Impacts of Predicted Changes in Tropospheric Stability on Tropical High Cloud Feedbacks

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Abstract

The largest source of uncertainty in global climate models' (GCMs) response to greenhouse gas forcing is the cloud feedback, which refers to changes in top-of-atmosphere radiative flux due to the response of clouds to warming. Better constraining this feedback could significantly narrow the range of predicted warming across GCMs. The goal of this study is to determine whether the inter-model spread of changes in tropical high cloud characteristics is directly related to inter-model variability of changes in tropospheric stability. We analyze data from 22 fully-coupled climate models to compute changes in tropical static stability profiles between a control and perturbed experiment and explore relationships to high cloud feedback values published in Dawson and Schiro (2025). We find that models with more positive high cloud feedbacks tend to exhibit weaker increases in upper-tropospheric static stability across the tropics, with significant anticorrelations between stability responses and high cloud altitude and optical depth feedbacks. To test potential mechanisms underlying the high cloud altitude feedback relationship, we correlate stability responses with changes to high cloud top temperature but find no significant relationship. Additionally, we highlight anticorrelations between stability changes and the high cloud optical depth and amount feedbacks along the equator. This more pronounced increase in high cloud amount and thickening in more stable models suggest links between cloud feedbacks, stability, and circulation changes that can be explored further in future work. In sum, this study highlights that inter-model spread in tropical upper-tropospheric stability is important for driving changes in high clouds' response to warming in the tropics across fully-coupled GCMs, and thus provides a potential avenue for mechanistically constraining high cloud changes across models.

Acknowledgements

I would first like to thank Emma Dawson who has been a phenomenal mentor throughout my research and thesis writing experience. She has used her extensive experience in atmospheric sciences to teach me the tools and information necessary to conduct this study. I am extremely grateful for her patience and dedication to helping me learn. I would also like to extend a tremendous thank you to Kathleen Schiro for offering to be my advisor for this thesis and for being an outstanding professor for the last two years. Her Atmosphere and Weather class is what originally sparked my interest in cloud variability and its greater impact on climate. I would like to thank the Environmental Science Department here at the University of Virginia as well, as it has provided me with a wide variety of learning opportunities and experiences that have allowed me to explore my interests. Lastly, I want to thank my Mom, Dad, and Max for supporting me throughout my learning career and for being my biggest fans at every step along the way.

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Introduction

Clouds are an essential part of Earth's energy budget, as they reflect incoming shortwave radiation and absorb and reemit outgoing longwave radiation. Overall, clouds have a net cooling effect of around -20 Wm^{-2} (Boucher et al., 2013). However, the increase in atmospheric levels of greenhouse gases due to anthropogenic activity is resulting in changes to clouds, which has a significant impact on the balance of radiation in Earth's system. This is known as the cloud feedback, and global climate models (GCMs) predict an amplification of global warming due to a positive cloud feedback (Ceppi et al., 2017). However, GCMs differ substantially on the numerical prediction of this amplification. This is in large part due to difficulties and different approaches in modeling smaller scale physical processes within GCM grids (Ceppi et al., 2017). Overall, the cloud feedback is the greatest source of uncertainty when it comes to warming, which is quantified by a metric known as equilibrium climate sensitivity (ECS), the global mean change in surface temperature due to a doubling of CO_2 relative to pre-industrial levels.

The impact that changes in clouds have on the magnitude of warming that GCMs predict is dependent on a variety of factors. Changes to characteristics such as the opacity, amount, and altitude of clouds can have a significant impact on warming, whether that be amplifying or dampening (Zelinka et al., 2012). In addition to this, cloud populations vary significantly across regions of the Earth, leading to a spatially heterogeneous cloud radiative effect (Zelinka et al., 2016). Almost all GCMs simulate three responses of clouds to warming: rising free tropospheric clouds (a longwave heating effect); decreasing low cloud amount in the tropics to midlatitudes (a shortwave heating effect); and increasing low cloud optical depth at high latitudes (a shortwave cooling effect) (Ceppi et al., 2017). However, variability in the magnitude of these cloud feedback components and disagreement among models surrounding other cloud feedback components contribute to substantial spread in the global mean net cloud feedback.

Cloud feedbacks in the tropics are specifically noteworthy when it comes to the variability of ECS across models and understanding the degree to which the cloud feedback will influence warming (Sherwood et al., 2020; Dawson & Schiro, 2025). The tropics receive the most sunlight and experience the most deep convective activity out of all regions on Earth. Spatially, the tropics also cover about half of Earth's surface area, accounting for a significant portion of the global energy balance. Moreover, some literature suggests that the tropics account for the largest uncertainty in cloud feedbacks globally (Sherwood et al., 2020). Thus, assessing underlying causes for the variability in tropical cloud feedbacks across GCMs presents a key step towards constraining climate sensitivity.

Low clouds have received a lot of attention in recent scientific research on cloud feedbacks, and there is a general consensus that low clouds will reduce under warming, creating a positive feedback (Ceppi et al., 2017; Sherwood et al., 2020). High clouds, however, have not received as much consideration and the disagreement between models in predicting these feedbacks has called for a more in-depth analysis of high cloud changes (Zelinka et al., 2022). The inter-model spread in high cloud feedbacks has been quantified by analyzing the standard deviations of individual components—specifically, altitude, optical depth, and amount feedbacks. Of note, the high cloud altitude feedback has the greatest number of models that fall outside of the expert-assessed ranges published by Sherwood et al. (2020). This study serves as the best estimate of the sign and magnitude of cloud feedbacks, so it is a cause for concern that current GCMs produce cloud feedbacks outside of these predicted ranges for high clouds specifically. Overall, the agreement of GCMs is important as we face the implications of global warming, and improving estimates of the amount of warming associated with greenhouse gas emissions will help more effectively mitigate and prepare for these impacts.

Whereas the low cloud feedback is dominated by changes to low cloud amount, analyzing separately the individual contributions of high cloud altitude, optical depth, and amount changes is imperative to understanding the net high cloud feedback. Recently, Dawson and Schiro (2025) found that the tropical net high cloud feedback is highly correlated with ECS (Figure 1), with significant contributions from inter-model variability in the tropical mean response of high cloud altitude and optical depth. While this study highlights a significant relationship between tropical high cloud feedbacks and climate sensitivity, additional work is needed to explore physical processes driving the spread in high cloud responses across models.

