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LETTER

Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards

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Abstract

Stratospheric aerosol geoengineering is a proposal to artificially thicken the layer of reflective aerosols in the stratosphere and it is hoped that this may offer a means of reducing average climate changes. However, previous work has shown that it could not perfectly offset the effects of climate change and there is a concern that it may worsen climate impacts in some regions. One approach to evaluating this concern is to test whether the absolute magnitude of climate change at each location is significantly increased (exacerbated) or decreased (moderated) relative to the period just preceding deployment. In prior work it was found that halving warming with an idealized solar constant reduction would substantially reduce climate change overall, exacerbating change in a small fraction of places. Here, we test if this result holds for a more realistic representation of stratospheric aerosol geoengineering using the data from the geoengineering large ensemble (GLENS). Using a linearized scaling of GLENS we find that halving warming with stratospheric aerosols moderates important climate hazards in almost all regions. Only 1.3% of land area sees exacerbation of change in water availability, and regions that are exacerbated see wetting not drying contradicting the common assumption that solar geoengineering leads to drying in general. These results suggest that halving warming with stratospheric aerosol geoengineering could potentially reduce key climate hazards substantially while avoiding some problems associated with fully offsetting warming.

1. Introduction

Stratospheric aerosol geoengineering, a proposal to add reflective aerosols to the stratosphere, might reduce the risks of climate change if used in combination with emissions cuts, carbon removal, and adaptation. Engineering assessments consistently find that lifting the required mass of material to the lower tropical stratosphere could be accomplished with commercially available aircraft technologies at a cost of a few billion dollars per million tons. And, the distribution of at least some aerosol precursors (such as SO_2) appears technically feasible (McClellan *et al* 2012, Smith and Wagner 2018, Bingaman *et al* 2020). Setting aside governance, which is likely the greatest challenge, the most salient technical question is whether these methods could reduce the overall magnitude of climate change without worsening impacts in some regions. That is, would stratospheric aerosol geoengineering create strong climate inequalities producing winners and losers?

As stated, the question is ill-posed. The effects of stratospheric aerosol geoengineering necessarily depend on how it would be deployed, particularly on choices about the spatial distribution and magnitude of the radiative forcing (Keith 2013, Kravitz *et al* 2016). Stratospheric aerosol geoengineering cannot perfectly offset the effects of climate change. Deploying it with a radiative forcing large enough to offset all temperature changes is simulated to, for example, weaken the global hydrological cycle, more-than-offsetting the strengthening expected under climate change

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(Govindasamy and Caldeira 2000, Tilmes *et al* 2013). However, modeling studies have found that if deployed to offset all warming it would nevertheless reduce many aspects of change to mean climate and climate extremes relative to a case without solar geoengineering (Boucher *et al* 2013, Kravitz *et al* 2013, Curry *et al* 2014, Jones *et al* 2018). In addition, there are side-effects of stratospheric aerosol geoengineering such as ozone loss and air pollution that are expected to grow as the scale of deployment grows (Crutzen 2006, Eastham *et al* 2018). For these reasons, several authors have suggested that deploying stratospheric aerosol geoengineering to limit warming rather than halt it would reduce climate risks without introducing some of the problems seen for larger scale deployments (Jones *et al* 2018, Keith and MacMartin 2015).

Irvine *et al* (2019), from here on Irvine19, evaluated the climate response in an idealized case where half the warming from a doubling of CO_2 was offset by a 1% reduction in solar constant. They applied a novel statistical test, evaluating whether the absolute magnitude of change (from a reference period) was statistically significantly increased (exacerbated) or decreased (moderated) by application of solar geoengineering. This test can be applied locally either in specific regions or grid-point-by-grid-point to examine whether solar geoengineering exacerbated or moderated local climate change. They compared results from the high-resolution GFDL HiFLOR model (Murakami *et al* 2015) with results from the Geoengineering Model Intercomparison Project's G1 experiment (Kravitz *et al* 2011). They found that halving warming roughly halved the magnitude of change in the variables they assessed, while only exacerbating change in specific variables over only a tiny fraction of the land area. They also found that the greater the magnitude of climate change in a region, the more likely solar geoengineering was to offset that change, and that those locations which saw the effects of climate change exacerbated were limited to those regions which saw the least change to begin with. As Irvine19 found most climate changes were moderated in most regions, tropical cyclone intensity was reduced, and other studies have demonstrated that sea-level rise should be reduced (Moore *et al* 2015, Irvine *et al* 2018), it is reasonable to hypothesize that such moderate deployments of solar geoengineering might reduce aggregate climate risks to society in all regions, rather than giving rise to regional winners and losers (Keith and Irvine 2016).

If the results and reasoning described above are robust, and a moderate deployment of solar geoengineering could substantially reduce climate risks overall without producing significant harms in some regions, this would have substantial political implications. One important limitation of Irvine19, however, was that it used solar constant reduction as an idealized proxy for stratospheric aerosol geoengineering. Unlike for a reduction in solar constant, stratospheric aerosols absorb radiation as well as scatter it, producing a warming of the lower stratosphere that has important impacts on regional hydroclimate (Simpson *et al* 2019). Another limitation was that in their warming scenario only CO_2 concentrations change, missing out on changes in tropospheric aerosol emissions that complicate the climate forcing pattern. These differences could mean that the findings of Irvine19 do not hold outside of their idealized case.

Here, we apply the analysis approaches developed in Irvine19 to evaluate whether their findings hold under a more realistic case of stratospheric aerosol geoengineering deployment using results from the stratospheric aerosol geoengineering large ensemble (GLENS, Tilmes *et al* 2018). The GLENS simulations represent a deployment of SO_2 at 15 and 30 degrees North and South of the equator that is tuned using explicit feedback to maintain 3 metrics of surface air temperature (global-mean, inter-hemispheric and pole-to-equator, see section 2.1) at 2020 levels as greenhouse gas concentrations rise along a business-as-usual trajectory (Kravitz *et al* 2018). The GLENS simulations are among the most comprehensive representations of stratospheric aerosol geoengineering to date, and thus provide an excellent test for whether the results of Irvine19 are robust.

