Supporting Information for "CLUBB reduces low-cloud dependency on shallow convective mixing in the Community Atmosphere Model: insight from stable water isotopes"

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Text S1: Analysis of *rasn* experiment

Halving autoconversion (*rasn*) leads to a weaker (but still positive) cloud-mixing relationship. Compared to CAM5, reducing autoconversion increases free troposphere moisture and cloud (Figure 9), bearing some similarity to the effects of adding MG2 to CAM5 (Figure 5). Both reduced autoconversion and the prognostic precipitation of MG2 have the effect of reducing weaker precipitation events (i.e., drizzle). That is, both reduce precipitation (conversion) efficiency such that clouds persist longer and retain more condensate. CLUBB reduces grid-mean humidity aloft such that clouds evaporate quickly, but the MG2 changes allow them to persist longer and maintain higher low-cloud fraction values with stronger mixing, as shown in Figure 3. Thus, combining CLUBB with MG2 recreates some dependency of low-cloud fraction on mixing as seen in CAM5 without CLUBB.

Text S2: Sensitivity tests

SI figures S2–S5 and S7–S8 reproduce main text Figure 3 with alternative choices of cumulus region definition, horizontal resolution, and vertical layer definition.

We varied the shallow cumulus (cul from the CASCADD data) threshold from 0.15 to 0.25. While cul = 0.25 (Figure S2; 99 of 864 tropical 5° × 5° grid boxes) looks slightly different from our selected threshold of cul=0.2, cul = 0.15 (Figure S3; 609 grid boxes) and cul = 0.20 (main text Figure 3; 397 grid boxes) look *very* similar. Furthermore, cul=0.25 would not qualitatively change any of our conclusions. Figure S4 shows output from the region defined by cul=0.20 but analyzed at model resolution 1.875 ° × 2.5° (2085 grid boxes) instead of at the lower 5° × 5° resolution used in the main text. Figure S5 implements more restricted vertical layer definitions compared to the main text: the

boundary layer and free troposphere here are 850–925 hPa and 600–750 hPa, respectively, as compared to 800–925 hPa and 600–800 hPa in the main text.

Figure S6 compares contours of omega (subsidence) at 500 hPa and lower tropospheric stability (LTS; the difference between the potential temperature at 700 hPa and at the surface) to the CASSCAD cul contours. Figures S7 and S8 utilize a region defined by subsidence and LTS from the CAM5_in6 and CAM6 runs, respectively. After Medeiros and Stevens (2011), we use subsidence $\geq$ 10 hPa/day and LTS $<$ 18.55 K to define the alternative study regions for our sensitivity analysis.

References

Eidhammer, T., Gettelman, A., Thayer-Calder, K., Watson-Parris, D., Elsaesser, G., Morrison, H., ... McCoy, D. (2024). An extensible perturbed parameter ensemble (PPE) for the Community Atmosphere Model version 6. *EGUsphere*, 1–27. doi: https://doi.org/10.5194/egusphere-2023-2165

Medeiros, B., & Stevens, B. (2011). Revealing differences in GCM representations of low clouds. *Climate Dynamics*, *36*, 385–399. doi: https://doi.org/10.1007/s00382-009-0694-5

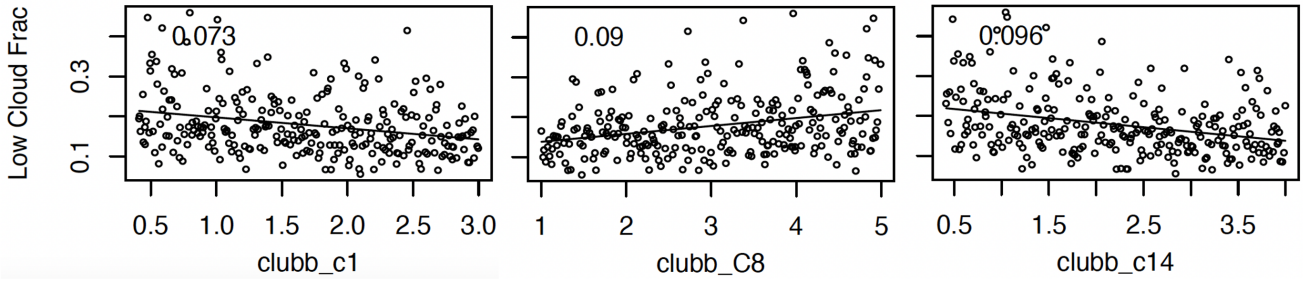


Figure S1. Selected results of perturbed parameter ensemble published in Eidhammer et al. (2024). Regression of tropical (between 30° N and S) low-cloud fraction on CLUBB parameters c1, c8, and c14.

