acp-2016-886: Thermodynamic and dynamic responses of the hydrological cycle to solar dimming

Reviewer Comments are written in black font, and Author Responses are in blue.

Reviewer 1

Thank you for your time in reviewing the article.

Reviewer 2

> I recommend this paper be rejected. It does not present interesting new science, and there are still flaws in the figures. The analysis of differences in climate change simulations in which the global average temperature does not change, with a scaling that depends on temperature differences, does not make sense to me. I do not understand why that part is in the paper.

The decomposition of P-E into thermodynamic, relative humidity, and dynamic components helps us to compare the mechanisms underlying rainfall changes in simulations of global warming and geoengineering. While thermodynamics capture P-E anomalies in global warming simulations reasonably well, they do not explain the changes in G1. We try to explain how the dynamics and the relative humidity anomalies alter P-E in G1 relative to piControl.

> I am very annoyed that the authors did not respond to one of the items in my previous review. The maps are still not plotted correctly. The longitude labels are still in the wrong place. And there is a border at the top, bottom and right edge of the maps with no shading. This gives me no confidence that the results are plotted correctly. You don't have to use GrADS, which would not have this problem, but there are many other graphics programs, such as NCL, ferret, and even Matlab that can do this. This refusal to fix this aspect of the paper alone makes me recommend to the Editor that this paper be rejected, and that if resubmitted the Editor makes sure the maps are of an acceptable quality.

In the new attached draft of the manuscript, we have corrected the longitude labels. We did not notice the white edges on the maps (due to NaN values), and have addressed this issue as well. The consistency of figures 1-3 with those in Kravitz et al. 2013a should assure readers that the data are correctly presented.

> Fig. 4 has no significance measures or error bars. How different from zero would the values have to be to merit consideration?

We can measure significance based on agreement between the models because we have an ensemble. Where a majority of the models agree on the sign of the change, we consider the result robust. In Fig. 4A, most of the models show drying at 10°N and 10°S, moistening poleward of that around 30°N/ S, and drying further poleward near 50°N/ S. In Fig. 4C, some models exhibit slightly positive anomalies, and some slightly negative, so the contribution of local relative humidity changes to P-E anomalies is either negligible or very small.

p. 4, last paragraph. No, the small differences between simple and extended scaling, and the large disagreement between them and the actual results, mean that this is not an appropriate way to analyze the results. First of all, you need statistical tests to show how different the scalings need to be from each other to even deserve consideration. To say that relative humidity (RH) plays a modest role is incorrect, and certainly should not be in the abstract. What is correct is that you cannot tell how important RH is.

We specify that the role of *local changes* in RH do not play an important role, since the extended scaling accounts for the effect of local RH changes on P-E in the second term (Eq. 3). We now explicitly acknowledge in the paper that changes in the gradient of RH could be responsible for some of the G1-piControl P-E changes. This effect does not explain discrepancies in the tropical P-E response between models because the RH response is robust across the model suite.

In various places in the paper, the authors say data are not available. But did they write to the modelers to obtain the data? Just because they are not posted to the websites they looked at does not mean they do not exist. In my experience, modelers are happy to send data in response to a request.

We made an earnest effort to obtain all the data needed for this study. The Earth System Grid Federation (ESGF) server was not fully operational, so we found data on other servers, and then contacted scientists from the modeling groups to fill in the gaps. We communicated with a coordinator of GeoMIP as well. We did not make any arbitrary exclusions in our data analysis.

If the authors are going to analyze RH and ITCZ location, and their changes with geoengineering, it is incumbent on them first to analyze the piControl runs to see if the models do a good job of simulating these in the first place. If not, then how can we trust small changes. It is traditional to through out models in such a comparison if their current climate differs quite a bit from observations, not because you were not able to get the model output.

We have plotted the ITCZ position in every month in each model and in the multi-model mean (Appendix Fig. ii). This plot shows that every model exhibits a sinusoid-like seasonal migration of the ITCZ similar to that seen in observations (Waliser and Gautier, 1993, J. Clim., Figure 4h). While there are biases in the ITCZ positions in the individual models, and the annual mean position is closer to the equator in GCMs than in the observations, the overall seasonal cycle is reasonably well captured, and when this cycle is dampened in every model, we think this tells us something important about the physics of the system. For the annual mean ITCZ, our focus is not on "trusting small changes" but on examining the spread between the different models and what might be responsible for them. Biases in the representation of tropical precipitation in GCMs have been analyzed elsewhere (e.g. Stanfield et al., 2016, Clim. Dyn.). These biases have not generally been invoked to argue against the publication of papers examining changes in the ITCZ under global warming simulations, so it does not seem reasonable to require that the models perfectly represent tropical convection before we can examine any changes in them under the G1 experiment.

The ITCZ shifts found here are very small (<1°) and completely expected given the N-S temperature change differences. Since the models differ so much in their simulation of the ITCZ, this does not seem an important result.

The ITCZ changes are indeed small in magnitude. They are, however, still interesting from a scientific perspective. As we write in the paper: “Small changes in the latitudinal range and strength of the Hadley circulation and associated precipitation have large local implications, especially on subannual scales (Kang et al., 2009).” In addition, the correlation of the annual mean shifts with the N-S temperature change differences demonstrates that the paradigm of the ITCZ "shifting toward the warmed hemisphere", which has been seen in numerous other studies, also applies to solar geoengineering. Quantifying the magnitude of the ITCZ shifts in the GeoMIP ensemble should also be of interest to the broader community given the current discussions of ITCZ shifts in slab ocean vs. fully coupled models. The reduction in the seasonal migration of the ITCZ, while small in percentage terms, is robust across the different models and helps us understand how the fundamental physics of the seasonal cycle are affected by solar vs. greenhouse gas forcings.

> For the seasonal analysis, why did the authors choose the unconventional JFM and JAS or the seasons rather than the more traditional DJF and JJA? Without any special reason this was the wrong decision and prevents comparison with the results of others.

The extreme ITCZ positions occur in February and August in the multi-model mean. We include a plot in the Appendix of this Author Response to illustrate this, as well as the reduced seasonal migration of the ITCZ in G1 (Fig. ii).

> There are 15 more comments in the attached annotated manuscript that would need to be addressed.

We have addressed all of these comments.

Reviewer 3

1. Derivation of Eqn (2): The authors should be careful when describing the assumptions that go into this equation - the derivation assumes small meridional AND zonal gradients of CHANGES in temperature, and further assumes that the vertically-integrated atmospheric moisture scales with the near-surface specific humidity (this assumption is not currently mentioned in the manuscript). The text should be modified to state these assumptions more carefully and in full.

The assumptions implicit in equation (2) are now explained more fully in the text. Thank you for this comment.

2. Page 3, lines 27-29: The difference between simulated P-E anomalies and the extended scaling does not perfectly isolate the role of dynamics as it also includes the horizontal temperature and RH gradient terms [see the last two terms on the RHS of Eqn (7) in Byrne & O'Gorman (2015)]. These terms are particularly important over land regions, and can also be important at high latitudes over oceans (because of polar-amplified warming). This is an issue for the paper as interpreting the dynamic component of changes in P-E is difficult because it currently includes these gradient terms. I suggest the authors calculate the full extended scaling of Byrne & O'Gorman (2015) and then compare that to the simulated d(P-E) to truly isolate the dynamic component (which can

also be calculated explicitly). Calculating the gradient terms may also give insights into how large RH changes over land influence P-E.

We were unable to complete the extended scaling, which we now note in the manuscript. GeoMIP modelers will need to archive daily mean model output for this calculation to be possible in a future study.

The largest P-E changes occur in the tropics (Fig. 2). We conclude that the relative humidity changes do not explain the varying tropical rainfall responses to G1, since the relative humidity changes are robust across the model suite, while the P-E shifts are not. The Hadley circulation analysis better captures the tropical P-E responses, which is where the largest P-E anomaly occurs. We have changed the abstract to reflect this.

We now explicitly acknowledge the limitations you describe in Section 3.

3. Page 4, lines 26-27: Byrne & O'Gorman (2015) also found, in global warming simulations, that local changes in RH do not affect P-E - it might be worth connecting to that result here.

We now refer to this result from Byrne & O'Gorman (2015).

4. Page 5, lines 10-17: A recent paper focusing on land relative changes in a range of climate models might be useful for the discussion here: Byrne & O'Gorman (2016): "Understanding Decreases in Land Relative Humidity with Global Warming: Conceptual Model and GCM Simulations", J. Climate

Thank you for this suggestion. To this paragraph we have added a sentence about the Willett et al. (2014) observational study of relative humidity changes, as well as two sentences discussing the ideas from Byrne and O'Gorman (2016).

5. Page 6, lines 7-10: Calculating the impact on P-E of gradients in RH changes will allow you to check explicitly whether these land-surface affects are important for hydrological cycle changes under solar dimming conditions.

We have revised this sentence.

6. Section 2.3: It is interesting that you find narrowing tendencies for the ITCZ in these simulations. The physical processes causing changes in the width of the ITCZ under global warming have received some attention in recent years [e.g., Byrne & Schneider (2016a,b) -> see https://climatedynamics.ethz.ch/people/mike/publications.html for copies of these papers). It would be good to connect with this evolving literature when discussing the changes you see in ITCZ - would also be really cool to use the analytical framework of Byrne & Schneider to diagnose what processes in these solar dimming simulations are driving the ITCZ width changes! This is beyond the scope of the current article but could be an interesting avenue to explore in the future.

We now refer to the two suggested papers in the last paragraph of Section 2.3.

7. Page 9, lines 14-16: I think it is difficult to be confident in this statement without calculating how gradients of changes in RH affect P-E over land - they may be an important influence compared to just the local RH changes [as is the case in Byrne & O'Gorman (2015)].

We have revised this paragraph.

8. Page 8, lines 27-29: A damped seasonal ITCZ migration is one possible explanation for reduced monsoon precipitation but there are several others (e.g., reduced monsoon circulation strength, zonal shifts in the monsoon, reduced moisture content). Without further analysis I think the authors should remove this statement (and a similar statement in the Conclusions).

On page 8, we now acknowledge that the reduced ITCZ migration possibly contributes to (but does not entirely explain) the results reported by Tilmes et al. 2013, and have removed the statement from the Conclusions.

Reviewer 4

Major Issues:

1. "The motivation for this study in the introduction is given as "to help improve our understanding of this issue" (impact of SRM on the water cycle). I think this is much too vague. There is a large number of papers that has dealt with this issue (with respect to GeoMIP e.g. Schmidt et al., 2012, Tilmes et al., 2013, Kravitz et al. 2013; and many others with and without connection to GeoMIP), and also have stated that the model response in the tropics is less conclusive than in middle and high latitudes. I think the introduction needs to briefly summarize what the state of knowledge and what the open questions concerning "this issue" are and to provide a more specific motivation for this study."

