

THESIS

REVISITING THE IMPORTANCE OF A SOUTHERN OCEAN PATTERN EFFECT

Submitted by

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ABSTRACT

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The spatial pattern of surface warming determines radiative feedbacks (“pattern effect”). The seminal work of Senior & Mitchell (2000) (SM00) argued that Southern Ocean clouds set the evolution of global radiative feedbacks in time and hence, determine climate sensitivity. We revisit their argument in current generation climate models: We quantify the time evolution of local atmospheric stability, clouds, and their local and global radiative effects as the Southern Ocean warming is catching up with global mean warming. SM00 argue that in the early period after a strong radiative forcing with CO₂, the Southern Ocean’s warming is delayed compared to the global mean (I) and that the faster warming tropics set the free tropospheric temperature over the Southern Ocean (II), creating a relatively stable lapse rate (III). While overall cloud cover shrinks, the loss of stratiform clouds is suppressed (IV) and convection is unfavorable (V) during this fast timescale. As Southern Ocean warming catches up with the rest of the globe (VI), the local Southern Ocean lapse rate destabilizes (VII) which accelerates the loss of stratiform clouds and creates a more favorable environment for convection(VIII). SM00 argue that the time-evolution of Southern Ocean clouds controls the local Southern Ocean cloud feedback (IX) and that the processes I-VIII dominate the time-evolution of the global net radiative feedback and hence, climate sensitivity (X). We find that current generation models are able to confirm SM00’s arguments up to the Southern Ocean controlling the local Southern cloud feedback (I-IX). However, the time evolution of Southern Ocean clouds does not reflect in the time evolution of the global net feedback (X). We propose that SM00 mistakenly assumed a causal connection between climate sensitivity and the Southern Ocean cloud evolution, while the actual link to climate sensitivity is the global sensitivity of shortwave clouds to warming and the remote effects of Southern Ocean heat uptake.

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Chapter 1

Introduction

Understanding how much warming to expect from anthropogenic climate change is a central problem in climate science. One way to approach this problem is through the analysis of the various ways the climate system energetically responds to a forcing, such as an increase in carbon dioxide (CO₂). These responses are broadly known as radiative feedbacks (Gregory et al., 2004; Shine et al., 2003), they describe how efficiently radiative forcings can be amplified or damped out in the climate system. These feedbacks can be broken into many parts, accounting for the various different responses of the climate system (e.g., Planck feedback, lapse rate feedback, water vapor feedback, etc.). While there is work done to understand how all of these feedbacks contribute to and change with global climate change (Hall & Qu, 2006; Held & Shell, 2012; Liu et al., 2018; Bao et al., 2021; Cronin & Dutta, 2023), cloud feedbacks have ended up receiving special attention to constrain future projections. This special attention is because of cloud feedbacks contributing the most uncertainty to future projections (Zelinka et al., 2020; Myers et al., 2021).

Early understanding of climate sensitivity, or how much warming you would expect from a doubling of CO₂, assumed that the global net feedback was constant through time. Senior and Mitchell (2000) showed that this assumption is largely inaccurate, owing largely to the time-evolution of clouds. More recently, work done by Gregory and Andrews (2016) shows that in the historical period, the global net feedback shows distinct time variance, evidently meaning that estimates of climate sensitivity must too. Rugenstein et al., (2020) argues for the importance of the length of a climate model simulation when trying to understand equilibrium climate sensitivity estimates. Ultimately, the summary of this line of research is that due to the time-dependence of climate sensitivity, when you determine the equilibrium response matters. Its also important to note that this erases our ability to accurately predict future climate change based on the previous climate alone.

Further, this idea of time-dependence is connected to the "pattern effect", or that the global net feedback is known to depend on the pattern of warming at the surface (Rugenstein et al., 2023;

Stevens et al., 2016). As surface temperature warming patterns evolve, the global net feedback is going to evolve. While the pattern effect is known to influence the global net feedback, it is still unclear just what regions are most relevant. One method to test the sensitivity of different regions of the globe is known as a "Greens Function" (Barsugli & Sardeshmukh, 2002). This method is conducted by applying "patch perturbations" around the global oceans of some variable of interest (sea surface temperature, Q-flux, etc.) and analyzing the global response of another variable of interest for each patch. You run your model for as many patches as you want to apply, save the global response for each individual patch, and "average" the results together to create a map identifying which regions when perturbed have the largest impact on your variable of interest. For example, Fig 1.1a shows that the tropical West Pacific, when perturbed with patches of SSTs, is the most influential in changing global mean temperature.

The power of the Greens Function method is that it allows you to identify which regions matter most. Greens Function approaches testing top of atmosphere radiation's sensitivity to a global SST (SST-GF, Fig 1.1a) or Q-flux patch perturbations (Q-GF, Fig 1.1b) (which change ocean heat uptake), seem to disagree. The SST-GFs identify the tropics, especially the tropical West Pacific (Dong et al., 2019; Dong et al., 2020; Rugenstein et al., 2020; Alessi & Rugenstein, 2023), while Q-GFs, relying on patterns of ocean heat uptake, identify the extratropics, especially the Southern Hemisphere (SH) (Rose et al., 2014; Rose & Rayborn, 2016; Rugenstein et al., 2016). Ultimately, these two approaches don't necessarily disagree with each other since a change in extratropical heat uptake can cause variations in tropical SST (Lin et al., 2021).

The discussion surrounding the pattern effect has focused almost entirely on the tropical West Pacific due to the influence of the SST-GFs. This is in spite of the fact that one of the earliest papers trying to understand radiative feedbacks, Senior and Mitchell (2000, hereafter SM00), proposes a Southern Ocean (SO) pattern effect. Papers that show the importance of the tropical Pacific have also shown that there may be a role for the SO in the discussion, but it is often limited to brief analysis or speculation (Andrews et al., 2015; Dong et al., 2020; Rugenstein et al., 2020). Work from the SO perspective arguing for a SO pattern effect (Kang et al., 2023b) largely relies on the

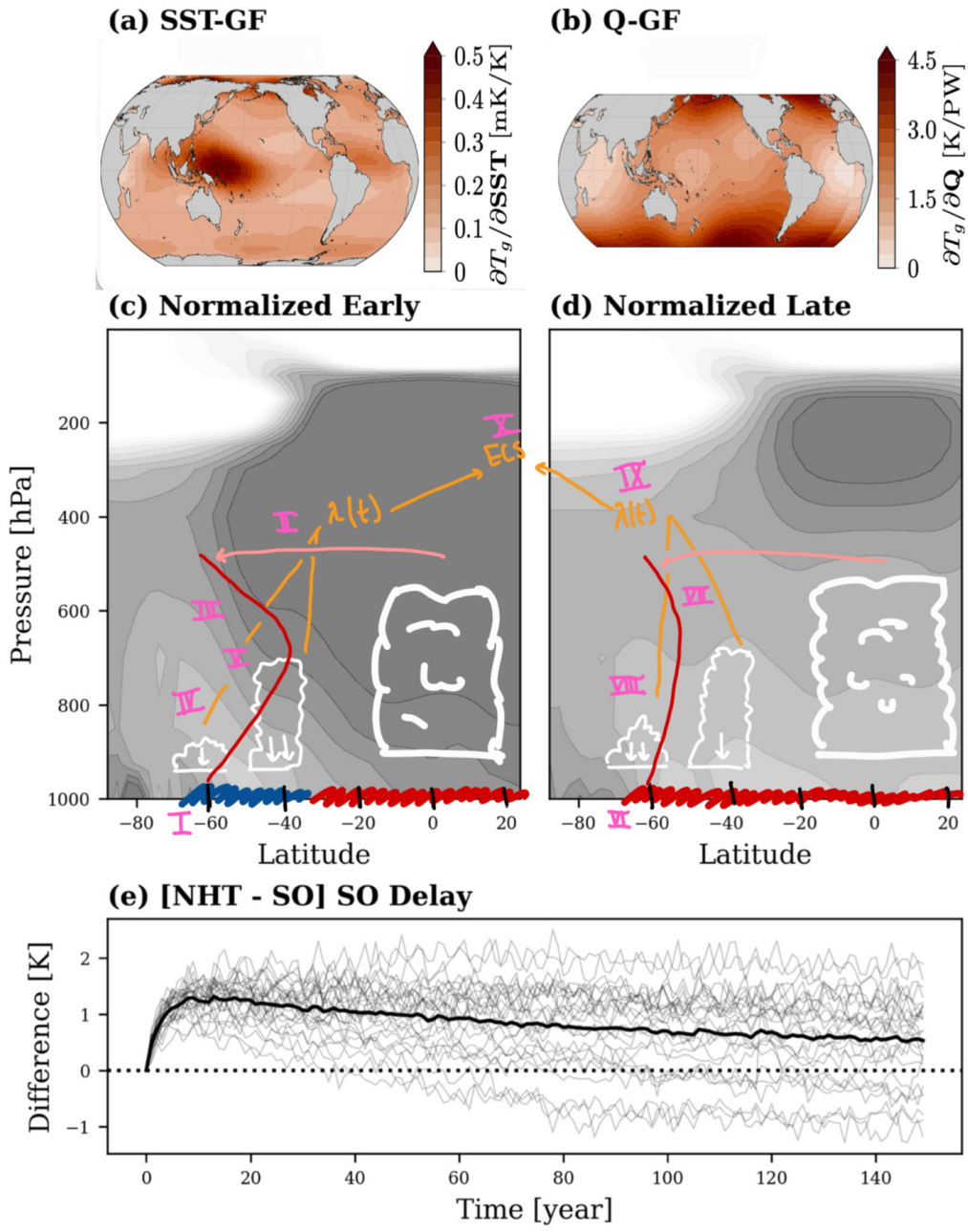


Figure 1.1: Understanding the role of the SO and SO temperature delay. (a) SST-GF map showing how SST perturbations cause changes in global temperature. (b) Q-GF map showing how Q-Flux perturbations cause changes in global temperature. (c-d) Schematic drawing out SM00’s hypothesis. Red lines indicate the lapse rate over the SO, yellow lines indicate radiative feedbacks. Surface warming is indicated with red and blue coloring at the 1000 hPa level. The gray-scale plotting in the background is global warming in a meridional slice normalized by SO warming in the average of the first 10 years (c) and the average of the last 10 years (d). (e) Time series of the difference between Northern Hemisphere + Tropics (40S-90N) temperatures and SO temperatures (60S-40S).

non-local effects of the SO. Quantifying the local and remote role the SO plays for the global radiative feedbacks and their time evolution is still an open conversation.