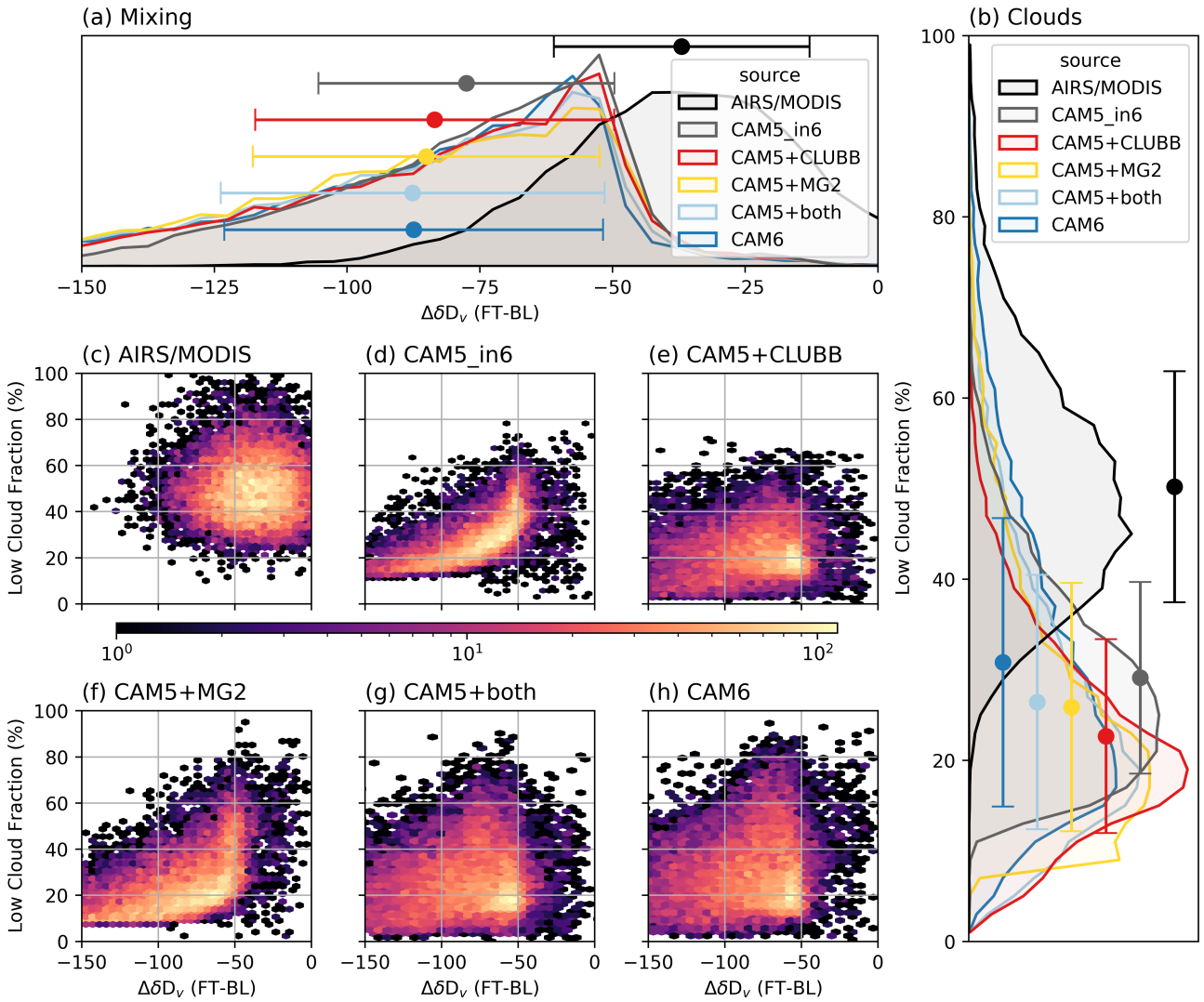


Figure S2. Like Figure 3 in the main text, but with a study region defined by CASCCAD cul = 0.25: distributions of $\Delta\delta D$ and low-cloud fraction for AIRS/MODIS satellite data and CAM5 to CAM6 transition experiments. Panels a and b show probability distributions with central dots representing the mean values and bars showing ±1 standard deviation. Panels c–h are density plots with binned $\Delta\delta D$ and low-cloud fraction from all included grid boxes and months for each source (AIRS/MODIS and each CAM5 to CAM6 transition experiment). Color bar represents count.

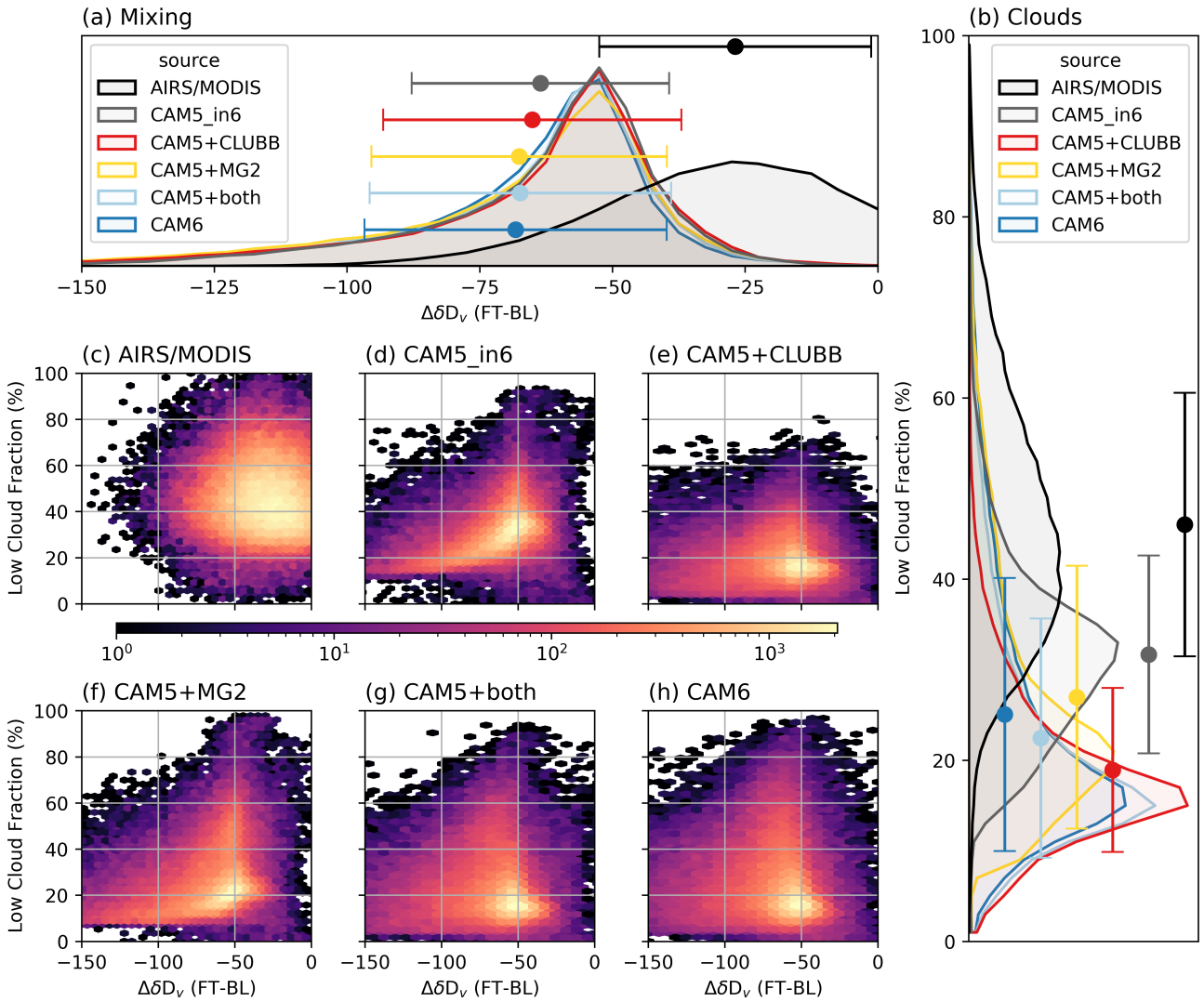


Figure S3. Like Figure 3 in the main text, but with a study region defined by CASCCAD cul = 0.15: distributions of $\Delta\delta D$ and low-cloud fraction for AIRS/MODIS satellite data and CAM5 to CAM6 transition experiments. Panels a and b show probability distributions with central dots representing the mean values and bars showing ±1 standard deviation. Panels c–h are density plots with binned $\Delta\delta D$ and low-cloud fraction from all included grid boxes and months for each source (AIRS/MODIS and each CAM5 to CAM6 transition experiment). Color bar represents count.

