Mean State High Cloud Relationships to Climate Sensitivity

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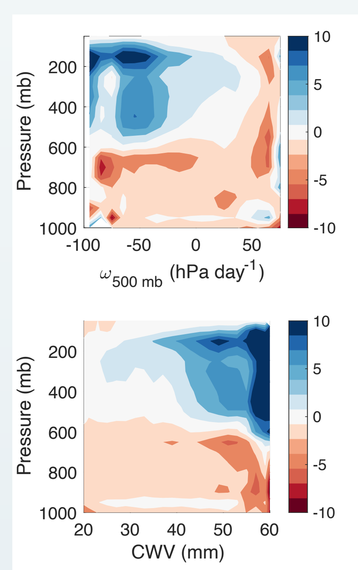
Abstract

Exploring relationships between mean state cloud characteristics and equilibrium climate sensitivity (ECS) provides much-needed insight into the role of clouds in intermodel variability of projected warming and an opportunity for new observational constraints. Assessment of the CMIP5 and CMIP6 historical model ensembles provides evidence that models with higher ECS have greater annual mean high cloud fraction (HCF) throughout the tropics. In order to isolate the mechanism driving this relationship, the cloud radiative kernel technique of Zelinka et al. (2012) is applied to models using published piControl and abrupt4xCO2 runs. Cloud fraction histograms organized in cloud top pressure-optical depth space demonstrate greater mean state 440-180 hPa tropical cirrus cloud fraction in high ECS models than low ECS models, yielding a larger increase in 180-50 hPa cirrus clouds in the abrupt4xCO2 scenario than in low ECS models. In other words, greater cirrus in the mean state means more cirrus find themselves at higher altitudes in the future, leading to a strong positive feedback on the climate. Therefore, we argue that observations of cirrus could be used to constrain the tropical high cloud altitude feedback. Finally, in exploring systematic relationships between deep convective characteristics and HCF among models, we find that models whose convection exhibits greater sensitivity to lower free tropospheric moisture have fewer high clouds. No relationship was found between large-scale metrics of precipitation efficiency or ITCZ width and HCF.

1. Motivation

- Relating mean state quantities to future changes permits much-needed observational constraints on future warming.
- High ECS models have greater mean HCF throughout the tropics than low ECS models, which is true for both CMIP5 and CMIP6 models.
- Therefore, we seek a physical explanation for this mean-state HCF relationship to ECS and explore potential systematic causes of the large intermodel spread in mean-state HCF among models.



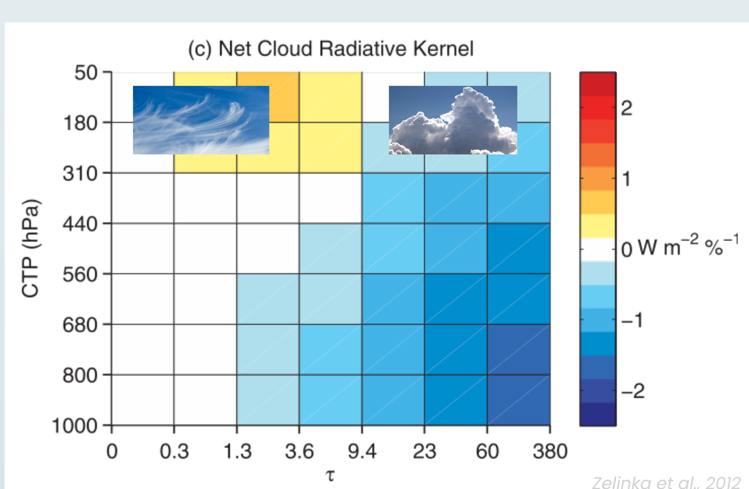
[right] The high minus low ECS difference in conditionally averaged cloud fraction (CF; %) as a function of (top) ω_{500} and (bottom) column water vapor (CWV) for CMIP6 models.

