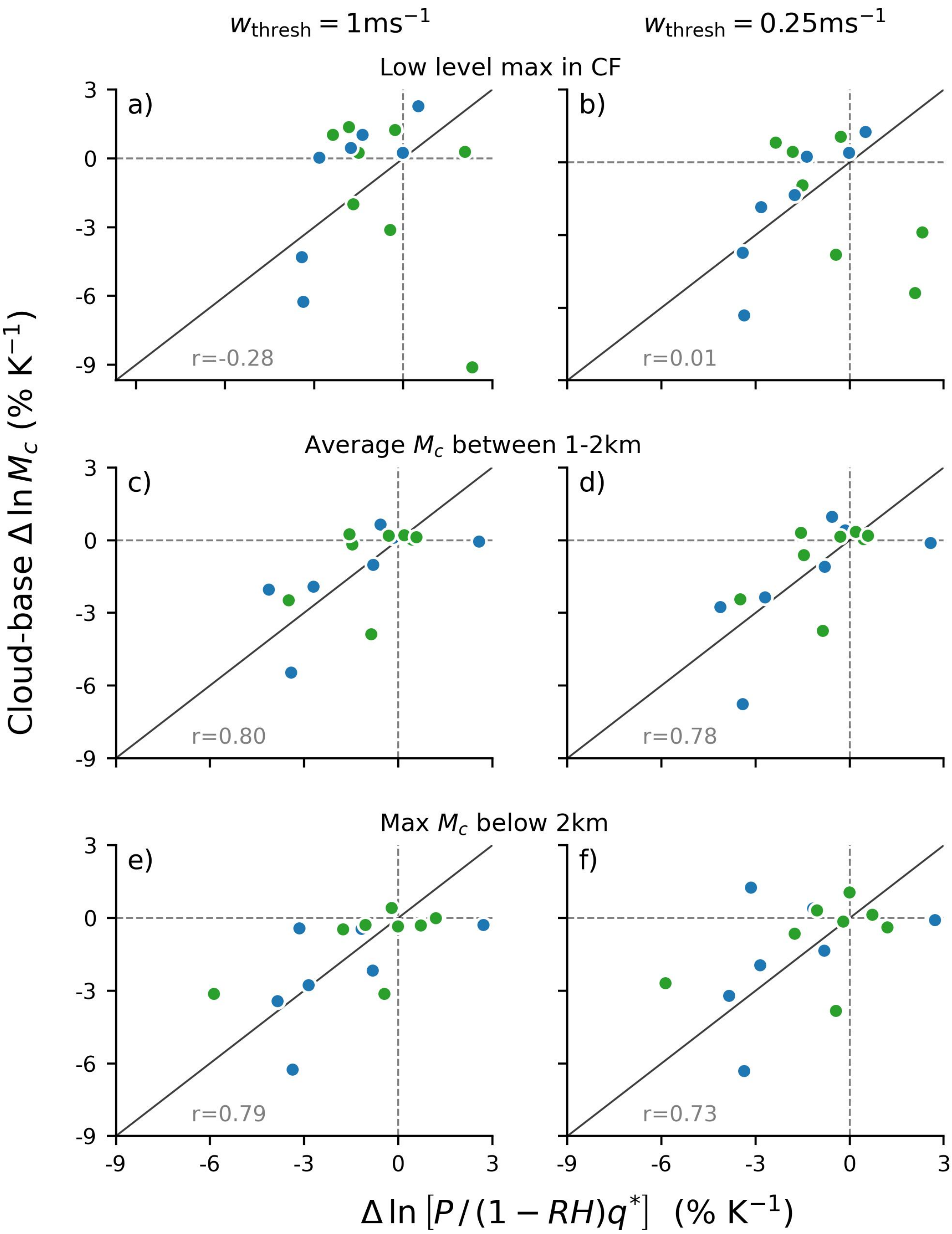

Figure S6. As in Figure S2, but for Eq. (4) of the main text.