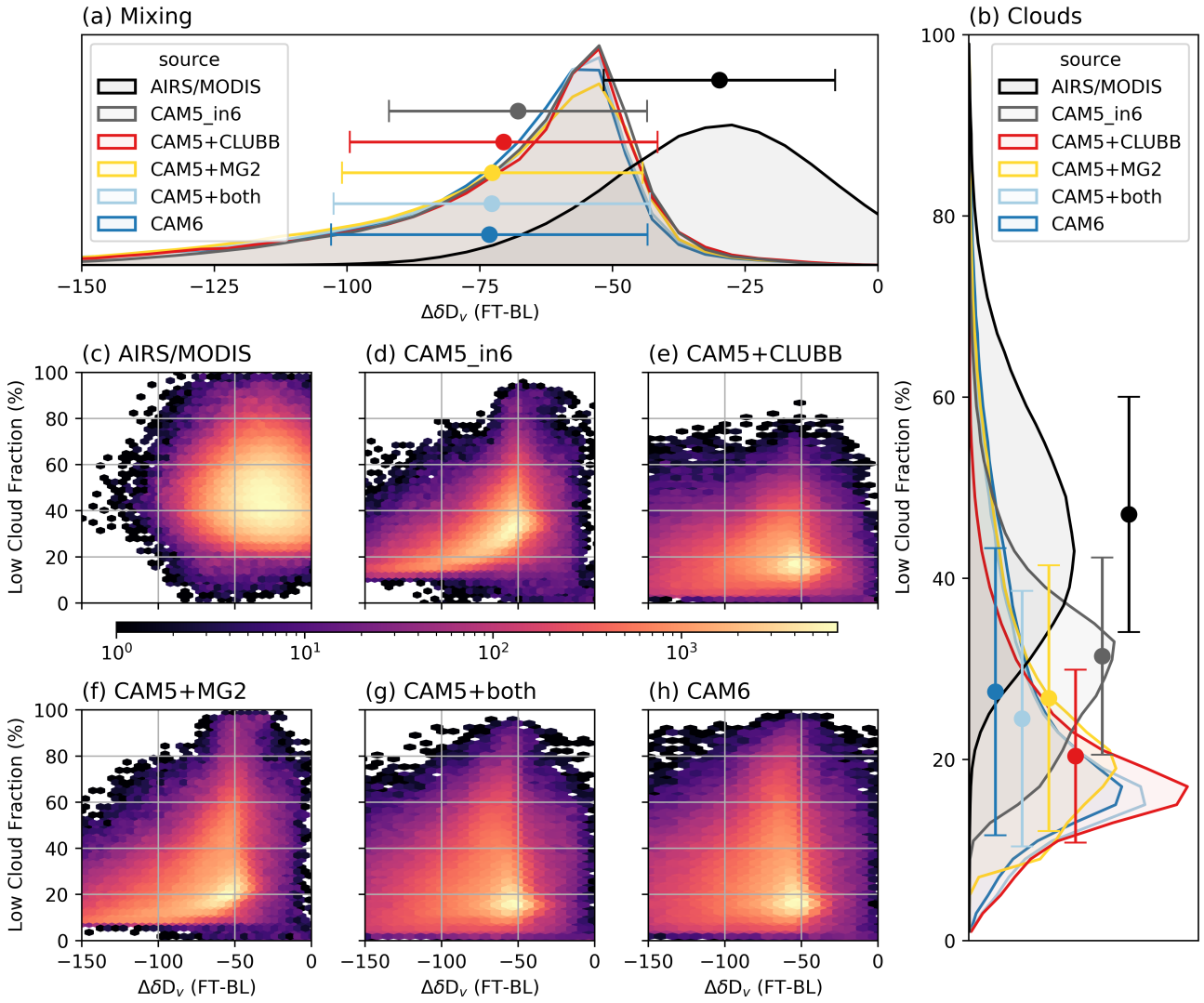


Figure S4. Like Figure 3 in the main text, but with model output analyzed at a grid resolution of 1.875° × 2.5° instead of the lower 5° × 5° resolution used in the main text: distributions of $\Delta\delta D$ and low-cloud fraction for AIRS/MODIS satellite data and CAM5 to CAM6 transition experiments. Panels a and b show probability distributions with central dots representing the mean values and bars showing ±1 standard deviation. Panels c–h are density plots with binned $\Delta\delta D$ and low-cloud fraction from all included grid boxes and months for each source (AIRS/MODIS and each CAM5 to CAM6 transition experiment). Color bar represents count.

