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Solar geoengineering could substantially reduce climate risks — A research hypothesis for the next decade

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Key Points:
- Solar geoengineering (SG) research needs policy-relevant hypotheses about performance of specific deployment scenarios and technologies
- Research needs to move beyond tests of SG as a substitute for mitigation to tests of the efficacy and risks of SG as a supplement
- As a testable claim, we suggest that if used to halve the temperature rise SG would reduce aggregate climate risks for all countries

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Abstract We offer a hypothesis that if solar geoengineering (SG) were deployed to offset half of the increase in global-mean temperature from the date of deployment using a technology and deployment method chosen to approximate a reduction in the solar constant then, over the 21st century, it would (a) substantially reduce the global aggregate risks of climate change, (b) without making any country worse off, and (c) with the aggregate risks from side-effects being small in comparison to the reduction in climate risks. We do not set out to demonstrate this hypothesis; rather we propose it with the goal of stimulating a strategic engagement of the SG research community with policy-relevant questions. We elaborate seven sub-hypotheses on the effects of our scenario for key risks of climate change that could be assessed in future modeling work. As an example, we provide a defence of one of our sub-hypotheses, that our scenario of SG would reduce the risk of drought in dry regions, but also identify issues that may undermine this sub-hypothesis and how future work could resolve this question. SG cannot substitute for emissions mitigation but it may be a useful supplement. It is our hope that scientific and technical research over the next decade focuses more closely on well-articulated variants of the key policy-relevant question: could SG be designed and deployed in such a way that it could substantially and equitably reduce climate risks?

1. Introduction

Crutzen's [2006] comment effectively broke the taboo on discussing solar geoengineering (SG), accelerating research on its central scientific question: to what extent could SG reduce the impacts of rising greenhouse gas concentrations? A decade later, a substantial body of research permits some conclusions about the efficacy and potential consequences of SG. However, the questions policymakers may ask about the utility (or lack thereof) of SG remain largely unanswered.

We argue that emerging research efforts on SG might be more effective if research were organized around scenarios that were more directly relevant to choices policymakers would face; and, if research focused on testing a limited set of clearly articulated hypotheses that were relevant to policymakers.

As an example, we propose the following hypothesis:

> *if SG were deployed to offset half of the increase in global-mean temperature from the date of deployment using a technology and deployment method chosen to approximate a reduction in the solar constant then, over the 21st Century, it would (a) substantially reduce the global aggregate risks of climate change, (b) without making any country worse off, and (c) with the aggregate risks from side-effects being small in comparison to the reduction in climate risks.*

We argue that hypotheses such as these are useful in directing research. We provide some basis to suggest that this hypothesis is plausible, but we do not claim that it is true. Rather, we argue that this hypothesis could be a useful tool to organize future research. Our evaluation is focused primarily on physical sciences and human impacts. We ignore questions of how SG might be governed, and ignore the deep question about whether a world in which SG was deployed would have a different (perhaps larger) emissions profile the world with no SG.

The remainder of this essay is organized as follows: first, we review the history of SG research, stressing the importance of scenario choice and framing, and arguing that research has, in part, been less effective than it might have been because too much effort has been expended assessing scenarios that do not directly illuminate the choices policymakers face. In Section 3, we elaborate the hypothesis, laying out some of the assumptions that lie behind it and providing a rationale for choices made in constructing it. In Section 4, we offer seven plausible sub-hypotheses that serve as an example of the kind of quantitative hypotheses that might guide future research. In Section 5, we provide a defence of our sub-hypothesis that our scenario of SG would generally reduce the risk of drought, as an example, while also identifying limitations to the ability to quantitatively evaluate this sub-hypothesis given existing research. And finally, in Section 6, we look forward and speculate about the kinds of research that could test our hypothesis over the next decade.