2. Materials and methods

2.1. The GLENS stratospheric aerosol geoengineering experiment

The GLENS simulations used the Community Earth System Model 1 (CESM1) with the Whole Atmosphere Chemistry Climate Model (WACCM) and the Community Land Model 4.5 (CLM4.5, Tilmes *et al* 2018). WACCM has a horizontal resolution of 0.9° in latitude and 1.25° in longitude and 70 vertical layers that extend up to 140 km. WACCM has interactive stratospheric chemistry and dynamics (it produces an internally generated quasi-biennial oscillation), it includes a modal aerosol model (MAM3), and it resolves the coupling between tropospheric aerosols, clouds and radiation (Mills *et al* 2017). In the configuration analyzed here, the land, ocean and sea-ice components are fully coupled, while GHG concentrations are specified and evolve over time.

The GLENS simulations are based on the RCP 8.5 business-as-usual scenario (Meinshausen *et al* 2011) with SO_2 injections at four locations, 30°N, 15°N, 15°S, and 30°S, all at 180° E. All injections occur in a single gridcell at an altitude 5 km above the climatological tropopause at the latitude of injection. The rate of injection is dynamically adjusted throughout the run to maintain 3 metrics of surface air temperature at 2020 levels: global-mean temperature, inter-hemispheric temperature difference, and pole-to-equator gradient. For a full description of the scenario and

feedback approach employed, and for a summary of the climate response see Kravitz *et al* (2018).

In this study we analyze climate differences between the following cases: RCP8.5 averaged over the period 2010–2029 (referred to as Baseline from hereon), RCP8.5 averaged over the period 2075–2094 (RCP8.5), GLENS averaged over the period 2075–2094 (Full-GLENS), and a synthetic scenario, Half-GLENS, produced by linearly scaling between the results of the RCP8.5 and Full-GLENS cases (see section 2.2). For all cases we evaluate the ensemble-mean response across the same 4 ensemble members (001, 002, 003, 021). To explore the role of natural variability, we also consider a second baseline case (Baseline-2) using 4 different ensemble members (004, 005, 006, 007).

2.2. Analysis approach

We follow the approach described in Irvine19 and define a region as seeing the effects of RCP8.5 moderated (exacerbated) when the absolute magnitude of climate change has been significantly reduced (increased) in the solar geoengineering scenario. We follow the same statistical approach as in Irvine19, i.e. applying T-Tests to determine whether the absolute magnitude of change is significantly different between RCP8.5 and the solar geoengineering case and whether the solar geoengineering case is significantly different from the baseline case. The full details of the statistical approach can be found in the methods and supplementary materials of Irvine19. As in Irvine19 we apply a 90% two-sided T-Test.

To produce the synthetic Half-GLENS scenario, we linearly scale the results of Full-GLENS to estimate the climate response of a scenario which offset only half the temperature change from the RCP8.5 scenario. As in Irvine19, the scaled results are calculated as follows:

$$X_f = X_{\mathrm{RCP8.5}} + f \cdot (X_{\mathrm{FullGLENS}} - X_{\mathrm{RCP8.5}}),$$

where X is the variable to be scaled and f is the fraction of the RCP8.5 temperature change to offset, i.e. 0.5 for Half-GLENS. The scaling is applied to both means and standard deviations for the purposes of calculating statistical significance. Previous work has demonstrated that the climate response to solar constant forcing can be well-approximated by a linear relationship (Irvine *et al* 2010, Moreno-Cruz *et al* 2012, MacMartin and Kravitz 2016).

In this study we focus on the same variables as Irvine19, i.e. annual-mean surface air temperature (T), maximum annual surface air temperature (Tmax), annual-mean precipitation minus evaporation ($P - E$, or water availability), with the exception that we use maximum annual precipitation rate (Pmax) instead of the maximum precipitation recorded over 5 consecutive days. These four variables represent a more policy-relevant set of variables than T and precipitation (P) which have been used in most previous studies of solar geoengineering's performance as they represent a more complete sampling of the key climate hazards identified by the Intergovernmental Panel on Climate Change (Field *et al* 2014). Furthermore, it is worth stressing that precipitation alone is a poor proxy for water availability changes in solar geoengineering studies as reductions in evaporation frequently more-than-offset local reductions in precipitation in solar geoengineering simulations (Kravitz *et al* 2013). However, we have included results for precipitation change in the supplementary figures.

We focus on the land area without Greenland and Antarctica in most analyses in this paper. Bounding boxes for Greenland and Antarctica were defined and the fraction of land in each was set to zero. The Antarctic definition included all land below 60° S and the Greenland definition was defined as a polygon with corners at the following coordinates: (−73.5° E, 78.8°N), (−73.5° E, 74.5°N), (−44.5° E, 57.5°N), (−10° E, 73.5°N), (−10° E, 84.5°N), (−37.5° E, 84.5°N), (−60.5° E, 82.5°N). We also include a population-weighting for some figures that was generated using the GPWv4 gridded population dataset to create a count of population in each model gridcell (GPWv4 2016). For each gridcell we summed all gridded GPWv4 population counts whose centroid was in the gridcell boundaries.

We also report results averaged over the Intergovernmental Panel on Climate Change's Special Report on Climate Extremes (SREX) regions (Seneviratne *et al* 2012). For each of our variables the land-area mean was taken and annual-average timeseries produced. From these timeseries, the mean and standard deviation were calculated over the averaging period for each case.

3. Results

Figure 1 shows that both Full-GLENS and Half-GLENS substantially reduce the overall magnitude and variance of climate anomalies over the ice-free land area as compared to RCP8.5 (similar results hold when weighted by population, see figure S1 available online at stacks.iop.org/ERL/15/044011/mmedia). Full-GLENS maintains global-mean temperature at baseline levels, resulting in a modest overcooling in some locations and a residual warming in others for both T and Tmax. Even though global mean temperatures are near the baseline in Full-GLENS, a small area, limited to the High Arctic, sees an exceptional >5 °C of warming in Tmax, much higher than anywhere else (not shown). The Half-GLENS T and Tmax response sits mid-way between RCP8.5 and Full-GLENS as expected from simple scaling. As for T and Tmax, Full-GLENS more-than-offsets the increase in Pmax in many places and leaves a small residual increase in others, and again the Half-GLENS response lies between the other scenarios.