2. Data and Methods

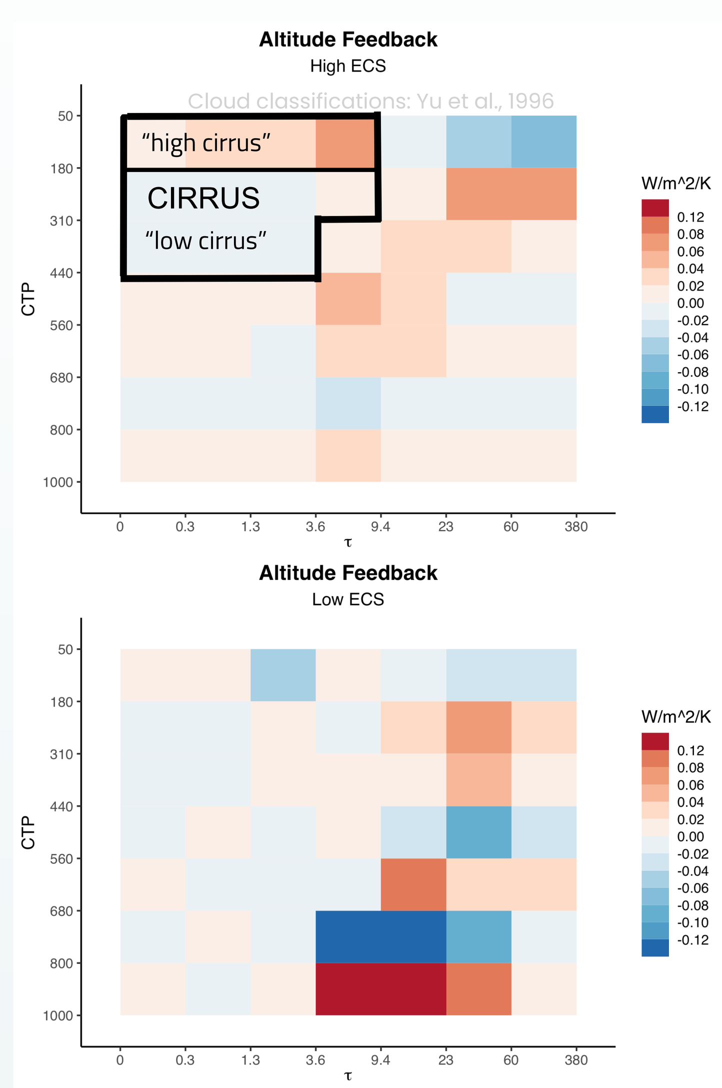
CMIP5/6 piControl and 4xCO2 runs are the primary datasets used. Historical output is used instead of piControl output to increase the sample size in instances where the variable of interest is highly correlated. Analysis is performed from 20ºS-20ºN, unless otherwise noted.

[Section 3] Using the Cloud Radiative Kernel methodology of Zelinka et al., the altitude feedback is computed from the change in cloud top pressure (CTP) distribution holding the cloud fraction and optical depth (τ) distribution fixed.

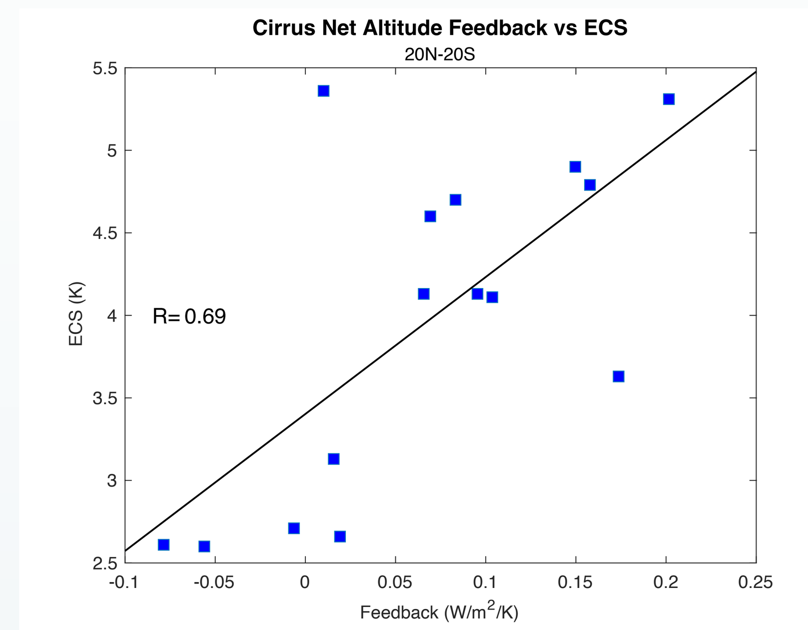
[Section 4] For convective onset statistics, 3-hourly precipitation and 6-hourly instantaneous 3D T and q are used from historical output. The first 3-hourly precip value in the 6-hour period is matched to the T and q profiles.



