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Towards a comprehensive climate impacts assessment of solar geoengineering

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Key Points:

- The paucity of climate impacts studies on solar geoengineering is a key missing link in the interdisciplinary research on this topic
- The climate impacts community can use existing tools and datasets to assess many solar geoengineering effects on natural and human systems
- Solar geoengineering could be tailored to produce different climate outcomes demanding innovative approaches to impacts assessment

Abstract Despite a growing literature on the climate response to solar geoengineering—proposals to cool the planet by increasing the planetary albedo—there has been little published on the impacts of solar geoengineering on natural and human systems such as agriculture, health, water resources, and ecosystems. An understanding of the impacts of different scenarios of solar geoengineering deployment will be crucial for informing decisions on whether and how to deploy it. Here we review the current state of knowledge about impacts of a solar-geoengineered climate and identify the major research gaps. We suggest that a thorough assessment of the climate impacts of a range of scenarios of solar geoengineering deployment is needed and can be built upon existing frameworks. However, solar geoengineering poses a novel challenge for climate impacts research as the manner of deployment could be tailored to pursue different objectives making possible a wide range of climate outcomes. We present a number of ideas for approaches to extend the survey of climate impacts beyond standard scenarios of solar geoengineering deployment to address this challenge. Reducing the impacts of climate change is the fundamental motivator for emissions reductions and for considering whether and how to deploy solar geoengineering. This means that the active engagement of the climate impacts research community will be important for improving the overall understanding of the opportunities, challenges, and risks presented by solar geoengineering.

1. Introduction

There is a growing international commitment to reduce fossil fuel emissions, as reflected in the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) 2015 21st Conference of Parties, which has as one objective: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" [*UNFCCC*, 2015]. However, global carbon dioxide (CO_2) emissions would need to decline substantially by 2050 and perhaps even turn negative by 2100 in order to achieve a 50% chance of avoiding a global warming of >2°C relative to preindustrial [*Meinshausen et al.*, 2009; *Clarke et al.*, 2014; *Fuss et al.*, 2014]. The slow progress on emission reductions to date (global emissions in 2014 were 65% higher than in 1990 [*Le Quéré et al.*, 2015]) and the possibility of substantial impacts even in the case of strong future mitigation efforts have motivated discussions of whether solar geoengineering could be a potential means of reducing some impacts of climate change [*Crutzen*, 2006; *Smith and Rasch*, 2012]. There are a number of solar geoengineering proposals that could prove feasible and potentially inexpensive to deploy relative to the costs of mitigation and adaptation [*Salter et al.*, 2008; *Robock et al.*, 2009; *McClellan et al.*, 2012]. These include stratospheric aerosol injection, a proposal to release megatons

Supporting Information:
- Supporting Information S1

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of sulfate or other types of aerosol particles into the stratosphere to scatter light [*Crutzen*, 2006; *Weisenstein et al*., 2015]; marine sky brightening, where sea-salt aerosols would be sprayed into the marine boundary layer to increase cloud reflectivity and also directly scatter light by the aerosol particles [*Latham*, 1990]; and surface albedo modification, which aims to increase the albedo of crop, urban, or other land surfaces [*Hamwey*, 2007].

Simply considering the physical consequences, it is clear that no form of solar geoengineering could obviate the need for mitigation. This is because solar geoengineering cannot fully offset the global and regional climatic changes induced by increases in atmospheric greenhouse gas (GHG) concentrations, and also because it would not address direct effects of higher atmospheric CO_2 concentrations, such as ocean acidification or altered plant growth and water use efficiency [*Boucher et al*., 2013; *Clarke et al*., 2014; *Schäfer et al*., 2015; *Shepherd et al*., 2009]. However, solar geoengineering may still offer a possibility to reduce some of the key risks posed by climate change, although it would also introduce novel risks. Whether the various forms of solar geoengineering could reduce the aggregated risks of climate change, how the risk burden would be redistributed, and what novel risks would be posed are all critical issues that need to be better quantified and brought forward for open discussion. However, scientific evidence on which to base such judgments is currently not sufficiently robust. While there have been many studies into the consequences of solar geoengineering on climate as such, there have been few studies of the subsequent impacts on natural and human systems that are vulnerable to these changes (Figure 1).