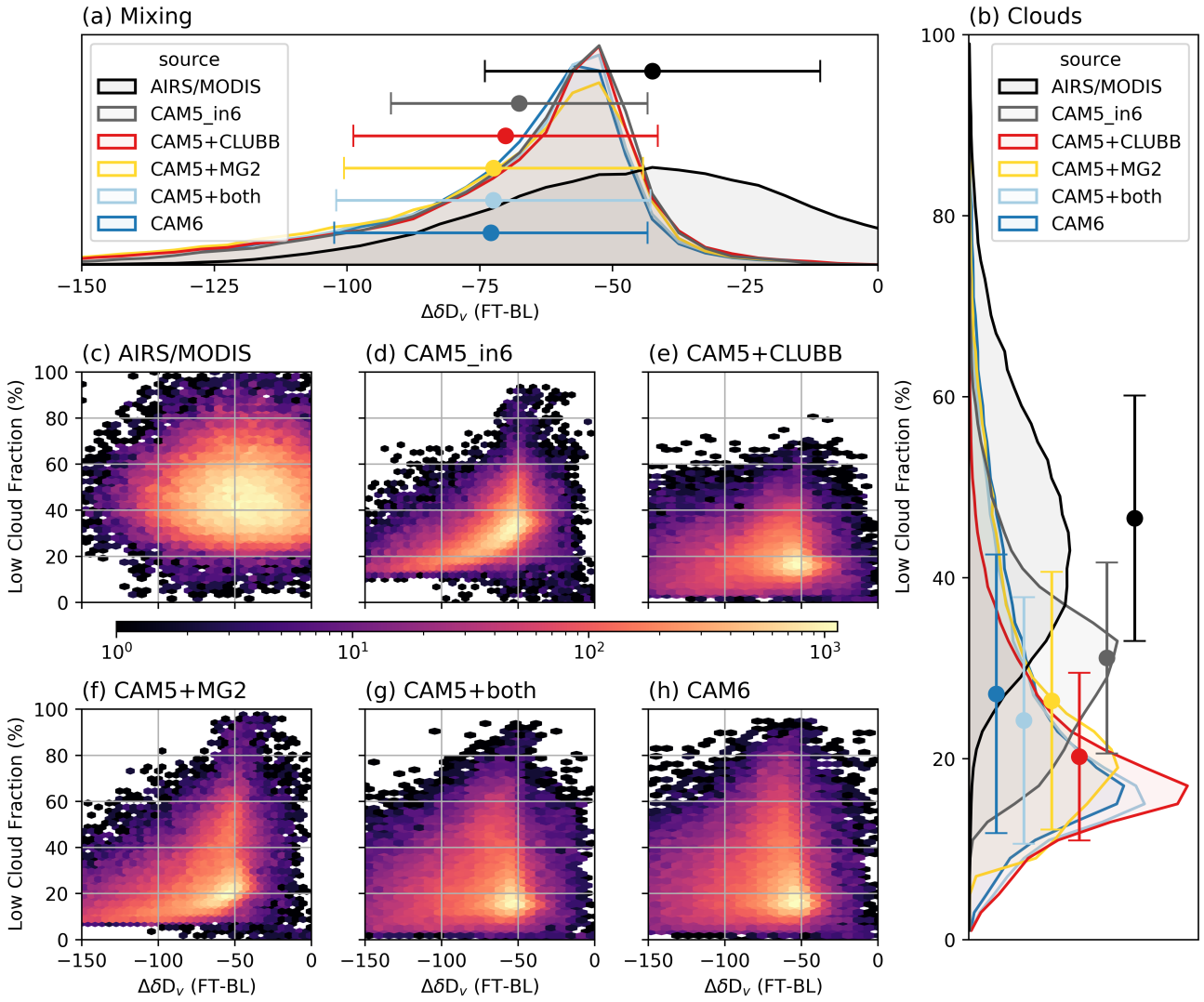


Figure S5. Like Figure 3 in the main text, but with the boundary layer and free troposphere defined as 850–925 hPa and 600–750 hPa, respectively (instead of 800–925 hPa and 600–800 hPa): distributions of $\Delta\delta D$ and low-cloud fraction for AIRS/MODIS satellite data and CAM5 to CAM6 transition experiments. Panels a and b show probability distributions with central dots representing the mean values and bars showing ±1 standard deviation. Panels c–h are density plots with binned $\Delta\delta D$ and low-cloud fraction from all included grid boxes and months for each source (AIRS/MODIS and each CAM5 to CAM6 transition experiment). Color bar represents count.

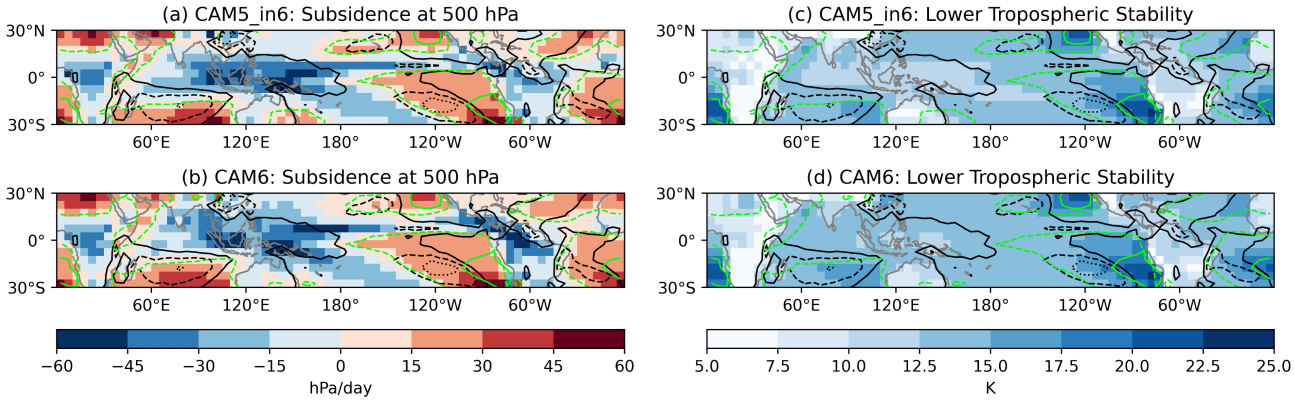


Figure S6. Comparison of thresholds for cumulus region definition: black lines represent values of cul from CASCADD of 0.2 (solid), 0.25 (dashed), and 0.3 (dotted). Dashed green line is where vertical pressure velocity at 500 hPa is 10 hPa/day; solid green line is where lower tropospheric stability (LTS) equals 18.55 K. Panels a and c represent vertical pressure velocity ("subsidence") and LTS from the CAM5_in6 run, while b and d represent values from the CAM6 run.