Since SM00, there has been a push and pull over the relevance of the SO. Trenberth and Fasullo (2010) showed that in CMIP3, SH TOA net radiation was correlated with the equilibrium climate sensitivity (ECS) of the model, but Grise et al. (2015) found that this was largely due to model biases in that generation of models and showed that CMIP5 models did not show this relationship. More recently the importance of the SO to global radiation is being emphasized, Kajtar et al. (2021) find that the baseline temperature of the SO in a model predetermines the capacity for change in the model. Kim et al. (2022) and Dong et al. (2022) identify the influence that the SO can have on low clouds, and their radiative feedbacks, in the southeast Pacific (SEP). They also argue for the SO's La Nina-like influence over the temperature gradient across the equatorial Pacific. Kang, Yu, et al. (2023) showed that the SO had important teleconnections all over the globe and Kang, Ceppi, et al. (2023) argues that the remote influences the SO has are important to the global net feedback through low cloud feedbacks in the SEP.

SM00 argues for a physical pathway connecting warming in the Northern Hemisphere (NH), via the tropics, to changes in the SH extratropics. They propose that these changes are connected to the time evolution of clouds and the global radiative feedback. Their pathway can be grouped into an early period (I-V) and a late period (VI-VIII), and the implications of the change between those two periods (IX-X). Stepping through the processes (visualized in Fig 1.1c-d):

- I SO warming is delayed relative to the rest of the globe
- II The tropics communicate the accelerated warming into the SO free troposphere
- III This establishes a relatively stable lapse rate
- IV The lapse rate supports a slower loss of stratiform clouds
- V The lapse rate also supports a suppression of convection
- VI SO temperatures catch up with the rest of the globe

VII The lapse rate over the SO becomes less stable

VIII The destabilized atmosphere supports less suppression of convection and an increased loss of stratiform clouds

IX The change in SO clouds controls the local net feedback

X This change in the SO local net feedback controls the global net feedback and is connected to the climate sensitivity

These processes, which will be referred to as “SM00’s hypothesis” throughout the manuscript, connects patterns of surface temperature change around the world to the radiation caused by changes to SO clouds. Figure 1.2 show that these physical processes (I-XIII) are unique to the SO. Delayed warming is especially noticeable in the SO (Fig 1.2a). The SO is the only region with enhanced stability in the early period, and this stability shifts to decrease by the end (Fig 1.2b). Stratiform cloud decreases are maximized in the SO (Fig 1.2c). There is no parallel occurrence of these phenomena in the NH or tropics.

In this study, the ability of current-generation models to recreate SM00’s hypothesis are explored. We find that models are able to recreate processes I-IX of SM00’s hypothesis. The delay and catch-up of SO temperatures is connected to a decrease in stability over the SO. This stability change is associated with enhanced decreases in stratiform clouds and reduced suppression of convection. The change in clouds in the SO is connected to a change in the local feedback. However, there is no relationship between the SO shortwave cloud local feedback and the global net feedback. After outlining data and methods (Chapter 2), the time evolution of SO temperature and its relationship to changing stability profiles over the SO (Chapter 3.1) are related to the cloud changes in the models and the similarity of the models to SM00’s hypothesis, i.e. the SM00-ness of the model (Chapter 3.2). The importance of SO clouds to global net feedbacks are then explored in the context of SM00-ness (Chapter 3.3). The results of current-generation models recreating SM00’s hypothesis are summarized and the implications are discussed in Chapter 4. Future research directions are also laid out in Chapter 4.

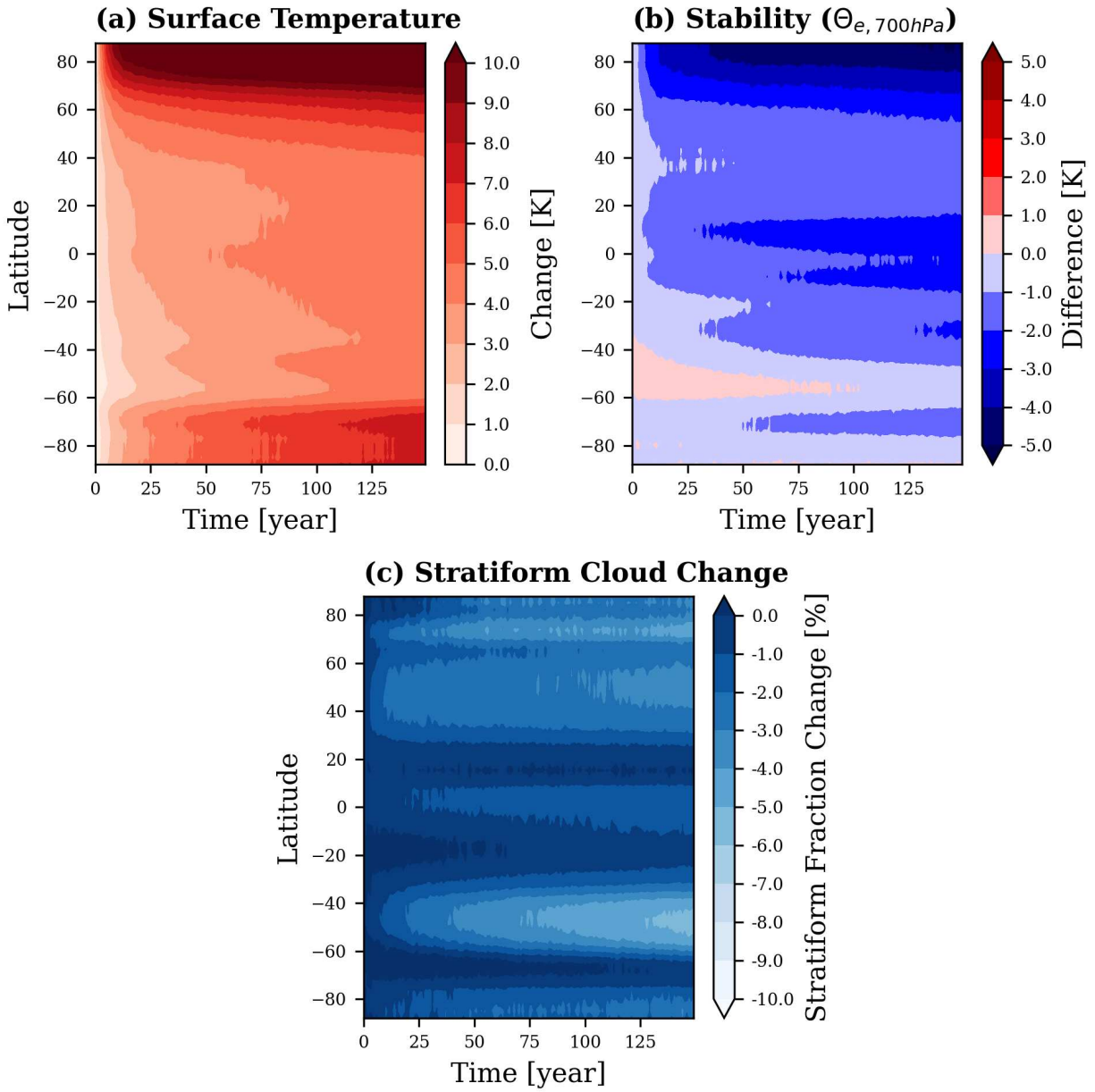


Figure 1.2: SO Processes are unique compared to the NH. (a-c) CMIP6 ensemble mean, all plots are averaged over all longitudes through time. (a) Surface temperature change relative to start of abrupt-4xCO₂ simulation. (b) Same as (a) but for equivalent potential temperature stability (explained in Chapter 3.1). (c) Same as previous but for stratiform cloud fraction change.

Chapter 2

Methods

This study utilizes a suite of 26 CMIP6 models (Eyring et al., 2016) (Table A.1), which provides surface temperature, atmospheric temperature, surface pressure, surface specific humidity, atmospheric specific humidity, total cloud coverage, atmospheric cloud coverage, incoming and outgoing shortwave radiation for all sky and clear sky, and outgoing longwave radiation for all sky and clear sky data for a preindustrial control experiment (piControl) and an abrupt CO₂ quadrupling experiment (abrupt-4xCO₂). All spatial fields are of a quantity conservatively regridded to the lowest common resolution (2.7° latitude by 2.8° longitude) before analyzing them.

Essential changes were made to recreate SM00's hypothesis in this work. Instead of separating the world into NH and SH, we've separated the world into NH + tropics (NHT, 90N-40S) and SO (40S-60S, box choices justified by boundaries of process occurrence in Fig 1.2). This is primarily to isolate the role of the SO and secondarily because in SM00's hypothesis the NH's warming is communicated through the tropics, so it makes sense to combine those two as one influence separate from the SO. Using abrupt-4xCO₂ experiments keeps the spirit of SM00's paper which uses an experiment that increases CO₂ by 1% per year until doubling. However, they have a much longer experiment at 800 years than the CMIP6 archive provides. The abrupt-4xCO₂ experiment allows us to maximize the data available for analysis after the forcing has occurred.