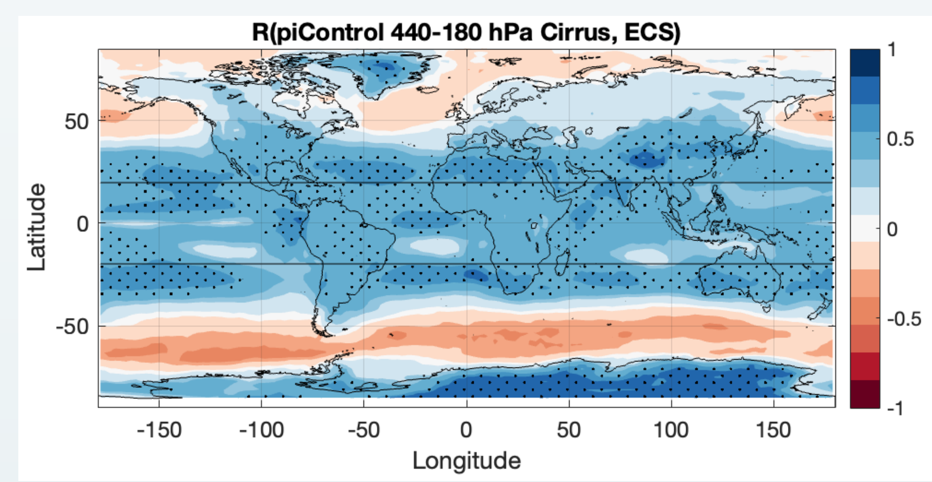
3. Relating mean state high cloud fraction to the cloud altitude feedback



The cirrus altitude feedback following the ISCCP categorization of Yu et al. (1996) (440-50 hPa) is highly correlated with ECS **[below]**, though the largest and most positive contribution is from the "high cirrus" category (180-50 hPa) **[left]**.

