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A multi-model assessment of regional climate disparities caused by solar geoengineering

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Abstract

Global-scale solar geoengineering is the deliberate modification of the climate system to offset some amount of anthropogenic climate change by reducing the amount of incident solar radiation at the surface. These changes to the planetary energy budget result in differential regional climate effects. For the first time, we quantitatively evaluate the potential for regional disparities in a multi-model context using results from a model experiment that offsets the forcing from a quadrupling of CO_2 via reduction in solar irradiance. We evaluate temperature and precipitation changes in 22 geographic regions spanning most of Earth's continental area. Moderate amounts of solar reduction (up to 85% of the amount that returns global mean temperatures to preindustrial levels) result in regional temperature values that are closer to preindustrial levels than an un-geoengineered, high CO_2 world for all regions and all models. However, in all but one model, there is at least one region for which no amount of solar reduction can restore precipitation toward its preindustrial value. For most metrics considering simultaneous changes in both variables, temperature and precipitation values in all regions are closer to the preindustrial climate for a moderate amount of solar reduction than for no solar reduction.

S Online supplementary data available from stacks.iop.org/erl/9/074013/mmedia

Keywords: geoengineering, GeoMIP, regional climate, climate modeling

1. Introduction

Solar geoengineering is a proposed means of reducing some of the climatic effects of increasing carbon dioxide by reducing the amount of incident solar irradiance at Earth's surface. Although an imperfect solution to anthropogenic climate change (Keith and Dowlatabadi 1992, Robock 2008, Shepherd *et al* 2009), particularly in the absence of major mitigation efforts, solar geoengineering could be used to offset some climate change, allowing additional time for mitigation efforts to be implemented or reducing impacts while mitigation is in progress (Crutzen 2006). Because compensation for increased trapping of infrared radiation by reductions in incident shortwave radiation modifies the surface and atmospheric energy budgets on regional scales (e.g., Govindasamy and Caldeira 2000, Kravitz *et al* 2013b), regional disparities in the effects of solar geoengineering would be expected (Ricke *et al* 2010).

Using output from 12 fully coupled atmosphere-ocean general circulation models participating in the Geoengineering Model Intercomparison Project (GeoMIP; Kravitz *et al* 2011, 2013a), we quantitatively evaluate regional disparities from global-scale geoengineering (GeoMIP experiment G1: offsetting an increase in CO_2 concentration from the preindustrial era via uniform solar irradiance reduction). Model names, descriptions, and references are given in table 1 of Kravitz *et al* (2013a). In this study, we exclusively consider changes in temperature and precipitation, as in many previous geoengineering studies (MacMartin *et al* 2013, Moreno-Cruz *et al* 2012, Ricke *et al* 2010, 2013). Although changes in these two fields cannot exhaustively describe all possible climates that may be experienced by particular regions, they underpin a large number of climate impacts, including flooding, drought, and heat waves. Moreover, their responses to CO_2 and solar forcing are qualitatively different (Irvine *et al* 2010); as such, evaluating their responses in this study serves as a useful illustration of competing or conflicting priorities in determining the goals of geoengineering.

In this paper, we apply and extend the method of Moreno-Cruz *et al* (2012) to an ensemble of climate models. This is the first time such examinations have been performed using a multi-model ensemble. Through our approach, we can identify aspects of model agreement and disagreement on the following questions:

1. How well can global-scale solar geoengineering restore CO_2-induced regional temperature and precipitation values to preindustrial levels?
2. How does the effectiveness of global-scale solar geoengineering in restoring these fields to preindustrial values depend upon the amount of geoengineering?
3. How does assessment of the effectiveness of global-scale solar geoengineering depend upon the relative weighting between temperature and precipitation (i.e., an individual region's prioritization of a particular climate variable)?

These questions explore the extent to which a limited amount of solar geoengineering (i.e., only partially offsetting change in global mean temperature) can alleviate regional inequalities from climate change.