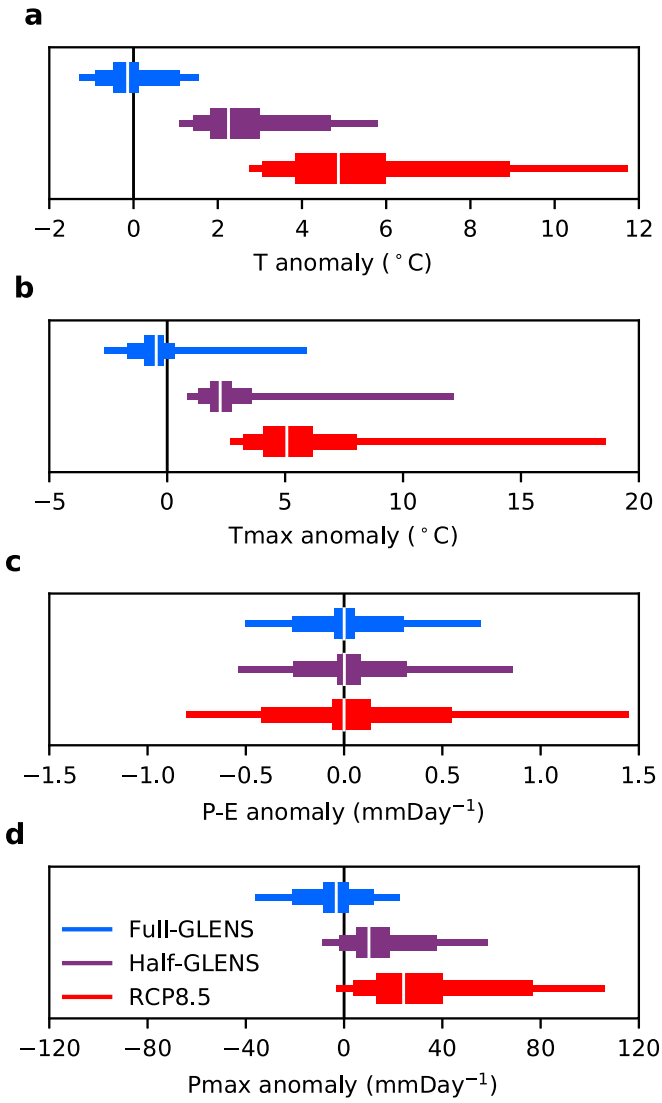

Figure 1. The distribution of climate anomalies relative to the 2010–2019 baseline. Annual-mean surface air temperature (T, (a)), maximum annual surface air temperature (Tmax, (b)), annual-mean precipitation minus evaporation ($P - E$, (c)) and maximum annual precipitation rate (Pmax, (d)) anomalies are shown for RCP8.5 (red), Full-GLENS (blue), and Half-GLENS (purple). The 1%–99% range of the distribution is shown by thin lines, the 5%–95% range by thicker lines, the interquartile range by the box and the median by the white vertical line. Results are weighted by land area excluding Greenland and Antarctica.

For T, Tmax and Pmax the distribution of climate anomalies narrows as the level of cooling increases from RCP8.5 to Half-GLENS, and again from Half-GLENS to Full-GLENS (figures 1(a), (b), (d)). For $P - E$, the distribution of climate anomalies is similar for Half-GLENS and Full-GLENS, both of which are narrower than RCP8.5, suggesting limited improvement beyond halving warming (figure 1(c)). However, as the Half-GLENS scenario was produced by linearly interpolating between the results of the RCP8.5 and Full-GLENS simulations, there is just as much change in local $P - E$ between Full-GLENS and Half-GLENS. This indicates that the aggregate distribution of anomalies plotted in figure 1 hides important regional differences in the response.

A reduction in the magnitude of a climate anomaly such as Pmax does not directly answer the question we posed in the opening paragraph of this paper: would stratospheric aerosol geoengineering create strong climate inequalities producing winners and losers?

We address inequality by evaluating whether local climate change is moderated or exacerbated in our stratospheric aerosol geoengineering scenarios. Following Irvine19, We test whether the absolute magnitude of change is significantly greater or lesser than under the RCP8.5 case (see section 2.2). Table 1 shows that both Half-GLENS and Full-GLENS moderate a similar fraction of local changes, i.e. T and Tmax are moderated in all locations, $P - E$ is moderated across roughly one third of the land area, and Pmax is moderated across roughly two thirds of the land area. However, Half-GLENS exacerbates change in a much smaller fraction of the land area than Full-GLENS does, 1.3% as compared to 9.1% for $P - E$.

To evaluate the effects of interannual variability on the results, we report results for a case without climate

Table 1. The fraction of the ice-free land surface that sees the effects of RCP8.5 significantly exacerbated or moderated by half-SG relative to the baseline. The percentage of the land area (excluding Greenland and Antarctica) experiencing a statistically significantly greater (exacerbated) or lesser (moderated) absolute magnitude of anomaly for the geoengineering cases and for Baseline-2 (alternative runs of the baseline case) compared to RCP8.5 (see section 2.2). The values do not sum to 100% as those places where there was not a significant change in the absolute magnitude of the anomaly are not shown.

	Fraction exacerbated		
	Full-GLENS	Half-GLENS	Baseline-2
T	0.0%	0.0%	0.0%
Tmax	0.0%	0.0%	0.0%
$P-E$	9.1%	1.3%	0.7%
Pmax	1.3%	0.0%	0.2%
	Fraction moderated		
	Full-GLENS	Half-GLENS	Baseline-2
T	100.0%	100.0%	100.0%
Tmax	99.9%	100.0%	100.0%
$P-E$	36.3%	30.2%	46.4%
Pmax	68.2%	59.4%	75.1%

change. This Baseline-2 case is simply another set of four ensemble members for the baseline period. We find that in this no climate change case, T and Tmax are perfectly offset but a small fraction of places see a statistically significant exacerbation of $P-E$ and Pmax, 0.7% and 0.2% respectively. This is due to interannual variability leading to apparently significant trends. We also find that $P-E$ and Pmax are moderated in only 46.4% and 75.1% of places, respectively. As Baseline-2 represents a perfect reversal of RCP8.5 climate trends, we can reinterpret this fraction moderated as an upper limit on performance. Therefore, in terms of moderation, Half-GLENS has achieved 65% of the upper limit of performance in this setup for $P-E$ and 79% for Pmax. Similarly, the 0.7% exacerbated for $P-E$ in Baseline-2 can be seen as an effective lower-bound on performance, and so the value of 1.3% found for Half-GLENS is only 0.6% above what would be expected due to interannual variability alone.