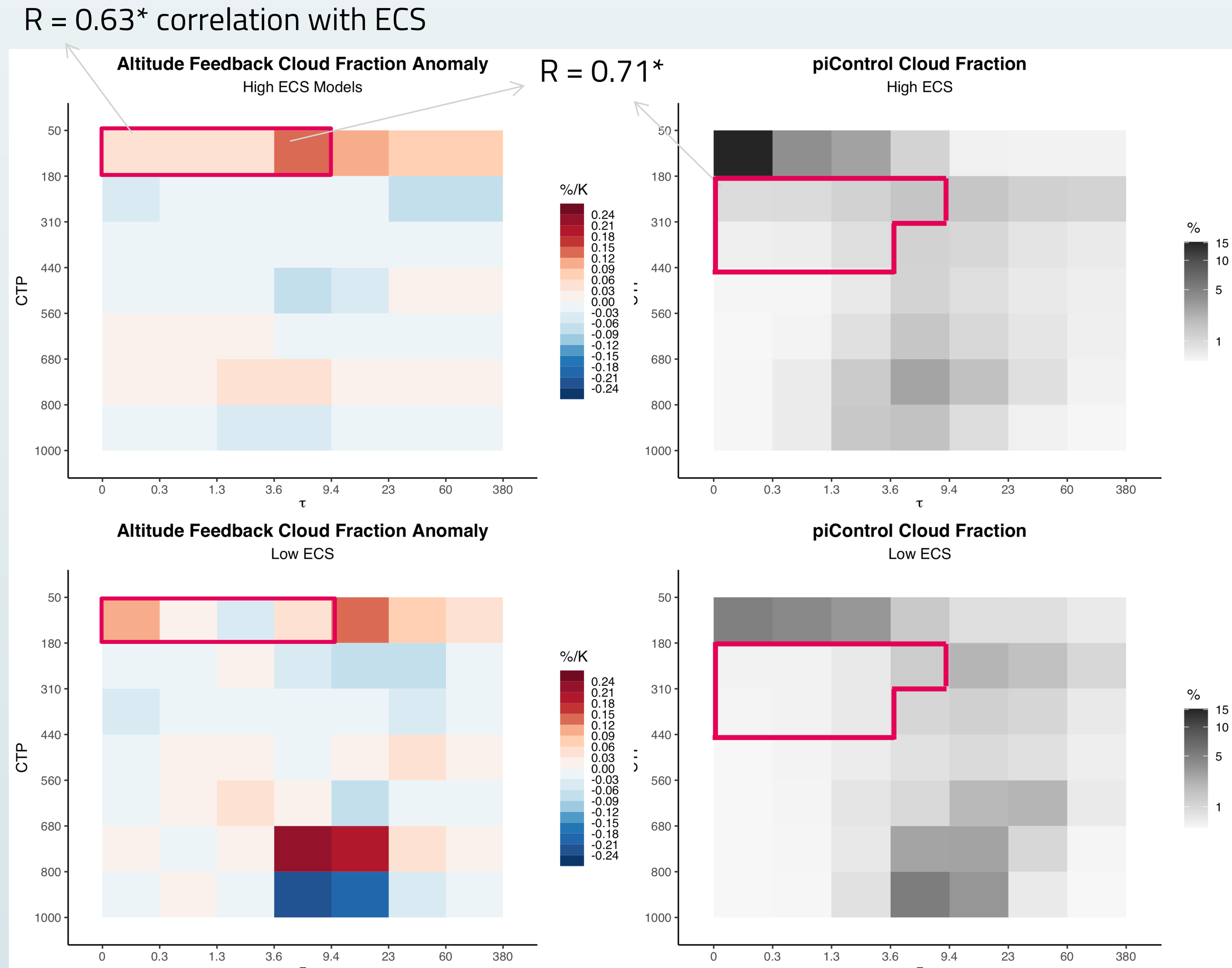


[below] The mean-state "low cirrus" is broadly, positively, and significantly correlated with ECS throughout much of the tropics and subtropics, extending into midlatitudes.



SUMMARY A statistically significant relationship between mean state low cirrus and ECS emerges because greater low cirrus fraction in the mean state means that more low cirrus rise under GHG warming, amplifying a strong positive cirrus altitude feedback that explains a large portion of the intermodel spread in ECS.

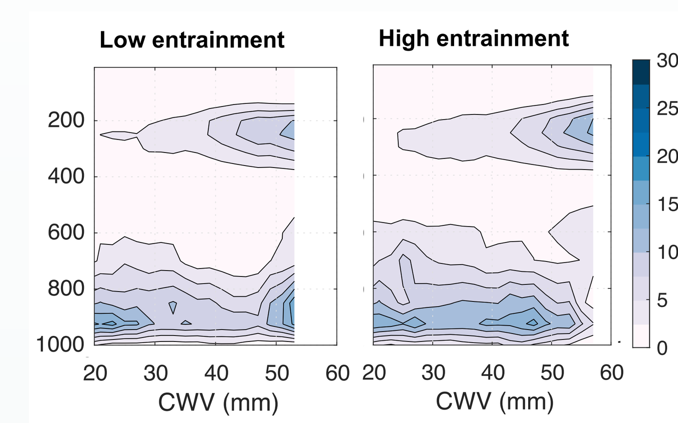
R = 0.63* correlation with ECS



[left] Low cirrus is greater in piControl for high ECS models (top right) than for low ECS models (bottom right), which is highly correlated (R = 0.71) with a greater increase in HCF in 4xCO2 runs relevant to the cloud altitude feedback calculation for high cirrus (180-50 hPa) in high ECS models (top left) than in low ECS models (bottom right).

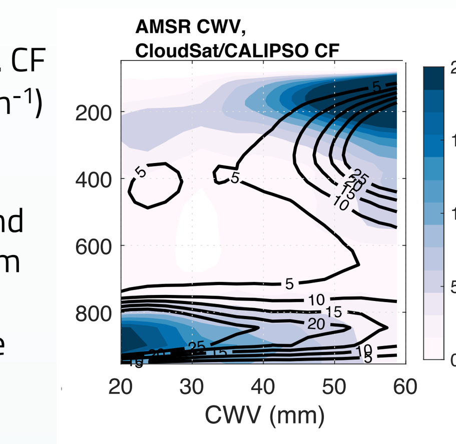
*CMIP5/6 intermodel spread correlation. We use historical data instead of piControl data to perform these correlations to increase the sample size.