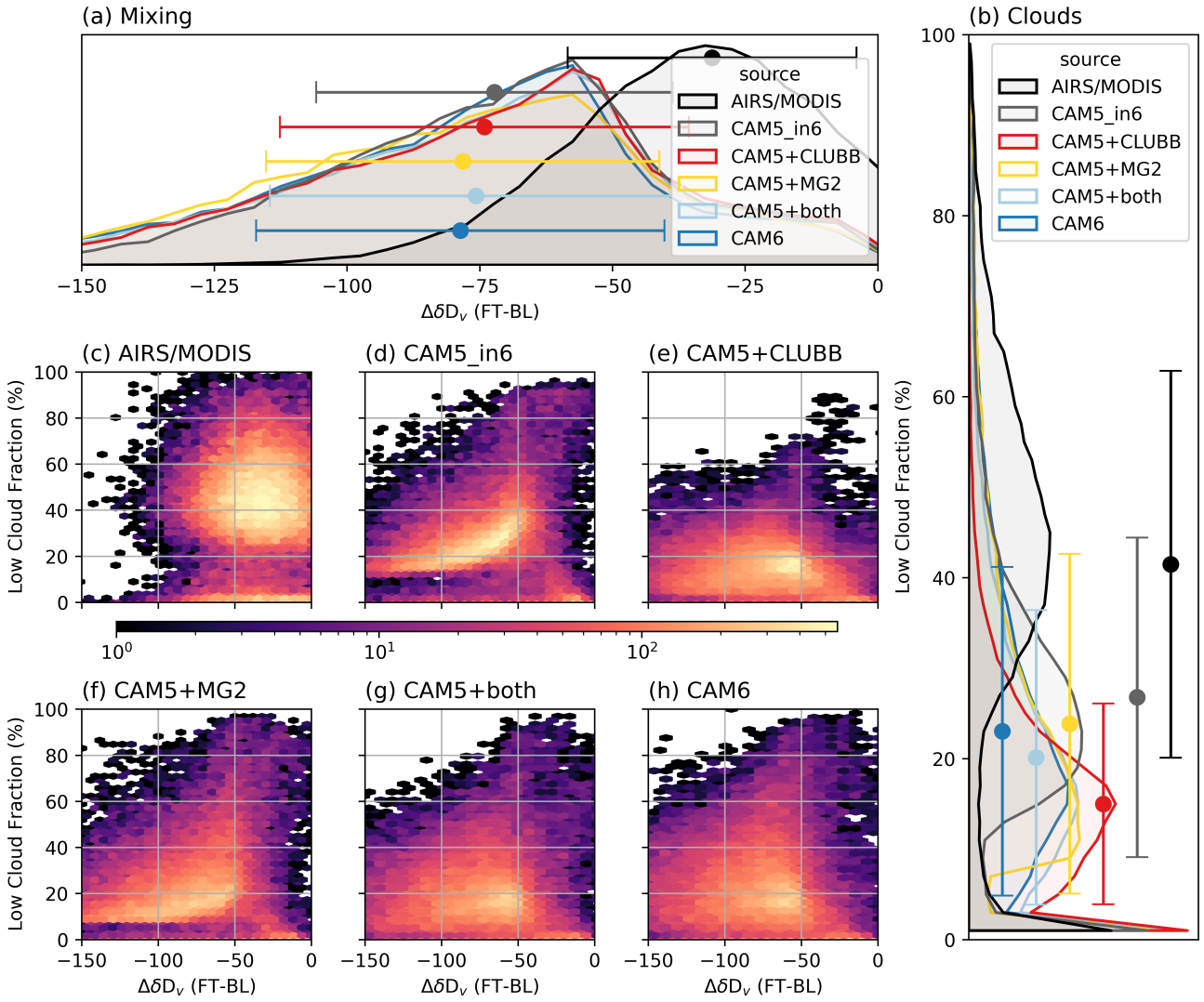


Figure S7. Like Figure 3 in the main text, but with a study region defined by veertical pressure velocity $\geq$ 10 hPa/day and LTS $<$ 18.55 K in the CAM5_in6 simulation (after Medeiros and Stevens 2011): distributions of $\Delta\delta D$ and low-cloud fraction for AIRS/MODIS satellite data and CAM5 to CAM6 transition experiments. Panels a and b show probability distributions with central dots representing the mean values and bars showing ± 1 standard deviation. Panels c–h are density plots with binned $\Delta\delta D$ and low-cloud fraction from all included grid boxes and months for each source (AIRS/MODIS and each CAM5 to CAM6 transition experiment). Color bar represents count.

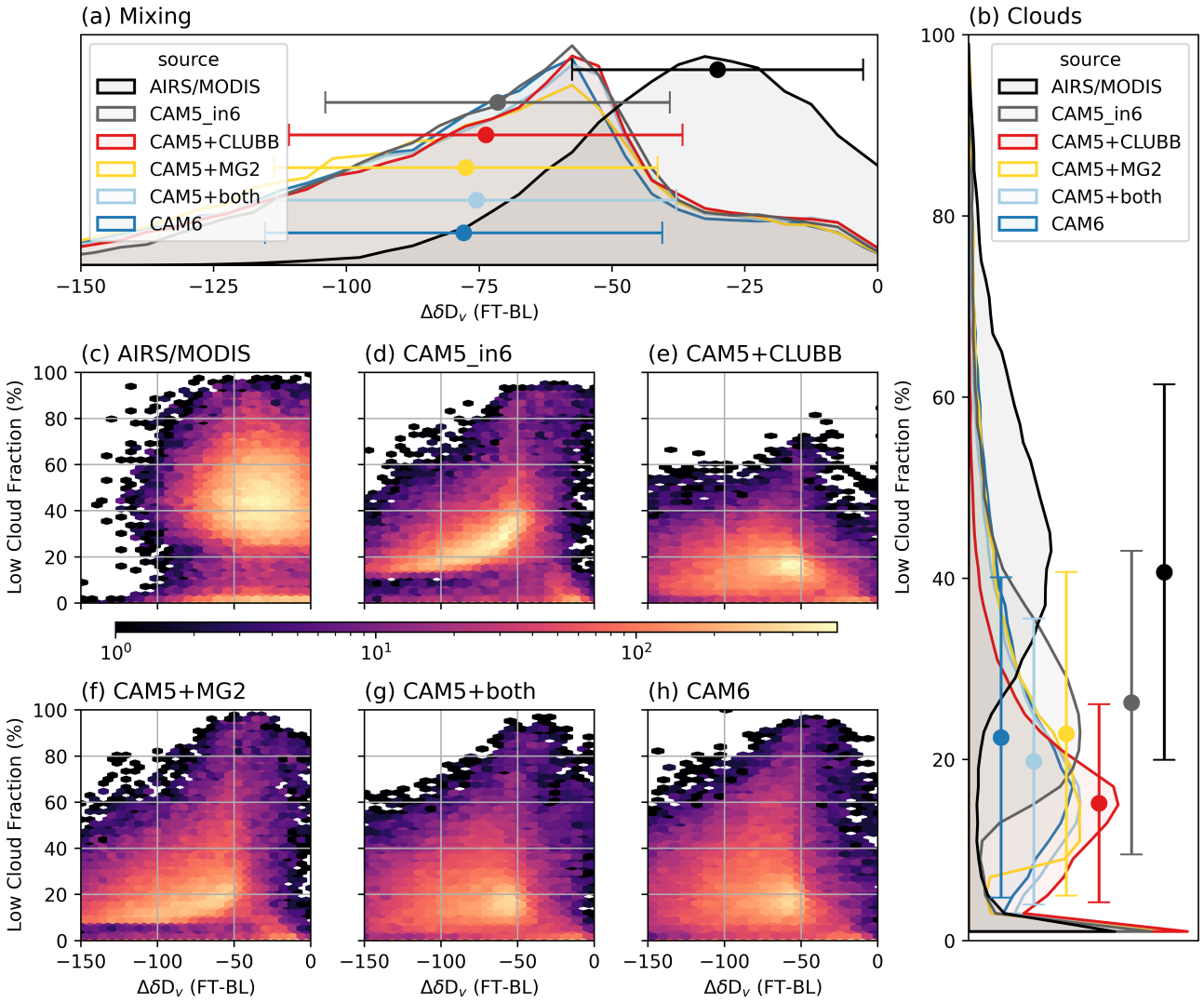


Figure S8. Like Figure 3 in the main text, but with a study region defined by vertical pressure velocity $\geq$ 10 hPa/day and LTS $<$ 18.55 K in the CAM6 simulation (after Medeiros and Stevens 2011): distributions of $\Delta\delta D$ and low-cloud fraction for AIRS/MODIS satellite data and CAM5 to CAM6 transition experiments. Panels a and b show probability distributions with central dots representing the mean values and bars showing ± 1 standard deviation. Panels c–h are density plots with binned $\Delta\delta D$ and low-cloud fraction from all included grid boxes and months for each source (AIRS/MODIS and each CAM5 to CAM6 transition experiment). Color bar represents count.