2. Context: What Questions Should Research Address?

Research in the last decade has done much to illuminate SG's benefits and risks. The Web of Science citation database now has more than 800 papers mentioning geoengineering, more than 10 times the cumulative total from 2006 and before. Tens of climate model studies have been published, including at least 25 from the Geoengineering Model Intercomparison Project (GeoMIP) [*Kravitz et al.*, 2011], an effort to evaluate standard SG experiments that has seen over 15 climate modeling groups participate. Scientific and technical evaluations of the stratospheric aerosol geoengineering proposal that Crutzen discussed have been made and continue to support the view that a substantial negative radiative forcing could be achieved [*Boucher et al.*, 2013] and at a cost of tens of billions of dollars per year [*Robock et al.*, 2009; *McClellan et al.*, 2012; *Arino et al.*, 2016]. Studies have explored the side-effects on stratospheric ozone [e.g., *Tilmes et al.*, 2008; *Pitari et al.*, 2014], on the quality of light [*Kravitz et al.*, 2012], and on the deposition of released aerosols [*Kravitz et al.*, 2009; *Eastham*, 2015]. The decade's new research extended well beyond stratospheric aerosol geoengineering, the focus of Crutzien's paper, to other methods such as increasing the albedo of low marine clouds [*Latham*, 1990] or suppressing the formation of upper-tropospheric cirrus clouds [*Mitchell and Finnegan*, 2009]. In addition to these scientific studies, a host of articles addressing the legal, governance, ethical, and other issues of SG have been published, see *Schäfer et al.* [2015] for a review.

Research in the last decade has provided far more information on SG—counting climate model runs or published papers—than all work prior to Crutzen's publication. Unfortunately, it has provided little clarity on the efficacy and risk of plausible SG deployment, in part, because research has not yet focused on the most policy-relevant scenarios.

Scenario analysis is a tool to aid decision making, in this case to inform climate policy. While field research on cirrus or marine cloud modification along with some other SG research may yield novel scientific insights, we would find it hard to justify funding research for climate model analysis of geoengineering scenarios, or even a broad SG research program, based on purely scientific goals. We think the central justification—and goal—of research on SG should be to inform policy choices about climate policy and the further development of the technology. Scenario used for evaluating SG should therefore be as policy relevant as is feasible while meeting other criteria such as simplicity.

Over the last decade, most studies have compared a low-GHG reference scenario with a high-GHG scenario that used sufficient SG to return global-average temperatures (or radiative forcing) to match the low-GHG baseline. If scenario analysis is seen as testing a hypothesis, this scenario choice seems most suited to testing some variant of the following hypothesis:

> *SG can perfectly compensate for the climate impacts of elevated GHG concentrations.*

The last decade's examination has resoundingly disproved this hypothesis [*Kravitz et al.*, 2013; *Niemeier et al.*, 2013]. SG cannot replace emissions cuts. In the long run, a stable climate requires near-zero net emissions. This is an important fact that bears repeating but in our view, this fact was clear long before Crutzen's comment [*National Academy of Sciences*, 1992].

It is useful to compare a high-GHG scenario with SG deployed to fully offset the warming from GHGs against a low-GHG baseline to learn about patterns of climatic response to SG (much of the fruitful work of GeoMIP has been done in this way). However, these results should not be used directly to make policy-relevant inferences about SG in general. First, to have policy relevance the cases compared should relate to practical policy options, e.g., the choice to deploy SG to offset the warming from GHGs or not. Second, the consequences of SG deployed in different ways would be very different and so it is necessary to consider this range of options.

Policymakers may (and in our view should) adopt policies that would rapidly eliminate GHG emissions, but past emissions mean that GHG concentrations are already elevated, so policymakers do not have the choice to simply return concentrations to pre-industrial levels. If scenario analysis is to inform policy choices, then it is not appropriate to draw conclusions about the risks or efficacy of SG directly from a comparison of a case with high-GHG and SG against a baseline with low-GHG concentration that are below what could be achieved by a rapid elimination of emissions.

While SG cannot substitute for emissions cuts, it *may* substantially reduce the risks of any given GHG emissions pathway. So, what scenarios can address policy-relevant questions about SG? Evaluating the risks and benefits of SG deployment requires comparing a specific deployment scenario against a scenario in which SG is not deployed.