4. Exploring high cloud relationships to systematic intermodel differences in deep convection

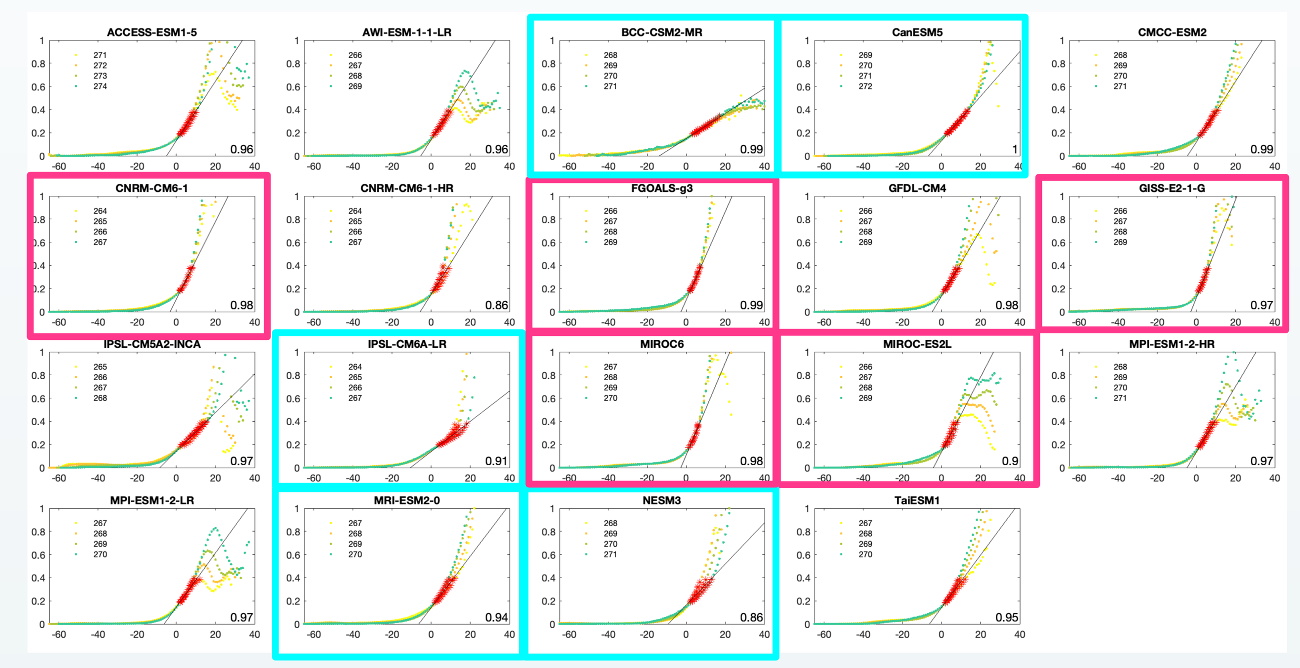


[left] Results from a perturbed physics ensemble using CAM5.3. CF (%) for low entrainment (0.08 km^{-1}) and high entrainment (1.5 km^{-1}) cases is shown (default in CAM5.3 is 1 km^{-1}) for 30ºS-30ºN.

SUMMARY The low entrainment run yields fewer low clouds and more high clouds than the high entrainment run in the 35-50 mm CWV range. In other words, deep convection is more frequent and/or more intense at the expense of shallow convection in the most frequently observed CWV regime.