Throughout the manuscript, "change" will indicate a difference between the average of years 141-150 ("late" period) and the first 10 years ("early" period) in the abrupt-4xCO₂ simulation. Our results qualitatively stay the same for defining "early" and "late" differently. The phrase "stability change" will refer to the following method: calculate the atmospheric temperature lapse rate in the early and late periods, subtract out the piControl climatology from both, subtract out the surface temperature of both profiles to shift them the surface temperatures to 0, then subtract early from late profile, i.e calculate the change (visual example in Figure A.1). To calculate stability

changes, the values were averaged over the SO first, but there is no difference in results if stability is calculated at each grid in the SO and then averaged.

Clouds are an important piece of SM00's hypothesis—their analysis is separated between "low level" and "convective" clouds. Most CMIP6 models did not output stratiform or convective clouds. Hence, the stratiform cloud fraction is defined as the maximum cloud fraction below 700 hPa and convective cloud fraction is defined as the difference between the total cloud fraction and the stratiform cloud fraction. This assumption works due to the coarse resolution of CMIP6 models, maps of our derived convective cloud fraction show agreement with observed climatology. Cloud ratio is defined as convective cloud fraction divided by stratiform cloud fraction.

In this paper, the pattern effect is largely diagnosed through the influence that the delayed SO warming has on the change in clouds in the SO through time. To that effect, local feedbacks, λ , are calculated by regressing annual-mean radiation onto temperature in a 30-year window sliding through time (Gregory & Andrews, 2016). Subscripts indicate what type of radiation, from what location in the numerator and what location the temperature comes from in the denominator (e.g. $\lambda_{swcld,so/so}$ refers to a feedback calculated with shortwave radiation from clouds in the SO against temperatures averaged over the SO).

Chapter 3

Results

3.1 Southern Ocean Temperature Evolution

Figure 1.1a shows the time evolution of temperature anomalies in the NHT compared to the SO in the abrupt-4xCO₂ simulation. Models agree that SO warming lags global warming but disagree strongly on timing and magnitude (Fig 1.1e). In some models, the SO warming fully catches up to and surpasses the NHT, while in others this never happens (Fig 1.1e). In the ensemble mean, SO warming begins to catch up to NHT (Fig 1.1e, thick black line approaching 0) but doesn't quite match NHT warming by the end of the experiment. Further, the grayed background coloring in Fig 1.1c&d shows the meridional temperature profile normalized by SO warming. In the ensemble mean, the SO is warming much slower than the rest of the world (dark grays in Fig 1.1c), but by the late period SO warming is more equivalent to the rest of the world (light grays in Fig 1.1d). Current-generation models confirm process I of SM00's hypothesis.

SM00's process II is that the tropics communicate the NHT's accelerated warming over the SO. This connection can be qualitatively seen and is robust across models (Fig 1.1c&d). Fig A.2 shows this relationship more clearly, the temperature evolution in the tropics surface is very well correlated with temperature evolutions in the SO free troposphere, confirming process II of SM00's hypothesis. Feldl et al. (2026) find a similar non-local control over the SO using a moist adiabatic feedback framework: in the transient period of an experiment, the SO region is dominated by non-local effects but transitions to being by local processes in the equilibrium period.

Unlike in SM00's hypothesis, using potential temperature alone does not show a destabilized SO atmosphere by the end of the abrupt-4xCO₂ experiment (III). Rather, potential temperature consistently, across models, suggests a stabilized atmosphere over the SO (Fig 3.1b, green lines). However, the equivalent potential temperature indicates a destabilization of the SO atmosphere (Fig 3.1b, pink lines). The increased vertical moisture gradient (Fig A.3) drives the increased

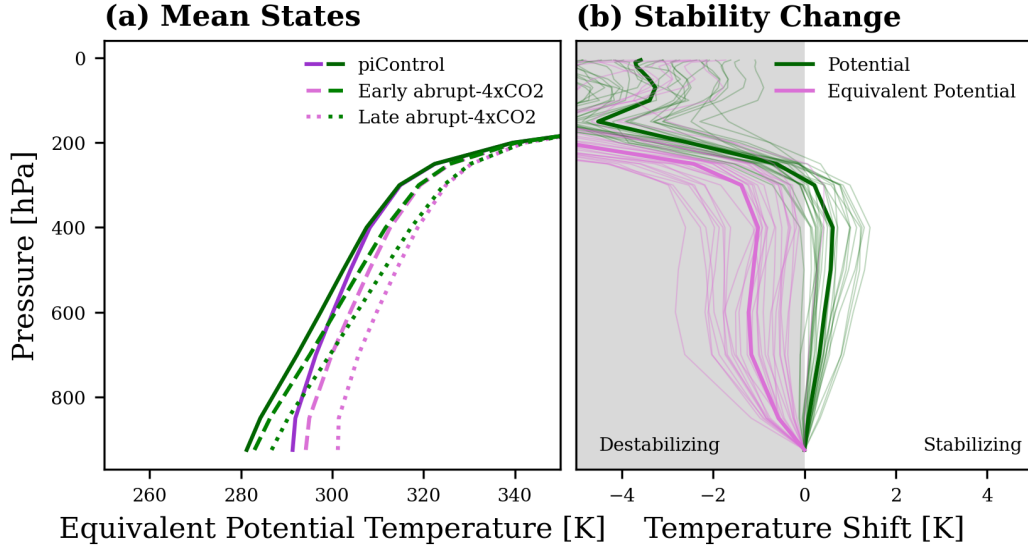


Figure 3.1: Moisture gradient changes are necessary for destabilization of the SO. (a) Mean state of the potential (green) and equivalent potential temperature (pink) profiles in the piControl climatology (solid), first 10 years of the abrupt-4xCO₂ simulation (dashed), and last 10 years of the abrupt-4xCO₂ simulation (dotted). (b) Change in stability (late - early) in potential temperature and equivalent potential temperature (individual models in the thin lines, ensemble mean in thick).

instability. CMIP6 models are able to recreate process III with a slight adjustment to SM00’s hypothesis.

Equivalent potential temperature is defined using Normand (1921)’s formula:

$$\theta_e = \theta \left[1 + \frac{L_v}{c_{pd}} r_v \right] \quad (3.1)$$

where θ is the potential temperature, L_v is the latent heat of vaporization, c_{pd} is the specific heat capacity for dry air at constant pressure, and r_v is the water vapor mixing ratio. In equivalent potential temperature, CMIP6 models are able to recreate SM00’s hypothesis regarding decreased stability over the SO through time. These stability decreases are very consistent (Fig 3.1b) across the models, regardless of if a model’s SO warming catches up to the NHT (Fig 1.1e).

Equivalent potential temperature can be thought of as a measure for cloudy air. In contemporary usage of equivalent potential temperature, the reference state at the surface is considered to be cloudy (Marquet & Stevens, 2022). This is especially powerful in this context, since we’re

explicitly interested in understanding the changes that would occur if clouds were present. Equivalent potential temperature does not account for the latent heat released from ice—or any effects of ice. However, shifting from ice to vapor is a larger release of latent heat and would be more destabilizing (e.g., McCoy et al., 2015; Morrison et al., 2012). Fig A.4 shows results from one model showing that using Tripoli and Cotton (1981)’s ice-liquid potential temperature equation indeed results in a more destabilized atmosphere.

3.2 Southern Ocean Clouds and Senior & Mitchell-ness

In SM00’s hypothesis, processes IV-V are about the impacts of the stability over the SO in the early period. They claim that even though there will be decreases in stratiform clouds (IV), it’s less than without the stability created through processes I-III. On the other hand, convection in the region is suppressed. Fig 3.2a-c shows that this is exactly what is modelled: over time the SO shows decreases in stratiform cloud fraction (Fig 3.2c) and moderate increases in convective cloud fraction (Fig 3.2b), and an increase in the ratio of the two (Fig 3.2a). In general, models that show large decreases in stratiform cloud fraction also show large increases in convective cloud fraction (and vice versa), indicating that some models, in terms of clouds, might generally just be more sensitive to SST changes. The magnitude of the change in the ratio scales well with the change in stability of the lower troposphere (using equivalent potential temperature) (Fig 3.2d). A less stable atmosphere should be have fewer stratiform clouds and more convective clouds. This confirms processes I-VIII of SM00’s hypothesis across models. SO warming catch-up (VI, Fig 1.1e) changes stability (VII, Fig 3.1b). A stronger decrease in stability is associated with a stronger decrease in stratiform clouds and an increase in convective clouds (VIII, Fig 3.2d-f, across model relationships).