Depending on the policy maker for whom the analysis is being performed, it may or may not make sense to use the same emissions scenario for the case with SG deployment as is used for the case without. If the goal is to evaluate the physical consequences of SG where other policy choices are held constant then the impacts of SG should be compared against the impacts of not deploying SG in a reference GHG scenario. If, on the other hand, the goal is a more integrated assessment then it would be necessary to consider the way other policies and behaviors may change if SG is implemented. One obvious and credible concern is that less effort will be expended on emissions mitigation in a world with SG implementation, though this effect is by no means certain [*Burns et al.*, 2016]. A world with SG implementation might be different in all sorts of ways, yielding either higher or lower emission scenarios along with changes in adaptation measures. All these possible social responses make the challenge of a full "general equilibrium" integrated assessment extraordinarily difficult. Our view is that analysis that focuses directly on the physical benefits and costs that come from the direct decision to employ SG—holding other decisions constant—is highly relevant, but must be interpreted with caution because all such large-scale decisions are inevitably interconnected.

In addition to the choice of baseline, the choice of SG deployment scenario matters. Using SG to restore pre-industrial temperatures (a common implicit assumption) would significantly reduce the hydrological cycle [Schmidt et al., 2012]. On the other hand, using SG to restore pre-industrial global-mean precipitation would only partially restore temperatures. Unfortunately, some studies report these scenario-dependent effects as universal effects of SG deployment [*Robock et al.*, 2008; *Crook et al.*, 2015]. SG-as-substitute clearly has substantial imperfections but it would be a mistake to interpret these as risks of deploying SG as some early studies did [Robock et al., 2008].

Beyond the choice of scenario, any evaluation of SG will be subject to deep uncertainty. One can't—of course—say a *priori* that the risks of a world with some moderate amount of SG would be less simply if the radiative forcing were reduced because of the many ways that SG is not "anti-CO_2", but nor should one claim that SG increases risk simply because it introduces some new risks.

We don't presume to prescribe universal decision criteria; but we believe understanding which state of the world is likely to carry more risk will be important to informing policy on solar geoengineering. Thus we argue that research should focus on evaluating comparative hypotheses like the one we outline here.

3. Elaborating the Hypothesis: Assumptions and Scope

First and perhaps most importantly, note the limited scope of our hypothesis. We do not address governance. Our hypothesis applies to a case where SG is implemented by rational—but not omniscient—decision makers with well-specified goals. One can imagine horrific outcomes of SG if it were implemented maliciously. This is not a minor omission. Disputes about implementation of SG could trigger military conflict, and these concerns have been voiced for at least a quarter century [*Keith and Dowlatabadi*, 1992]. The governance of SG is a hard problem, but we are not convinced by claims that the technology is inherently ungovernable [*Hulme*, 2014], because many of the claims about the impossibility of governing it would apply with equal force to other large-scale technologies for which there is some form of effective albeit imperfect global governance (e.g., management of infectious diseases, the internet, or central banking.).

Second, we assume that the decisions about implementation of SG are independent of decisions about emissions reductions. One of the central concerns about SG is that it will sap efforts to cut emissions. The concern is entirely legitimate, but early evidence is mixed [*Burns et al.*, 2016], with some studies suggesting an effect [*Corner and Pidgeon*, 2014], whereas others suggest the opposite, that learning about SG increases interest in emissions reductions [*Kahan et al.*, 2015; *Merk et al.*, 2016]. We believe it is important to understand the efficacy and risks of SG used independently as a means to reduce climate risks, while separately studying behavioral and political links between emissions mitigation and SG.

Now returning to the hypothesis, which we restate below with italicization of key phrases which we elaborate in the remainder of this section:

> if SG were deployed to offset *half of the increase in global-mean temperature* from the date of deployment using a *technology and deployment method chosen to approximate a reduction in the solar constant* then, over *the 21st Century*, it would (a) substantially reduce the global *aggregate risks of climate change*, (b) without making any *country* worse off, and (c) with the aggregate risks from *side-effects* being small in comparison to the reduction in climate risks.