2. Methods

We obtained output from each of the 12 models for three simulations: (i) piControl: a stable preindustrial control simulation; (ii) abrupt4xCO2: from the climate of piControl, CO_2 concentrations are instantaneously quadrupled; and (iii) G1: the top-of-atmosphere net radiation changes in abrupt4xCO2 are offset by a uniform reduction in solar irradiance. For each of these simulations in each of the 12 models, as well as the 12-model ensemble mean, we consider temperature and precipitation values averaged over the years 11–50 of the simulations. (We discuss seasonal averages in Supplemental section 2, available at stacks.iop.org/erl/9/074013/mmedia, for which we averaged only June-July-August or December-January-February values from this period.) Although piControl and G1 have approximately reached steady state, the climate in abrupt4xCO2 continues to evolve over this period (Kravitz *et al* 2013a, Tilmes *et al* 2013). However, the patterns of spatial distributions of temperature and precipitation changes are different for the different regions discussed here, and as such, using a transient simulation will not affect our conclusions. (Also see Supplemental section 2 and Supplemental figure 22)

As a next step, we calculated temperature and precipitation changes at the grid scale, both in absolute terms and normalized by the standard deviation of interannual natural variability in the piControl simulation $\sigma_{T,\mathrm{piControl}}$ or $\sigma_{P,\mathrm{piControl}}$. That is,

$$\Delta\mathcal{T}_{\mathrm{abrupt4xCO2}} = \frac{T_{\mathrm{abrupt4xCO2}} - T_{\mathrm{piControl}}}{\sigma_{T,\mathrm{piControl}}} \quad (1)$$

$$\Delta\mathcal{P}_{\mathrm{abrupt4xCO2}} = \frac{P_{\mathrm{abrupt4xCO2}} - P_{\mathrm{piControl}}}{\sigma_{P,\mathrm{piControl}}} \quad (2)$$

where T (units of $^\circ$ C) and P (units of mm day^{-1}) are absolute values of temperature and precipitation, respectively, and $\mathcal{T}$ and $\mathcal{P}$ (unitless) are the absolute changes normalized by the standard deviation.

To determine the temperature and precipitation departures from preindustrial levels for an arbitrary level of solar reduction g, denoted $\Delta\mathcal{T}(g)$ and $\Delta\mathcal{P}(g)$, we linearly interpolated between $\Delta\mathcal{T}_{\text{abrupt4xCO2}}$ and $\Delta\mathcal{T}_{\text{G1}}$ and between $\Delta\mathcal{P}_{\text{abrupt4xCO2}}$ and $\Delta\mathcal{P}_{\text{G1}}$. Models show that responses of temperature and precipitation to CO_2 and global-scale solar geoengineering are approximately linear in the range of forcings examined here (Allen and Ingram 2002, Andrews *et al* 2009, Ban-Weiss and Caldeira 2010, Irvine *et al* 2010 Moreno-Cruz *et al* 2010 O'Gorman and Schneider 2008, Ricke *et al* 2010, Modak and Bala 2013), allowing interpolation of the climate metric to different levels of solar reduction (also see Supplemental section 1). This linear trend was then extrapolated to levels of geoengineering that exceed the solar reductions in G1. More specifically, we define a normalized level of solar reduction $g = \Delta S/\Delta S_{4\text{xCO2}}$, where ΔS is solar reduction, and the denominator denotes the reduction in solar irradiance that returns the globally averaged temperature to its preindustrial value ($g = 1$). This quantity is computed for each model and for the 12-model ensemble average. In all of our calculations, g ranges between 0 (no geoengineering) and 2 (twice the required amount of geoengineering to return global mean temperature to its preindustrial value; also see Supplemental section 1).

Uniform solar reduction captures many of the qualitative features of the temperature and precipitation responses to other methods of uniform solar geoengineering, such as creation of a stratospheric sulfate aerosol layer (Ammann *et al* 2010), although there remain some subtle differences, particularly related to the hydrological cycle (Fyfe *et al* 2013, Niemeier *et al* 2013, Ferraro *et al* 2014). Nevertheless, many practical implementations of solar geoengineering would likely lead to non-uniform distributions of radiative forcing that would have regional effects differing from those analyzed here (also see Supplemental section 2). Some examples of non-uniform solar geoengineering include non-uniform distributions of solar reductions (Ban-Weiss and Caldeira 2010, MacMartin *et al* 2013) or marine cloud brightening techniques (Jones *et al* 2011, Latham 2012, Rasch *et al* 2009).