Across all the models, Fig 3.2d shows that the models are generally able to recreate the physics that SM00 proposes: models with a stronger stability decrease increase their ratio of convective to stratiform clouds (decreased stability through time causing an increasing cloud ratio). However, the fact it’s not a more ideal correlation indicates that some models have a more closely-coupled re-

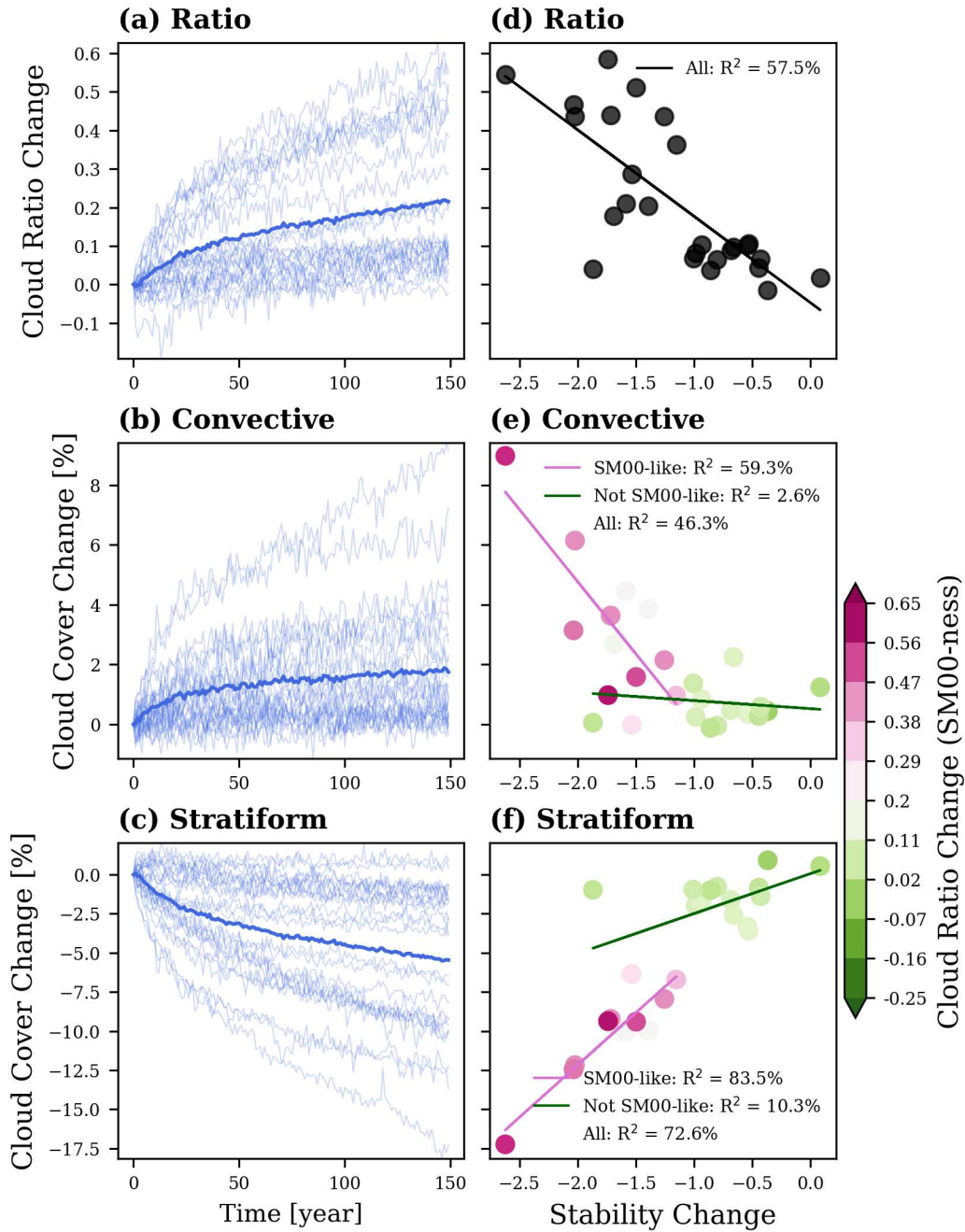


Figure 3.2: Senior and Mitchell-ness is both the stability change and the cloud evolution. (a-c) Time evolution of cloud ratio, convective, and stratiform clouds. (d-f) Relationship between total change in cloud ratio, convective, or stratiform clouds and the 700 hPa stability change. (e-f) Points colored by their total change in cloud ratio, average of last 10 years minus first 10 years of the abrupt-4xCO₂ experiment.

relationship between the time evolution of clouds and stability changes than others. The relationship is weaker when considering convective cloud fraction (Fig 3.2e) and stronger when considering stratiform cloud fraction (Fig 3.2f). Indicating that relationship relies on the change in low-level stratiform clouds.

Trying to determine how similar a model is to SM00's original hypothesis—the SM00-ness of the model—is not so straightforward. SM00's argument relies on a qualitative look at the time-evolution of clouds and hypothesis about the connection between physical pathways and clouds and radiation. In that sense, the models can be compared to SM00 in two ways: (1) the physics of the model, is the change in stability actually related to the change in clouds? And (2) how similar the actual time-evolution of the SO clouds is.

The differences across the models between these time series can be largely attributed to how strongly the stratiform cloud fraction decreases and the convective cloud fraction increases throughout the abrupt-4xCO₂ experiment (Fig 3.2 a-c). This is how we can determine how similar to SM00's hypothesis a model is. Taking the difference between the average cloud ratio in the late period to the early period, a model's total cloud ratio change can be calculated. We subjectively split the models at .2, where models with a higher change than that are more SM00-like and models less than .2 are less SM00-like. This cloud ratio change is the SM00-ness of the model.

Applying this simple grouping to the Fig 3.2e&f reveals an important role for the SM00-ness of the models. Its only the SM00-like models that create the relationships between stability change and cloud fraction change. Looking at Fig 3.2f specifically, including all the models has an R² of 72.6%, but the relationship with only SM00-like models has an R² of 83.5%, in stark contrast to the nonSM00-like models' R² of 10.3%. Only models with SM00-like physics are creating SM00-like temporal evolutions of SO clouds. Important to note that this still holds even without grouping the models, the nonSM00-like models are still contributing to the “all model” relationship, but the SM00-like models are what really drive this relationship.

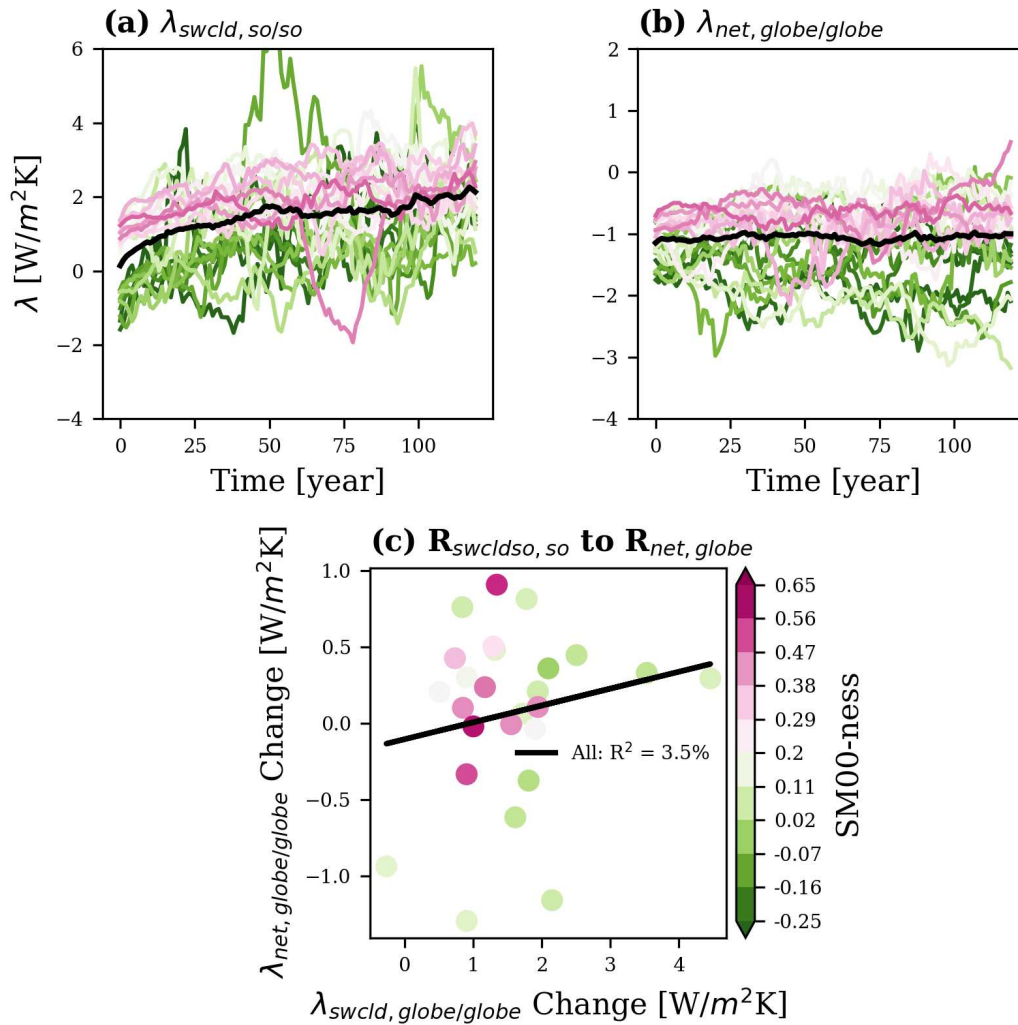


Figure 3.3: SO clouds don't control the global net feedback. (a-b) Radiative feedbacks through time for (a) SO local shortwave cloud feedback and (b) global net feedback. (c) The relationship between the change in the feedbacks plotted in (a) and (b).