The results reported in table 1 are broadly similar to those of Irvine19, which showed $P-E$ exacerbated in 0.4% of places in their simulated Half-SG scenario with the GFDL HiFLOR model and estimated that this would rise to over 5% in their linearly extrapolated Full-SG scenario. For the 12 GeoMIP models analyzed in Irvine19, the median fraction exacerbated in the Half-SG case for $P-E$ was 1.9%, very similar to the value reported here. Differences between the values reported in this paper and Irvine19 depend not only on the differences between the response to an idealized solar constant reduction and a realistic stratospheric aerosol geoengineering deployment but also on the statistical power of the experiments. The Half-SG experiment of Irvine19 is based on a doubling of CO_2 concentrations and produced a smaller signal than the experiment studied here, which may explain the fact that the fraction moderated for $P-E$ is higher in this paper than in Irvine19. It is also worth noting that we assessed a different measure of extreme precipitation, maximum precipitation calculated at the model time-step as compared to 5 d maximum precipitation in Irvine19, so these results are not directly comparable.

If solar geoengineering exacerbates the climate trends in RCP8.5 in locations where the RCP8.5 trends are relatively large, then we may expect greater harms than in locations where they are relatively small. Figure 2 plots the Full-GLENS and RCP8.5 anomalies against one another for $P-E$ and Pmax. This scatter plot shows points where Full-GLENS moderates or exacerbates the effects of RCP8.5 as a function of the RCP8.5 anomaly. Figure 3 shows the same but for the Half-GLENS scenario. Full-GLENS generally over-compensates for Pmax, in the sense that many points that saw an increase in Pmax under RCP8.5 see instead a decrease in Full-GLENS, both relative to the Baseline. For some of these points the reduction in Pmax under Full-GLENS is larger than the increase under RCP8.5 (figure 2(b), such exacerbated points fall within the pink areas). However, only a small fraction of these points exacerbated under Full-GLENS are statistically significant (table 1), and those almost exclusively see a small positive trend becoming a larger negative trend (figure 2(b)). In Half-GLENS, the overshoot in Pmax seen in Full-GLENS is avoided and nowhere sees a significant exacerbation (figures 3(b), (d)).

For $P-E$ in Full-GLENS, the picture is more complicated. While the bulk of points see a reduced magnitude of both positive and negative changes in $P-E$ in Full-GLENS compared to RCP8.5, there is a much greater spread in response than for Pmax and many places see significantly greater change in $P-E$, with some getting wetter and others drier than under RCP8.5 (figure 2(a)). However, it should be noted that in the 2D anomaly histograms, the periphery of the distribution is made up of individual gridcells (darker colors) and that orders of magnitude more points are concentrated around the origin (lighter colors). Figure 2(c) shows that just as for Pmax, $P-E$ is moderated in most locations and that places which are exacerbated tend to have the smaller anomalies. Note, however, that this effect is not as pronounced as in Irvine *et al* (2019). In the Half-GLENS case, the $P-E$ response is clearer. The effects of RCP8.5 on $P-E$ are partially offset, with both positive and negative anomalies reduced in most places. Only a few places see $P-E$ exacerbated and they are the places with the smallest magnitude of absolute change under RCP8.5 or Half-GLENS (figures 3(a), (c)). This type of response suggest that there have been modest shifts in the patterns of precipitation and evaporation, likely due to shifts in circulation, and that some locations which were at the boundary between a wetting and drying trend under RCP8.5 are now on one side or the other. However, natural variability will lead to some