We thank the reviewer for this suggestion, which has improved the framing of the paper. We have added several background paragraphs to the end of the introduction to describe the relevant results presented in Kleidon et al. 2014, Kravitz et al. 2013b, Tilmes et al. 2013, Bala et al. 2008, and Schmidt et al. 2012.

2. The analysis in 2.1 mainly relies on an "extended scaling" estimate of the P-E change presented by Byrne and O'Gorman (2015). The authors just use two of the four terms of the original equation. They state that they "exclude changes in the horizontal gradient of Hs" but don't mention that they also exclude potential changes in the temperature gradient. It's not sufficient to argue with the "sake of simplicity", in particular when in the end the residual is interpreted as "driven by atmospheric circulation". There needs to be a discussion of why the two excluded terms are considered unimportant.

We now use more accurate language in this section. It would certainly be valuable to calculate the full scaling to quantify the role of relative humidity more fully, but it is not possible with the existing GeoMIP simulations, as daily mean output was not archived for most models in G1. However, the combination of our extended scaling with the analysis of the spatial distribution of relative humidity anomalies (Section 2.2) allows us to identify the regions where the gradients might play an important role. We then focus on understanding the tropical variability amongst the models, which is well explained by our analysis of the Hadley circulation and ITCZ shifts. Where relative humidity changes are large, they are also robust, so we know that the inter-model spread is rooted in dynamics.

3. "One of the main conclusions (3rd sentence of the "Conclusion") seems to be that "thermodynamic scaling and relative humidity changes may be important for "smaller scale responses to geoengineering". A similar statement is made at the end of section 2.2. I'm wondering why the authors do not attempt to substantiate this claim. In fact, if I haven't misread 2.2, little effort is made there to analyze the spatial pattern of the effect of relative humidity changes that goes beyond what had been said already in 2.1, although 2.2 is introduced to provide this. 2.2 tries to summarize a lot of earlier work, but it is difficult to identify a clear goal of this section and an analysis that justifies the statements mentioned at the beginning of this paragraph. Later in the conclusions it is said that "we also present evidence that land-sea contrasts in evaporation rates, resulting in land-sea contrasts in relative humidity contribute to small changes in P-E with solar dimming". This evidence is hard to find in the manuscript. In fact, spatial patterns are in general very little discussed, as are the precipitation and evaporation patterns presented in Fig. 3. With the existing discussion of results, I don't see the use of this Figure."

Thank you for this comment. We have reorganized the paper so that the extended scaling, which quantifies the impact of local relative humidity changes on P-E, is in Section 2.2. In addition, we have added text to Section 2.2 where we describe the reductions in relative humidity over South America and sub-Saharan Africa. We also elaborate on the role of relative humidity in paragraph 3 of the conclusions. Given the small deviations of the extended scaling from the simple scaling, and that the signs of the deviations vary amongst models (Fig. 4C), we now more carefully state that local relative humidity changes *may* play a small role in the P-E response to G1.

4. The final suggestion are studies of "targeted solar geoengineering". However, my main impression is that in the perceived focus region of this study, the tropics, results seem to be very model dependent. This doesn't come as a surprise as the simulated tropical hydrological cycle is strongly influenced by parameterized convection. Earlier studies have discussed uncertainties introduced by convection schemes. I think such studies need to better referenced here. Instead of suggesting another sensitivity study that may be hampered by the same issues, I'd rather suggest to more concisely discuss potential reasons for the apparent difficulty to estimate tropical responses and suggest potential ways forward if there are any.

We have now added references regarding the sensitivity of tropical convection to the convection scheme, and suggest in a new sentence at the end that improvements in model representation of convection and clouds could help improve our understanding of hydrological cycle changes under solar geoengineering. However, we have not taken out the suggestion of additional sensitivity studies because we think these can be useful even if there are inter-model differences.

Minor Issues

P4l5 and l8: Why are temperature anomalies "minimal" and why mention as a contrast that hydrological effects are not eliminated? Temperature are not eliminated, either.

Thank you for this question. We have changed the phrasing in several sentences in these paragraphs to emphasize that neither temperature nor P-E are entirely restored to preindustrial values. However, temperature anomalies are smaller than P-E changes, relative to their climatological values. The G1 experiment is designed to minimize temperature anomalies due to elevated carbon dioxide concentrations. In the tropics, where temperature anomalies are smallest (less than 1 K), the P-E anomalies are largest.

P4l17: It is said that the "ensemble mean reflects strong reductions … in the subtropics (Fig. 3)". I don't see such reductions in the subtropics.

This sentence has been made more specific: "The ensemble mean precipitation response reflects strong reductions in subtropical precipitation across the Pacific Ocean (Fig. 3)." The red color around 15° N/S across the Pacific Ocean denotes drying, which is consistent with a narrowing of the ensemble mean ITCZ.

P4l20 "stronger … effects that cancel out in the ensemble mean (Fig. 4A)" Stronger than what? Why not show the ensemble mean? I don't think that effects cancel out.

We have changed the phrasing in this paragraph to clarify the meaning. We mean that since zonal mean P-E shifts northward in some models and southward in others, the amplitude of the ensemble mean P-E anomalies is reduced relative to those individual model results. Figure 2 shows the ensemble mean P-E spatial pattern, and Figure 4A shows the zonal mean for individual models. The ensemble zonal mean is included for reference in the Appendix of this Author Response (Fig. i). The pattern over the Pacific Ocean dominates the zonal mean picture, and the amplitude of the changes is within 0.2 mm/day. Many of the individual models in Fig. 4A have much stronger zonal mean responses (approaching 0.6 mm/day).

P5l15: This sentence is confusing. Is that true only for high vertical resolution models? Can the models of this intercomparison be considered of high vertical resolution?

This sentence has been eliminated in favor of the three new sentences describing relative humidity analysis by Willett et al. (2014) and Byrne and O'Gorman (2016).

P5L26 abrupt4xco2 is not a GeoMIP but a CMIP simulation.

"GeoMIP" has been changed to "CMIP5."

P8l31 It is stated that the damped seasonal ITCZ migration "would likely mean a reduction of precipitation in areas …" If this is considered an important result, why not look at it in the models at hand?

While we discuss reduced seasonal migration as a possible explanation for the overall narrowing of tropical precipitation, the effect may be too small to show up strongly in specific land areas.

A detailed regional analysis is beyond the scope of this paper, which we now mention in the Conclusions.

> P9l2 The second sentence of the conclusions is confusing because it compares two things ("thermodynamic scaling captures the general spatial structure of P-E changes under global warming and "large scale rainfall changes in … geoengineering") which seem difficult to compare. If comparing global warming and geoengineering simulations one should do the comparison with respect to the same parameters for both cases.

This was a problem of poor phrasing; we indeed mean to compare P-E changes in the two climate states. We have changed the sentence to read: "While thermodynamic scaling captures the general spatial structure of P-E changes under global warming, it does not do so for idealized simulations of solar geoengineering."

> The caption of Fig. 4 is inaccurate in several places ("dP – E difference" etc.).

The caption of Fig. 4 means to say both "delta" and "difference" because it represents the difference of the P-E anomaly for G1-piControl calculated by the extended scaling, minus the G1-piControl P-E anomaly predicted by the simple scaling. We have modified the caption to hopefully enhance clarity.

Appendix

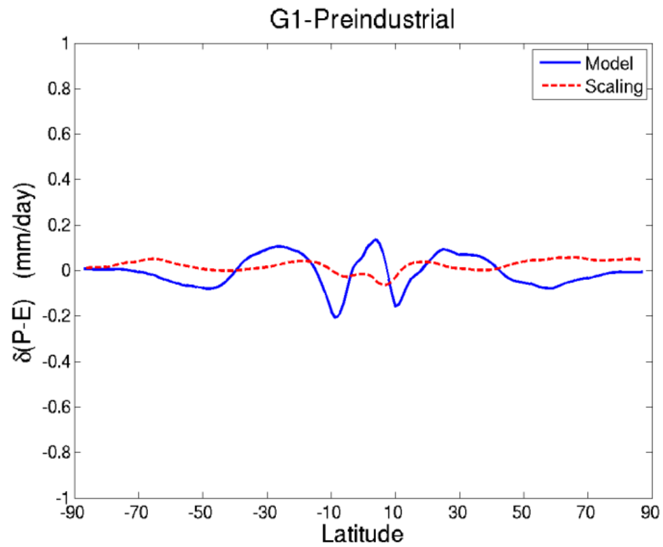

Fig. i. The ensemble zonal mean P-E anomaly for G1 minus piControl.

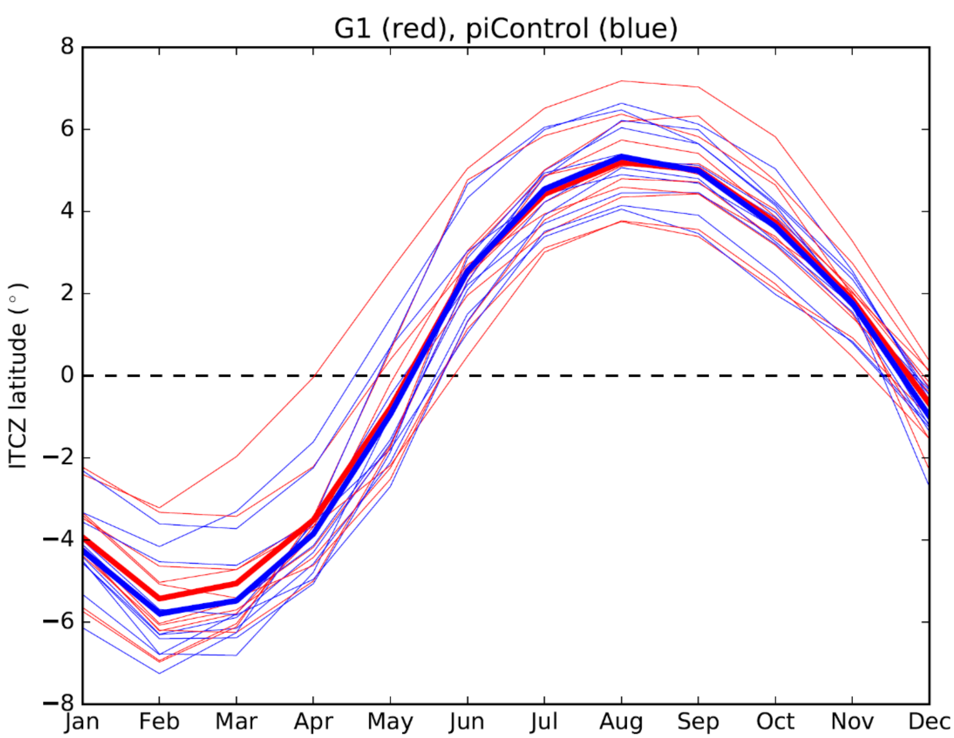

Fig. ii. The monthly ITCZ location in individual models and the ensemble mean (bold lines) for both G1 and piControl.