For each value of g, the temperature and precipitation responses were averaged over 22 geographic regions, as defined by Giorgi and Francisco 2000 (Supplemental section 2 and Supplemental figure 1). Although the so-called 'Giorgi regions' include both land and ocean model grid boxes, using these regions primarily assumes an anthropocentric viewpoint and, for example, omits assessments of how changes in ocean ecosystem services may affect human populations. Using Giorgi regions to assess the effects of solar geoengineering is one perspective and is not meant to represent all global changes.

The climate change metric D in a given Giorgi region i for a particular level of geoengineering g and weight w is defined by

$$D_i(w;\, g) = \sqrt{(1 - w)\,[\Delta\mathcal{T}(g)]^2 + w\,[\Delta\mathcal{P}(g)]^2} \qquad (3)$$

where w is a dimensionless weight parameter with values in [0, 1]. An equal weighting of $\Delta\mathcal{T}$ and $\Delta\mathcal{P}$ in calculating D corresponds to $w = 0.5$. We have chosen this metric because it has been used previously (MacMartin *et al* 2013, Moreno-Cruz *et al* 2012, Ricke *et al* 2010, 2013), and because it is analytically tractable. One potential shortcoming of regional averaging is the implicit assumption that climate changes are uniform across an entire region, but we do not expect this assumption to affect our methodology or conclusions (Supplemental section 2).

The dimensional quantities only make sense for the special cases of $w = 0$ and $w = 1$. In these cases, the equations for D degenerate into

$$D_i(g) = \left|g\Delta\mathcal{T}_{\text{G1}} + (1 - g)\Delta\mathcal{T}_{\text{abrupt4xCO2}}\right| \qquad (w = 0) \qquad (4)$$

$$D_i(g) = \left|g\Delta\mathcal{P}_{\text{G1}} + (1 - g)\Delta\mathcal{P}_{\text{abrupt4xCO2}}\right| \qquad (w = 1) \qquad (5)$$

For ease of assessing the results, one can also express D for precipitation changes in terms of percent change:

$$D_i(g) = \left| g\left(\frac{P_{\text{G1}} - P_{\text{piControl}}}{P_{\text{piControl}}}\right) + (1 - g)\left(\frac{P_{\text{abrupt4xCO2}} - P_{\text{piControl}}}{P_{\text{piControl}}}\right)\right| \times 100 \quad (w = 1) \qquad (6)$$

In all calculations, we excluded changes that were not statistically significant, i.e., if we did not have confidence in our ability to discern the sign of the change due to either CO_2 increases or solar reductions. (See Supplemental section 1 for details.)

There are multiple ways of weighting climate change in different regions (Supplemental figure 2). Here we use the Pareto criterion (introduced by Moreno-Cruz *et al* 2012) to determine the largest amount of achievable solar reduction (beginning at no geoengineering) in which no region's mean climate can be moved closer to its preindustrial value without moving another region's mean climate farther away from its own preindustrial value:

$$\overline{D}_{Pareto}(w) = \min_i \left\{ \max_{g \geqslant 0} \left[D_i(w;\, g) \right] \right\} \qquad (7)$$

That is, the amount of geoengineering is increased ($g > 0$) until no region i can have $D_i(w;\, g)$ decrease without having $D_j(w;\, g)$ increase for a different region j. The Pareto criterion is a decision rule that is the most sensitive method for minimizing overall impacts when faced with different results in different regions. We chose this method for simplicity, although we do acknowledge that it has an implicit weighting of different regions (as does any method).

3. Results

Figure 1 shows all-model ensemble averages for temperature and precipitation changes in each of the 22 regions as a function of the amount of geoengineering. When only considering temperature (equation (4), all regions show temperatures closer to preindustrial values for at least 90% of the amount of geoengineering that would return global mean temperature to its preindustrial value (i.e., $\overline{D}_{Pareto}(0) = 0.9$).