3.1. Half of the Increase in Global-Mean Temperature

Following *Keith and MacMartin* [2015], we choose a "moderate" scenario in which the amount of SG is chosen to halve the increase in global-mean temperature. We make no claim of optimality, but note that such a scenario is likely to yield a more favorable ratio of benefits to harms than a scenario that offsets the full increase in global-mean temperature. A halving of the increase in global-mean temperature means that the intensity of the global hydrological cycle would change little rather than rising substantially as in the no-SG scenario or falling substantially as in a scenario where SG fully offsets the increase in temperature [*Irvine et al.*, 2010; *Tilmes et al.*, 2013], though there will nevertheless be changes in regional hydrology.

3.2. Technology and Deployment Method Chosen to Approximate a Reduction in the Solar Constant

At one extreme, one might choose an arbitrary technology and deployment scenario and assume that it is representative of what is possible with SG in general. This would include ineffective methods and high-risk deployment scenarios. The other extreme would be to choose an SG technology that optimized for some specific climatological objective and assume that it would evolve rapidly with new technological variants being continuously introduced to correct any problems. Neither extreme is credible.

We assume that a technology is chosen and deployed to approximate a spatially and temporally uniform reduction in solar constant. Taking stratospheric aerosols as an example, this would mean choosing a distribution of aerosol injection that was continuously adjusted with feedback from observations to approximate a uniform change in solar constant. It would also mean examining choices of stratospheric aerosols that might reduce side-effects such as forward scattering, warming of the lower stratosphere, or ozone loss [*Dykema et al.*, 2016]. While stratospheric aerosols may be the easiest way to produce such uniform forcing it might be that a combination of stratospheric aerosols and other methods could do a better job of approximating a uniform adjustment of the solar constant. Any approach chosen will fall short of perfectly reproducing the effects of a solar constant reduction, but it is a straightforward goal and we provide reasons to believe that it would satisfy our hypothesis.

There is evidence that climate risks might be more effectively reduced on a region-by-region basis by using methods that deliberately introduced non-uniform radiative forcing [*Ban-Weiss and Caldeira*, 2010; *Kravitz et al.*, 2016], but our choice of hypothesis ignores that potential benefit in favor of the simplicity of approximating a change in solar constant. This allows the analysis problem to be roughly broken into two halves. First, choose methods for approximating the radiative forcing from a uniform reduction in solar constant, analyze how well they can do so, and evaluate the non-climatic risks associated with these methods. Second, examine the climate changes resulting from deployments of these methods and, with caution, draw insights from simulations of the climate changes resulting from a uniform change in solar constant.

3.3. The 21st Century

We restrict the time horizon to the current century. SG cannot be simply discontinued at century's end without large impacts. A policy for the 22nd century might entail carbon removal to draw down concentrations coupled with a gradual phase out of SG [*Smith and Rasch*, 2012]. We nevertheless choose a single century because a shorter time horizon reduces uncertainties. We note that much climate policy analysis (e.g., global warming potentials) has focused on a one-century time horizon.

3.4. Country

The choice of spatial scale at which to aggregate risks is both important and arbitrary. We choose the country scale because benefits and harms are more readily re-distributed inside state boundaries than between them, and because states are a central locus of policymaking.

3.5. Aggregate Risks of Climate Change

As with choice of spatial scale, the choice of risks to evaluate and of the means to aggregate them is both important and arbitrary. As a starting point we suggest using the key risks of climate change identified by the Intergovernmental Panel on Climate Change (IPCC) and using a weighting based on an endpoint such as morbidity and mortality or monetized impacts as a fraction of income.

3.6. Side-Effects

Any SG technology will have non-climatic side-effects, such as reduction in stratospheric ozone or increase in surface air pollution, and the harms of these need to be evaluated using the same metrics as are used for climate risks. Where appropriate, changes to mortality and morbidity due to side-effects of SG should be compared to changes in mortality and morbidity due to the benefits of SG. Aggregate risks are—of course—not all that matters; the unequal distribution of risks between impacted groups demands particular attention.