Thermodynamic and dynamic responses of the hydrological cycle to solar dimming

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Abstract. The fundamental role of the hydrological cycle in the global climate system motivates thorough evaluation of its responses to climate change and mitigation. The Geoengineering Model Intercomparison Project (GeoMIP) is a coordinated international effort to assess the climate impacts of solar geoengineering, a proposal to counteract global warming with a reduction of incoming solar radiation. We assess the mechanisms underlying the rainfall response to a simplified simulation of such solar dimming (G1) in the suite of GeoMIP models and identify robust features. While solar geoengineering nearly restores preindustrial temperatures, the global hydrology is altered. Tropical precipitation changes dominate the response across the model suite, and these are driven primarily by shifts of the Hadley circulation cells. We report a damping of the seasonal migration of the intertropical convergence zone (ITCZ) in G1, associated with preferential cooling of the summer hemisphere, and annual mean ITCZ shifts in some models that are correlated with warming of one hemisphere relative to the other. Dynamical changes better explain the varying tropical rainfall anomalies between models than do changes in relative humidity or the Clausius-Clapeyron scaling of precipitation minus evaporation ($P-E$), given that the relative humidity and temperature responses are robust across the suite. Strong reductions in relative humidity over vegetated land regions are likely related to the CO_2 physiological response in plants. The uncertainty in the spatial distribution of tropical $P-E$ changes highlights the need for cautious consideration and continued study before any implementation of solar geoengineering.

1 Introduction

Solar geoengineering has been proposed as a way to counter the effects of global warming induced by anthropogenic greenhouse gas emissions (e.g., Crutzen, 2006; Robock et al., 2009). By reducing incoming solar radiation, solar geoengineering would bring the climate with elevated concentrations of CO_2 into radiative balance. It would compensate for a change in surface temperature from increased CO_2 trapping of outgoing longwave radiation with a reduction of incoming shortwave radiation. Solar geoengineering is a controversial proposal, but should it come into favor due to continued greenhouse gas emissions, it is critical that the climate effects be understood before deployment (NRC, 2015).

The Geoengineering Model Intercomparison Project (GeoMIP) is intended to determine robust responses of the climate to various simulations of solar geoengineering, in experiments that range from simple representations of the solar dimming, to realistic representations of stratospheric aerosol emissions or marine cloud brightening (Kravitz et al., 2010). The GeoMIP experiments are based on the Coupled Model Intercomparison Project Phase Five (CMIP5), which is a protocol for experiments using coupled atmosphere-ocean climate models (Table 1). The GeoMIP G1 experiment counteracts the forcing from quadrupled atmospheric CO_2 levels with a simple reduction of the solar constant across all wavelengths. The G1 experiment was run from the steady state preindustrial control (piControl) run, followed by an abrupt quadrupling of CO_2, and a simultaneous solar constant reduction for 50 years. The idealized nature of this simulation is conducive to multimodel comparison. It superimposes two large and opposite climate forcings, which offset one another nearly completely in terms of global mean net radiation balance at the top of the atmosphere and near-surface atmospheric temperature, but do not cancel in their hydrological effects, especially on local scales (Kravitz et al., 2013b).

We analyze twelve fully coupled models from the G1 experiment (Table 1). There are serious errors in the precipitation output files from the EC-Earth model and it is thus excluded from any analysis involving the precipitation field. The models differ in their ocean, ice sheet, land surface and atmospheric components. The latter two components are particularly relevant for this study. Some, but not all models, feature dynamic vegetation distributions. The 11 models include a wide range of parametrizations and configurations, allowing for strong conclusions about robust climate responses that appear across models (Kravitz et al., 2013a).

The water cycle impacts agriculture, economies, as well as the welfare of ecosystems and human civilizations (IPCC, 2014). It is imperative to understand the effects of solar geoengineering on global hydrology, to evaluate whether the risks or unintended consequences of such an approach are likely to outweigh the benefits.

While Bala et al. (2008), Schmidt et al. (2012), and Kravitz et al. (2013b) have reported the uncertainty of tropical rainfall responses to geoengineering, no previous authors have presented the Hadley circulation changes in the annual mean or seasonally. Davis et al. (2016) found that the Hadley cell edge latitudes do not change in G1 relative to piControl, but do not examine changes in fluid motions within the Hadley cell. Bala et al. (2008) evaluate a single model and discuss how tropical precipitation might be suppressed when insolation is reduced because this cools the surface relative to the overlying atmosphere, stabilizing the troposphere and reducing convection. Insolation changes affect the surface energy budget more than greenhouse gases, and thus necessitate a stronger response by the sum of latent and sensible heat fluxes. Schmidt et al. (2012) examine ITCZ changes in G1, but only in four of the GeoMIP models, and they do not attempt to explain causes of variability within the suite. They find that the global average precipitation increase in abrupt4xCO2 is about two times larger than the precipitation reduction in G1, but note that the precipitation change in G1 is still substantial. By assessing changes in the surface and atmospheric energy budgets, Kravitz et al. (2013b) conclude that precipitation changes are mostly explained by evaporation changes, implying that annual mean circulation changes are likely small. They identify an analysis of circulation changes in G1 as a fruitful future research direction. We build upon their findings by analyzing the Hadley circulation changes in G1 on both annual mean and seasonal timescales.

Kleidon et al. (2015) also underscore the importance of the surface energy balance in making robust predictions of the hydrological effects of radiative forcing. They decompose the hydrological response into fast and slow components, and infer hydrologic changes using analytic expressions of physical constraints. Our study, on the other hand, focuses on the steady state response and utilizes decomposition to understand simultaneous physical response modes. Tilmes et al. (2013) note reduced global evaporation in the G1 ensemble, and a reduction in global precipitation of approximately 4.5%, with stronger reductions in monsoon regions. Precipitation extremes are reduced by around 20% in G1.

This paper makes progress towards understanding the global impacts of geoengineering by analyzing the thermodynamic, relative humidity, and dynamic components of the hydrological change. We identity robust conclusions across the suite, and present a possible explanation for the discrepancies in tropical rainfall shifts. We assess the contributions of several different effects to changes in precipitation minus evaporation ($P-E$) in the GeoMIP G1 experiment, as follows:

1. In Section 2.1, we analyze the thermodynamic response of $P-E$ to geoengineering.
2. In Section 2.2, we assess the role of changes in relative humidity on $P-E$.
3. In Section 2.3, we investigate the extent to which atmospheric circulation patterns, namely changes in the Hadley cell strength and position, drive $P-E$ changes in the models on both annual and seasonal timescales.

2 Analysis & Results

2.1 Thermodynamic Scaling of $P-E$

Precipitation minus evaporation determines the soil moisture and the amount of runoff on land, and is crucial in setting the salinity of the mixed layer of the ocean (Byrne and O'Gorman, 2015). We here discuss the component of $P-E$ changes driven by residual surface temperature changes (G1- piControl). Surface heating increases the temperature and the evaporation rate, which increases the atmospheric moisture content, or specific humidity q (e.g., Trenberth, 1999). We have confidence about certain aspects of the hydrological cycle's response to greenhouse gas warming, particularly those tightly coupled to the increase in saturation vapor pressure with warming (Held and Soden, 2006). The Clausius-Clapeyron expression (Eq. (1)), where R is the gas constant, L is the latent heat of vaporization, and α is the Clausius-Clapeyron scaling factor, relates the derivative of the natural log of saturation vapor pressure e_s with respect to temperature (T) to temperature itself.

$$\frac{d\ln e_s}{dT} = \frac{L}{RT^2} \equiv \alpha(T) \qquad (1)$$

At typical near-surface temperatures, saturation vapor pressure increases at 7 $\%\mathrm{K}^{-1}$.

Precipitation minus evaporation follows Clausius-Clapeyron scaling, as in Eq. (2), where δ indicates the change between climate states, given three important assumptions (Held and Soden, 2006).

$$\delta(P-E) = \alpha\,\delta T\,(P-E) \qquad (2)$$

First, it assumes small meridional and zonal gradients of temperature anomalies relative to $P-E$. Second, the relationship assumes that there is no change in near-surface relative humidity between climate states, and that the total moisture flux divergence in the atmosphere scales with near-surface specific humidity. Third, it assumes that there is no change in the atmospheric flow. Though it is known that relative humidity and atmospheric circulation are not constant in a changing climate, the thermodynamic scaling is a useful way to represent the role of a simple physical mechanism (i.e., the Clausius-Clapeyron scaling of saturation vapor pressure with temperature) on global $P-E$ anomalies (Byrne and O'Gorman, 2015). This thermodynamic scaling equation represents the component of $P-E$ change driven directly by surface temperature perturbations.

This study evaluates the extent to which the basic physical relation between saturation vapor pressure and temperature accounts for the hydrological response to a combination of large-magnitude forcings: greenhouse gas warming and solar dimming.

We investigate how well thermodynamic scaling predicts hydrologic changes in a geoengineered climate for each model by comparing the prediction using Eq. (2), calculated in each grid box with annual mean data and then averaged zonally, to the annual and zonal mean $P-E$ anomaly between G1 (years 11-50) and piControl (all years) in the model simulations. We also consider the annual-mean global distribution of precipitation minus evaporation anomalies.

To provide reference points for our analysis, we have re-plotted some thermodynamic variables in Figures 1-3 that originally appeared in the G1 overview paper by Kravitz et al. (2013a). The experimental design results in small temperature anomalies (relative to climatological temperatures) between G1 (years 11-50) and piControl (all years) (Fig. 1), with less than 1 K of residual temperature change across most of the globe. The ensemble mean change in $P-E$ shows greater hydrological changes (up to 1 $\mathrm{mm/day}$) in the tropics than at higher latitudes (Fig. 2). Figure 3, which separates the precipitation and evaporation changes, reveals that most of the spatial structure in the $P-E$ anomaly comes from the precipitation change.

In contrast, the thermodynamic scaling captures virtually no change in global $P-E$ patterns, since by experimental design the temperature anomaly is small between the G1 and piControl scenarios (Fig. 4B). The ensemble mean temperature anomalies between G1 and piControl show residual warming exceeding 1 K at high latitudes and cooling at low latitudes as a robust feature across the suite (Fig. 1) (Kravitz et al. 2013a). Such temperature anomalies are generally not sufficient to generate appreciable thermodynamic changes in $P-E$. Deviations of the ensemble mean simulated precipitation minus evaporation anomaly from the thermodynamic scaling are largest in the tropics, where temperature anomalies are small (Fig. 4). In BNU-ESM, thermodynamic scaling predicts a $P-E$ enhancement over the anomalously warm high latitudes, where the temperature response to quadrupled CO_2 levels is poorly compensated by solar dimming (annual mean G1-piControl anomalies >2K at polar latitudes, results not shown here).