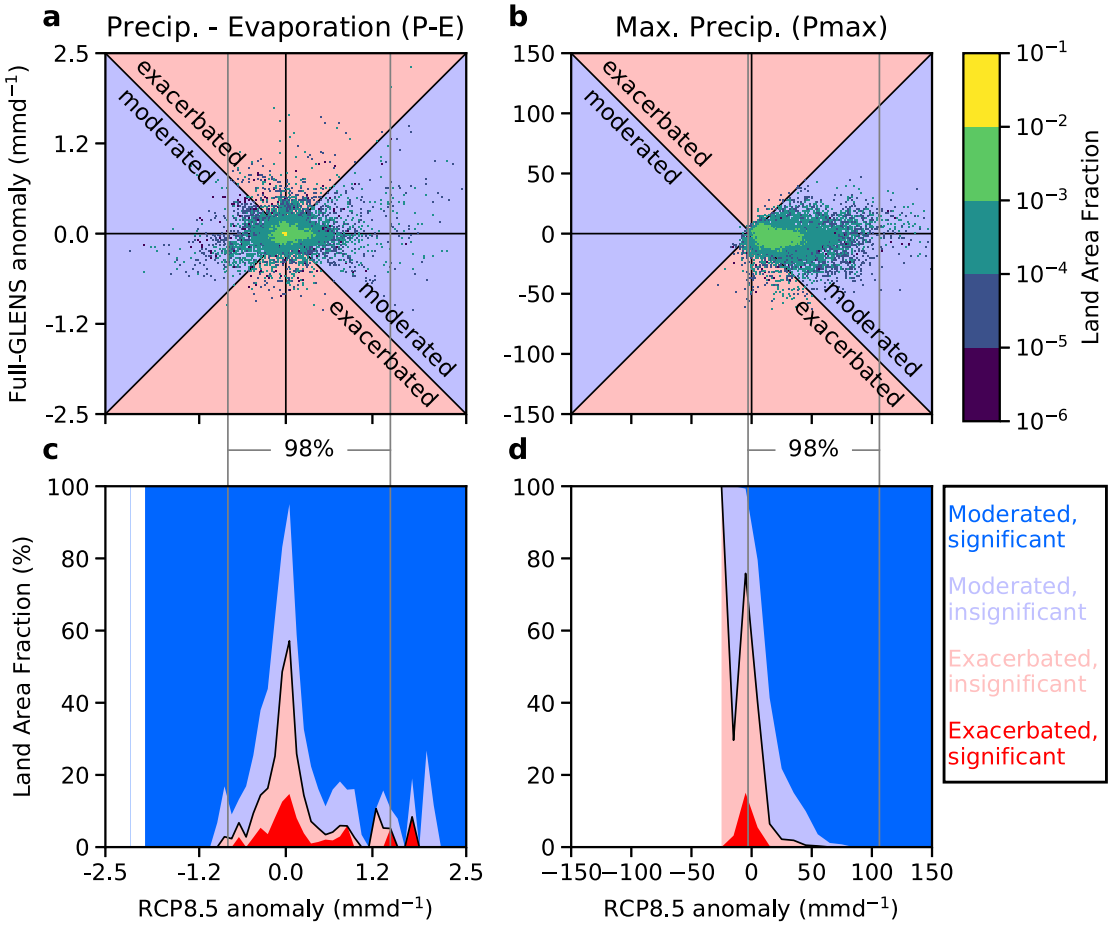

Figure 2. The joint distribution of RCP8.5 and Full-GLENS anomalies versus the baseline (a), (b) with results for the fraction of the ice-free land surface where Full-GLENS exacerbates or moderates the climate trend (c), (d). Two-dimensional anomaly histograms show the distribution of the RCP8.5 and Full-GLENS anomalies versus the baseline for annual-mean precipitation − evaporation ($P - E$, (a)) and maximum annual precipitation rate (Pmax, (b)). The fraction of the land area, excluding Greenland and Antarctica, with anomalies that fall into each bin are indicated by the color scale, and empty bins are not plotted. To generate the bins for the 2D anomaly histograms, the x and y axes are divided into 200 intervals. Note that all points, including those that do not see significant change, are plotted. The bottom panels show the fraction of the area in which the impacts of RCP8.5 are exacerbated (red) or moderated (blue) by Full-GLENS as a function of the RCP8.5 anomaly versus the baseline for precipitation − evaporation ($P - E$, (c)) and maximum annual precipitation rate (Pmax, (d)). These fractions are calculated over an interval of 0.1 mm d^{-1} for $P - E$ and 10 mm d^{-1} for Pmax. Bold colors indicate results which passed a 90% T-Test (see section 2.2), and results are only plotted where there are data in that interval. Vertical gray lines show the 1%–99% range of RCP8.5 anomalies.

such shifts and may be responsible for around half of this exacerbation (see table 1 and the discussion of the Baseline-2 results). Supplementary figure S2 shows the Full-GLENS results for precipitation which shows similar behavior to $P - E$. Supplementary figure S3 shows the Full-GLENS results for T and Tmax, which are significantly moderated in all locations.

Suppose some policy analysis traded off risks of increasing solar geoengineering, including exacerbation of climate change, against the benefits of reduced climate changes. Offsetting all the radiative forcing might be too much in that it results in a significant fraction of regions seeing exacerbation of some variables. We examined a case where solar geoengineering is used to offset half of the radiative forcing from greenhouse gases (Half-GLENS) because halving the forcing is a simple assumption that has been used in some prior analysis (Keith and MacMartin 2015). There is no reason to expect that halving would be the optimum.

To explore these trade-offs we examine the climate response across a range of metrics as a function of the amount of solar geoengineering using linear interpolation (see section 2.2). Panel (a) of figure 4 shows the well understood result that a scenario which offsets all warming overcompensates precipitation, turning a large increase into a decrease of roughly half the magnitude (Schmidt *et al* 2012, Tilmes *et al* 2013). Whereas if radiative forcing is chosen to exactly offset the change in global mean precipitation then, in this linearized model, only 72% of the warming is offset.

Panel (b) shows the root mean squared (RMS) anomalies computed over model grid points and normalized by the RMS anomaly of RCP 8.5. This normalized RMS measure is motivated by the fact that climate impacts analysis often assume that impacts are

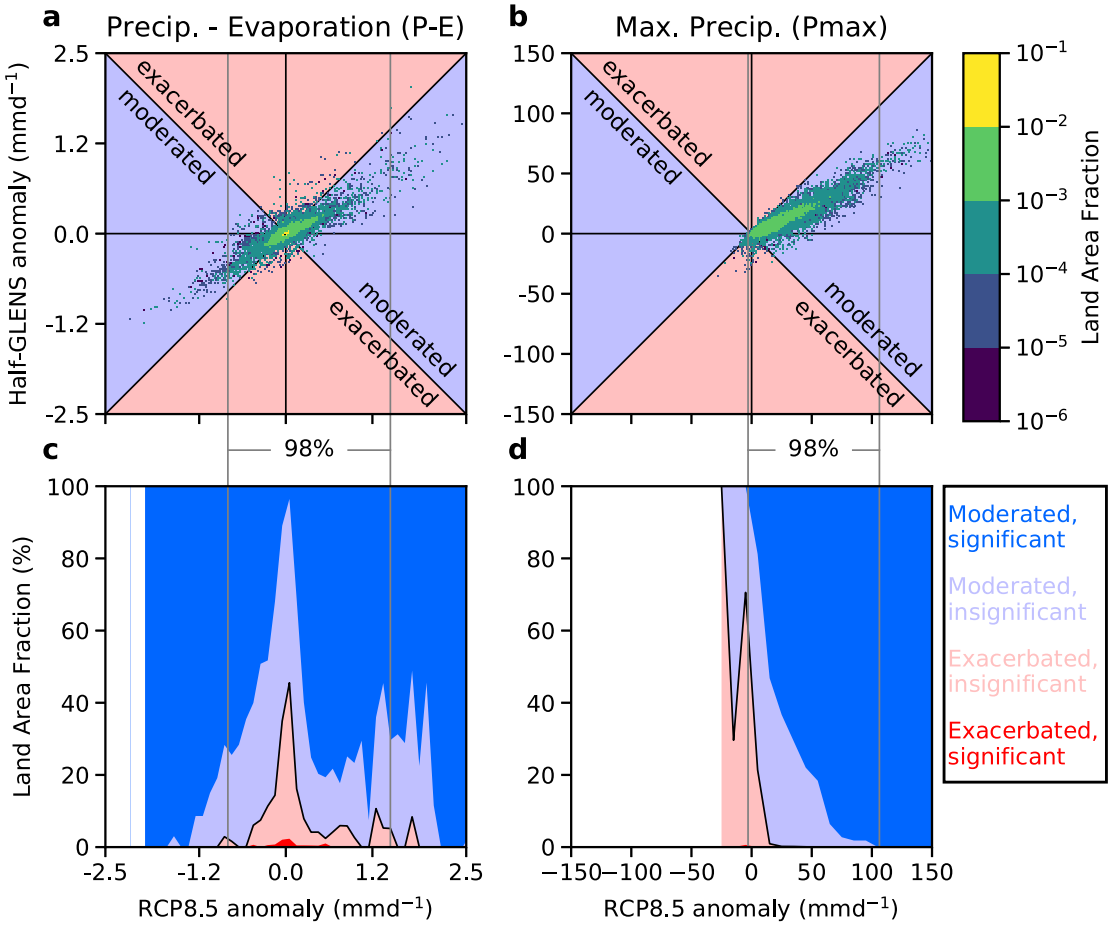

Figure 3. As figure 2 but for the Half-GLENS case.