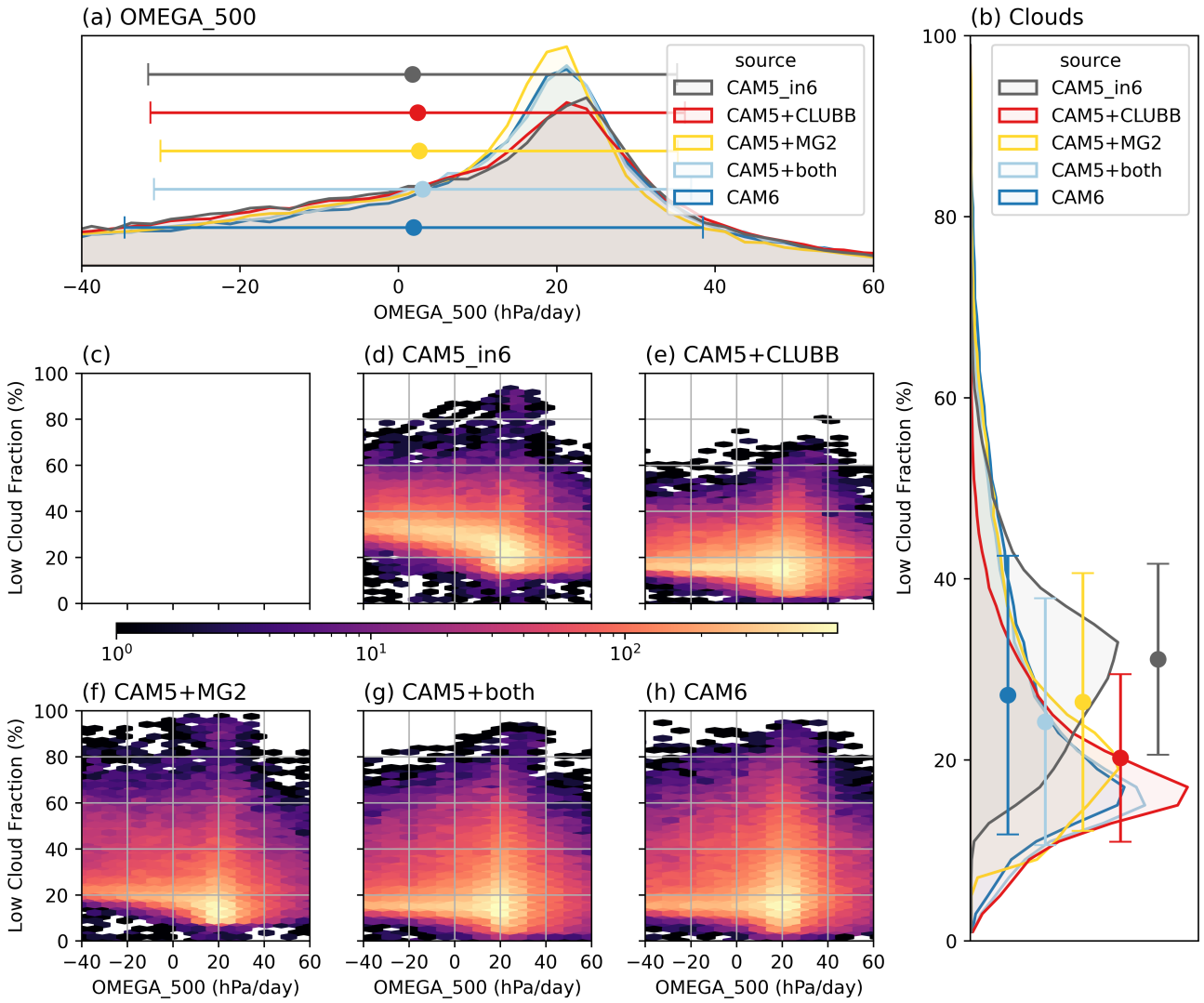


Figure S9. Distributions of vertical pressure velocity (omega, ω) at 500 hPa and low-cloud fraction for CAM5 to CAM6 transition experiments. Panels a and b show probability distributions with central dots representing the mean values and bars showing ± 1 standard deviation. Panels d–h are density plots with binned ω and low-cloud fraction from all included grid boxes and months for each source (each CAM5 to CAM6 transition experiment). Color bar represents count. Note panel c is intentionally left blank.