The ensemble mean precipitation response reflects strong reductions in subtropical precipitation across the Pacific Ocean (exceeding 0.8 $\mathrm{mm/day}$) (Fig. 3). The precipitation changes are larger in magnitude than the evaporation changes, so this spatial structure is apparent in the ensemble mean $P-E$ as well, with drying around 15°N and 15°S across the Pacific Ocean (Fig. 2). Previous research has suggested that this is a result of the nature of the G1 experiment forcing. Solar geoengineering might suppress tropical precipitation since the reduction in shortwave radiation cools the surface more than the mid-troposphere, increasing atmospheric stability and reducing convection (Bala et al., 2008). However, individual model behavior is not consistent with this ensemble mean picture of suppressed off-equatorial precipitation. Rather, the zonal mean $P-E$ shifts in different directions in individual models so that higher amplitude changes cancel out in the ensemble mean (Fig. 4A). The HadCM3, HadGEM2-ES, and CESM-Cam5.1-FV models show $P-E$ anomalies indicating a northward shift in the Intertropical Convergence Zone (ITCZ), while those of GISS-E2-R, Can-ESM2, and MIROC-ESM demonstrate a southward shift. Annual mean anomalies in the zonal mean $P-E$ exceed 0.6 $\mathrm{mm/day}$ in the GISS-E2-R and HadGEM2-ES simulations. In CCSM4, IPSL-

CM5A-LR, and NorESM1-M models, the ITCZ appears to narrow, with precipitation increasing at the equator and decreasing near 10°N and 10°S.

To better understand the role of relative humidity (H_s) changes in the hydrological response to G1, we investigate the contribution of local changes in H_s to $\delta(P-E)$ as well as the global distribution of annual mean H_s changes in the following section. We will then investigate the dynamical changes in the tropics in Section 2.3.

2.2 Relative Humidity

The simple thermodynamic scaling described above (Eq. 2) assumes no changes in relative humidity between climate states. In this section, we assess the role that relative humidity changes play in the $P-E$ response to uniform solar dimming. Relative humidity is the ratio of actual vapor pressure to saturation vapor pressure ($\frac{e}{e_s}$), or almost equivalently, specific humidity to saturation specific humidity ($\frac{q}{q_s}$). It can change with the water availability or temperature, with the latter affecting the saturation vapor pressure as in Eq. (1). The atmospheric boundary layer provides moisture to the free troposphere, where water vapor plays an important role in radiative transfer, the hydrological cycle, and climate sensitivity (Willett et al., 2010). The near-surface relative humidity parameter is also of interest in climate change studies for evaluating the risk of human heat stress, under both high and low H_s extremes (Sherwood et al., 2010; Souch and Grimmond, 2004).

The assumption of constant relative humidity in the simple thermodynamic scaling of $P-E$ (Eq. (2)) relies on the availability of moisture. In a moisture-limited regime (i.e., over land) q may not increase proportionally with temperature, breaking the assumption of constant relative humidity. Under this circumstance, relative humidity adjustments would contribute to changes in the $P-E$ between climate states. An observational study found decreasing surface relative humidity from 1998-2008 over low and midlatitude land areas due to inhomogeneities in surface heating and moisture availability (Simmons et al., 2010). This was corroborated by a later observational study, though the global long-term relative humidity trend was statistically insignificant (Willett et al., 2014). Previous studies have proposed that simulated and observed land-sea contrasts in relative humidity responses to global warming can be explained by the stronger temperature-driven increase in saturation specific humidity over land, which is not sufficiently compensated by moisture transport from the ocean (Byrne and O'Gorman, 2016). Byrne and O'Gorman (2016) develop a conceptual box model which quantitatively supports that this ocean-control mechanism, as well as changes in evapotranspiration, explain simulated relative humidity anomalies over land.

To better understand the contribution of local relative humidity changes to the $P-E$ response, we calculated an "extended scaling" adapted from Byrne and O'Gorman (2015). Our extended scaling includes the first two terms from Byrne and O'Gorman's equation,

$$\delta(P-E) = \alpha\,\delta T\,(P-E) + \frac{\delta H_s}{H_s}\,(P-E) \tag{3}$$

where H_s is the relative humidity at the surface. The calculation takes local changes in H_s into account, but it excludes the horizontal gradients of changes in H_s and T since the moisture flux calculation requires daily mean model output, which was not archived for the G1 experiment for most models. We calculated the difference between the zonal mean $P-E$ anomalies in the extended and simple scalings to quantify the influence of local changes in H_s. We also calculated the difference between simulated $P-E$ anomalies and the extended thermodynamic scaling. Relative humidity data for this analysis were unavailable for CESM, HadC, and MPI due to limited functionality of the central GeoMIP model data server, the Earth System Grid Federation (ESGF).

The deviations of the extended scaling from the simple scaling are less than 0.1 $\mathrm{mm/day}$ in all models (Fig. 4C). This demonstrates that the local changes in relative humidity under solar dimming (ignoring the gradient of H_s changes) play at most a modest role in the zonal mean $P-E$ response. Local relative humidity changes were also found to be of minimal importance to $P-E$ anomalies in global warming simulations (Byrne and O'Gorman, 2015). Figure 4D indicates that most of the zonal mean $P-E$ anomalies are not captured by the Clausius-Clapeyron scaling or by local relative humidity changes. We therefore attribute the residual simulated $\delta(P-E)$ to atmospheric circulation changes, or gradients of changes in H_s and T. Despite the limited impact of local relative humidity changes on zonal mean $P-E$ changes, regional impacts could still be large and important.

To supplement this analysis, we consider the absolute changes in the relative humidity distribution to explain $P-E$ anomalies between G1 (years 11-50) and piControl (all years) simulations unaccounted for by thermodynamic or dynamic mechanisms. In six of the eight models presented here, relative humidity is reduced over land and conserved over ocean (Fig. 5). The relative humidity reductions are largest over tropical South America and sub-Saharan Africa. The reductions are up to 15% (0.15) in GISS-E2-R and HadGEM2-ES (calculated as the G1 relative humidity (%) minus the piControl relative humidity (%)). Relative humidity is not uniformly reduced over land. Over the deserts of Saudi Arabia, northern Africa, and Australia, relative humidity changes are negligible or in some models, slightly positive. A similar spatial pattern is evident in the evaporation anomaly field, with the most strongly suppressed evaporation in tropical South America, Africa, and Southeast Asia (Fig. 3). This robust spatial pattern suggests that the relative humidity reductions are driven by the CO_2 physiological effect, a mechanism included in the land models of 11 GeoMIP simulations, all but EC-Earth (Table 1). In response to elevated ambient CO_2 concentrations, plants constrict their stomata, which reduces evapotranspiration in the high CO_2 simulations, including the G1 simulations (Kravitz et al., 2013b; Cao et al., 2010). In the global warming (abrupt4xCO2) CMIP5 simulations, this effect is partially offset by the increased net primary productivity in a warmer world. However, in G1, this net primary productivity effect is muted by the reduction in insolation. Tilmes et al. (2013) found that the plant physiological response in G1 is qualitatively the same as for abrupt4xCO2. In another study, biogeochemical cycling was found to influence global precipitation as much as the radiative reduction itself (Fyfe et al., 2013).

In the National Center for Atmospheric Research (NCAR) Community Land and Community Atmosphere Model, Cao et al. (2010) isolated the CO_2 physiological effect from a doubling of atmospheric CO_2. They reported patterns of reduced latent heat flux and relative humidity from this vegetative forcing that closely resemble those we observe in the GeoMIP suite, in Fig. 3 and Fig. 5. This is also consistent with the reasoning of Bala et al. (2008) in that the surface energy budget constrains the response to the shorwave forcing of the G1 experiment. When the downward shortwave flux decreases, the surface fluxes must respond, and in this case the latent heat flux dominates the response. Evaporation decreases, and precipitation follows (Fig. 3). In the present study, since strong and significant reductions in relative humidity over land are largely constrained to regions with extensive vegetation in the form of boreal, temperate or tropical forests, we consider the biogeochemical effect of CO_2 to be the dominant cause of the relative humidity change. The role of these local H_s changes is minimal in zonal mean climate (Fig. 4C), but the gradient of the changes in H_s could be responsible for some of the simulated $P-E$ changes, particularly at smaller spatial scales, such as over sub-Saharan Africa and the tropical rainforests of South America. We leave investigation of this effect to future research.

2.3 Dynamically Driven Precipitation

The third factor we consider in decomposing the $P-E$ response to geoengineering is the atmospheric circulation. Large-scale meridional circulations are driven by energy gradients imposed by the uneven distribution of sunlight on Earth. The Hadley circulation cells are responsible for most of the poleward heat transport in the tropics, where the annual solar input is highest (Hill et al., 2015). The net energy flux of the Hadley circulation is in the flow direction of its upper branch (Held, 2001). The ascending motion of the Hadley cell drives the seasonally-migrating tropical rainfall known as the ITCZ, and there is evidence that its position is determined by meridional gradients in the vertically-integrated atmospheric energy budget (Shekar and Boos, 2016). The Hadley circulation is crucial for balancing global energy, so high-latitude temperature anomalies can drive shifts of the ITCZ (Yoshimori and Broccoli, 2008). The ITCZ is sensitive to interhemispheric energy contrasts set up by aerosols, clouds, or antisymmetric heating (Seo et al., 2014). A thorough analysis of Hadley circulation changes is a crucial outstanding task for understanding the hydrological response to solar geoengineering (Kravitz et al., 2013b). We will quantify changes to the Hadley circulation with the meridional streamfunction. The meridional streamfunction is derived from the continuity equation, and either $\bar{v}$, the meridional wind vector, or $\bar{w}$, the vertical wind vector, can be used to fully define the two-dimensional, overturning flow (Eq. (4)):

$$\Psi(\phi,p) = 2\pi a \cos\phi \int_0^p \bar{v}\, \mathrm{d}p/g. \tag{4}$$

where ϕ is the latitude, p is pressure, a is the Earth's radius, $\bar{v}$ is the meridional velocity, and g is gravity.

Changes in top of atmosphere (TOA) energy fluxes influence the direction and strength of ITCZ shifts (Kang et al., 2008). Numerous studies have noted the strong relationship between ITCZ position and the hemispheric temperature contrast as well. The correlation between interhemispheric temperature contrasts and annual mean ITCZ position is a robust result and is related to extratropical energy transport (e.g., Broccoli et al., 2006; Toggweiler and Lea, 2010). Schneider et al. (2014) explain how this is consistent with an energetic framework: the hemisphere with the higher average temperature typically has a smaller meridional temperature gradient due to the near symmetry of tropical temperatures about the equator. This corresponds to reduced poleward extratropical eddy transport in that hemisphere, and increased energy flux by the atmosphere across the equator and out of the hemisphere by the upper branch of the Hadley cell. The ITCZ is drawn towards the warmed hemisphere because moisture is transported in the opposite direction as energy by the Hadley cell. Therefore, we investigate the possibility that differing dynamical responses to solar dimming among the models are due to differences in the temperature restoration of the Northern and Southern Hemispheres.