proportional to the average magnitude of the local deviation from pre-industrial. For all variables, the normalized RMS anomaly initially declines linearly with an increase in solar geoengineering. At the point where warming is halved, RMS is roughly halved in all variables except for $P-E$ where it is reduced by ~40%. This stands in contrast to the results of Irvine19 where RMS in all variables is roughly halved (see their supplementary figure 5). Another difference is that here, RMS for both hydrological variables is minimized at 87% and for Irvine19 it is somewhat earlier at ~75%. One possible driver of this difference is that global mean precipitation in Irvine19 is restored at ~60% rather than 72% as in this study.

Finally, figures 4 (c) and (d) show the tradeoff with increasing solar geoengineering between the fraction of the ice-free land surface in which a variable is moderated or exacerbated. As in Irvine19 the fraction moderated saturates after a little greater than half of the warming is offset (c), and the fraction exacerbated grows with the level of cooling. The point at which an appreciable fraction of the land area sees $P-E$ exacerbated occurs earlier in this study, at around 30% cooling, than in Irvine19, where it occurs a little before 50%. Figure S4 reproduces figure 4 but with precipitation included in all panels, showing roughly similar behavior to $P-E$ except a substantially greater fraction is moderated.

Figure 5 shows the regional-mean hydrological response over the SREX regions (see section 2.2) for RCP8.5, Full-GLENS and Half-GLENS. Pmax is substantially increased everywhere in RCP8.5 and Full-GLENS generally moderates this change, leaving small residual positive or negative trends in all regions, except for South Africa which is moderated but sees a substantial absolute reduction in *P*max, i.e. a substantial overshoot (panel (a)). For $P-E$ (b) RCP8.5 produces substantial increases in some regions and substantial decreases in others. Full-GLENS moderates these positive and negative $P-E$ trends in 16 of the 26 regions, though in 4 of these regions there is a significant overshoot and the sign of the trend is flipped (note, if the sign of change is flipped but the result is not significantly different from the baseline using a 90% T-Test we have not counted this as an overshoot). For $P-E$, Full-GLENS exacerbates a significant trend seen in RCP8.5 and keeps the sign unchanged in only 1region, and turns a small or insignificant trend of one sign into a much larger trend of another sign in 4 regions. For $P-E$, Full-GLENS leads to a significant overshoot in 7 regions, one of which, Southern Australia, sees greater absolute change as a result. Half-GLENS prevents overshoot in all these cases except for Southern Australia which still sees a change of sign but no statistically significant increase in the magnitude of

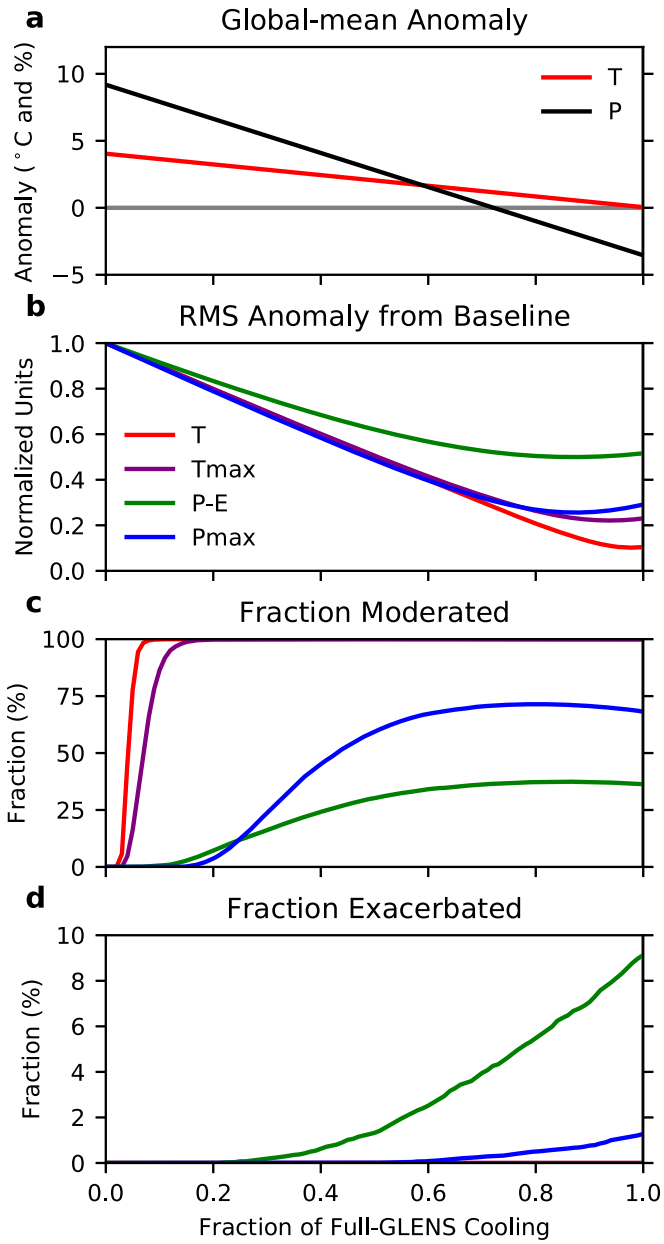

Figure 4. Performance across a range of metrics as a function of level of cooling. Results for a range of fractions of the Full-GLENS cooling are shown with results interpolated as they were to generate Half-GLENS (see Methods). The panels show global-mean surface air temperature (*T*) and precipitation (*P*) (a), the root mean square (RMS) anomaly with all variables normalized to 1 at 0 (b); fraction moderated (c) and fraction exacerbated (d). Points are exacerbated when the absolute magnitude of the solar geoengineering anomaly is statistically significantly greater (90% T-Test) than the RCP8.5 anomaly, and vice versa for moderated (see section 2.2).

change. Broadly similar results are found for precipitation, though the regions affected in the above-mentioned ways differ (figure S5).