4. Elaborating the Hypothesis: Sub-Hypotheses

An SG research effort organized around testing policy-relevant hypotheses, such as the one we advance here, would need to articulate subsidiary hypotheses that were more narrowly and quantitatively defined.

We propose a set of plausible sub-hypotheses, as a worked example which we hope might serve as a basis for helping the research community think about narrowly drawn questions which could be resolved by SG research. We propose one sub-hypothesis for all-but-one of the "key risks of climate change" identified by the IPCC in the technical summary of working group 2's contribution to the fifth assessment report and listed there in Table TS.3 [*Field et al.*, 2014]. Our sub-hypotheses describe quantifiable effects of SG on the physical hazards that drive each key risk of climate change. We exclude risk *iii*: "Novel hazards yielding systemic risks," as unlike the other risks, this one has no straightforward physical hazard that can be assessed directly.

Each of the sub-hypotheses makes a claim about the impact of a scenario of SG deployment which halves the increase in global-mean temperature, as defined above. All changes described are relative to a scenario with the same GHG concentration pathway but without SG unless otherwise stated. In each case, we include in italics the corresponding row number in Table TS.3 [*Field et al.,* 2014].

Our specific quantitative choices in the scenarios are purely illustrative. Some of these might well be disproved by careful hypothesis testing which showed realistic cases that violated them. Following each sub-hypothesis, we provide very brief notes on the reasoning behind our specific choices, but this reasoning is not intended to be a rigorous argument that the hypothesis is true. In fact, we encourage readers to review the literature we cite and consider possible alternative sub-hypotheses.

Sea-level rise and coastal flooding including storm surges (*i*):

> *The increase in global sea-levels would be reduced by at least 20% and the increase in the average height of storm surges would be reduced by at least 30% compared to the no-SG scenario. Coastal flood risks along more than 90% of coasts would be reduced.*

Notes: *Irvine et al.* [2012] evaluate an SG scenario approximately matching our description and find that global sea-level rise is reduced by around a quarter. Theoretical considerations suggest that storm intensity, like precipitation intensity, will scale with temperature rise and a study of SG, which applied an empirical model of historical storm surge height to ocean temperature also suggests a reduction of storm surge intensity [*Moore et al.*, 2015].

Extreme precipitation and inland flooding (*ii*):

> *The intensity of precipitation would be reduced over more than 75% of the land surface area and increased over more than 5%. The projected global-average increase in the intensity of 5-day maximum precipitation in the no-SG scenario would be reduced by more than 50%.*

Notes: There is robust model evidence that SG would reduce mean precipitation in most but not all regions [*Tilmes et al.*, 2013], and strong theoretical and modeling evidence that extreme precipitation would be reduced most strongly [*Curry et al.*, 2014].

Increasing frequency and intensity of extreme heat (*iv*):

> *The intensity of extreme high temperature events would be reduced over more than 95% of the land area of the world. The land area average increase in the temperature of the warmest day in the no-SG scenario would be reduced by 50% or more.*

Notes: Evidence from GeoMIP shows that temperature is one of the variables for which SG most uniformly and effectively offsets the effects of GHG forcing [*Kravitz et al.*, 2013, 2014]. In addition, SG cools most during summer and during the day, which suggests that it would reduce peak temperatures more strongly than the mean, a result that is borne out in model simulations [*Curry et al.*, 2014].

Agricultural impacts (driven by warming, drought and precipitation variability, *v*):

> *Agricultural yields would increase over more than 70% of current agricultural areas and decrease over more than 5%.*

Notes: Simulations suggest SG would reduce warming, drought (see below and Section 5) and precipitation variability in most regions [*Curry et al.*, 2014], which should reduce the risk of crop failure. Crop model simulations of the effects of SG predict increased yields of most crops in most regions, though cold regions are a notable exception [*Pongratz et al.*, 2012; *Xia et al.*, 2014].