To discern the component of the precipitation change caused by changes in large scale atmospheric dynamics, we calculated the change in the Hadley circulation between the G1 (years 11-50) and piControl (final 40 years) simulations. For each model, we computed the meridional streamfunction over this 40 year averaging period based on the modeled meridional wind vector, as in Eq. (4). Data were unavailable for the CESM and HadC models. We examined annual and seasonal mean dynamical changes to understand the response of the zonal mean hydrological cycle, including the periods July-August-September (JAS) and January-February-March (JFM). (We chose these averaging periods because the multi-model mean ITCZ position extremes occur in August and February.) To better interpret the dynamical changes, we assessed the annual mean and seasonal changes in the interhemispheric temperature contrast between G1 and piControl for each model by calculating area-weighted hemispheric averages of the surface temperature, averaged over a 40 year period (years 11-50 of G1 and 1-40 of piControl). The ITCZ shift between G1 and piControl is defined as the shift of the precipitation centroid. This is the latitude between 15°N and 15°S at which half the precipitation is to the north and half is to the south.

The annual mean Hadley circulation changes vary in magnitude and direction amongst the GeoMIP ensemble members and contribute to dynamic moistening and drying. The meridional streamfunction plots suggest that the northward (HadGEM2-ES) and southward (GISS-E2-R, MIROC-ESM) ITCZ shifts, characterized by counterclockwise or clockwise tropical anomalies respectively, are dynamically driven (Fig. 6). The anomalous ascent at the equator in CCSM4 and NorESM1-M accounts for the narrowing of the ITCZ noted in the zonal mean $P-E$ figure. The mean circulation does not seem to provide a dynamical basis for the annual mean constriction of the ITCZ in the MPI-ESM-LR and IPSL-CM5A-LR models, in which anomalies are less than 10^{10} kg s^{-1}. Small changes in the latitudinal range and strength of the Hadley circulation and associated precipitation have large local implications, especially on subannual scales (Kang et al., 2009). Boreal summer (JAS) and winter (JFM) meridional streamfunction anomalies are in every model stronger than the annual mean (Figs. 7, 8). In HadGEM2-ES, for example, the JAS meridional mass flux anomaly exceeds 4×10^{10} kg s^{-1}. On the opposite extreme, the IPSL-CM5A-LR model JAS and JFM mass flux anomalies are below 1.5×10^{10} kg s^{-1}. In general, the JAS streamfunction changes rather than the JFM anomalies set the pattern for the annual mean circulation change (Figs. 6-8). In the JAS average, there is anomalous energy transport toward the summer hemisphere (NH) in eight of nine models (all but HadGEM) (Fig. 7). In the JFM average, there is again anomalous energy transport toward the summer hemisphere (SH), though the result is less consistent across the suite (seven of nine models) (Fig. 8). These changes in the Hadley cell mass flux are consistent with the relative cooling of the summer hemisphere throughout the year (Fig. 9b,c).

We find that the shifts of annual mean tropical rainfall in the models are correlated with the interhemispheric surface temperature contrasts (Correlation coefficient $(r)=0.71$, Fig. 9a). Models with higher annual mean surface temperatures in the Northern Hemisphere under geoengineering tend to display northward shifts of the ITCZ. This is consistent with previous research that shows a strong relationship between the ITCZ position and the hemispheric temperature contrast (e.g., Kang et al., 2008; Frierson and Hwang, 2012). Modeling studies by Haywood et al. (2013, 2016) have shown that increasing the albedo by injecting stratospheric aerosols into only one hemisphere could cause substantial shifts in the ITCZ toward the other hemisphere. Our analysis of the G1 experiment suggests that similar effects could occur, albeit on a smaller scale, even with a hemispherically symmetric injection strategy, which is approximated by reducing the solar constant. Despite the hemispherically symmetric forcing induced by solar dimming, the ensemble mean residual high-latitude warming is larger in the Arctic than in the Antarctic (Fig. 1), and in 9 out of 11 models the Northern Hemisphere is warmed relative to the Southern Hemisphere after geoengineering (Fig. 7a). This suggests that there could be an intriguingly close relationship between the degree of Arctic warming amplification and the tropical hydrological response to geoengineering in models. The relationship between ITCZ shifts and energy transport in G1 will be further explored in a future study.

One response of the ITCZ to the G1 experiment that is consistent across all 11 models is that the seasonal migration of the ITCZ is dampened. Figure 10 shows the annual, boreal winter (JFM), and boreal summer (JAS) mean position of the ITCZ in each model in piControl (years 1-40) and G1 (years 11-50). In each model, the distance between the seasonal mean positions of the ITCZ is reduced. In some models there is a poleward shift in the ITCZ in one of the seasons, but in each of these cases there is a greater equatorward shift in the opposite season, with an annual mean ITCZ shift and a reduction in the seasonal migration occurring simultaneously.

The reduction in the seasonal ITCZ migration is consistent with the physical mechanism relating sulfate aerosols and ITCZ shifts during 1971-1990 described by Hwang et al. (2013; see their Figure 4). There is more available sunlight in the summer hemisphere, which results in a greater cooling there when the solar constant is reduced. To compensate for the loss of energy in the summer hemisphere, the climatological energy flux out of the summer hemisphere and towards the winter hemisphere is reduced. Indeed, in G1, most models show an anomalous Hadley circulation in which winds aloft, and therefore energy, move towards the summer hemisphere (Figs. 7, 8). This is accompanied by anomalous flow towards the winter hemisphere in the lower branch of the Hadley cell, which weakens moisture transport towards the summer hemisphere and moves the summer ITCZ position away from the summer pole. The warming of the winter relative to the summer hemisphere and the ITCZ shift toward the winter hemisphere are correlated between the different models (Fig. 9b,c), and are consistent with the proposed physical mechanism.

Damped seasonal ITCZ migration provides a possible physical mechanism for the narrowing of the annual mean ITCZ in the various models. Other processes that could affect the width of the ITCZ include changes in gross moist stability, the net energy input to the atmosphere, or the advection of moist static energy by the Hadley cell mean flow or transient eddies, as analyzed by Byrne and Schneider (2016a; 2016b) for global warming simulations. A more comprehensive analysis of the processes responsible for the contraction of tropical precipitation in solar geoengineering experiments would be a useful avenue for future study. Reduced seasonal ITCZ migration due to summer hemisphere cooling is also one possible physical explanation for the reduction in summer monsoon precipitation in the G1 experiment found by Tilmes et al. (2013).

3 Conclusions

Hadley circulation changes play a significant role in driving the $P-E$ changes in climate model simulations of uniform solar dimming. While thermodynamic scaling captures the general spatial structure of $P-E$ changes under global warming, it does not do so for idealized simulations of the response to increased CO_2 combined with solar geoengineering. Hadley circulation changes are in qualitative agreement with zonal mean features of the hydrological response to G1, so we conclude that they play a primary role in the response. Thermodynamic scaling and relative humidity changes may be important to explain $P-E$ anomalies over rainforests or at high latitudes where the CO_2 physiological response and residual temperature anomalies are more important, respectively.

The models can be divided into three groups characterized by different tropical $P-E$ responses to geoengineering: either a southward shift, northward shift, or narrowing of the ITCZ. Our results support that changes in tropical dynamics, namely shifts of the Hadley circulation, are largely responsible for these alterations to the $P-E$ distribution. In a previous study, convection scheme parameters were determinative of the tropical precipitation response to extratropical forcings (Kang et al., 2009), and other studies (Song and Zhang, 2009; Liu et al., 2010) have also found tropical precipitation to be sensitive to the convection scheme. The partitioning of cross-equatorial fluxes between atmospheric and oceanic components is also important for the resulting ITCZ shift, so differences in the oceanic component of the models could emerge as significant (Kang et al., 2008).

We also present evidence that land-sea contrasts in evaporation rates, resulting in land-sea contrasts in relative humidity anomalies, may contribute to small changes in $P-E$ with solar dimming. We do so by examining the spatial distribution of relative humidity and evaporation anomalies, and by calculating an extended thermodynamic scaling that accounts for the response of $P-E$ to the local relative humidity change. We reason that these relative humidity changes are related to the effect of CO_2 on the stomatal conductance in plants, a phenomenon noted in previous studies of geoengineering. It would be interesting to examine the relative humidity anomalies in G1 on shorter temporal scales given the important role of vegetation, a seasonally varying feature of the climate, in its modulation. It would also be valuable to analyze the influence of gradients of changes in relative humidity on $P-E$, as this was shown to be an important influence over land in previous work by Byrne and O'Gorman (2015).

Tropical precipitation is sensitive to solar perturbations and would be altered by an implementation of globally-uniform solar geoengineering. Based on our inter-model comparison, there is substantial uncertainty regarding the nature of the tropical precipitation response, in terms of the direction and strength of the ITCZ shift, as well as its variation on seasonal time scales. We present evidence that residual warming of one hemisphere relative to the other under geoengineering draws annual mean tropical rainfall into that hemisphere. On seasonal timescales, preferential cooling of the summer hemisphere results in a damping of the seasonal migration of the ITCZ, which may help explain the apparent narrowing of the tropical peak in annual mean precipitation. A reduced seasonal migration of the ITCZ could have catastrophic consequences for semi-arid areas like the Sahel region, which lies at the northern margin of the current seasonal ITCZ excursion. The potential for such regional impacts under geoengineering warrants further study. Our results reinforce the finding that uniform solar dimming cannot restore preindustrial conditions in terms of $P-E$ patterns, a fundamental aspect of climate. An investigation of the ability of spatially targeted solar geoengineering to offset these $P-E$ changes would be a valuable future direction. In light of the considerable inter-model differences, improvements in model representation of processes including clouds and tropical convection will also help improve our understanding of hydrological cycle responses to solar geoengineering.

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FIGURES

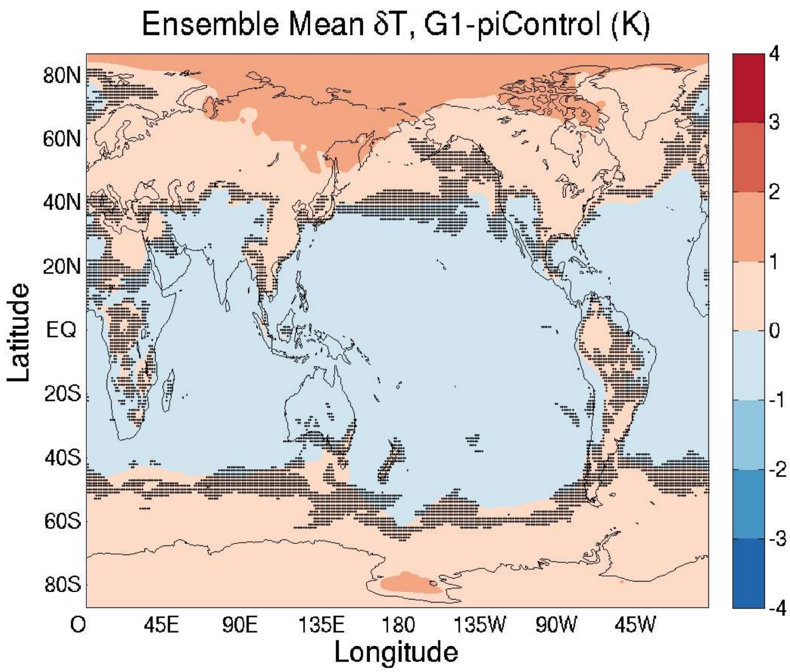


Figure 1. The annual mean distribution of near-surface atmospheric temperature anomalies (K) between G1 (years 11-50) and piControl (all years). Stippling denotes regions where fewer than 66% of the 12 ensemble members agree on the sign of the change. These results appear in Kravitz et al. 2013a.