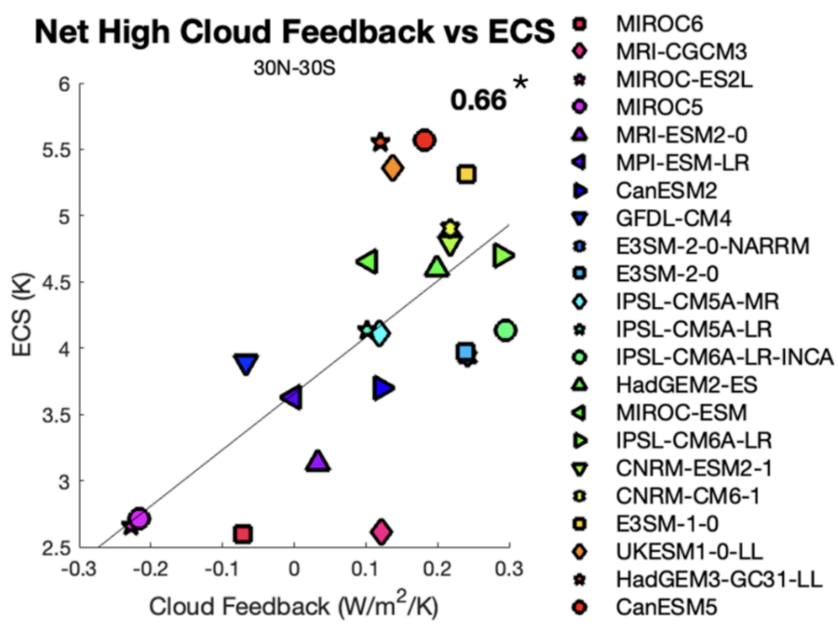

Figure 1. Scatterplot displaying the relationship between net high cloud feedbacks and equilibrium climate sensitivity across 22 CMIP models. Adapted from Dawson and Schiro (2025).

The altitude feedback is supported by physical mechanisms and theory, and it is expected to be robustly positive. According to observations, tropical high clouds have risen over the last twenty years (Richardson et al., 2022; Raghuraman et al., 2024) with accompanying evidence from GCMs that high clouds increase in altitude as a response to surface warming (Zhou et al., 2014; Zelinka & Hartmann, 2011). To explain this phenomenon, Hartmann and Larson (2002) proposed the Fixed Anvil Temperature (FAT) hypothesis, followed by Zelinka and Hartman (2010) creating the Proportionally Higher Anvil Temperature (PHAT) hypothesis. The PHAT hypothesis argues that an increase in stability in the upper troposphere due to warming will cause a slight warming of cloud tops such that high clouds maintain near-constant longwave emission to space. This ultimately results in a net positive feedback as surface temperatures rises while outgoing longwave radiation stays relatively the same (Ceppi et al., 2017). While there is strong physical theory underlying the altitude feedback, recent inter-model comparisons show a wide spread in the altitude feedback across GCMs, warranting further research into potential mechanisms driving this variability (Zelinka et al., 2022).

Dawson and Schiro (2025) also find that models disagree on the sign of the tropical high cloud optical depth feedback, with roughly half of the ensemble (the warmer models) tending to display a net thinning and the other half (the cooler models) a net thickening. The mechanisms underlying the high cloud optical depth feedback are uncertain. The upper troposphere has been shown to stabilize with an increase in surface temperature, leading to a loss of anvil coverage (Bony et al., 2016; Zelinka & Hartmann, 2010). However, the redistribution of cloud fraction across optical depths accompanying the reduction of high cloud amount is unclear, necessitating further investigation into potential controls on the response of high cloud opacity to surface warming.

Lastly, the amount feedback accounts for the radiative effect of changes to overall cloud amount. While models show that the tropical mean high cloud amount feedback is uncorrelated with ECS and likely is not the main reason for the inter-model spread in climate sensitivity (Dawson & Schiro, 2025), there has been substantial work to understand the underlying mechanisms for the loss of tropical high clouds under warming. The Iris Feedback proposed by Linzen et al. (2001) suggests that high clouds in the tropics contract due to surface warming to allow more outgoing longwave radiation to escape, similar to an iris of an eye. Zelinka and Hartmann (2010) and Bony et al. (2016) later modified this hypothesis, instead proposing the Stability Iris Hypothesis. They postulate that increased stability in the upper troposphere will reduce convective outflow, leading to a reduction in high cloud fraction. However, other studies argue that the net radiative effect of anvil clouds is approximately neutral (Hartmann & Berry, 2017), potentially constraining the impact of stability responses on radiative effects due to change in high cloud amount to be small.

In summary, although changes to upper-tropospheric stability have been linked to high cloud feedbacks, no research to date has explored the Coupled Model Intercomparison Project (CMIP) inter-model spread in upper-tropospheric stability and its links to the inter-model spread in high cloud feedbacks. The purpose of this study is to fill this knowledge gap by exploring whether systematic inter-model differences in the response of tropospheric stability to warming can help explain variability in high cloud changes across an ensemble of fully-coupled climate models.

Data & Methods

This study assesses the extent to which changes to tropical upper-tropospheric stability are related to inter-model variability of tropical high cloud feedbacks among an ensemble of 22 fully-coupled models used in Dawson and Schiro (2025). This ensemble consists of 8 models from CMIP5 and 14 models from CMIP6 (see Table 1 for list of models and characteristics). Published tropical mean and local high cloud feedback values, including the net high cloud feedback, high cloud amount feedback, high cloud altitude feedback, and high cloud optical depth feedback, in addition to the accompanying global mean change in surface temperature, are taken from Dawson and Schiro (2025). These feedbacks were computed using the cloud radiative kernels and decomposition methods of Zelinka et al. (2012; 2013) and quantify the radiative effect of changes to tropical high clouds by comparing output from years 1-10 and years 131-140 of the abrupt-4xCO2 runs, an experiment wherein CO_2 is quadrupled relative to pre-industrial levels and then held fixed (Eyring et al., 2016).