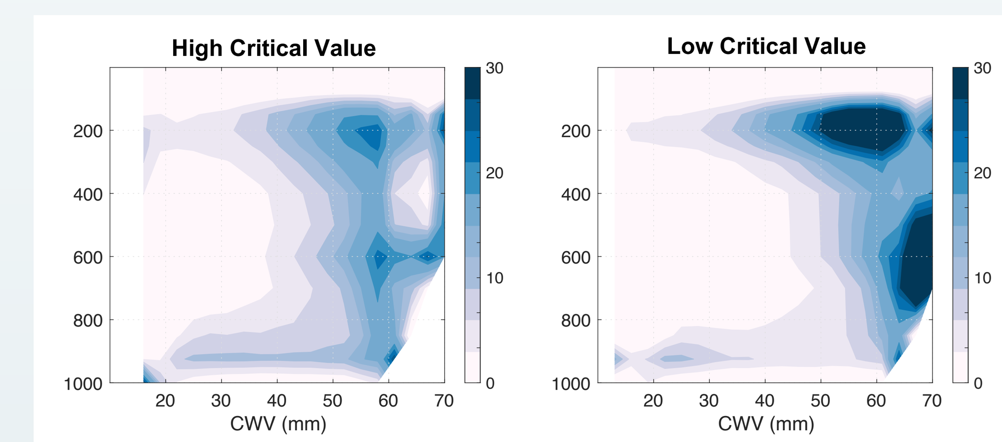
[top right] Observed profiles of cloud fraction (shading) and cloud water content (liquid+ice; contours) from CloudSat/CALIPSO and CWV from AMSR-E (30ºS-30ºN).

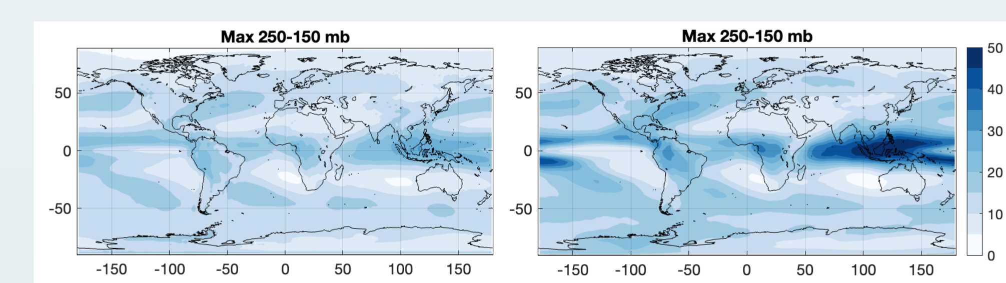


[left] Conditional mean precipitation (mm hr^{-1}) as a function of a rescaled column relative humidity (CRH) for the four most common column-averaged temperatures in each model (colors; T is in K). The curves are collapsed by subtracting the CRH value at 0.15 mm hr^{-1}. The red asterisks signify the range over which a line is fit to the curve. The rescaled critical CRH value is determined from where the line crosses the x-axis. Results are shown for all 19 CMIP5/6 models used in our analysis (20ºS-20ºN). Six-hourly average output is used. Numbers in the bottom right are correlation coefficients for the linear regression.

[right] Conditionally sampled profiles of CF (%) from five models with the highest critical CRH values (MIROC-ES2L, CNRM-CM6-1, GISS-E2-1-G, MIROC6, and FGOALS-g3; pink boxes above) and five with the lowest critical CRH values (BCC-CSM2-MR, IPSL-CM6A-LR, NESM3, CanESM5, and MRI-ESM2-0; cyan boxes above).

[right bottom] Maps of the maximum CF in the 250-150 mb layer averaged for models with high critical CRH values (left) and low critical CRH values (right)





SUMMARY Models with a weaker pickup of precipitation as a function of column relative humidity (low critical values) – and are thus less sensitive to dry air entrainment – have greater mean-state HCF for all CWV.

ADDITIONAL NOTES There is no systematic relationship between the intermodel spread in mean-state HCF and the intermodel spread of the following mean-state quantities:

- Large-scale precipitation efficiency (Li et al. 2023)
- Tropical ascent area fraction (Su et al. 2017)

5. Conclusions

1. Models that have more mean-state low cirrus have a greater increase in high cirrus in the future and a more positive cirrus altitude feedback.
2. Models whose deep convection is more sensitive to lower free tropospheric moisture (e.g., have higher rates of entrainment) have fewer high clouds tropics-wide than models whose deep convection is less sensitive to lower free tropospheric moisture. Deep convection is more frequent and/or more intense at the expense of shallow convection, providing a larger source of detrained condensate for high clouds.
3. There is no systematic relationship between the intermodel spread in mean-state HCF and the intermodel spread in large-scale metrics of precipitation efficiency or tropical ascent area fraction.

6. Future Directions

1. Evaluate relationships between mean state HCF and convective clustering/organization metrics
2. Explore these relationships in additional model ensembles to increase sample size and use observed HCF to constrain future warming.

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