Following Irvine19 figure 3, figure 6 provides a summary of which regions see the effects of RCP8.5 moderated and exacerbated by the Half-GLENS scenario. *T*, *T*max and *P*max are significantly moderated in all regions, whereas $P - E$ is significantly moderated in 15 regions and significantly exacerbated in 4, out of a total of 26. In Irvine19 for the GFDL HiFLOR model, no region sees a significant exacerbation of any variable, all regions are significantly moderated for *T* and *T*max, 14 regions are significantly moderated for 5-day maximum precipitation (a different extreme precipitation index from the one used here), and 12 regions are for $P - E$. Alongside differences in the climate response, the weaker signal for GFDL HiFLOR in Irvine19 and the use of a different extreme precipitation index, may explain the differences in the results.

As solar geoengineering weakens the global-mean hydrological cycle and suppresses precipitation, there has been concern about the risk of drought and aridity under solar geoengineering (Robock *et al* 2008). Here, we find that for all those regions where Full-GLENS exacerbates $P - E$ change, it leads to those regions becoming wetter, not drier, than either RCP8.5 or the baseline. Irvine19 noted the same response in their study, with several of the GeoMIP models reporting

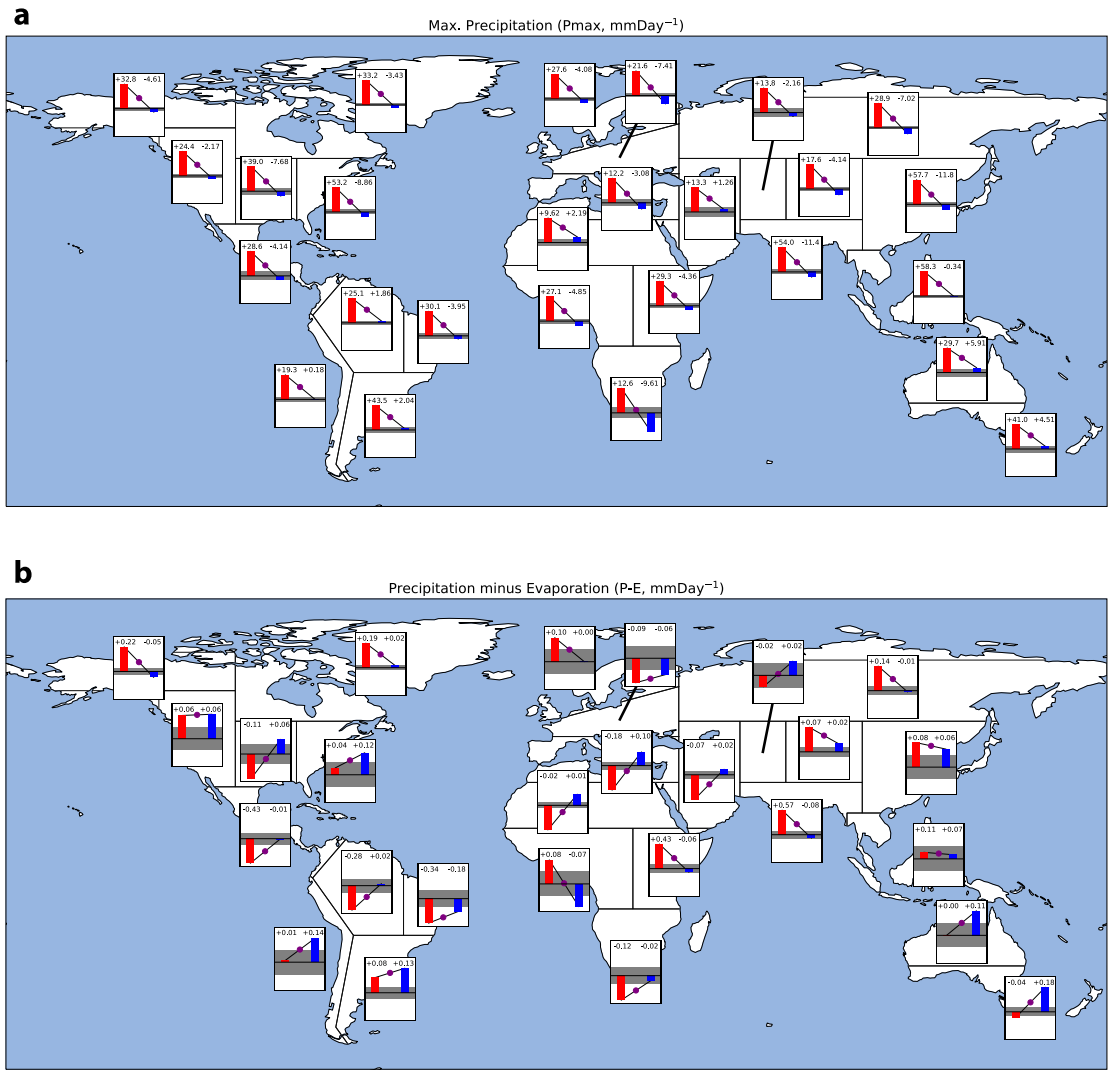

Figure 5. Regional climate response to RCP8.5 (red) and Full-GLENS (blue). Max Precipitation (a), precipitation minus evaporation (b) anomalies are shown relative to the baseline. The response for lesser amounts of cooling is illustrated with a black line between these two anomalies, and the Half-GLENS case is shown with a purple dot. The gray bar indicates the magnitude of anomalies from the baseline for which a 90% T-Test with the baseline would fail. The regions plotted are the SREX regions (see section 2.2).

that $P - E$ trends were exacerbated in some regions but that in all cases these regions were made wetter. Full-GLENS does reduce $P - E$ in many regions but in all such cases it offsets a positive RCP8.5 trend, and for those regions where there is an overshoot (such as West Africa), this is avoided in the Half-GLENS scenario. This suggests that moderate deployments of stratospheric aerosol geoengineering would not worsen aridification.