Drought and water scarcity (*vi*):

> *There would be an increase in runoff in more than 75% of the driest quartile of the non-ice covered land area in the low-GHG baseline. There would also be a decrease in runoff in more than 85% of the wettest quartile of the land area. The length of dry spells would be reduced over 75% or more of sub-tropical land areas.*

Notes: A more complete justification for this sub-hypothesis is given in the following section.

Ocean ecosystem impacts (driven by rising ocean temperatures, ocean acidification, and loss of arctic sea ice (*vii*):

> *Ocean ecosystem impacts would be reduced over more than 95% of the surface ocean area*.

Notes: SG would reduce surface air and ocean temperatures and offset some of the losses in Arctic sea ice [*Kravitz et al.*, 2013]. Simulations suggest that SG may have a small positive effect on ocean acidification, primarily due to an enhanced terrestrial carbon sink and reduced permafrost emissions, though this is uncertain [*Matthews et al.*, 2009]. Simulations of the effects of SG on coral reefs suggest that it could help to preserve these ecosystems [*Couce et al.*, 2013; *Kwiatkowski et al.*, 2015].

Terrestrial ecosystem impacts (driven by rising land temperatures, changes in precipitation patterns and in the frequency and intensity of extreme heat (*viii*):

> *Terrestrial ecosystem impacts would be reduced over more than 80% of the land surface.*

Notes: SG would reduce changes in mean and extreme temperature but would have a mixed effect on precipitation, offsetting changes in many places and worsening them in some places [*Kravitz et al.*, 2014]. Theoretical considerations suggest that with less change to the climate there would be less pressure for species to migrate or adapt and so that SG would generally reduce terrestrial ecosystem impacts.

5. Evaluating Evidence for the Sub-Hypothesis on Drought and Water Scarcity

The sub-hypotheses outlined in the previous section were illustrative and the reasoning presented was not intended to demonstrate them but rather to show that these hypotheses were plausible. As a worked example of the way that the specific sub-hypothesis might be defended, challenged, and evaluated we examine the drought and water scarcity sub-hypothesis.

We focus on the drought and water scarcity sub-hypothesis as it has been widely reported that SG poses a substantial risk of drought, particularly for monsoon regions, and we believe that this is not necessarily the case. Thus, there is a danger that if we simply stated our sub-hypothesis we could be thought to be overly optimistic and even wilfully blind of a widely understood risk of SG. The reason that the effects of SG on drought and water availability are often misunderstood is that a number of factors must be considered together. In the following paragraphs, we address the three most significant factors that shape the effect of SG on drought and water availability: the magnitude of cooling, the spatial distribution of hydrological change, and the temporal distribution of precipitation change.

SG to halve the temperature response to rising GHG concentrations would produce smaller changes in regional precipitation than SG to fully offset temperature change. Tilmes et al. [2013] assess the hydrological response of the GeoMIP ensemble in a pre-industrial control (piControl), a scenario with instantly quadrupled CO_2 concentrations ($4 \times CO_2$), and a scenario with instantly quadrupled CO_2 concentrations and a reduction in solar constant sufficient to restore pre-industrial radiative forcing and temperature (G1). They report an ensemble-mean +6.9% increase in global-mean precipitation for $4 \times CO_2$-piControl and −4.5% reduction for G1-piControl, suggesting a small net increase for our scenario which halves the warming from elevated GHG concentrations. *Tilmes et al.* [2013] report a similar pattern of response in most monsoon regions with, for example, an ensemble-mean +10.2% and +8.1% increase in Indian and West-African precipitation for $4 \times CO_2$-piControl and a −2.5% and −3.0% decreased for G1-piControl (see their figure 14b). This suggests that a scenario of SG deployment which halved the increase in temperature would reduce the projected increase in precipitation in these monsoon regions rather than producing a net reduction in precipitation, which would occur in a full deployment scenario. Whilst this general pattern holds over most of the monsoon regions *Tilmes et al.* [2013] studied, it should be noted that SG does exacerbate GHG precipitation trends in some regions [*Kravitz et al.*, 2014].