As described by Zelinka et al. (2012; 2013), cloud radiative kernels are a key tool for quantifying cloud feedbacks in climate models. Radiative kernels represent the radiative flux at the top of the atmosphere (TOA) that results from a change in a climate variable such as cloud fraction. The cloud radiative kernels of Zelinka et al. (2012) use cloud fraction data from the International Satellite Cloud Climatology (ISCCP) simulator, which is incorporated into model runs to mimic observational satellite output and reports cloud fraction across 49 different histogram bins based on cloud top pressure (CTP) and optical depth (τ). The cloud radiative kernels represent how the presence of clouds in each bin affects radiative fluxes at the top of the atmosphere. Zelinka et al. (2012; 2013) compute radiative kernels for each CTP-τ bin by calculating the difference in radiative flux between a cloud in that CTP-τ group and the radiative flux under clear skies. This calculation is done for each latitude, month, and three different surface albedo values (0, 0.5, and 1). As a result, each bin is representative of the change in radiative flux in W m^{-2} $\%^{-1}$ that corresponds to a 1% increase in cloud fraction for that cloud type. As shown below in Figure 2, high, thin clouds have a net warming effect and high thick clouds have a net cooling effect.

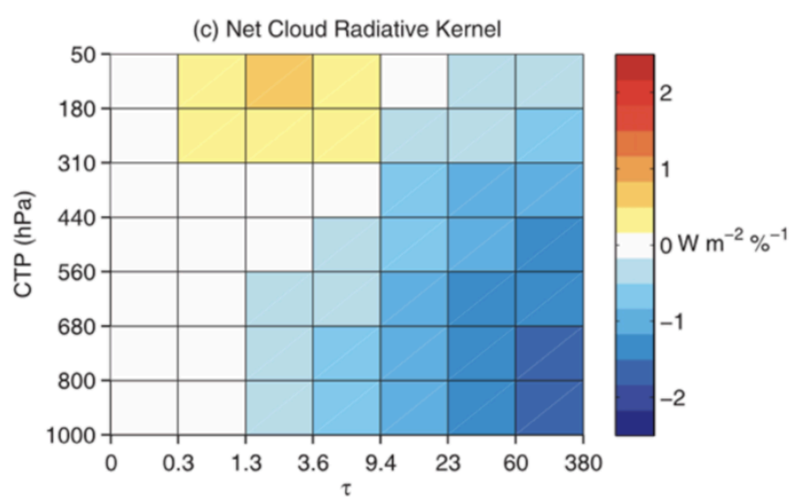

Figure 2: Net ISCCP cloud radiative kernels from Zelinka et al. (2012a).

In order to apply cloud radiative kernels, early period cloud fraction (years 1-10) is subtracted from late period cloud fraction (years 131-140) of the abrupt-4xCO2 run, and the difference between the two is normalized by the global average change in surface temperature. Next, these matrices are multiplied by the cloud radiative kernels at the corresponding latitude, surface albedo, and month. The net cloud feedback is then represented in units of W m^{-2} K^{-1}. Lastly, the net cloud feedback is decomposed into the amount, altitude, and optical depth feedbacks using the methods of Zelinka et al. (2013):

$$\Delta R_C = K_0 \Delta C_{tot} + \sum_{p=1}^{P} \left(K_p' \sum_{\tau=1}^{T} \Delta C_{p\tau}^*\right) + \sum_{\tau=1}^{T} \left(K_\tau' \sum_{p=1}^{P} \Delta C_{p\tau}^*\right) + \sum_{p=1}^{P} \sum_{\tau=1}^{T} K_R' \, \Delta C_{p\tau}^* \quad (1)$$

In this formula, the net cloud induced radiative anomalies (ΔR_C) are equal to the sum of the amount of feedback (first term), altitude feedback (second term), optical depth feedback (third term), and the residual (fourth term). Additionally, Dawson and Schiro (2025) define high cloud feedbacks as radiative anomalies from contributions of clouds between 680 and 50 hPa and $0.3 < \tau < 380$, the top 5 rows and 6 rightmost columns of the ISCCP histogram.

To characterize tropical upper-tropospheric stability, we utilize publicly available output from CMIP5/6 archive through the Earth System Grid Federation (ESGF) architecture (https://aims2.llnl.gov/search). We employ the methods of Kemsely et al. (2024) to compute upper-tropospheric static stability for the 22 models analyzed in Dawson and Schiro (2025). *Static stability* is the vertical gradient of potential temperature. Static stability profiles are computed as follows:

$$S_P = \frac{R_c}{C} \frac{T_P}{P} - \frac{dT}{dP} \quad (2)$$

Here, S_p is the static stability at pressure level P (K hPa^{-1}), R_c is the gas constant (287 J kg^{-1} K^{-1}), C is the specific heat at constant pressure (1005 J kg^{-1} K^{-1}), T_P is the temperature at pressure level P (K), and dT/dP is the change in temperature with respect to pressure (K hPa^{-1}). Commonly, the ratio $\frac{R_c}{C}$ is simplified to κ (0.2854), yielding:

$$S_P = \kappa \frac{T_P}{P} - \frac{dT}{dP} \quad (3)$$

Utilizing this method requires only vertical temperature profiles. We download monthly 3D temperature (*ta*) data for each of the 22 models noted in Table 1 for years 1-10 and 131-140 of the abrupt-4xCO2 experiment. To avoid the complication of interpreting results over land regions, static stability is computed over ocean regions only by constraining data through landmasks from each model's land fraction output (*sftlf*) and is reported as a tropics-wide (30°N to 30°S), area-weighted mean. Following Kemsley et al. (2024), temperature profiles are interpolated using cubic spline interpolation to 100 evenly-spaced pressure levels between the lowest and highest pressure level outputted at each grid box within each model to moderate the effects of coarseness of model output in the vertical dimension and more accurately represent the second term of Equation 2. This term is approximated using finite central differences. Changes to the tropical upper-tropospheric stability are calculated by subtracting the average upper-tropospheric static stability calculated from years 1-10 of the abrupt-4xCO2 experiment from average static stability calculated from years 131-140 and normalized by the global mean change in surface temperature.

Table 1. Ensemble of CMIP models analyzed, as in Dawson and Schiro (2025). Models are listed in order of increasing climate sensitivity.