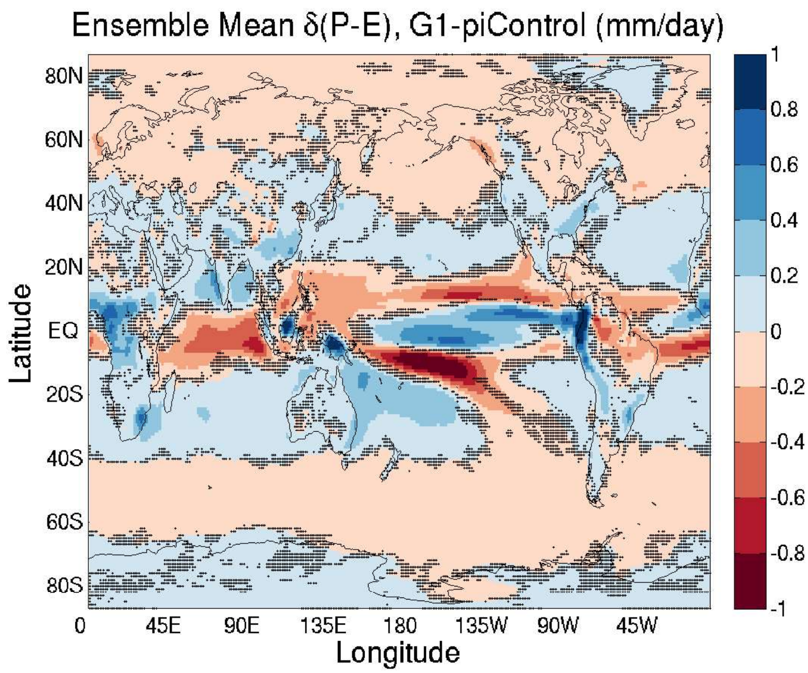


Figure 2. The annual mean distribution of precipitation minus evaporation rate anomalies (mm/year) between G1 (years 11-50) and piControl (all years), averaged among 11 models (EC-Earth excluded due to unphysical result). Stippling indicates where fewer than 64% of models agree on the sign of the change. These results appear in Kravitz et al. 2013a.

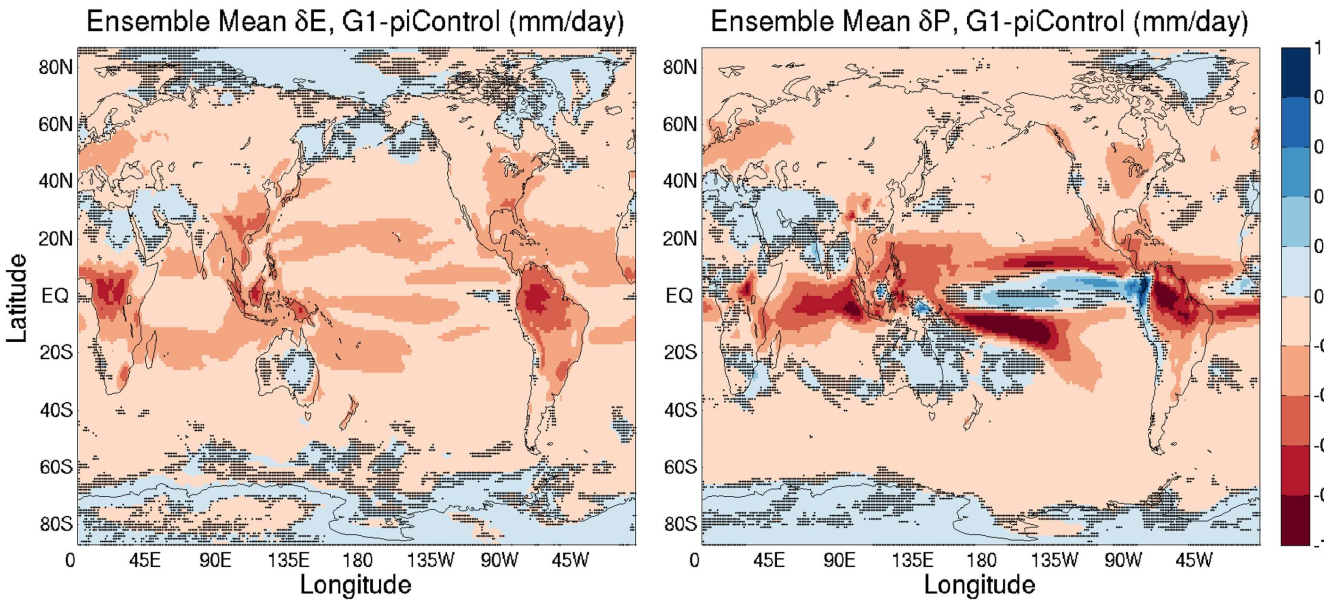


Figure 3. The annual mean distribution of evaporation (left panel) and precipitation (right panel) rate anomalies (mm/year) between G1 (years 11-50) and piControl (all years), averaged among 11 models (EC-Earth excluded due to unphysical result). Stippling indicates where fewer than 64% of models agree on the sign of the change. These results appear in Kravitz et al. 2013a.

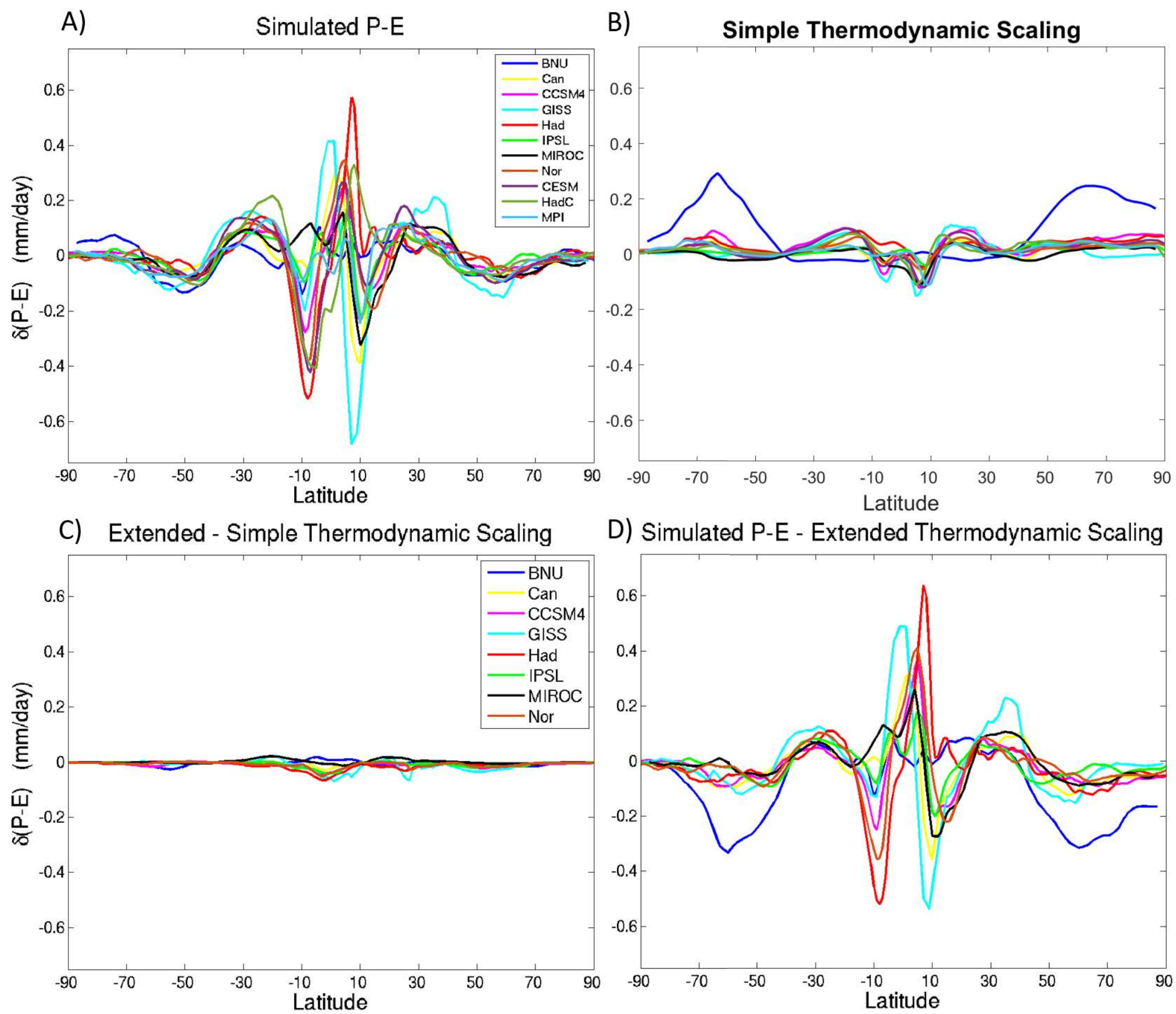


Figure 4. A) shows the zonal mean $\delta(P - E)$ for G1-piControl simulated in 11 climate models, and B) is the $P - E$ anomaly predicted by the simple thermodynamic scaling in Eq. (2). C) shows the difference of the G1-piControl $\delta(P - E)$ predicted by the extended (Eq. (3)) and simple (Eq. (2)) scalings. This isolates the contribution of local relative humidity changes to the $P - E$ anomalies. D) is the difference between the simulated G1-piControl $\delta(P - E)$ and the $P - E$ anomaly predicted by the extended scaling, and represents the changes in dynamically driven rainfall. (EC-Earth excluded due to unphysical result).