SG generally dries wet regions and makes dry regions less dry. Global warming will increase the intensity of the hydrological cycle and also amplify the disparities in water availability with wet regions tending to get wetter and dry regions tending to get drier, the "rich-get-richer" pattern of change [*Held and Soden*, 2006]. *Kravitz et al.* [2013] assessed the distribution of the precipitation-evaporation (*P-E*) response, a simple proxy for water availability, in the GeoMIP ensemble. They reported that for $4 \times CO_2$-piControl reductions in *P-E* of more than 20% were found in 13% of land grid-cells, whereas for G1-piControl only 5% of grid-cells reported a reduction of this magnitude (values are approximate and were extracted using a plot digitizer tool from their figure 6). Similarly, 49% of land grid-cells reported an increase in *P-E* for $4 \times CO_2$-piControl of 20% or more compared to only 11% for G1-piControl. Thus, we expect our moderate scenario of SG to generally increase runoff in regions projected to get drier under global warming and to reduce the projected increase in runoff in wet regions.

Simulations suggest SG reduces precipitation variability and shortens dry spells. Global warming has produced an observed increase in mean rainfall but the increase in extreme rainfall is rising at a much greater rate [*Berg et al.*, 2013]. This intensification of precipitation events, means that even in regions which are projected to see no change in mean rainfall, there is still projected to be greater flood risks in the future; it also means that dry periods will tend to be more intense and longer lasting [*Held and Soden*, 2006]. *Curry et al.* [2014], evaluating the GeoMIP ensemble, report a substantial increase in the length of dry periods across sub-tropical regions for $4 \times CO_2$-piControl, which is not seen in G1-piControl. Thus, we expect our moderate scenario of SG to reduce the length of dry periods in sub-tropical regions.

The evidence presented above is far from a conclusive demonstration that our sub-hypothesis is true. The following is a list of caveats or reasons that existing evidence is insufficient to make conclusive statements about this sub-hypothesis:

- *Non-linearity of model response*. The arguments above assume linear scaling of climate response to radiative forcing, while there is evidence for this [*Irvine et al.*, 2010; *MacMartin et al.*, 2013], it would be better to have simulations of the specific SG scenario.
- *Non-equilibrium response.* The evidence presented above is drawn from the quasi-equilibrium responses to instantaneous changes in forcing, which cannot capture the transient response of the scenario we propose.
- *SG is not equivalent to a reduction in solar constant.* Our scenario assumes SG is deployed to most closely replicate the effects of a solar insolation reduction, but the model results we drew on above simply applied an adjustment to the solar constant. The absorption of radiation by stratospheric aerosols, which could be diminished but not eliminated through optimal choice of aerosol particles, will warm the stratosphere altering atmospheric dynamics and producing a greater reduction in the intensity of the hydrological cycle than an equivalent forcing from a solar insolation reduction [*Niemeier et al.*, 2013; *Aquila et al.*, 2014].
- *Shifts in atmospheric circulation*. Shifts in atmospheric circulation and in modes of climate variability, which affect regional hydrology may occur. The location of the critically important peak precipitation band of the inter-tropical convergence zone may be affected by SG [*Haywood et al.*, 2013]. There are also regions which are projected to see little change in net water availability under global warming, for example, while Southern Europe is projected to see a drying and Northern Europe to see an increase in water availability, the band between is projected to see little change. The location of such bands of favorable conditions may also change.
- *Climate risks depend on more than simply changes in physical hazards.* We have only considered the physical aspects of water availability and a more complete evaluation of this risk must consider human demands for water. Water stress in many regions is increasing due to growing demand from growing populations and economies. In some regions, this anthropogenic increase in water stress is being offset to some extent by increasing water availability due to climate change [*Arnell et al.*, 2013]. In these regions, our scenario of SG would seem likely to reverse this projected benefit of global warming and so exacerbate water stress relative to the scenario without SG. To fully assess this risk would require the use of dedicated climate impacts models.