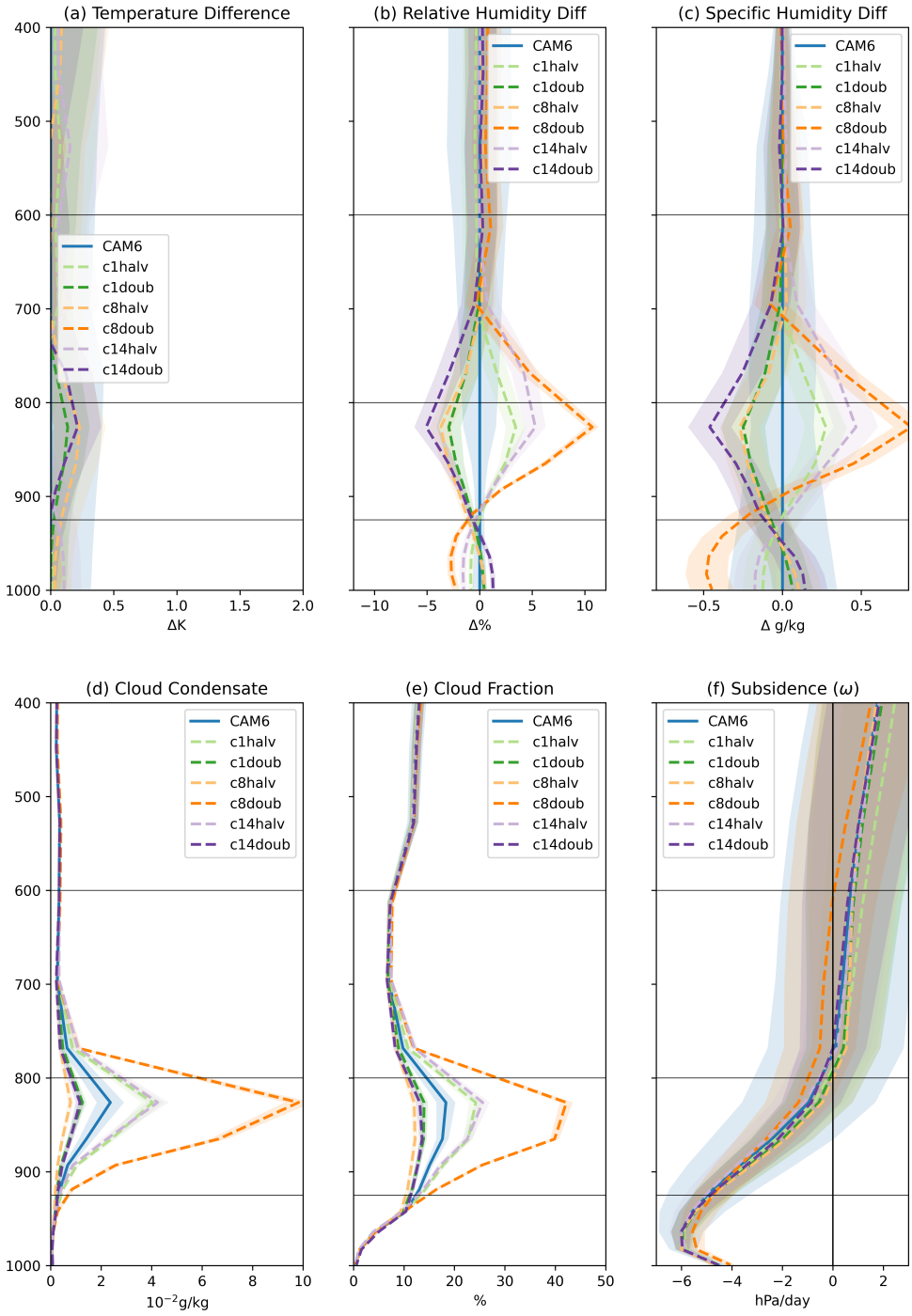


Figure S10. Like Figure 7 in the main text but with altered x-axis scales to show complete profiles: vertical profiles of meteorological variables for the CAM6 parameter experiments within the defined cumulus region. Panels a–c show the difference in the variable between each experiment and the CAM6 control. The color-shaded regions depict ±1 standard deviation among the seasonally de-trended grid-box/time data points.

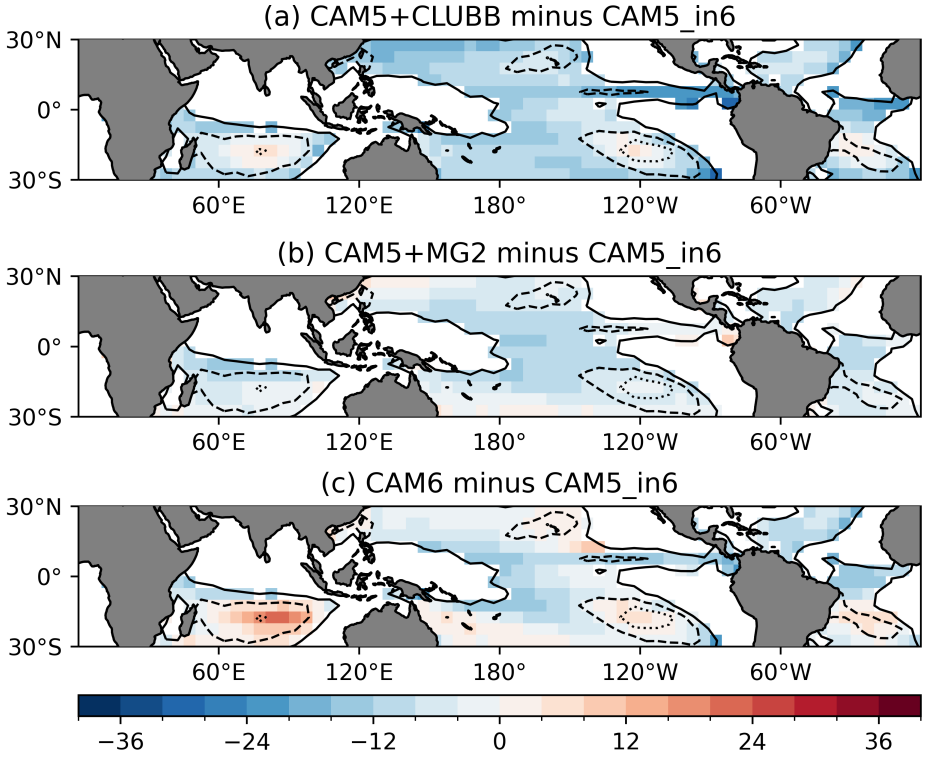


Figure S11. Difference in low-cloud fraction between selected CAM5 to CAM6 transition experiments and the CAM5_in6 control run; descriptions in Table 1. Low-cloud fraction units are %. Contour lines show where the CASCCAD shallow cumulus fraction is 0.2 (solid), 0.25 (dashed), and 0.3 (dotted).