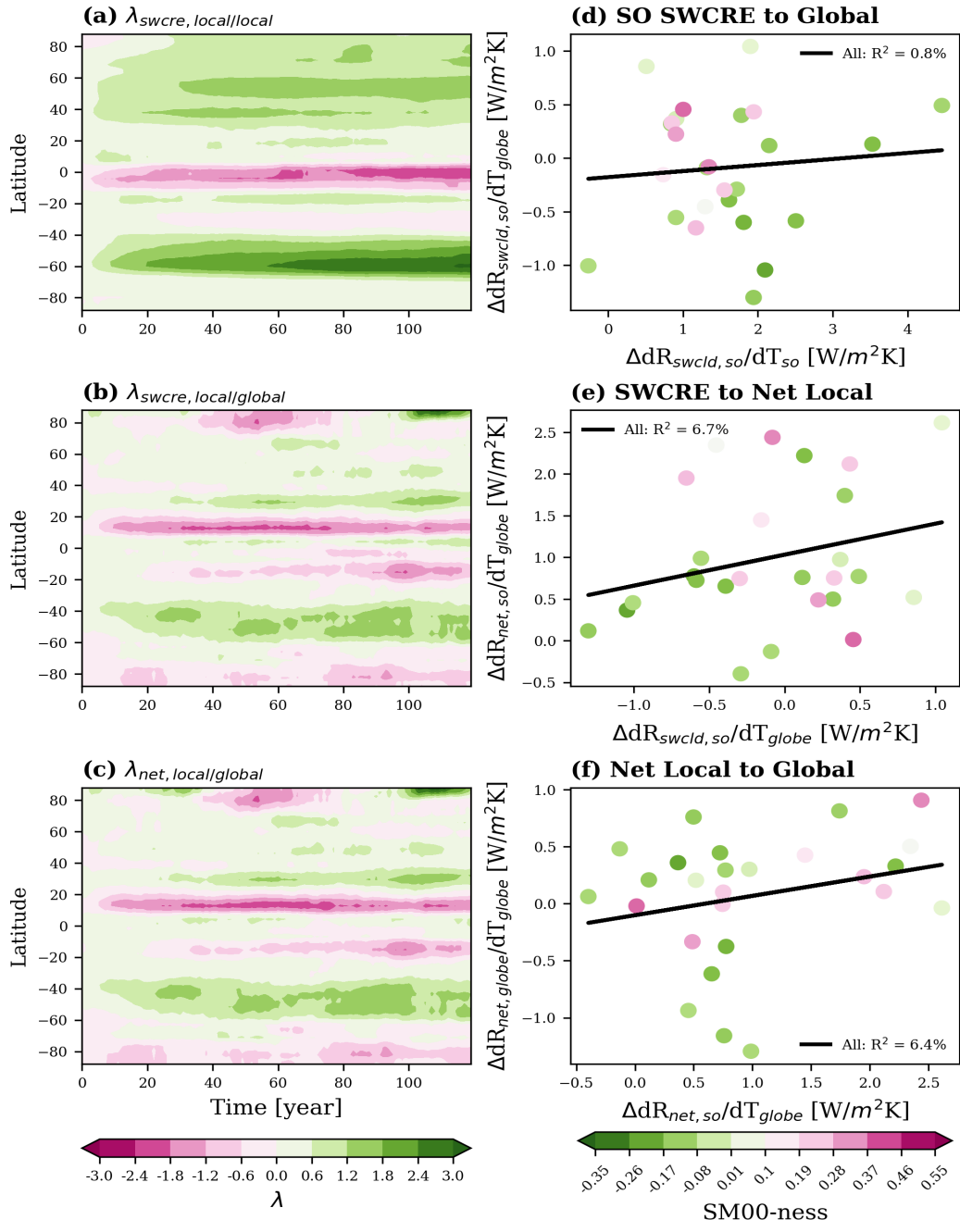


Figure 3.4: The lack of strong time-evolution in the SWCRE feedback calculated with global mean temperature change breaks the link between processes IX and X. (a-c) CMIP6 ensemble mean, all plots are averaged over all longitudes through time for the feedback indicated in the panel title. (d-f) Relationships between the change in feedbacks indicated on panel axes through time.

3.3 The Southern Ocean's Eminence?

The radiative effects of clouds are known to be an important factor in determining the change in climate sensitivity through time in models (Andrews et al., 2015, SM00). SM00 propose that the time-evolution of SH clouds controls the time-evolution of climate sensitivity. Given that the physical mechanisms that create the time evolution of clouds exists, to varying degrees across models, in current generation models, their radiative impact should be the driving force in the global net feedback, according to SM00's hypothesis.

There is indeed a strong time evolution of SO local shortwave cloud feedback, meaning dR_{SO}/dT_{SO} (process IX, Fig 3.3a). However, no matter a model's SM00-ness, there is a similar amount of change (Fig 3.3c, x-axis). This indicates that processes I-IX of SM00's hypothesis is not the driving factor in determining the radiative impact of SO clouds. This can be confirmed by the time evolution of the global net feedback (Fig 3.3b), which which changes from -1.4 to +1 through time. The SO has no strong imprint, like suggested by SM00 (their Fig 1.1c compared to their Fig 3.1). There is no relationship across models between the change in the SO local feedback with the global net feedback (process X, Fig 3.3c).

Its unclear from figure 3.3 where exactly the link between processes I-IX and the final process (X) breaks down. Models show a time-evolution in the SO SWCRE that matches with SM00's hypothesis (Fig 3.4a). As discussed in figure 3.3, this SWCRE's strong change throughout the abrupt-4xCO2 experiment is not reflected in the global net feedback (Fig 3.4c). This can be attributed to the fact that going from a completely local feedback in SWCRE in the SO (Fig 3.4a) to a local SWCRE feedback calculated with global mean temperature change (Fig 3.4b) breaks down the strength of the time-dependence. Across models, there is no relationship between the change in the local SO SWCRE feedback and the SWCRE feedback calculated with global mean temperature change (Fig 3.4d), in other words, the strength of the time-evolution in the SO's SWCRE feedback is not reflected when calculated with global mean temperature change. This is ultimateley where SM00's proposed link between SO clouds and the global net feedback breaks down (processes IX-X). Trying to connect the SWCRE feedback calculated with global mean temperature to a sim-

ilar feedback with net radiation instead shows a similarly weak relationship (Fig 3.4e), and trying to connect local net feedback to a global net feedback also fails to create a compelling link (Fig 3.4f). Not only is there a weak time-dependency in the feedbacks calculated with global temperature change (Fig 3.4b-c), there is also an opposite sign and at least equivalently strong feedback occurring in the tropics. This cancellation is also partially explaining the SO's weak influence in the global net. Further, the SO is a relatively small area of the total globe's surface area, potentially further damping its global influence.

The SO pattern effect proposed by SM00 cannot be confirmed in CMIP6 models when considering the SO alone. SM00's hypothesis is accurate for processes I-IX, including the change of clouds in the SO controlling the local feedback (process IX, Fig A.5). However, the SO's local shortwave cloud feedback's time evolution is not controlling the global net feedback time evolution (process X), no matter the SM00-ness of the model.

Chapter 4

Conclusions & Future Work

4.1 Conclusions

Models generally are unable to accurately recreate the observed trend in SO temperatures (Wills et al., 2022). Work on the relative importance of the SO in models with more realistic trends shows it has a strong non-local influence on the rest of the world, and especially on low level clouds off the west coast of South America (Kang, Yu, et al., 2023; Kang, Ceppi, et al., 2023). It is unknown, however, what the SM00-ness of the observed world is. While not observations, historical model simulations provide more realistic forcing scenarios to compare to. Using the same CMIP6 models (Fig A.6), it can be seen that even with a smaller (more realistic) increase in CO₂, models show signs of creating SM00's physical pathways. While weak, there is a relationship between SM00-ness derived from the abrupt-4xCO₂ simulation and the stability shift from the weakly forced historical simulation. The observed world has shown a delayed SO warming (Armour et al., 2016), the first process (I) in SM00's hypothesis. If the SM00-ness of the observed world was known this could provide a constraint on, for example, the climate sensitivity of the models if there was a relationship between the two. It could also provide a constraint on processes I through IX, connecting warming to the changes in SO clouds and radiation.

Models are broadly able to recreate the physical pathway of SM00's original hypothesis (Figures 1.1 and 3.1). The degree to which they can recreate it is summarized by a relationship between the change in the ratio of convective to stratiform cloud fraction change and the stability change (Figure 3.2). The amount of change in the cloud ratio is applied to categorize the models based on how similar they are to SM00's hypothesis, i.e. SM00-ness. (Interestingly, two of the most SM00-like models (HadGEM3-GC31-LL and HadGEM3-GC31-MM) are descendants of the model that was used in SM00's original paper (HADCM2) (Johns et al., 1997), underscoring the connective

tissue between their arguments and SM00-ness and the importance of model ancestry to understanding model performance.)

In the debate surrounding the Greens Function and the identification of which regions are the most important to the changes in the global net feedback, there has been conflicting evidence on what role the SO really plays. Lin et al. (2021), Dong et al. (2022), Kim et al. (2022), and Kang et al. (2023b) argue for a strong nonlocal influence of the SO. Here, retracing SM00's hypothesis, and quantitatively connecting the physical pathways they hypothesized with the radiative impacts they qualitatively deduced reveals no significant role for the SO's local cloud feedbacks in the global net feedback, and hence, climate sensitivity. The SM00-ness of a model has no bearing on this either (Fig 3.3c, colors have no clear relationship). This would indicate that SST-GFs are right to attribute no global radiative impact of local surface temperature perturbations to the SO.

Fig 3.3a & b show that SM00-like models are generally less stabilizing than the other models. Somehow, the less stabilizing nature of SM00-like models in the SO local feedback is carried forward into the global net feedback. This indicates its not truly about SM00's hypothesis and the ability of the models to correctly recreate processes I-IX, but rather something about model properties more broadly, potentially linked to the low cloud feedback (Datseris et al., 2022; Frey et al., 2017; Ford et al., 2025; Myers et al., 2021; Zelinka et al., 2020). The role of the SO in global net radiation is still an open question, though. Our work indicates that locally the SO has no particular importance. Its ability to influence other regions, such as the SEP or the tropical Pacific (Dong et al., 2022; Kang et al., 2023a; Kim et al., 2022; Lin et al. 2021) is not disputed or analyzed in this work.