6. The Next Decade

SG is a technology not a natural phenomenon, it is the application of scientific knowledge and technological capability to achieve some set of goals [*Kravitz et al.*, 2016]. Just as one cannot assess infrastructure proposals, or any other applications of technology, without reference to the goals that they are designed to achieve, the assessment of SG cannot be usefully abstracted from the goals it might be designed to achieve. If it is to inform decisions about deployment of SG — including decisions to not deploy — then assessment of the efficacy and risks of SG needs to be coupled with further development of the technology such as the investigation of alternative options in hopes of finding ways to reduce risks or improve efficacy.

Furthermore, evaluating the specifics of the deployment scenarios such as the type, amount, and location of aerosol injection, should be coupled with the means of monitoring and modifying any such deployment in response to new information. For example, if some specific deployment of stratospheric aerosol geoengineering is found to shift the location of the Inter Tropical Convergence Zone, then researchers should explore ways to modify the deployment to counter this shift, such as by adjusting the north–south asymmetry in stratospheric aerosol radiative forcing [*Haywood et al.*, 2013; *Kravitz et al.*, 2016].

Our hope is that both the technology and the tools for assessment, particularly tools for assessing human and ecological impacts, will improve substantially over the next decade. Progress will require a structured, policy-relevant, and iterative approach. We propose that the articulation of well posed policy-relevant hypotheses that can be examined by multiple research groups using a diversity of methods may help to coordinate research so that it can better inform policy.

We proposed a (moderately) specific testable hypothesis of direct policy relevance to SG. We expect that it will be useful to agree on shared hypotheses and quantitative sub-hypotheses that more narrowly specify the objectives (e.g., reduce sea ice loss or reduce deviation of annual precipitation from pre-industrial), and the kinds of SG technology (e.g, stratospheric aerosols or marine cloud brightening) to be evaluated.

Improved assessments of SG, particularly the testing of policy-relevant hypotheses, will require features that have been notably absent from most previous studies. Such features include:

- An explicit choice of the baseline for comparison that is suited to addressing the hypothesis under investigation, for example, in our case this was the same GHG emissions scenario as for the SG scenario but without SG deployment.
- The use of reasonable heuristics for climate risks or else direct use of impacts model results, rather than, for example, using mean precipitation change as a guide to water availability, ignoring factors such as evaporation and transpiration.
- An approach which addresses the full range of impacts, rather than, for example, identifying a single harm or benefit that may increase or decrease in a specific region.
- The use of transparent and reasonable choices about the technology and its deployment strategy, rather than, for example, simulating injection of SO_2 to offset all future increase in GHG forcing.

More generally, the evaluation of any such hypothesis depends on the choice of climate impacts over which the efficacy of SG is to be evaluated and on the method for aggregating benefits and harms across space, time, and climate impact. There will always be particular choices of impact metrics, such as the "precipitation guardrails" proposed by *Stankoweit et al.* [2015], under which many (or all) SG proposals are not acceptable. A fair policy-relevant test of hypotheses about the impacts of SG, should however, use a choice of impact metrics and aggregation consistent with choices made for evaluation of other climate policies. Or, in more colloquial language, "no cherry picking."

We expect that a central challenge will be balancing the breadth of approaches to be studied against the depth with which individual technologies and deployment scenarios are to be examined. While the GeoMIP G1 scenario is, for example, a poor proxy for policy-relevant deployment of SG, it has the advantage of being thoroughly examined by many researchers. To be policy relevant and effective, the technical community needs to focus most of its effort on analyzing the efficacy and risks of a small set of technologies and deployment scenarios that show the most promise.

To conclude, research over the last decade has explored a wide range of scenarios, but we argue that too much of that effort was devoted to a scenario choice that was suited to testing the performance of SG as a substitute for emissions reductions, rather than to more policy-relevant questions. Emissions cuts are a central part of any sane climate policy. Research on the science and technology of SG needs embrace a design question: can a choice of technology, deployment, and monitoring scenario be found that allows a significant reduction in climate risk? We propose — as a research hypothesis — that a moderate deployment scenario and reasonable choice of technologies can allow SG to substantially reduce climate risks.

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