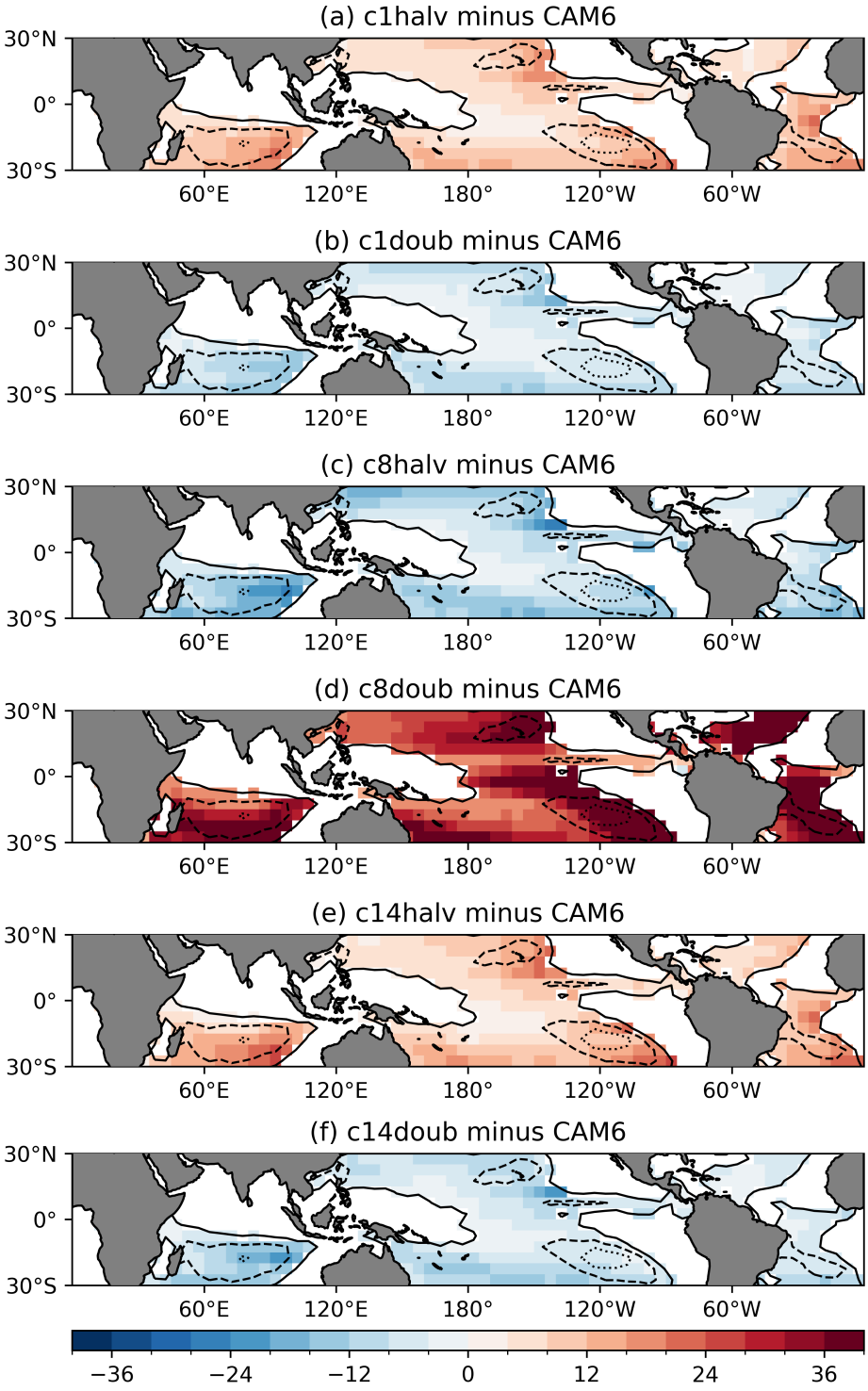


Figure S12. Difference in low-cloud fraction between CAM6 parameter experiments and the CAM6 control run; descriptions in Table 1. Low-cloud fraction units are %. Contour lines show where the CASCCAD shallow cumulus fraction is 0.2 (solid), 0.25 (dashed), and 0.3 (dotted).

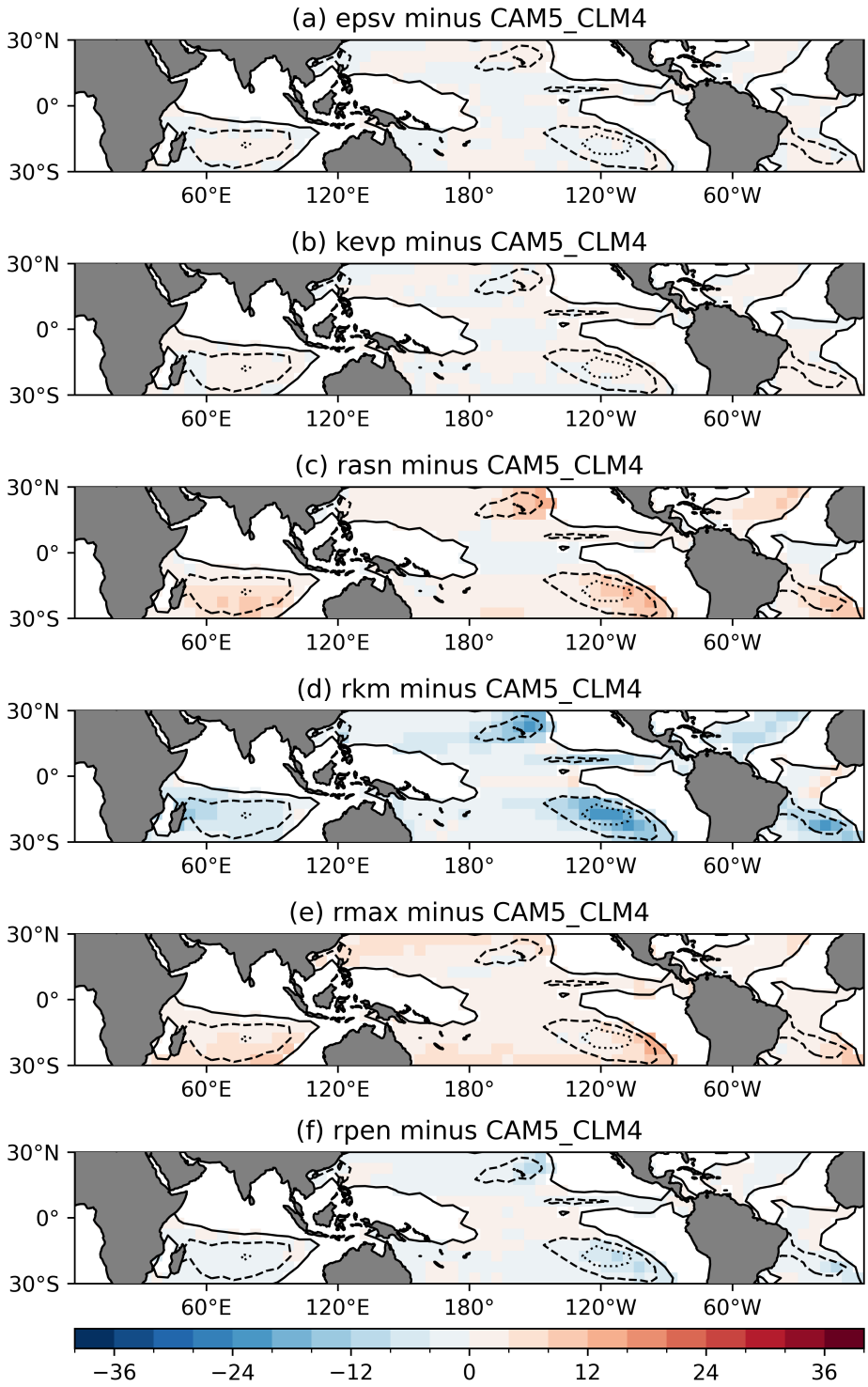


Figure S13. Difference in low-cloud fraction between CAM5 parameter experiments and the CAM5_CLM4 control run; descriptions in Table 1. Low-cloud fraction units are %. Contour lines show where the CASCCAD shallow cumulus fraction is 0.2 (solid), 0.25 (dashed), and 0.3 (dotted).