Model	CMIP Generation	Variant
MIROC6	CMIP6	r1i1p1f1
MRI-CGCM3	CMIP5	r1i1p1
MIROC-ES2L	CMIP6	r1i1p1f2

Model	CMIP Generation	Variant
MIROC5	CMIP5	r1i1p1
MRI-ESM2-0	CMIP6	r1i1p1f1
MPI-ESM-LR	CMIP5	r1i1p1
CanESM2	CMIP5	r1i1p1
GFDL-CM4	CMIP6	r1i1p1f1
E3SM-2-0-NARRM	CMIP6	r1i1p1f1
E3SM-2-0	CMIP6	r1i1p1f1
IPSL-CM5A-MR	CMIP5	r1i1p1
IPSL-CM5A-LR	CMIP5	r1i1p1
IPSL-CM6A-LR-INCA	CMIP6	r1i1p1f1
HadGEM2-ES	CMIP5	r1i1p1
MIROC-ESM	CMIP5	r1i1p1
IPSL-CM6A-LR	CMIP6	r1i1p1f1
CNRM-ESM2-1	CMIP6	r1i1p1f2
CNRM-CM6-1	CMIP6	r1i1p1f2
E3SM-1-0	CMIP6	r1i1p1f1
UKESM1-0-LL	CMIP6	r1i1p1f2
HadGEM3-GC31-LL	CMIP6	r1i1p1f3
CanESM5	CMIP6	r1i1p2f1

Results

a. Profiles of Stability Changes

First, we consider the relationship between the response of static stability and high cloud feedbacks. Models are composited into two groups such that the high group consists of the 7 models with the most positive feedback and the low group consists of the 7 models with the least positive feedback (or most negative feedback, depending on the feedback and the range of signs). The tropical mean profiles of the change in static stability are averaged across each group and compared for the net feedback in Figure 3A. We see that stability increases throughout most of the profile and that the increase in stability maximizes in the upper troposphere, as anticipated

(Merlis et al., 2024). The net high cloud feedback exhibits the greatest difference between the high and low groups between 300 and 150 hPa, the portion of the upper troposphere where tropical high cloud extent tends to maximize (Hartmann & Larson, 2002; Zelinka & Hartmann, 2011). In this pressure range, models with more positive net cloud feedbacks (the high group) experience a lesser increase in stability in response to warming, whereas models with less positive net cloud feedbacks (the low group) experience a greater increase in stability.

Next, to further isolate the contributions of the different feedback components to the relationship between the net feedback and change in stability, we analyze the profiles composited by the altitude, optical depth, and amount feedbacks (Figure 3B-D). Comparisons of the high and low composited groups for the altitude and optical depth feedbacks both demonstrate weaker increases in stability associated with more positive feedbacks, suggesting that they are playing a significant role in driving the difference shown between high and low stability groups in the net feedback. In contrast, the stability in the 300-150 hPa range does not show much variability among high and low amount feedback groups. Following these results, we define the change in upper-tropospheric static stability as the change in stability averaged between 300 and 150 hPa, as this is the location in the profile where the largest differences are observed among high and low feedback groups, consistent with expectations (as these are the altitudes where stability changes most and high clouds are most extensive).

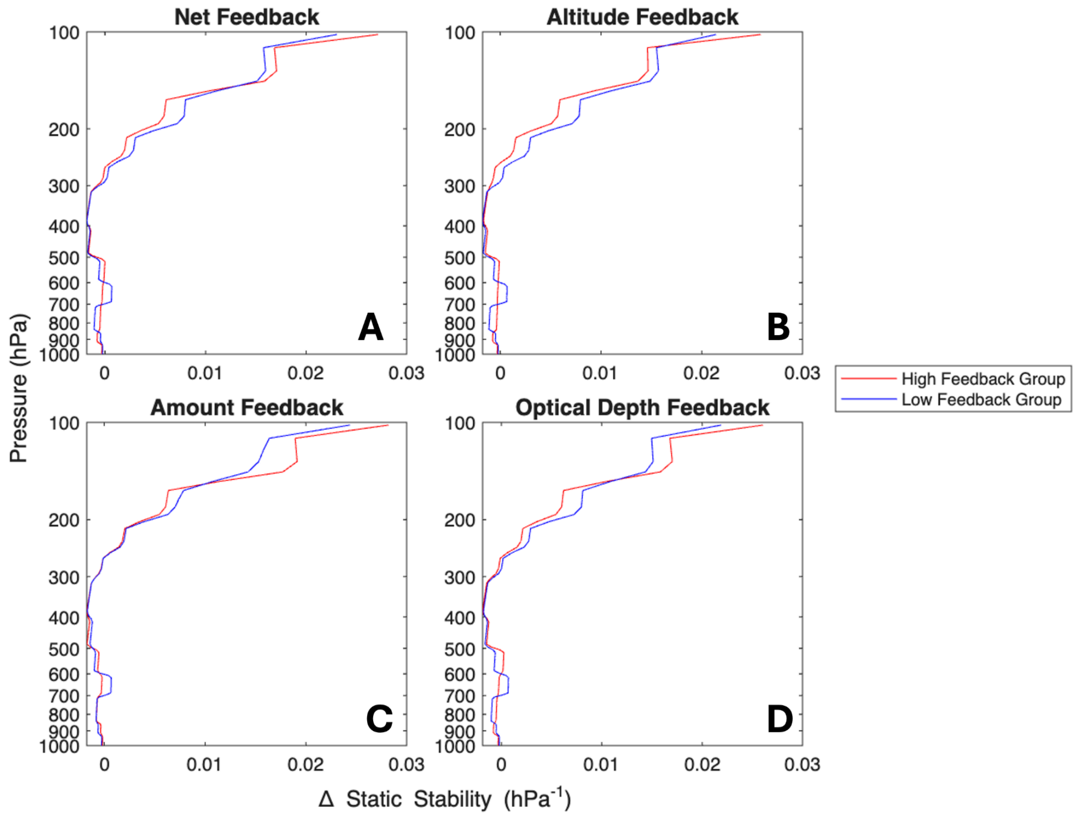

Figure 3. Tropical mean change in static stability vertical profiles for high (positive) and low (less positive/more negative) high cloud feedback groups composited separately for the A) net, B) altitude, C) optical depth, and D) amount feedbacks. The high feedback group is an average of the 7 models that have the most positive feedback and the low group is an average of the 7 models with the least positive (or most negative) cloud feedback. Tropical means are taken from 30°N to 30°S.

b. Relationship of Upper-tropospheric Stability Change and Feedbacks

Next, to assess the spatial relationship between the tropical mean change in stability and cloud feedbacks, we correlate the local cloud feedbacks with the tropics-wide change in upper-tropospheric static stability (150-300 hPa) and visualize this relationship over space.