4.2 Future Work

The analysis of SM00's processes defined and discussed in this manuscript would argue that there is no connection between the time-evolution of SO clouds and the global net feedback, and thus no relationship with ECS. Curiously, there is a relationship between the SM00-ness of a model and that model's ECS ($R^2 = 47.9\%$, not shown). This cannot be true if the rest of the analysis is

true: SM00-ness is defined solely based on the strength of cloud changes in the SO and figures 3.3 and 3.4 identify why the relationship between the cloud changes and their associated radiative changes are not connected to the global net feedback. There is reason to believe that SM00-ness is less a feature of SO cloud sensitivity and more connected to a global SWCRE sensitivity. As stated earlier, it happens that SM00 in their original work were using an incredible SM00-like model, i.e. a model with a very high sensitivity in the clouds to surface temperature change.

Applying cloud ratio calculations to the whole globe (Fig 4.1) shows how strongly clouds change everywhere. Grouping the models by how strongly their SO clouds change (SM00-ness defined in Fig 3.2), models with strong positive SO cloud changes are also models with broadly strong positive global cloud changes (Fig 4.1a), while not SM00-like models tend to have globally negative cloud changes (Fig 4.1b). This indicates that SM00-like models could be showing strong SO cloud changes because they have a global sensitivity, Fig 4.1c supports this idea with a strong relationship between SO SM00-ness and the global SW cloud feedback.

Figure A.6 shows processes from SM00's hypothesis related to SO delay (Fig A.6a) and the destabilization of the SO atmosphere. In historical simulations, where forcings more closely follow those observed from 1850-2014. While there is no connection between SO clouds and the global net feedback, processes I-IX being confirmed in CMIP6 models could be used to constrain model results. If more was known about the SM00-ness of the observed world, you could use any observations that relate to the confirmed processes to constrain projections in models. While Fig A.6 doesn't show observations, it does show that models in more realistic (i.e., closer to observations) simulations are indicating that SM00-ness is already happening. Fig A.6d specifically also pointing to the fact that models that are more SM00-like in the abrupt-4xCO₂ experiment are also more SM00-like in historical experiments.

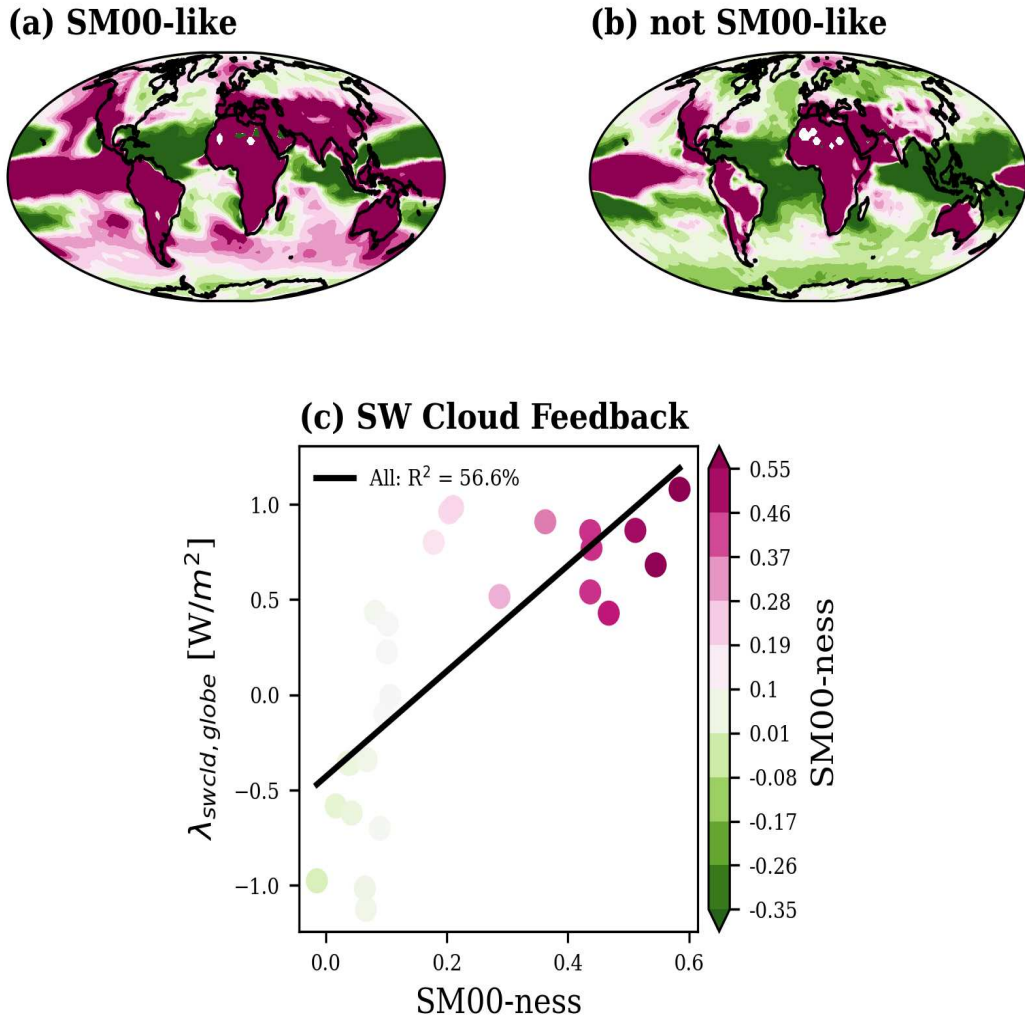


Figure 4.1: SM00-ness may actually be a function of global cloud sensitivity in SW radiation, not SO sensitivity. (a) Global cloud ratio change, averaged over models that are SM00-like (SO cloud ratio change $> .1$). (b) Same as (a) but for not SM00-like models (SO cloud ratio change $< .1$). (c) Relationship between SO cloud ratio change and the global shortwave cloud feedback across models.

Chapter 5

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Appendix A

Supplemental Material

Table A.1: CMIP6 models included in analysis

Model Name	SM00-ness	Citation
FGOALS-g3	-0.014475	Li et al. (2020)
MIROC6	0.016668	Tatebe et al. (2019)
FGOALS-f3-L	0.036615	He et al. (2019)
CNRM-CM6-1	0.039612	Voldoire et al. (2019)
MPI-ESM-1-2-HAM	0.042900	Neubauer et al. (2019)
EC-Earth3-AerChem	0.064670	van Noije et al. (2021)
MPI-ESM1-2-LR	0.066504	Mauritsen et al. (2019)
MRI-ESM2-0	0.067894	Yukimoto et al. (2019)
ACCESS-ESM1-5	0.081333	Ziehn et al. (2020)
MPI-ESM1-2-HR	0.089548	Müller et al. (2018)
CanESM5	0.096718	Swart et al. (2019)
CMCC-CM2-SR5	0.101300	Cherchi et al. (2018)
BCC-CSM2-MR	0.102593	Wu et al. (2019)
CMCC-ESM2	0.106702	Lovato et al. (2022)
CESM2-FV2	0.178383	Danabasoglu et al. (2020)
CESM2	0.203939	Danabasoglu et al. (2020)
CESM2-WACCM	0.210515	Gettelman et al. (2019)
SAM0-UNICON	0.287074	Park et al. (2019)
ACCESS-CM2	0.362724	Bi et al. (2020)
UKESM1-0-LL	0.436798	Sellar et al. (2020)
E3SM-1-0	0.436923	Golaz et al. (2019)
E3SM-2-0	0.439055	Golaz et al. (2022)
TaiESM1	0.467481	Lee et al. (2020)
HadGEM3-GC31-LL	0.511443	Sellar et al. (2020)
CIESM	0.544973	Lin et al. (2020)
HadGEM3-GC31-MM	0.584338	Sellar et al. (2020)

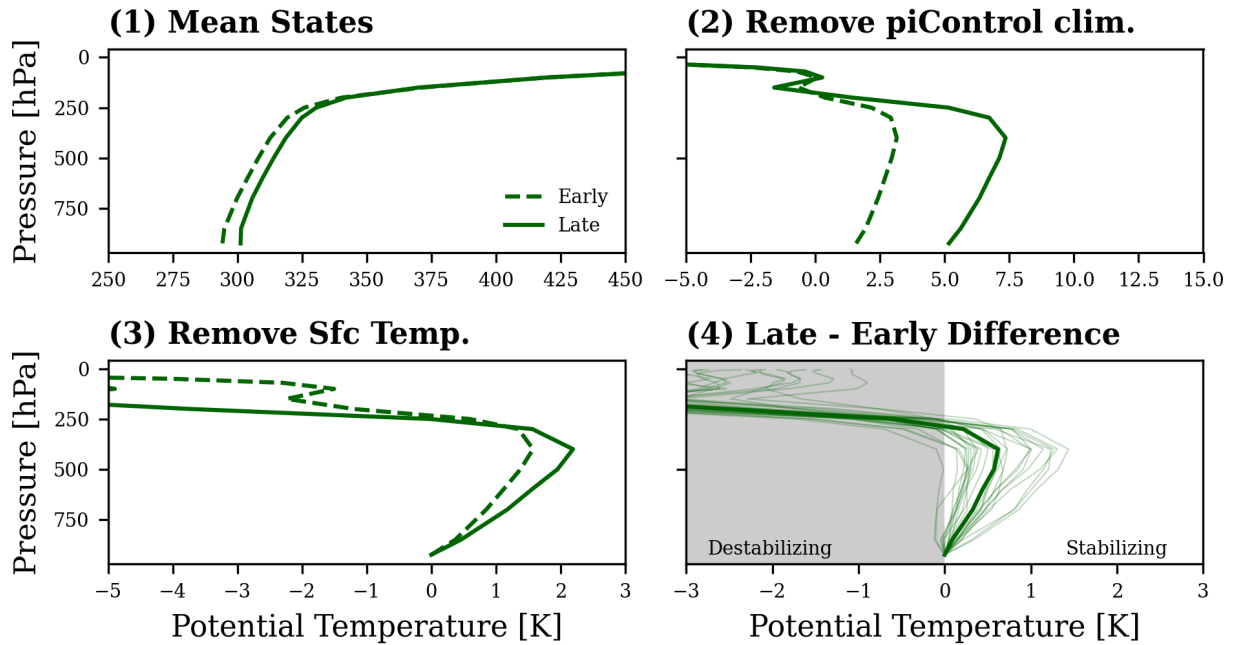


Figure A.1: Example showing calculation of the stability change in the atmosphere profile. (a) Mean states of the model, just the average over the SO through their respective time period. (b) Subtract the climatology calculated from the piControl from both profiles. (c) Remove the surface temperature to directly compare the shapes of the two profiles. (d) Late - early difference, the “change”.