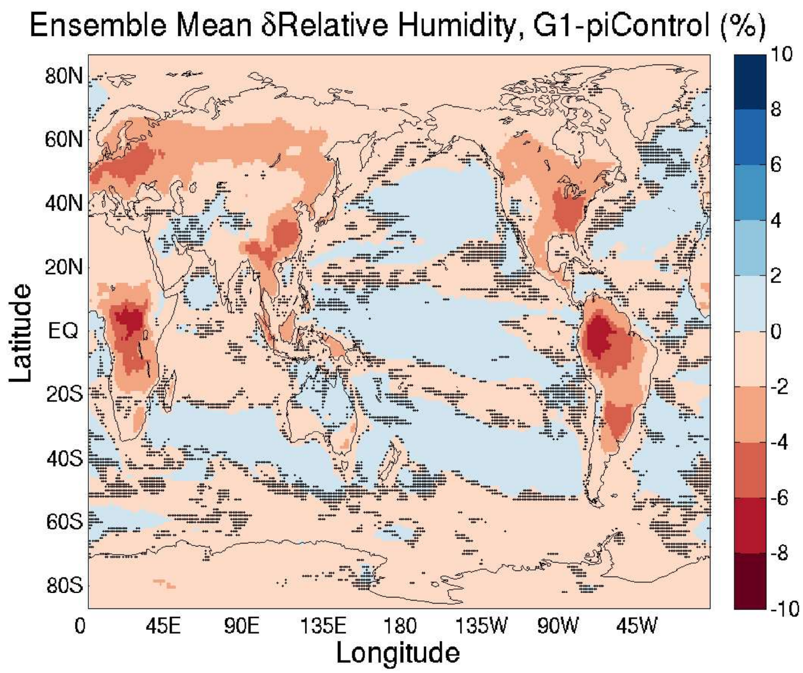


Figure 5. The annual mean near-surface relative humidity anomaly between G1 (years 11-50) and piControl (all years) in eight GCMs. Stippling indicates that fewer than 62.5% of the models agree on the sign of the change. (Data unavailable for HadC, CESM, and MPI models; EC-Earth excluded).

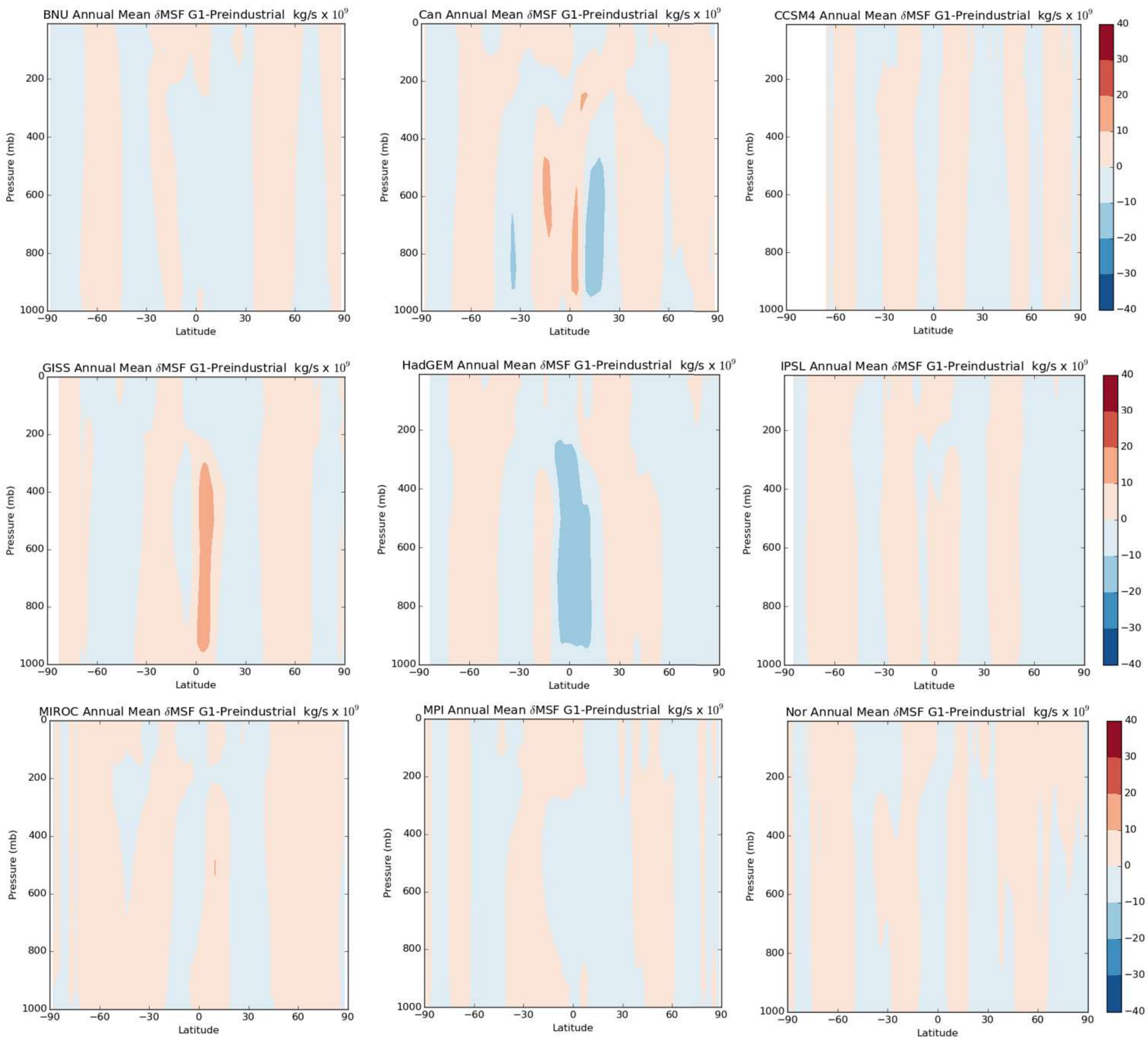


Figure 6. The annual mean meridional streamfunction anomaly between G1 (years 11-50) and piControl (last 40 years) in each model, as calculated in Eq. (4). Blue colors indicate counterclockwise motion. (Data unavailable for HadC and CESM models).

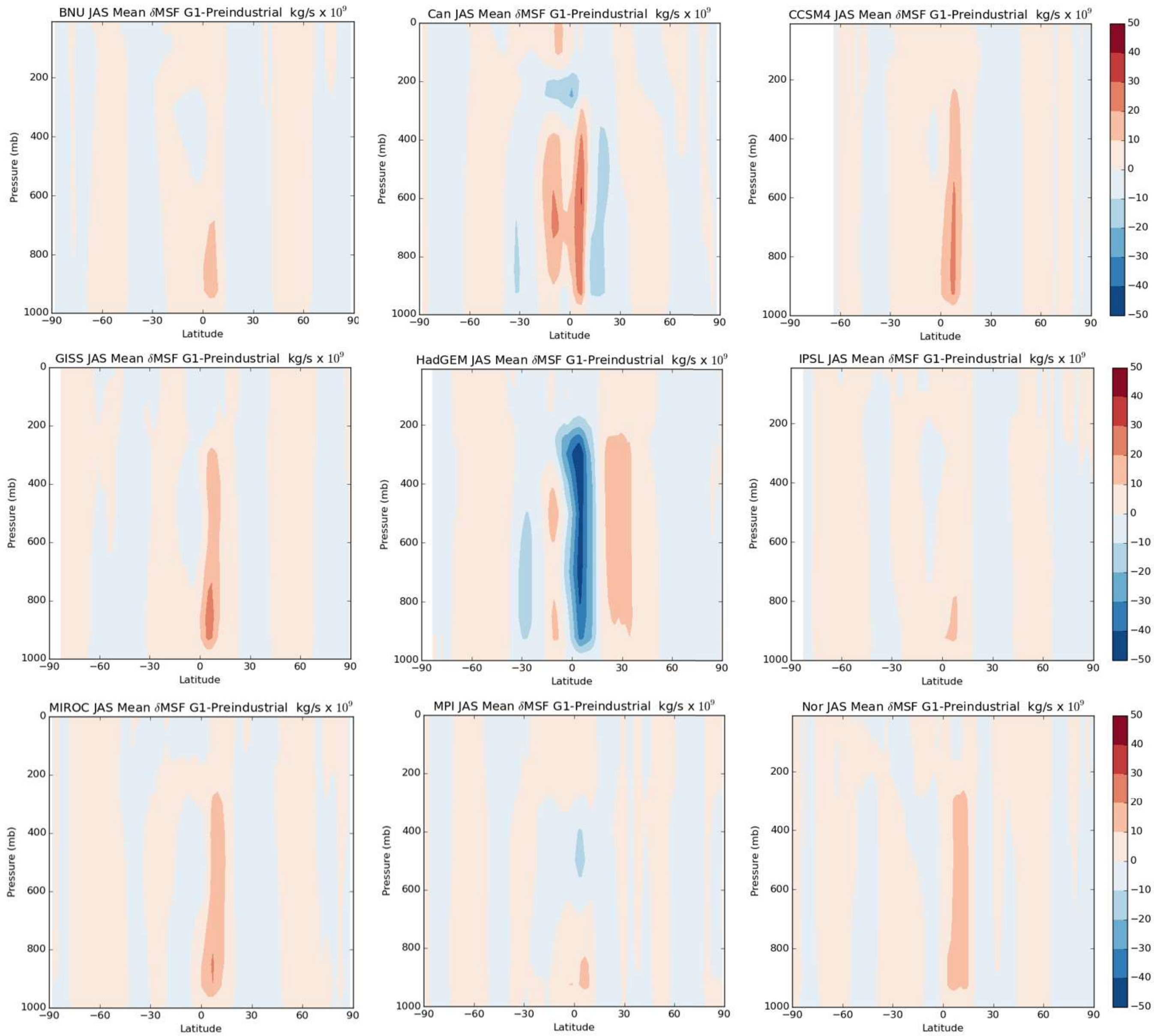


Figure 7. The JAS mean meridional streamfunction anomaly between G1 (years 11-50) and piControl (last 40 years) in each model, as calculated in Eq. (4). Blue colors indicate counterclockwise motion. (Data unavailable for HadC and CESM models).