Additionally, we compare maps of cloud feedbacks averaged across the 7 models exhibiting the greatest increase in upper-tropospheric stability (high group) with the 7 models exhibiting the smallest increase in upper-tropospheric stability (low group).

The response of upper-tropospheric stability has a significant, negative correlation (R= -0.647; p = .001) with the tropical mean net high cloud feedback across the ensemble. These anticorrelations between local net high cloud feedbacks and the change in tropics-wide upper-tropospheric static stability are present across equatorial oceanic regions in addition to the Warm Pool and East Pacific (Figure 4A). Models that exhibit a greater increase in stability predict a more negative net high cloud feedback (or cooling) in tropical equatorial regions (Figure 4B) in contrast to the muted feedbacks in these regions present in models with a weaker increase in stability (Figure 4C). Comparing the two, it is evident that the greatest difference in net feedback between high and low groups occurs in the equatorial tropics, generally aligning with the regions showing significant anticorrelations across the ensemble. This suggests that the significant relationships shown in Figure 4A are also indicative of regions where the net high cloud feedback varies the most among models with the response of static stability.

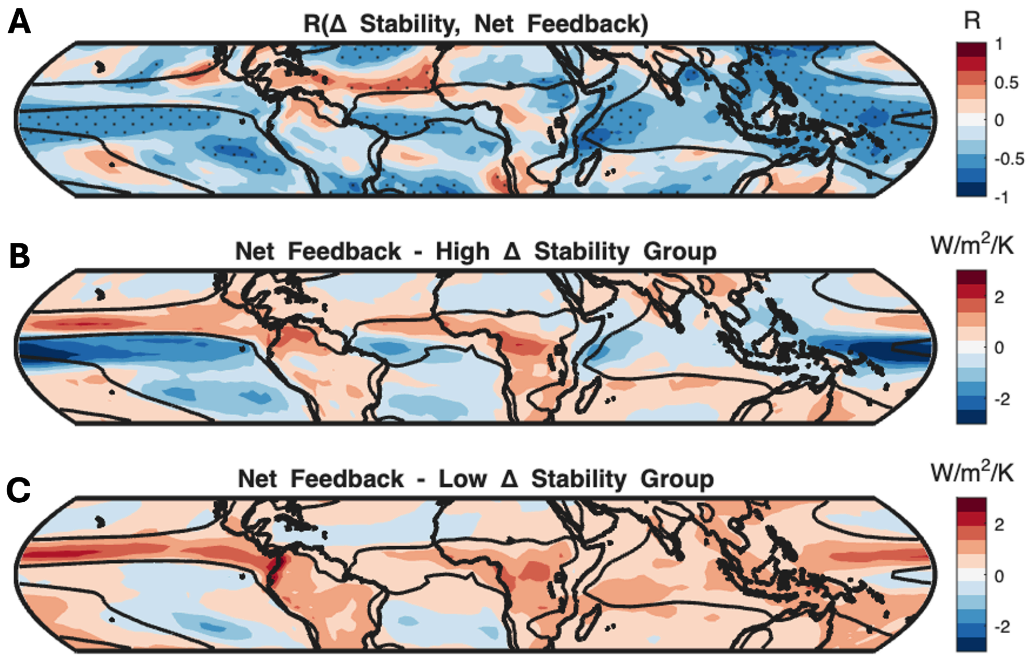

Figure 4. Maps of the A) Pearson correlation coefficient between the local net high cloud feedback and change in tropical-mean stability and tropical high cloud feedbacks averaged between the B) 7 models with the greatest increase in stability and C) 7 models with the weakest increase in stability. Stippling indicates a significant local correlation ($p < 0.05$), and the black contour denotes the multi-model mean contour where vertical pressure velocity ω at 500 hPa = 0 hPa/day across years 1-10 of the abrupt-4xCO2 experiment, generally indicating convective margins.

Next, we consider how the altitude, optical depth, and amount feedbacks vary with the response of upper-tropospheric stability across the ensemble. The altitude feedback is significantly anticorrelated ($R = -0.671$; $p = 0.0006$) with the change in stability in the tropical mean, and demonstrates significant local anticorrelations across the Warm Pool and East Pacific (Figure 5A). While both groups of models demonstrate positive altitude feedbacks in the East

Pacific and Atlantic Intertropical Convergence Zones (ITCZ), models that exhibit the greatest increase in stability (high group) have a muted altitude feedback (cooling) across the equatorial Pacific (Figure 5B). In contrast, the models that show the weakest increase in stability have broadly positive altitude feedbacks (warming) (Figure 5C). The most apparent discrepancy between the high and low groups occurs in the Maritime Continent and Warm Pool region where climatological high cloud coverage is high.

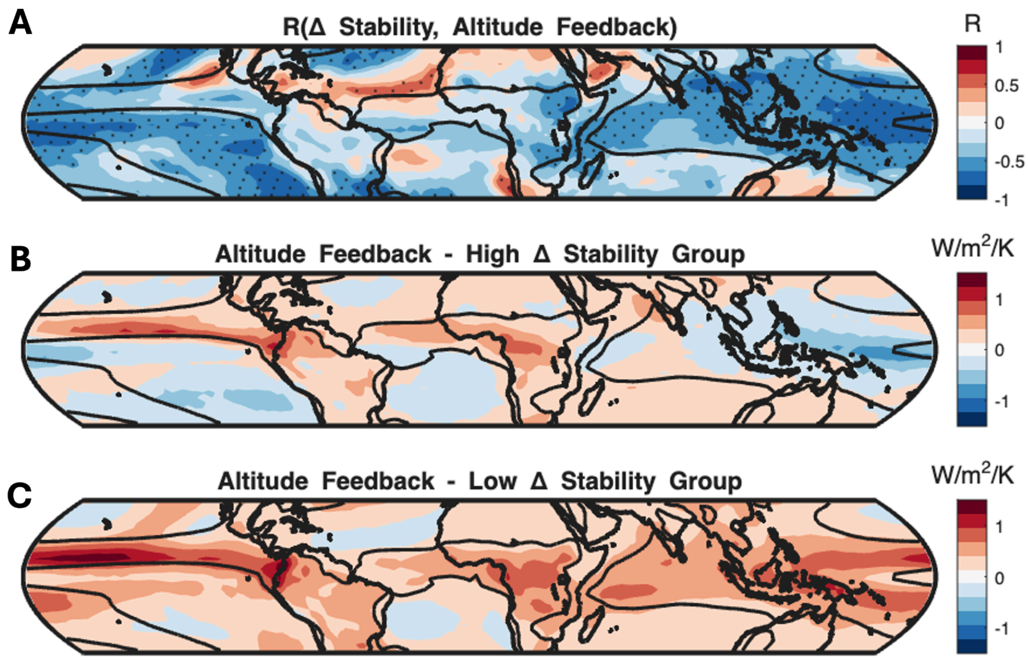

Figure 5. As in Figure 4, but for the high cloud altitude feedback.