4. Discussion and conclusions

We found that stratospheric aerosol geoengineering deployed to halve warming might substantially reduce the overall magnitude of climate change, while exacerbating hydrological change in only a small fraction of places. Deployed to offset all warming, stratospheric aerosol geoengineering in the Full-GLENS simulation overshoots on global-mean hydrological change, turning the intensification of the hydrological cycle under unabated climate change into a weakening. In Full-GLENS most regions see local hydrological change moderated, though some experience a substantial overshoot and a change in sign, and some see the hydrological impacts of climate change exacerbated. In Half-GLENS, regions which would have seen an overshoot instead see the effects of climate change more effectively offset, without experiencing a change in sign and only a few regions see exacerbation of any climate variable.

The results presented are broadly similar to those presented in Irvine19, which focused on an idealized solar constant reduction experiment as a proxy for stratospheric aerosol geoengineering. There are important differences in the radiative forcing and climate response between both the background warming scenarios and the solar geoengineering deployment scenarios in this study and Irvine19 that might be expected to give rise to very different outcomes. A

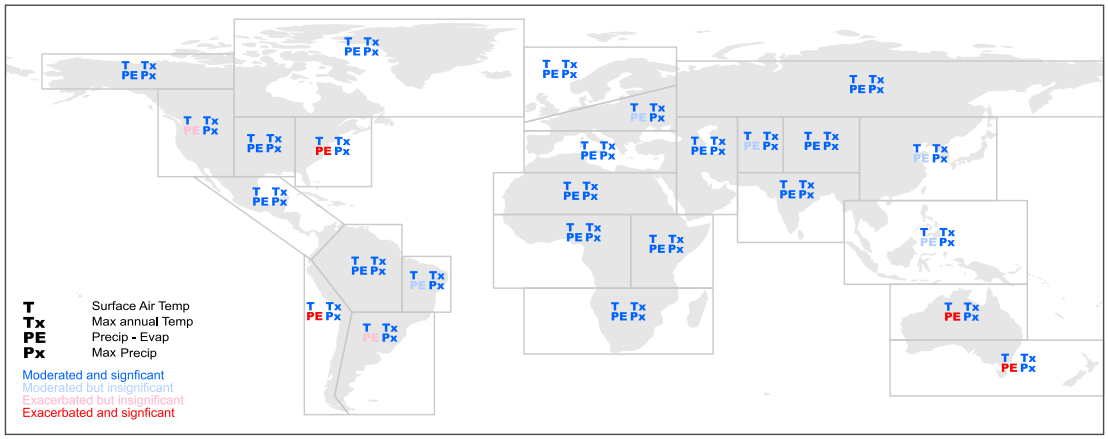

Figure 6. Regional distribution of where Half-GLENS moderates or exacerbates the absolute magnitude of RCP8.5 anomalies (for T, Tmax, P − E and Pmax). Regions where half-GLENS moderates (blue) or exacerbates (red) the absolute magnitude of the RCP8.5 climate anomalies relative to the Baseline are illustrated. Statistically significant results (90% T-Test) are indicated with bold colors whereas insignificant results are shown with pale colors.

leading difference being that sulphate aerosols absorb near-infrared solar band and thermal infrared radiation warming the lower stratosphere (Dykema *et al* 2016). This stratospheric warming will change stratospheric circulation and is a significant driver of the tropical hydrological response (Simpson *et al* 2019). There are undoubtedly important differences in the details of the climate response to a solar constant reduction and stratospheric aerosol geoengineering (Niemeier *et al* 2013, Kalidindi *et al* 2014). Yet, these differences do not change the main conclusions of Irvine19: halving warming with either a solar constant reduction or stratospheric aerosol geoengineering could substantially reduce climate change overall, exacerbating change in only a small fraction of places.

It is interesting to note that in both this study and Irvine *et al* (2019) the level of cooling at which the overall magnitude of change in precipitation minus evaporation (measured here in RMS terms) is minimized occurs just after the point at which global-mean precipitation is restored to baseline levels, ~70% and ~60% respectively. Future work could investigate whether this link is robust across models with a range of hydrological sensitivities to solar geoengineering and greenhouse gas forcing.

The analysis conducted in this study was motivated by the concern that some regions may experience greater climate risks if stratospheric aerosol geoengineering were deployed, however we did not directly evaluate changes in the risks faced by societies and ecosystems. It seems reasonable to assume, all else equal, that a reduced magnitude of climate change would lead to reduced harms, but this will not be true in all cases. For example, in water stressed regions if climate change were to increase water availability (P-E) this could be judged beneficial, and if solar geoengineering were to offset this gain, it could reasonably be judged harmful. Thus to evaluate the benefits and risks of climate change and solar geoengineering in depth requires going beyond assessing changes in climate variables alone to also considering the specific geographic, economic and cultural factors that shape the vulnerability to these changes (Irvine *et al* 2017). A comprehensive evaluation of climate risks was beyond the scope of the current study but should be a priority for future work in this field.

Our results are limited by the linear-scaling used to produce the Half-GLENS scenario, and some aspects of the circulation response to solar geoengineering and CO_2 forcing are not well approximated as a simple linear combination of the response to the separate forcings (Russotto and Ackerman 2018). It would therefore be useful to see similar ensemble model runs of moderate geoengineering scenarios to make such linearization unnecessary. Yet, we suspect that explicit simulation of our halving scenario would yield the same basic response because the response to stratospheric aerosol loading in the GLENS simulations has been shown to be reasonably linear to the aerosol injection rate (MacMartin *et al* 2017)

The level of radiative forcing is among the most important choices that society will have to make about solar geoengineering. It is therefore crucial to ask of any specific scenario of solar geoengineering deployment: what would have occurred if more, or less, cooling had been applied? A benefit of linearized analysis is that it allows this question to be addressed directly. For example, Tilmes *et al* (2013) is widely cited to provide evidence that solar geoengineering would produce a net weakening of monsoon rainfall but this is contingent on solar geoengineering being deployed to offset all warming. Applying a simple linear scaling of their results makes clear that a scenario which halved warming would instead effectively offset most of the increase in monsoon precipitation projected under their high-CO_2 scenario.

A goal of solar geoengineering research ought to be to understand and communicate clearly the consequences of specific deployment choices. This will require new models and observations to address uncertainties. It also requires appropriate analysis approaches that make clear how choices around solar geoengineering deployment, particularly around the level of cooling, would affect its outcomes.

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Data availability

The data that support the findings of this study are openly available doi:10.5065/D6JH3JXX

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