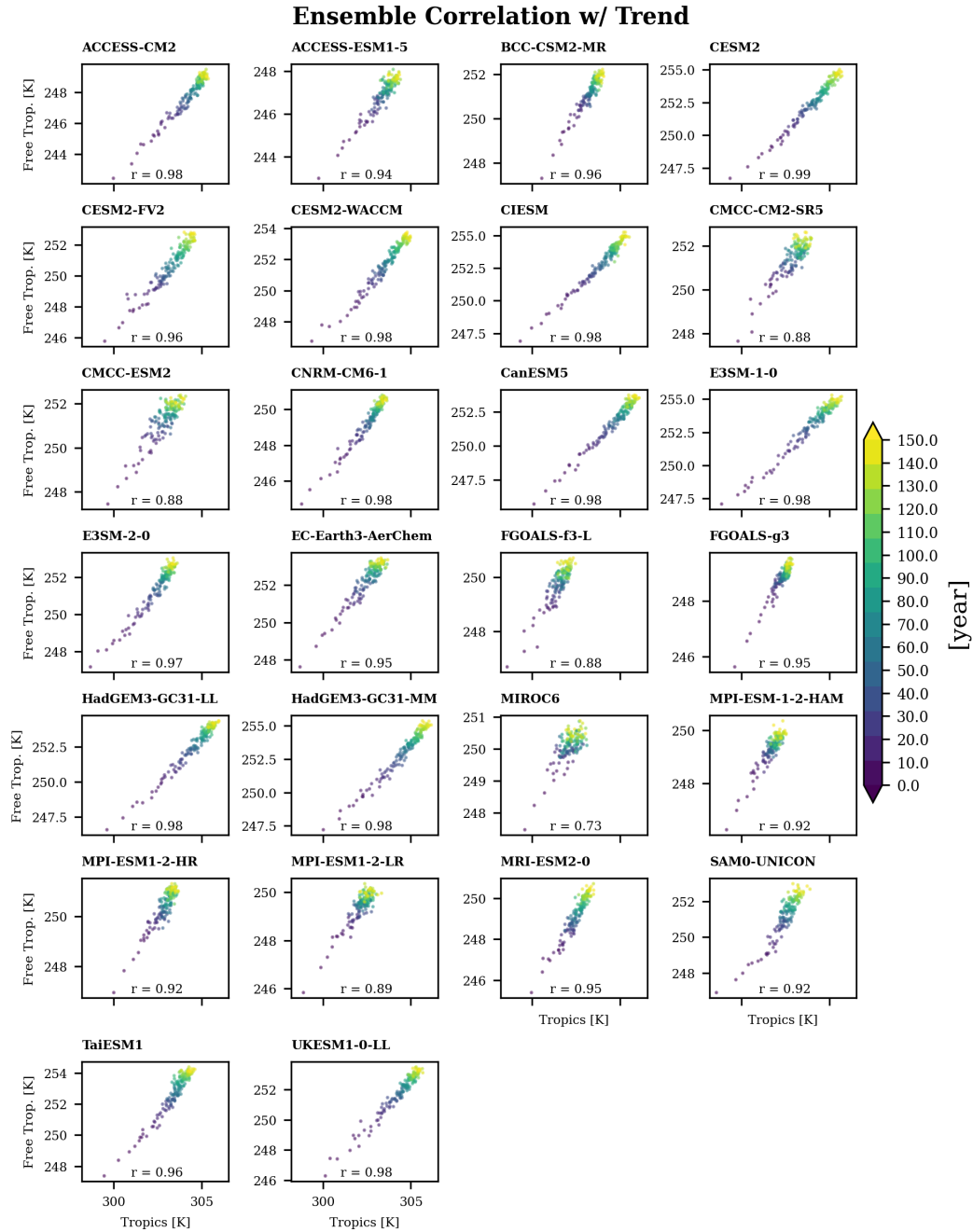


Figure A.2: Tropical connection to SO free troposphere. Individual model relationship between surface temperature in Tropics (20S-20N) and Southern Ocean Free Troposphere (60S-40S, 700-200[hPa]) temperatures.

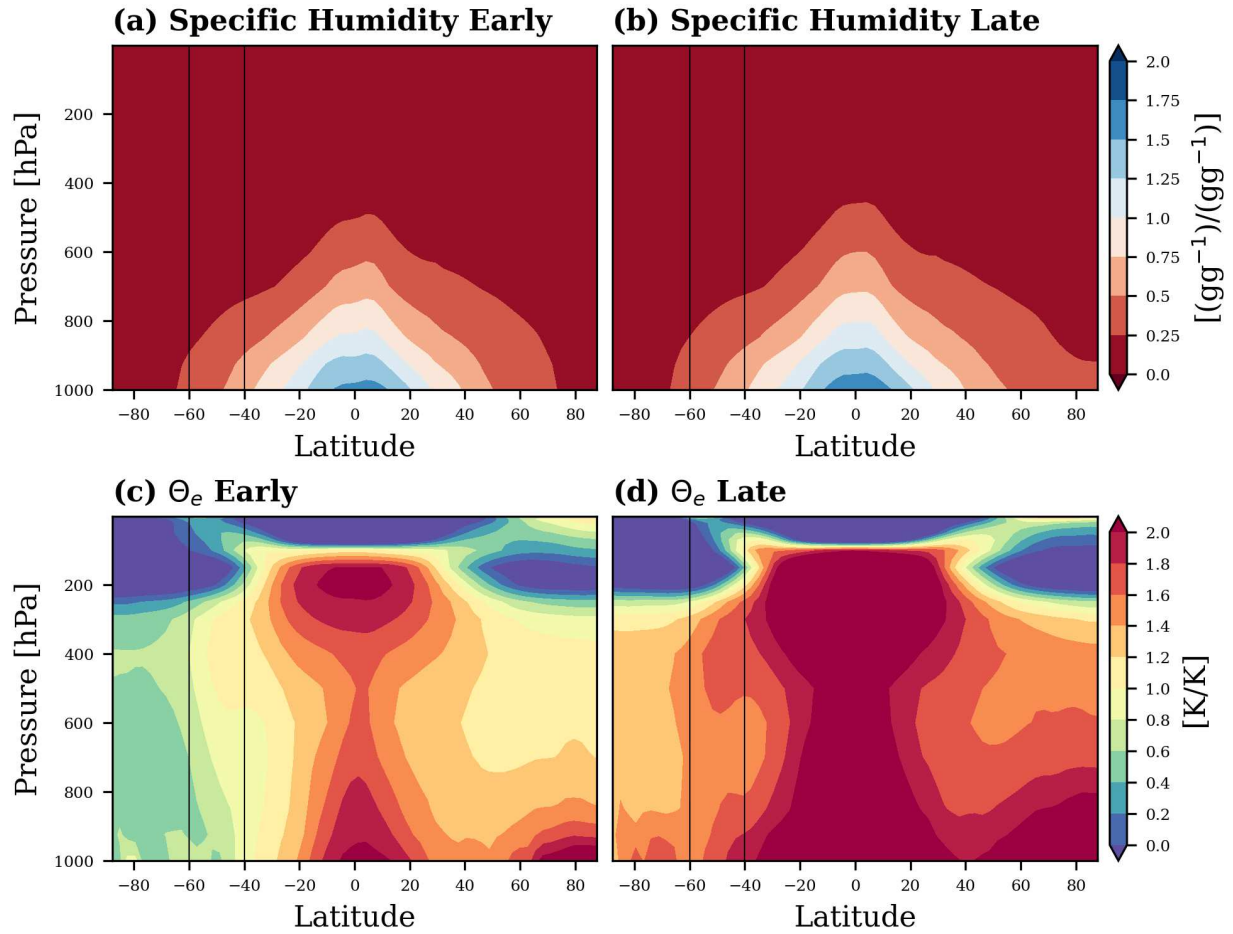


Figure A.3: Moisture gradient changes drive stability changes. (a) and (b) Ensemble mean atmospheric specific humidity for the first 10 and last 10 years of the abrupt-4xCO₂ experiment normalized by global mean surface specific humidity. (c) and (d) Ensemble mean atmospheric equivalent potential temperature normalized by global mean surface equivalent potential temperature.