Here we argue that a thorough climate impacts assessment is needed to better evaluate societally relevant consequences of deploying solar geoengineering. First, we present a brief review of research to date on the climate responses to solar geoengineering deployment. We then argue that the difference between the climate response to solar geoengineering and the response to elevated GHG concentrations is substantial enough to warrant a comprehensive assessment of the former's climate impacts. We review the few studies that have assessed the impacts of the various forms of solar geoengineering on natural and human systems, highlighting the paucity of such impact studies as a critical research gap. We then elaborate additional challenges that solar geoengineering poses for climate impacts research, which arise from the fact that how solar geoengineering is deployed would be a choice and a wide range of climate outcomes would be possible. We conclude with recommendations for how to conduct a comprehensive climate impacts assessment of solar geoengineering deployment scenarios as well as recommendations for addressing the novel questions raised by the possibility to tailor solar geoengineering deployment to achieve particular objectives.

2. The Climate Response to Solar Geoengineering

Simulations show that the climate response to global solar geoengineering is markedly different from a simple reversal of the effects of GHGs on the climate. Rather than providing a detailed review of the climate effects of solar geoengineering, as has been done recently by *Schäfer et al*. [2015], *Mcnutt et al*. [2015], and *Irvine et al*. [2016], we instead provide a short summary of the effects of solar geoengineering on temperature, the hydrological cycle, and sea level rise. A more thorough summary of the climate response to idealized "sunshade" geoengineering, that is, reduced solar insolation, as well as a summary of the differences between this and other more feasible forms of solar geoengineering can be found in Appendix S1 of the Supporting Information [see also *Niemeier et al*., 2013, *Kalidindi et al*., 2014 and *Ferraro et al*., 2014]. The citations made in the supporting information are detailed in Appendix A.

All methods of solar geoengineering have the potential to cool the planet, with spatial patterns of climate response that depend on the pattern of the exerted forcing, climate feedbacks, and teleconnections that cause nonlocal effects [*Alterskjær et al*., 2013; *Haywood et al*., 2013]. The intensity of the hydrological cycle is expected to increase in response to global warming, and has been found to decrease in response to solar geoengineering, resulting in net reductions in precipitation and evaporation if solar geoengineering fully offsets the GHG forcing [see *Schmidt et al*., 2012, *Kravitz et al*., 2013, and Figure S2). No known method of solar geoengineering can simultaneously restore both global temperature and global precipitation to earlier, low-GHG values as the response of these two measures to solar and GHG forcing is markedly different [*Niemeier et al*., 2013; *Tilmes et al*., 2013]. Solar geoengineering offsets many GHG-forced changes to both mean climate and extreme event probabilities [*Curry et al*., 2014]. Solar geoengineering could reduce sea