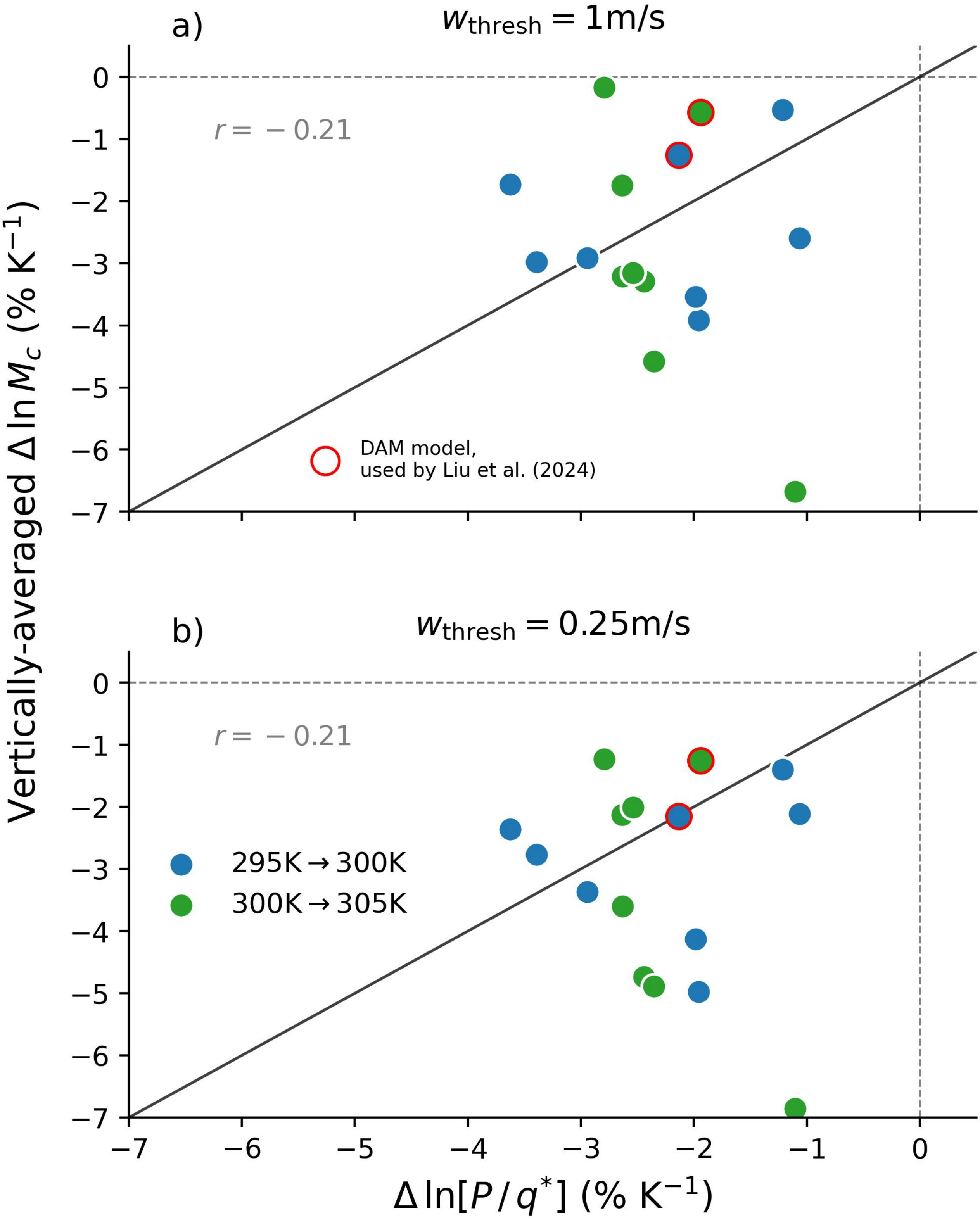

Figure S7. Testing the Liu et al. (2024) scaling on convective mass fluxes. Panels (a) and (b) represent two different vertical velocity thresholds for calculating the convective mass flux. Pearson correlation coefficients are shown in both panels, neither are statistically significant.