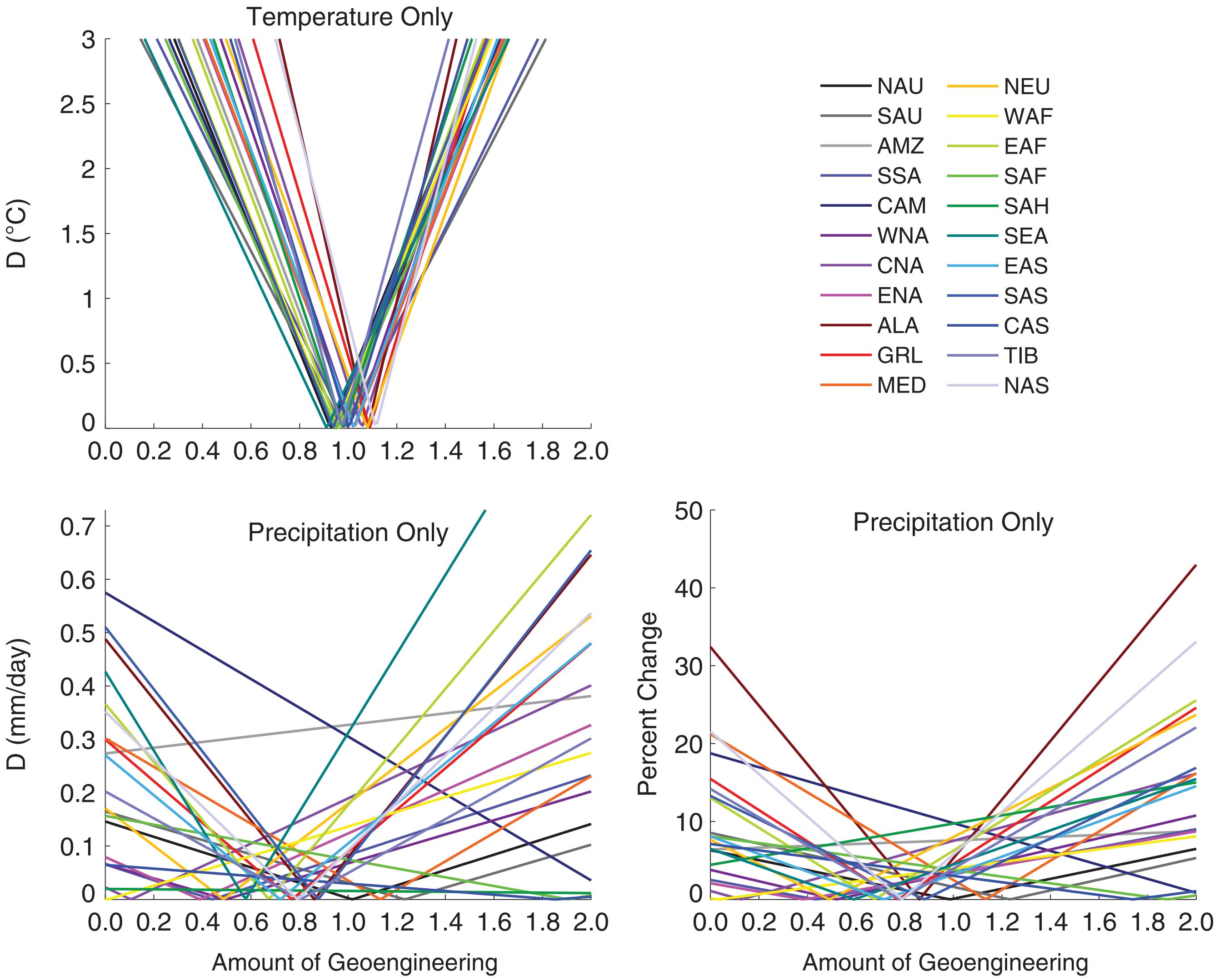

Figure 1. Regional changes in temperature (top panel) and precipitation (bottom panels) as a function of the amount of geoengineering (g). Each line indicates the all-model ensemble mean response (D, equations (4)–(6) of one of the 22 Giorgi regions (Supplemental figure 1). For temperature (top panel), all regions show reductions in this metric for g up to 0.9. This is not true for precipitation (bottom panels), where at least one region shows some increase in the metric for any non-zero g.

In contrast, precipitation shows varying results: some regions show that precipitation continues to approach its preindustrial value for increasing amounts of geoengineering, whereas others show that any amount of geoengineering increases the departure from preindustrial (i.e., $\overline{D}_{Pareto}(1) = 0$). Assessing the physical mechanisms governing regional precipitation changes would require a thorough understanding of the individual parameterizations and feedback strengths in each model, which is beyond the scope of this paper.