Next, we consider the high cloud optical depth feedback. The high cloud optical depth feedback exhibits a significant negative correlation (R = -0.481; p = 0.0235) with the change in stability tropics-wide. Local relationships are weaker than those demonstrated by the net and altitude feedbacks, but significant negative correlations are present along convective margins (ω at 500 hPa = 0 hPa/day) in the equatorial Pacific and Atlantic ITCZs (Figure 6A). Models that predict a greater increase in static stability (high group) exhibit a strong negative optical depth feedback (thickening) in the equatorial Pacific and weak positive optical depth feedbacks (thinning) within the climatological ITCZ (Figure 6B). On the other hand, models that predict a weaker increase in static stability (the low group) also demonstrate thinning within the ITCZ but show a relatively more muted negative optical depth feedback equatorially in comparison to the high group (Figure 6C). These results suggest that models experiencing a stronger increase in upper-tropospheric stability in response to warming experience significantly greater thickening of high clouds along the equator. We had previously hypothesized that the high cloud optical depth feedback would respond to an increase in stability in the form of thinning high clouds due to reduced convective activity, resulting in a more positive feedback. However, these results run counter to our expectations.

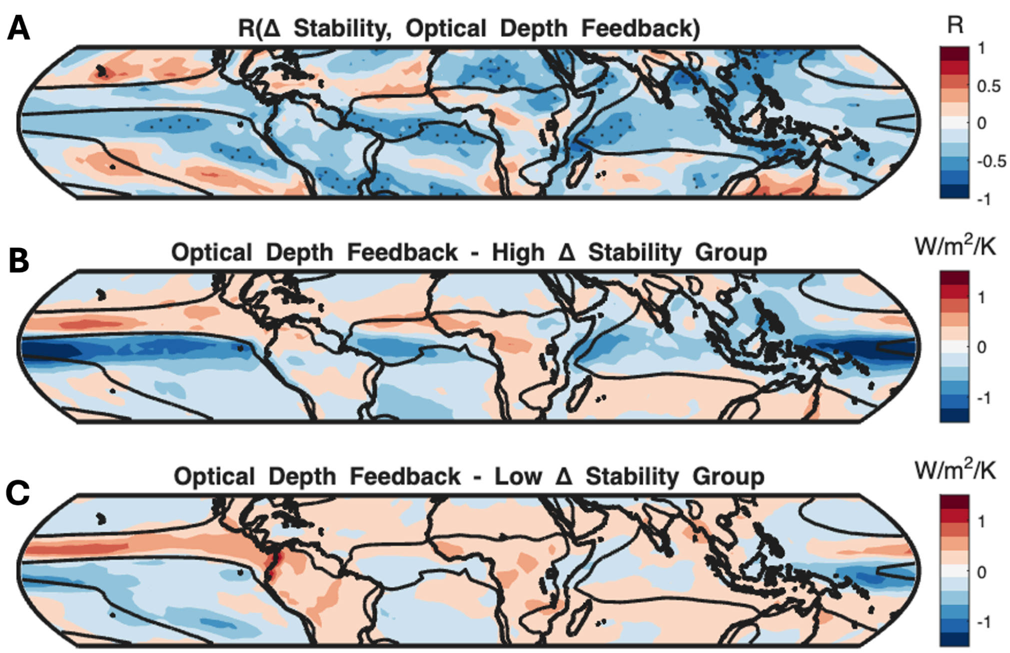

Figure 6. As in Figure 4, but for the high cloud optical depth feedback.

Finally, we consider the high cloud amount feedback. Unlike the altitude and optical depth feedbacks, the relationship between the response of stability to warming and the amount feedback is not significant tropics-wide ($R = -0.174$; $p = 0.4399$). Spatially, moderate anticorrelations are present at the equator in the Atlantic and West Pacific (Figure 7A), but they are weaker and less extensive than displayed by the optical depth feedback. Comparing the composited maps (Figure 7B-C) demonstrates that the equatorial Pacific exhibits a more negative amount feedback and corresponding greater increase in high cloud fraction in models that predict a greater increase in static stability (high group) than the models that yield a weaker increase in stability (low group). Qualitatively, the difference in the spatial pattern of the amount feedback between the two groups is similar to that of the optical depth feedback (Figures 6B-C), suggesting that while the amount feedback does not vary significantly with changes in upper-tropospheric static stability in the tropical mean (Figure 3C), significant local relationships exist along the equator that contribute to the relationship between the net feedback and changes in stability in this region highlighted previously (Figure 4A).