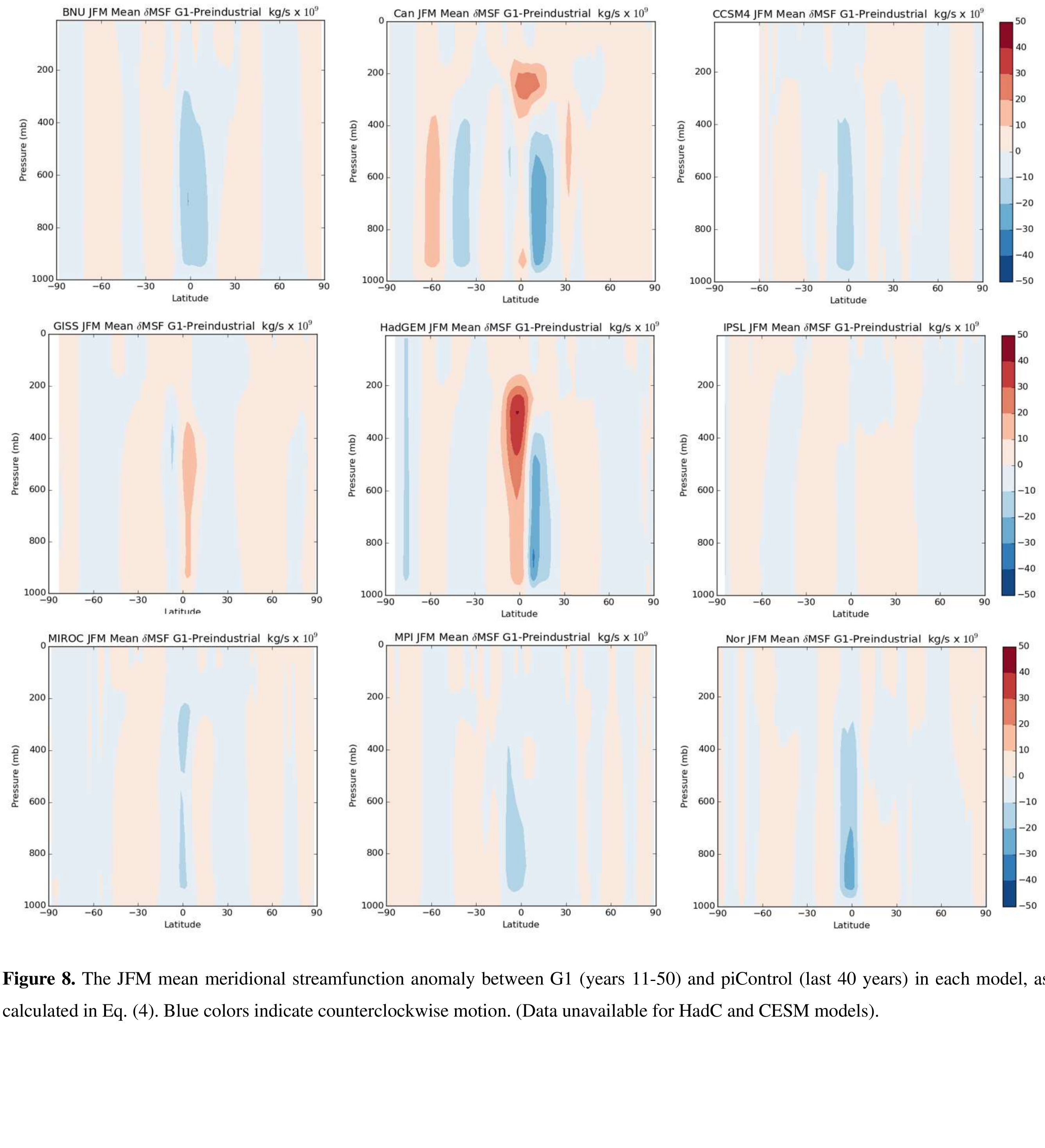
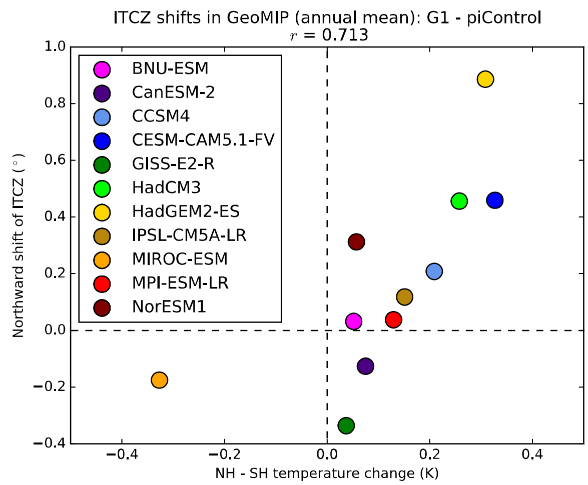
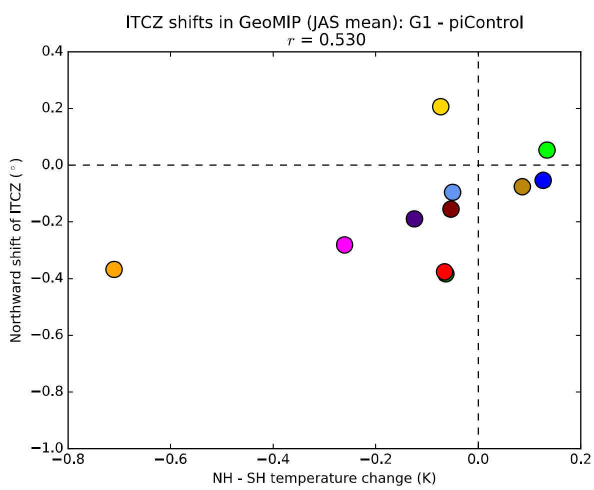


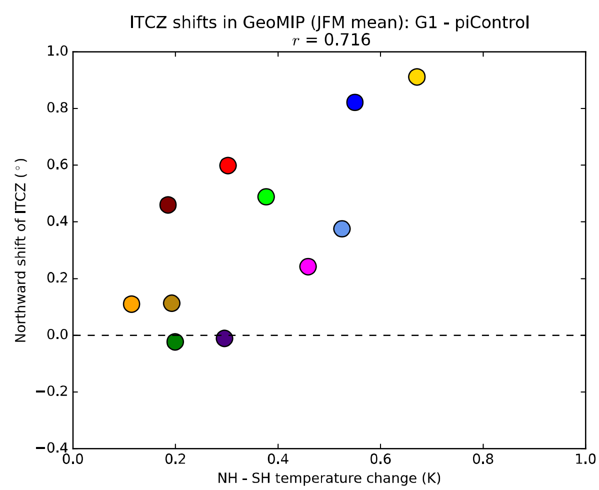
Figure 8. The JFM mean meridional streamfunction anomaly between G1 (years 11-50) and piControl (last 40 years) in each model, as calculated in Eq. (4). Blue colors indicate counterclockwise motion. (Data unavailable for HadC and CESM models).



(a)



(b)



(c)

Figure 9. The ITCZ shift vs. the anomaly of the interhemispheric temperature contrast between G1 (years 11-50) and piControl (years 1-40), where r is the correlation coefficient. Panel a) shows the annual mean, b) is the JAS mean, and c) is the JFM mean.

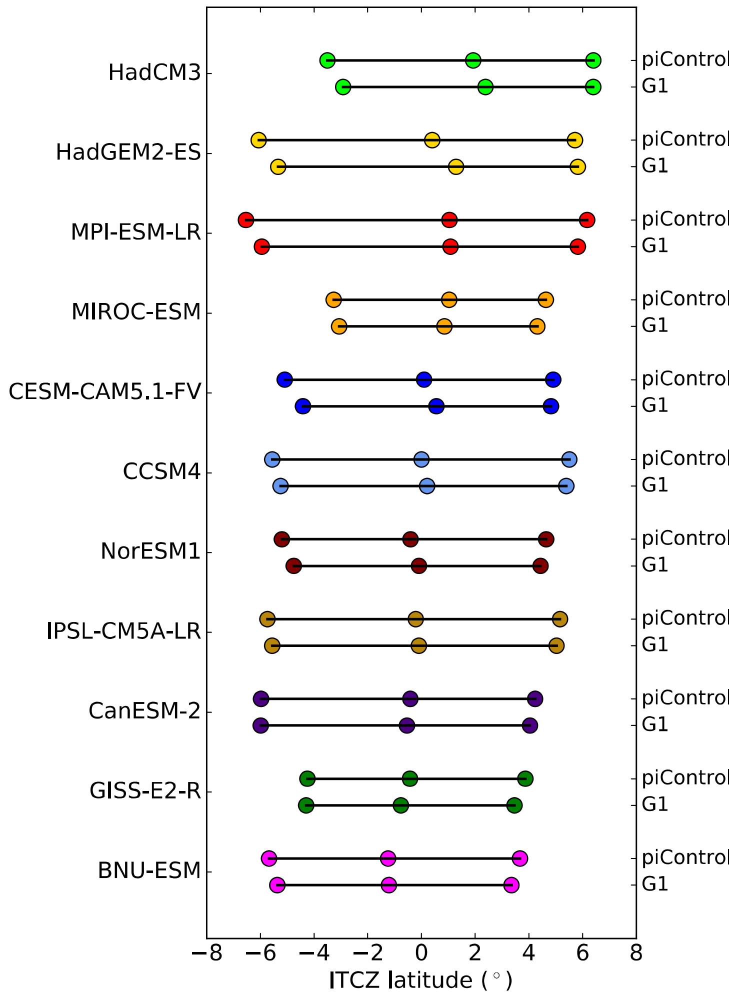


Figure 10. Annual and seasonal mean positions of the ITCZ in piControl (years 1-40) and G1 (years 11-50). For each model, the top row of dots shows piControl positions, and the bottom row of dots shows G1 positions. In each row of dots, the left dot shows the JFM mean position, the middle dot shows the annual mean position, and the right dot shows the JAS mean position. Models are ordered by the annual mean ITCZ position in piControl.

Table 1. GeoMIP Model Specifications. In certain figures models are labeled with the shortened name in parenthesis. Column 3 refers to the CO_2 physiological effect in plants. The solar constant (S_0) reduction is a percentage. Information courtesy of Kravitz et al. (2013a)

Model[1]	Dynamic Vegetation	Phys. Effect	S_0 Reduction	References
BNU-ESM (BNU)	no	yes	3.8	Ji et al. (2014)
Can-ESM2 (Can)	yes	yes	4.0	Arora et al. (2011)
CCSM4 (CCSM4)	no	yes	4.1	Gent et al. (2011)
CESM-CAM5.1-FV (CESM)	no	yes	4.7	Hurrell et al. (2013)
EC-Earth	no	no	4.3	Hazeleger et al. (2012)
GISS-E2-R (GISS)	no	yes	4.5	Schmidt et al. (2014)
HadCM3 (HadC)	no	yes	4.1	Gordon et al. (2000)
HadGEM2-ES (Had)	yes	yes	3.9	Collins et al. (2011)
IPSL-CM5A-LR (IPSL)	yes	yes	3.5	Dufresne et al. (2013)
MIROC-ESM (MIROC)	yes	yes	5.0	Watanabe et al. (2011)
MPI-ESM-LR (MPI)	no	yes	4.7	Giorgetta et al. (2013)
NorESM1-M (Nor)	no	yes	4.0	Bentsen et al. (2013)

1. Full Names: BNU-ESM, Beijing Normal University-Earth System Model; CanESM2, The Second Generation Canadian Earth System Model; CESM-CAM5.1, The Community Climate System Model Version 5.1; CCSM4, The Community Climate System Model Version 4; EC-EARTH DMI, European Earth System Model based on ECMWF Models (Seasonal Forecast System), Danish Meteorological Institute; GISS-E2-R, Goddard Institute for Space Studies ModelE version 2; HadCM3, Hadley Centre coupled model 3; IPSL-CM5A-LR, Institut Pierre Simon Laplace ESM; MIROC-ESM, Model for Interdisciplinary Research on Climate-Earth System Model; MPI-ESM-LR, Max Planck Institute ESM; NorESM1-M, Norwegian ESM.