Figure 2 shows that these conclusions hold for individual models and the all-model average: all regions in all models show that temperatures continue to shift closer to their pre-industrial values as the amount of geoengineering is increased, for up to 85% of the amount that would return global mean temperature to its preindustrial value. Only beyond 85% is the temperature in at least one region over-compensated. Conversely, 11 of the 12 models show the amount of geoengineering determined by the Pareto criterion to be zero if only considering precipitation changes. In nine of the 22 Giorgi regions, at least one model shows that pre-cipitation changes get farther from pre-industrial levels with any amount of solar reduction. (Supplemental figure 7 shows the associated values of D, Supplemental figure 10 shows the avoided climate change due to geoengineering, and Supplemental figure 13 shows whether geoengineering reduces or increases D for each region and model.) There is no region for which every model agrees that any amount of solar geoengineering exacerbates precipitation changes due to a CO_2 increase.

We next follow the approach of previous studies (MacMartin *et al* 2013, Moreno-Cruz *et al* 2012, Ricke *et al* 2010, 2013), normalizing the temperature and pre-cipitation changes by the standard deviation of the pre-industrial control, as described by equations (1) and (2). This allows us to compare different weights (w) on temperature and precipitation with a single metric D (equation (3); for

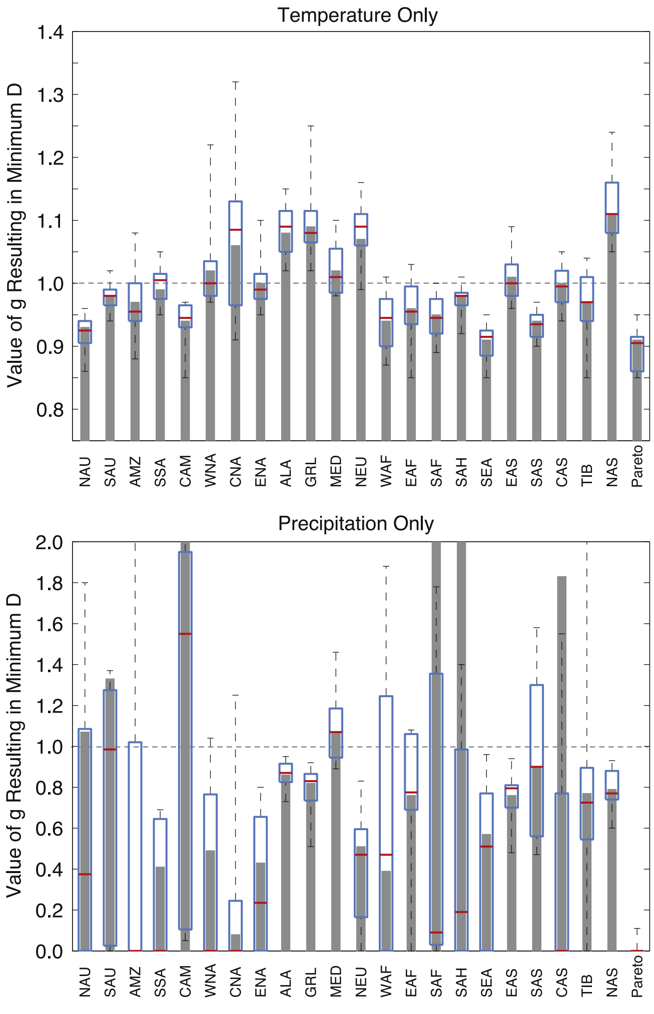

Figure 2. The amount of geoengineering (g) that minimizes regional changes (D, equations (4) and (5) in temperature (top) and precipitation (bottom) for each region (x-axis). Dashed grey line indicates g = 1, in which global mean temperature is returned to the preindustrial value. Red lines denote the median response of the 12 models, blue boxes denote 25th and 75th percentiles of model response, and black whiskers indicate the range of model spread. Grey bars show the response for the all-model ensemble mean. Note that ordinates have different scales.

example, small changes in normalized precipitation might be more important in some regions than small changes in normalized temperature. This has the advantage of simultaneously considering multiple climate fields in a single metric. Normalized temperature changes due to high CO_2 alone are an order of magnitude greater than normalized precipitation changes, and thus temperature changes will dominate D values for many relative weights (w) of temperature and precipitation.