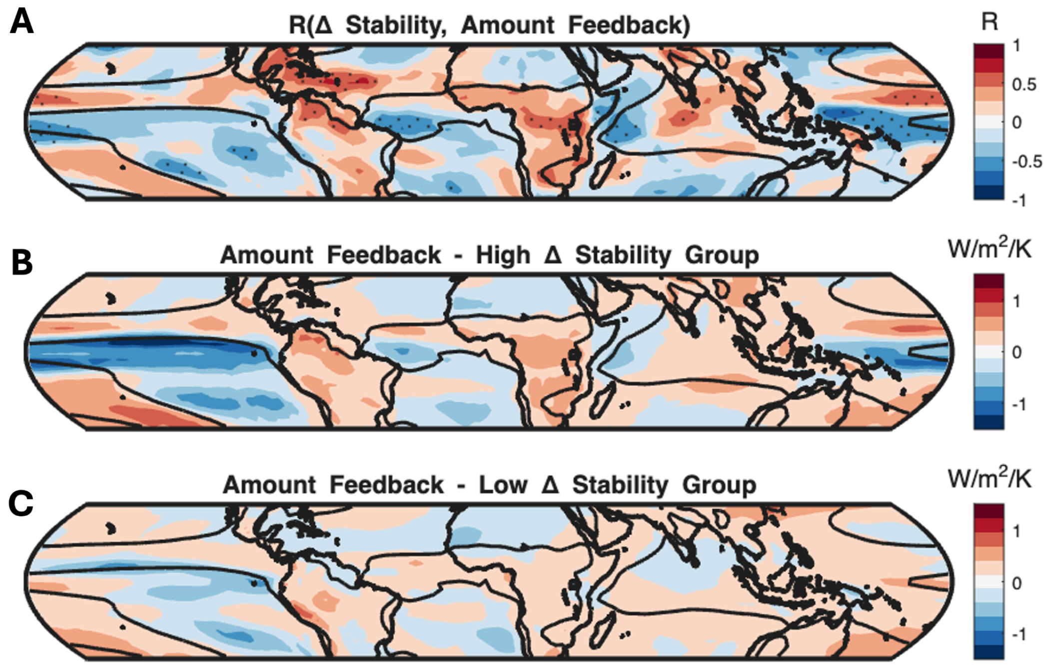

Figure 7. As in Figure 4, but for the high cloud amount feedback.

c. *Testing the PHAT Hypothesis*

Following the result that the high cloud altitude feedback has the strongest relationship to changes in stability across the tropics (and therefore has the greatest impact on the relationship between the net high cloud feedback and the change in stability), we choose to test a hypothesis that plausibly links the altitude feedback with stability changes in the upper troposphere based on previously established physical theory. The Fixed Anvil Temperature (FAT) hypothesis proposed by Hartmann and Larson (2002) explains that clouds tend to remain at the same temperature in response to surface warming, which results in cloud tops emitting constant longwave radiation to space. Under these conditions, downwelling radiation increases but upwelling radiation stays the same, yielding a positive altitude feedback as the surface warms. Zelinka and Hartmann (2010) later proposed the Proportionally Higher Anvil Temperature (PHAT) hypothesis as a modification of FAT, arguing that when clouds rise, they rise into a more stable atmosphere, causing a slight warming of cloud tops, albeit smaller in magnitude than surface warming. This still results in a positive feedback, but not as positive as FAT. Following PHAT, we hypothesize that the altitude feedback could be mechanistically linked to changes in stability across our ensemble such that models that see a greater increase in stability experience stronger warming of cloud tops and a less positive altitude feedback.

To test this hypothesis, we correlate the change in high cloud top temperature with the change in upper-tropospheric stability across the ensemble. To isolate anvil clouds, we first constrain cloud fraction to regions where air is rising, denoted by grid boxes where vertical velocity at 500 hPa is negative. Next, maximum cloud fraction is extracted between 600 and 100 hPa and the temperature of the corresponding pressure where cloud fraction maximizes is extracted from the vertical temperature profile. Finally, area-weighted values of anvil temperature are taken for both periods of the abrupt-4xCO2 experiment. These values are then differenced and normalized by the global mean change in surface temperature.

All models demonstrate an increase in upper-tropospheric stability, and 21 of 22 models see an increase in high cloud temperature, in line with PHAT rather than FAT (Figure 8). However, there is not a significant relationship ($R = 0.02$) between the change in high cloud temperature and the change in stability across the ensemble. This result suggests that PHAT is not the primary mechanism underlying the significant anticorrelation between the high cloud altitude feedback and stability response.

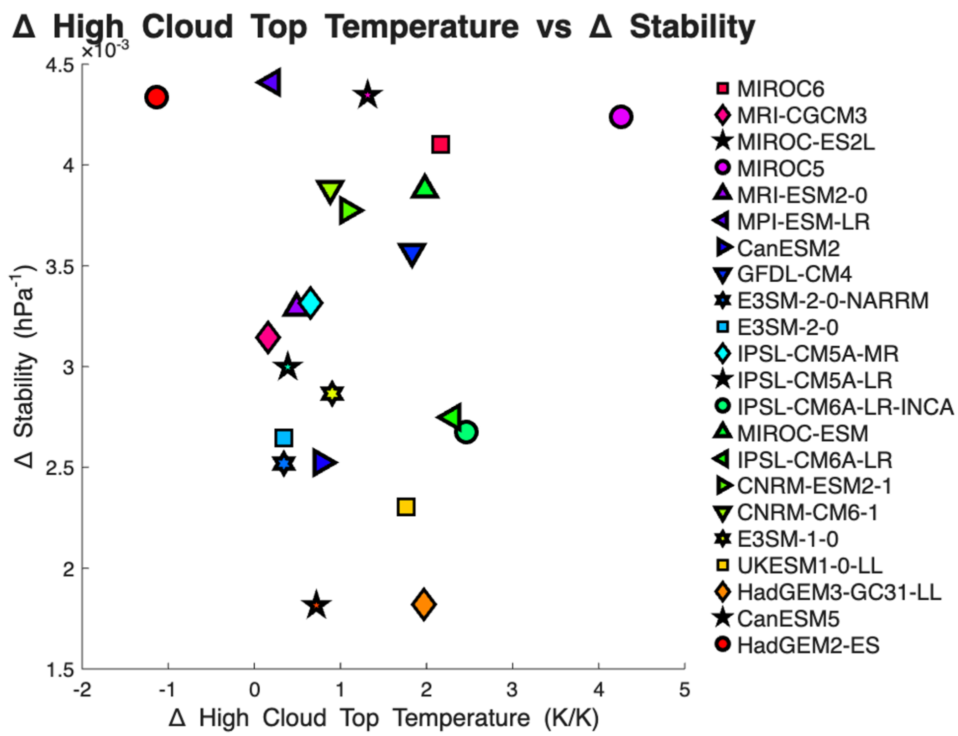

Figure 8. Scatterplot illustrating the correlation between the change in stability (1/hPa) and the change in high cloud temperature (K/K) of the 22 CMIP models.