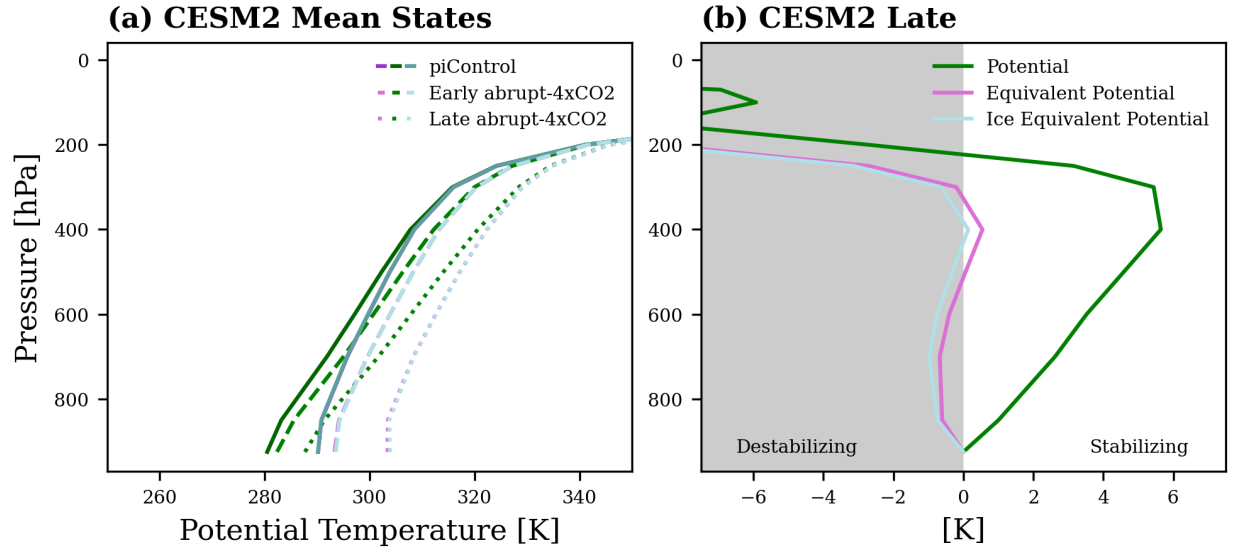


Figure A.4: Including ice processes destabilizes the atmosphere more. (a) and (b) same for Figure 2a & b, but just for CESM2 and including ice equivalent potential temperature.

$$\theta_{ice} = \theta \exp\left(\frac{L_{lv}q_v - L_{il}q_i}{q_d c_{pd} T}\right) \quad (\text{A.1})$$

Where θ_{ice} represents the Ice Equivalent potential temperature (Tripoli & Cotton, 1981), θ is potential temperature, L_{lv} is the latent heat of vaporization, q_v is the specific humidity of water vapor, L_{il} is the latent heat of sublimation, q_i is the specific humidity of ice water, q_d is the specific humidity of dry air, c_{pd} is the specific heat capacity for dry air at constant pressure, and T is for temperature.

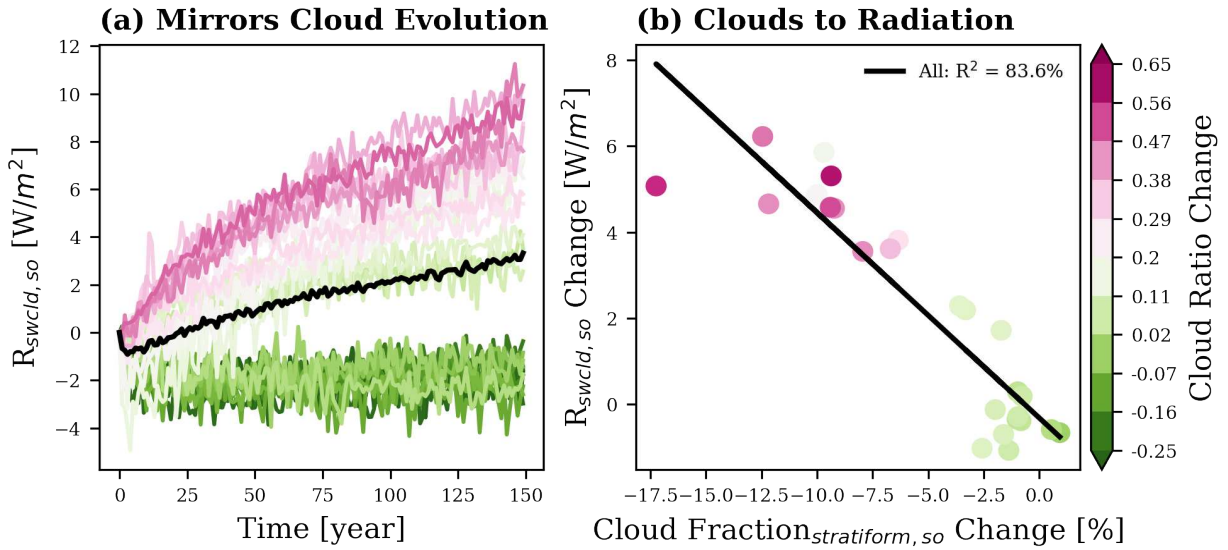


Figure A.5: Cloud changes create accurate radiation changes. (a) Time evolution of shortwave cloud radiative effect (SW CRE), colored by SM00-ness; black line represents the ensemble mean. (b) Correlation between the change in stratiform clouds in the SO and the change in SW CRE in the SO.

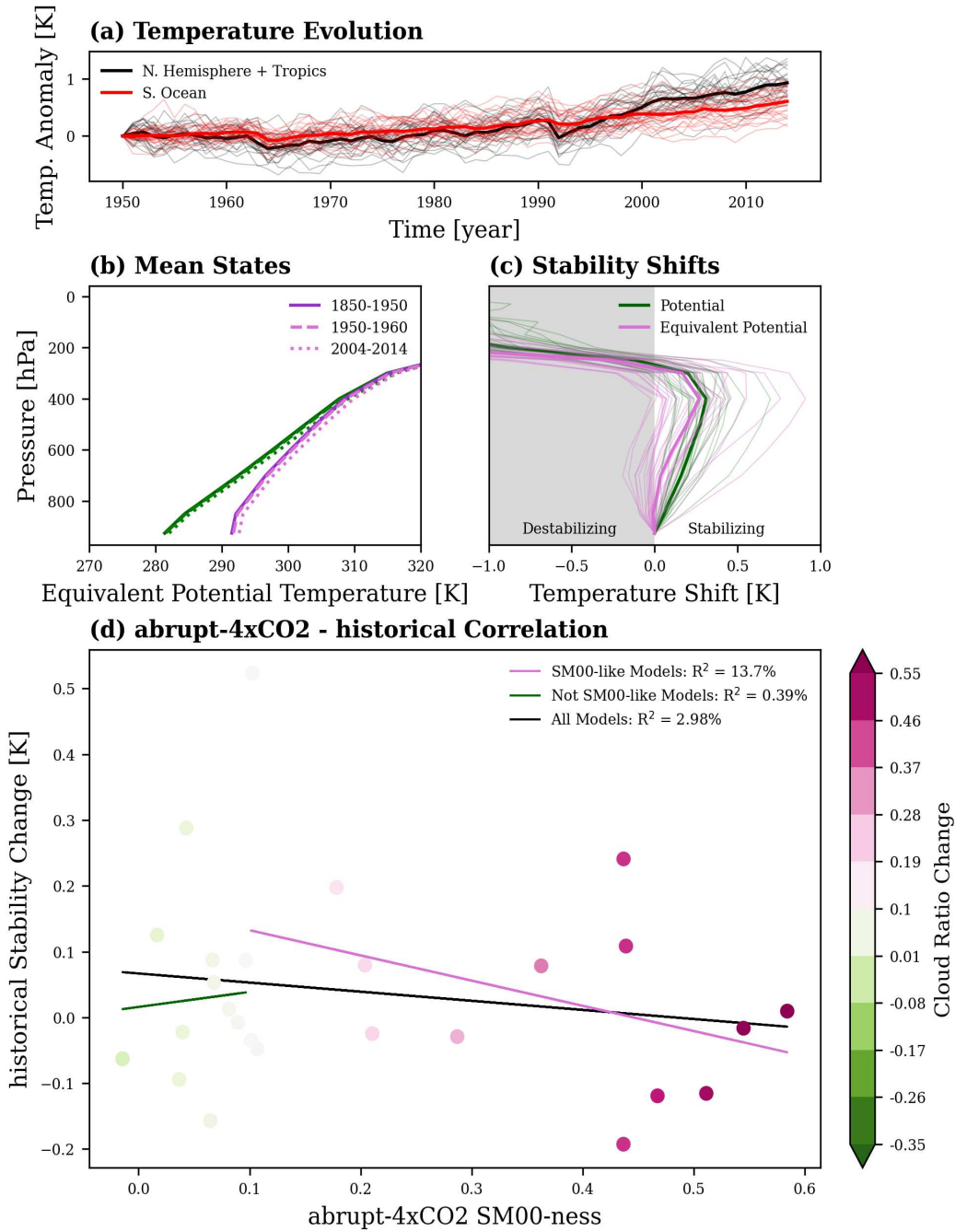


Figure A.6: The most SM00-like models in abrupt-4xCO2 are still the most destabilizing with a historical forcing. (a) Temperature evolution as in Fig 1a, with respect to the climatology of the first 100 years of the historical forcing. (b) Mean state and stability changes as in Fig 2a & b. (d) Relationship between abrupt-4xCO2 SM00-ness (determined from total cloud ratio change, see colorbar/Fig 3) and the historical stability change.