Figure 3 shows the amount of geoengineering as determined by the Pareto criterion for different weights of temperature and precipitation (equation (7). This amount of geoengineering is zero only if nearly all of the weighting is on precipitation. For almost all other combinations of temperature and precipitation, the maximum amount of geoengineering before violating the Pareto criterion is greater than zero, meaning the combination of temperature and

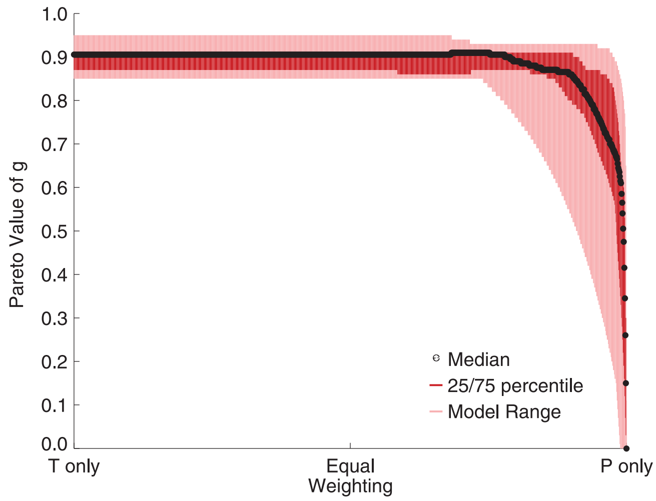

Figure 3. The maximum amount of geoengineering (g) as determined by the Pareto criterion (7) as a function of the relative weighting (w) between temperature and precipitation. Values shown represent the median, quartiles, and range of the 12 models included in this study.

precipitation (as given by the metric D; equation (3) everywhere is closer to the preindustrial climate for a moderate amount of geoengineering than for no geoengineering. Moreno-Cruz *et al* (2012) found that the maximum g under the Pareto criterion for $w = 0.5$ is $g = 0.78$, which is slightly lower than any model in our study (median g = 0.91 with range g = 0.86 – 0.96. It is unclear whether the difference between their results and ours is inherent to the model they used or is due to a difference in experimental design, such as the representation of solar geoengineering.

The qualitative features of the results presented here are not dependent upon using annual averages; summer or winter averages yield similar conclusions (Supplemental figures 3–6, 8, 9, 11, 12, 14 and 15).

4. Discussion and conclusions

Our multi-model results suggest that using moderate amounts of global-scale solar geoengineering that only partially restore global mean temperature to its preindustrial level could reduce the overall degree of anthropogenic temperature and precipitation changes. However, for some regions under some metrics (e.g., most of the weight assigned to precipitation), any amount of solar geoengineering can exacerbate climate changes that are due to CO_2 alone. As such, our simple example of using mean temperature and precipitation illustrates that solar geoengineering would involve trade-offs. MacMartin *et al* (2013) showed that non-uniform solar geoengineering could partially but not entirely alleviate these trade-offs for certain climate metrics, so our conclusions are likely to hold even for some non-uniform geoengineering implementations.

The nature of this study is highly idealized, both in terms of climate change (an abrupt quadrupling of the CO_2 concentration from its preindustrial value) and solar geoengineering (a reduction of insolation). Actual deployment of geoengineering, should society develop the will to do so, would undoubtedly be in a different form than the simulations depicted here would indicate. The results presented here are indicative of some of the issues in geoengineering as a whole, and the conclusions from the simulations are to some degree more broadly applicable to other representations of solar geoengineering (Supplemental section 1). However, such an idealized setup is necessarily limited in its applicability to different methods of geoengineering that could be realistically deployed.

The Pareto criterion is rooted in utility theory (Pearce 1992). When we use the Pareto criterion, we implicitly treat D as a dis-utility function, i.e., a metric of climate damage. A quadratic function for impacts of climate change (e.g., Nordhaus 2008) is widely used, although real damages are certainly not always quadratic, and assigning a single functional form to climate damages can be somewhat arbitrary (Weitzman 2010). The values reported in figures 1 and 2 do not depend upon the assumption that D is quadratic, but the curve in figure 3 does. Despite this dependence, our conclusions still hold that for most combinations of temperature and precipitation, global-scale solar geoengineering results in some amount of restoration of climate in all regions for all models in this study. The functional form of D does not change the conclusion that for all weighting on precipitation, applying the Pareto criterion results in the optimal level of geoengineering being no geoengineering at all.