Discussion

This study highlights a significant anticorrelation between the tropical high cloud altitude feedback and the response of upper-tropospheric static stability to warming across an ensemble of GCMs. Although we hypothesize that physics underlying the PHAT hypothesis may be driving this relationship such that a greater increase in stability causes a greater warming of cloud tops as they rise, a lack of relationship between the change in high cloud temperature and change in static stability suggests that other mechanisms may be driving this relationship, and identifying them is beyond the scope of this project. One potential factor that prevents this relationship from being clear is that the temperature and cloud fraction profiles of models' native vertical profiles may be too coarse to accurately capture small changes in cloud top temperature between the two experiments. Testing different methods of characterizing high cloud temperature changes could help to confirm whether or not the lack of relationship between stability and cloud top temperature responses truly indicates that PHAT does not govern the underlying physics. Additionally, changes in stability could be related to a mean state variable that also happens to be related to the high cloud altitude feedback, yielding a relationship that may be significant but not indicative of direct causation between the two variables. For example, Dawson and Schiro (2025) highlight that models with climatologically more high clouds have a more positive altitude feedback, so it is plausible that a climate variable not explored here — mean state static stability, for example — could relate to both stability responses and the altitude feedback but not link the two mechanistically. However, due to the strength of the tropical mean relationship in addition to the broad spatial arrangement between the altitude feedback and upper tropospheric static stability responses, we suspect that the relationship is not spurious and should be investigated further in future work.

Interestingly, the optical depth and amount feedbacks demonstrate similar spatial patterns when comparing the high and low groups (Figure 6B-C; Figure 7B-C). Both feedbacks display a strong, negative band in the equatorial Pacific in models that exhibit a greater increase in stability. This spatial pattern is indicative of a greater increase of high cloud fraction and thickening of the high cloud population along the equator. We interpret this as representing a stronger shifting of the ITCZ, a planetary-scale band of deep convective clouds near the equator, southward across models that have a greater increase in stability. Studies show that under warming, the ITCZ will undergo a “deep-tropics squeeze” where it narrows and strengthens in core ascent regions. However, the physical understanding of why the ITCZ appears to shrink equatorward in climate change simulations is limited, and represents a key challenge in climate dynamics (Byrne et al., 2018). One theory for this shift and narrowing of the ITCZ is its relationship to sea surface temperatures (SSTs) and shifting SST patterns and gradients under anthropogenic warming. Another is related to changes in atmospheric stability that are "upping the ante" for convection onset, whereby deep convection can no longer occur along convective margin regions, as these regions are no longer meeting instability criteria for triggering deep convection. The relationship between changes to upper tropospheric stability, the location of tropical convection, and SSTs in response to anthropogenic forcings could be explored in future work.

While sea surface temperatures may directly affect the locations of tropical deep convection and high cloud cover, research on a phenomenon known as the Pattern Effect suggests that SSTs could play a role in remote changes to upper tropospheric stability. The Pattern Effect, defined as the relationship between different patterns of sea surface temperature changes and the strength of climate feedbacks, has been linked to the inter-model spread in ECS among CMIP5 and CMIP6 models (Dong et al. 2020). Zhou et al. (2017) determined that warming in the west Pacific leads to negative cloud feedbacks and warming in the east Pacific results in only a local positive cloud feedback. They find that these feedbacks are linked mostly to changes in low clouds with loss of cloud cover in the eastern Pacific under warming. However, even though the Pattern Effect has been linked mostly to low clouds, it also influences upper tropospheric stability and therefore plausibly affects high cloud changes as well. The West Pacific is characterized by climatological ascent, which allows for the effective communication of surface warming upwards into the troposphere. As a result, this warming will spread more widely in the upper troposphere and across the tropics, creating greater stability tropics-wide. In contrast, the East Pacific descent regions are expected to trap any surface warming under an inversion layer resulting in relatively muted warming aloft and a weaker increase in upper-tropospheric stability in comparison to a scenario in the west Pacific. In future studies, the relationship between the Pattern Effect, changes in tropospheric stability, and tropical high cloud feedbacks could be assessed to determine whether sea surface temperature patterns lead to changes in high cloud feedbacks.

Conclusion

High cloud feedbacks in the tropics represent a significant source of uncertainty in modelling the amount of warming that will occur as a result of anthropogenic greenhouse gas emissions. Thus, identifying underlying mechanisms that may drive the spread in high cloud feedbacks across fully-coupled global climate models remains a critical area of research. This study seeks to investigate one potential mechanism by examining relationships between inter-model variability in the response of upper-tropospheric static stability and tropical high cloud feedbacks across an ensemble of GCMs.

Analyzing the change in static stability profiles across the ensemble demonstrates that while the troposphere is projected to become more stable in the future, the magnitude of the response varies appreciably in the upper troposphere where climatological high cloud fraction maximizes, motivating further investigation of linkages to high cloud changes. We find that the net high cloud feedback is significantly anticorrelated with the change in upper-tropospheric static stability at a tropics-wide scale, highlighting that models with relatively strong cloud feedbacks that act to enhance surface warming also illustrate a weaker increase in tropical stability in the upper atmosphere. Additionally, the high cloud altitude and high cloud optical depth feedbacks demonstrate significant anticorrelations to stability responses in the tropical mean. Significant relationships between the altitude feedback and stability response across the Pacific motivate further analysis of the relationship between changes in stability and cloud top temperature following the PHAT theory (Zelinka & Hartmann, 2010). However, as stability increases, high cloud top temperature does not increase accordingly, requiring further work to identify the processes driving this relationship. Furthermore, significant anticorrelations between the optical depth feedback and stability response demonstrate a stronger thickening of high clouds equatorially in models that become more stable. While insignificant in the tropical mean, similar anticorrelations are present for the amount feedback, hinting at a greater equatorward shift of deep convection (commonly referred to as a "deep-tropics squeeze" or "ITCZ narrowing") in models that become more stable. Identifying mechanisms underlying the potential linkage between stability changes and circulation changes across the ensemble is beyond the scope of this work, but topics such as the Pattern Effect (relating inter-model spread in changing SST patterns to spread in stability changes and high cloud feedbacks) could be analyzed further to help explain this relationship.

Overall, this study finds that inter-model differences in high cloud feedbacks are significantly linked to variability in upper-tropospheric static stability. This helps clarify one potential reason for the spread in tropical high cloud feedbacks and ultimately equilibrium climate sensitivity (ECS) across GCMs. By understanding the strength and location of the relationships between stability and the altitude, optical depth, and amount high cloud feedbacks, climate scientists can work to better constrain ECS. These findings are critical not only for improving the accuracy of climate projections, but also for creating global mitigation and adaptation strategies in the face of accelerating climate change.

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