There are many other effects that could be incorporated into assessments of regional disparities from solar geoengineering. These include other climate effects, such as changes in the occurrence of extreme events (Curry *et al* 2014), or an increase in crop productivity due to reductions in heat stress and fertilization effects of increased atmospheric CO_2, despite precipitation decreases (Jones *et al* 2011, Kravitz *et al* 2013a, Pongratz *et al* 2012). However, stratospheric sulfate aerosol injection may enhance ozone depletion (Tilmes *et al* 2013) and have other dynamical effects, which in turn could affect local temperature and precipitation patterns, that differ from the effects of partial sun-shade geoengineering (Ferraro *et al* 2014). We acknowledge that terrestrial plant health depends upon more than just precipitation and temperature changes; future assessments of hydrological changes due to geoengineering could incorporate evaporation, soil moisture, and runoff changes as well.

Moreover, climate impacts are more complicated than an aggregation of climate effects. There are also issues that are not addressed in this study, such as geopolitical strife over attempts to implement geoengineering and the effects of geoengineering on socioeconomic decisions about mitigation. There is no universally satisfactory, objective metric of climate change that incorporates all possible effects and impacts. Weighing these different regional effects and interests is one of the many challenges of geoengineering governance.

When comparing the results of global-scale solar geoengineering with the preindustrial climate, one can arrive at very different conclusions about the effectiveness of geoengineering than if one compared those results to a climate with high CO_2 and no geoengineering. Many of the arguments in this paper have been phrased in terms of restoring the climate to a preindustrial state, although many stakeholders (e.g., Arctic shipping or high latitude agricultural interests) have already adapted to some amount of climate change and may thus prefer a different, warmer climate than the preindustrial one. While the analysis presented here makes use of idealized scenarios for which the preindustrial climate is an appropriate baseline, the same kinds of effects (albeit of different magnitudes) would be observed for more realistic scenarios and baselines.

Related to our study is the often stated claim that geoengineering will create winners and losers (Caldeira 2009, Hegerl and Solomon 2009, Irvine *et al* 2010, Moreno-Cruz *et al* 2012, Shepherd *et al* 2009, Scott 2012). One interpretation of this claim is that some regions of the world would experience a greater degree of climate change, and hence climate impacts, if geoengineering were deployed than if it were not. For the time-mean of the two variables analyzed here, if only moderate amounts of global-scale solar geoengineering are used, there is no model-based evidence to support this concern, provided that both temperature and precipitation changes are relevant in every region and sufficiently representative of the relationship between climate changes and climate impacts.

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References

Allen M R and Ingram W J 2002 Constraints on future changes in climate and the hydrological cycle *Nature* **419** 223–32

Ammann C M, Washington W M, Meehl G A, Buja L and Teng H 2010 Climate engineering through artificial enhancement of natural forcings: magnitudes and implied consequences *J. Geophys. Res.* **115** D22109

Andrews T, Forster P M and Gregory J M 2009 A surface energy perspective on climate change *J. Climate* **22** 2257–570

Ban-Weiss G A and Caldeira K 2010 Geoengineering as an optimization problem *Environ. Res. Lett.* **5** 034009

Boucher O *et al* 2012 Reversibility in an earth system model in response to CO_2 concentration changes *Environ. Res. Lett.* **7** 024013

Caldeira K 2009 Geoengineering to shade earth *State of the World 2009: Into a Warming World* (Washington, DC: Worldwatch Institute) pp 96–98

Crutzen P J 2006 Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Climatic Change* **77** 211–20

Curry C L *et al* 2014 A multi-model examination of climate extremes in an idealized geoengineering experiment *J. Geophys. Res.* **119** 3900–23

Ferraro A J, Highwood E J and Charlton-Perez A J 2014 Weakened tropical circulation and reduced precipitation in response to geoengineering *Environ. Res. Lett.* **9** 014001

Fyfe J C, Cole J N S, Arora V and Scinocca J F 2013 Biogeochemical carbon coupling influences global precipitation in geoengineering experiments *Environ. Res. Lett.* **40** 651–5

Giorgi F and Francisco R 2000 Evaluating uncertainties in the prediction of regional climate change *Geophys. Res. Lett.* **27** 1295–8

Govindasamy B and Caldeira K 2000 Geoengineering Earth's radiation balance to mitigate CO_2-induced climate change *Geophys. Res. Lett* **27** 2141–4

Hegerl G C and Solomon S 2009 Risks of climate engineering *Science* **325** 955–6

Irvine P J, Ridgwell A and Lunt D J 2010 Assessing the regional disparities in geoengineering impacts *Geophys. Res. Lett.* **37** L18702

Jones A, Haywood J and Boucher O 2011 A comparison of the climate impacts of geoengineering by stratospheric SO_2 injection and by brightening of marine stratocumulus cloud *Atm. Sci. Lett.* **12** 176–83

Keith D W and Dowlatabadi H 1992 A serious look at geoengineering *Eos Trans. AGU* **73** 292–3

Kravitz B *et al* 2011 The geoengineering model intercomparison project (GeoMIP) *Atmos. Sci. Lett.* **12** 162–7

Kravitz B *et al* 2013a Climate model response from the geoengineering model intercomparison project (GeoMIP) *J. Geophys. Res.* **118** 8302–32

Kravitz B *et al* 2013b An energetic perspective on hydrological cycle changes in the geoengineering model intercomparison project (GeoMIP) *J. Geophys. Res.* **118** 13087–102

Latham J *et al* 2012 Marine cloud brightening *Phil. Trans. Roy. Soc.* A **370** 4217–62

MacMartin D G, Keith D W, Kravitz B and Caldeira K 2013 Managing trade-offs in geoengineering through optimal choice of non-uniform radiative forcing *Nature Climate Change* **3** 365–8

Modak A and Bala G 2013 Sensitivity of simulated climate to latitudinal distribution of solar insolation reduction in SRM geoengineering methods *Atmos. Chem. Phys. Discuss.* **13** 25387–415

Moreno-Cruz J B, Ricke K L and Keith D W 2012 A simple model to account for regional inequalities in the effectiveness of solar radiation management *Climatic Change* **110** 649–68

Niemeier U, Schmidt H, Alterskjær K and Kristjànsson J E 2013 Solar irradiance reduction via climate engineering–climatic impact of different techniques *J. Geophys. Res.* **118** 11905–17

Nordhaus W 2008 *A Question of Balance: Weighing the Options on Global Warming Policies* (New Haven, CT: Yale Univ. Press)

O'Gorman P A and Schneider T 2008 The hydrological cycle over a wide range of climates simulated with an idealized GCM *J. Climate* **21** 3815–32

Pearce D W 1992 The MIT dictionary of modern economics 4th ed (Cambridge, MA: MIT Press)

Pongratz J, Lobell D B, Cao L and Caldeira K 2012 Crop yields in a geoengineered climate *Nature Climate Change* **2** 101–5

Rasch P J, Latham J and Chen C-C 2009 Geoengineering by cloud seeding: influence on sea ice and climate system *Environ. Res. Lett.* **4** 045112

Ricke K L, Morgan M G and Allen M R 2010 Regional climate response to solar-radiation management *Nature Geoscience* **3** 537–41

Ricke K L, Moreno-Cruz J B and Caldeira K 2013 Strategic incentives for climate geoengineering coalitions to exclude broad participation *Environ. Res. Lett.* **8** 014021

Robock A 2008 20 reasons why geoengineering may be a bad idea *Bull. Atom. Sci.* **64** 14–18 59

Scott D 2012 Geoengineering and environmental ethics *Nature Education Knowledge* **3** 10

Shepherd J G S *et al* 2009 *Geoengineering the Climate: Science, Governance and Uncertainty* RS Policy document 10/09 (London, UK: The Royal Society)

Tilmes S *et al* 2013 The hydrological impact of geoengineering in the geoengineering model intercomparison project (GeoMIP) *J. Geophys. Res.* **118** 11036–58

Weitzman M 2010 What is the damages function for global warming-and what difference might it make? *Clim. Change Econom.* **1** 57–69