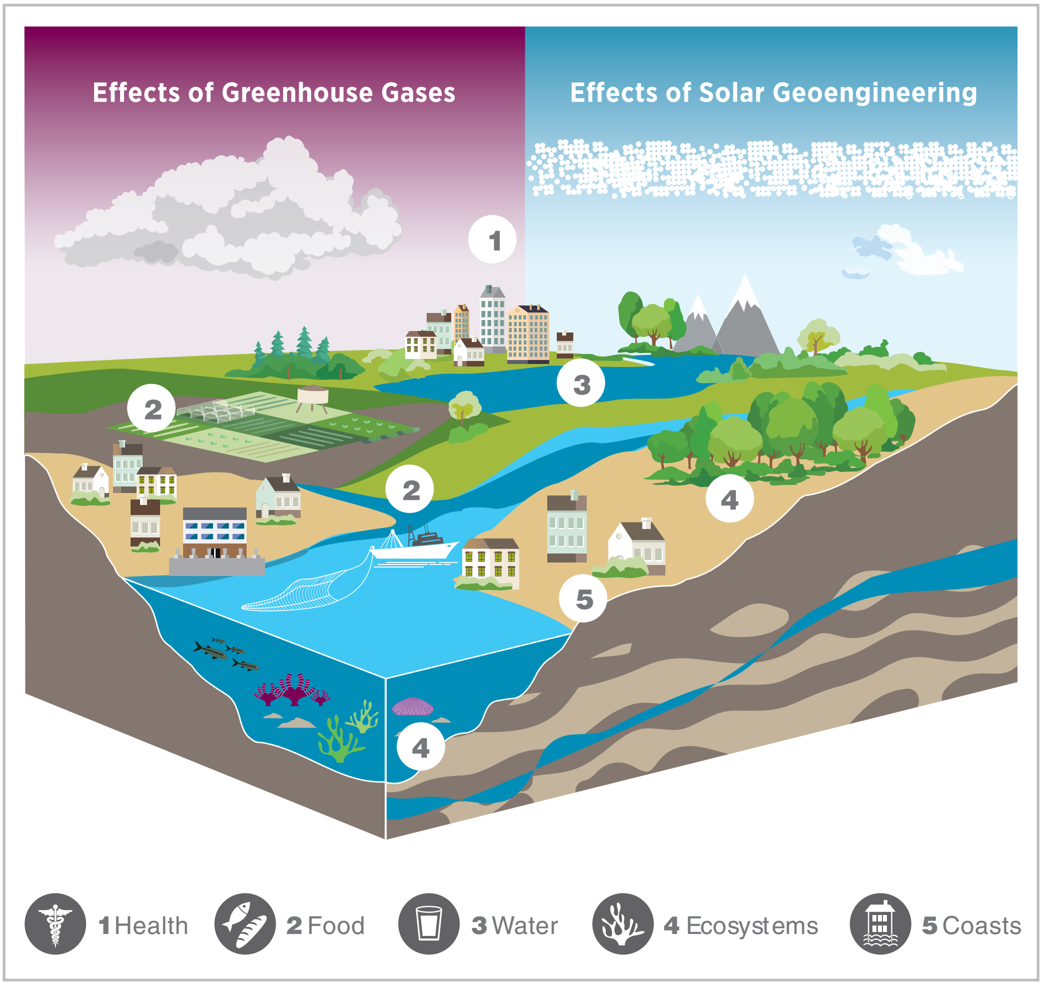

Figure 1. Elevated greenhouse gas concentrations and associated climate change will impact many sectors, as would solar geoengineering, yet in different ways. Five key sectors of climate impacts are shown: (1) Health, for example, mortality and morbidity due to heatwaves, air quality, and vector-borne diseases; (2) Food, for example, crop yields and fish stocks; (3) Water, for example, freshwater availability and flooding; (4) Ecosystems (terrestrial and aquatic), for example, loss of habitat and other pressures on biodiversity; (5) Coasts, for example, erosion of coasts and coastal inundation.

level rise by slowing the melt of land-ice and reducing the warming of the oceans [*Irvine et al*., 2009, 2012; *Moore et al*., 2010]. However, a substantial amount of future sea level rise could be committed before any potential deployment begins as some ice masses are already unstable in current conditions [*Applegate and Keller*, 2015; *McCusker et al*., 2015].

These effects apply to all global solar geoengineering methods. In contrast to GHG forcing, the effect of solar geoengineering on the climate system would depend upon the particular proposal and the manner of its deployment. Fundamentally, the consequences of deploying solar geoengineering will vary depending on how much cooling is exerted. Different proposals will have different climate effects: for example, sulfate aerosol injections into the stratosphere resulting in a cloud with global coverage would produce a markedly different climate response compared to tropical marine cloud brightening [*Jones et al*., 2011]. Moreover, different solar geoengineering proposals have different associated degrees of freedom that could be modified to exert some control over the climate response. For example, the effects of stratospheric sulfate aerosol injection depend on the amount, latitude, altitude, and season of injection [*Robock et al*., 2008; *Niemeier et al*., 2011; *Niemeier and Timmreck*, 2015]. We discuss some of these "design" aspects of solar geoengineering later, but we note that quantifying the potentials and limitations of geoengineering is an active area of research [e.g. *Kravitz et al*., 2016].

3. Progress on Climate Impacts Assessments of Solar Geoengineering

The results summarized above suggest that global solar geoengineering could be effective at offsetting some GHG-induced climate trends [*Boucher et al*., 2013; *Niemeier et al*., 2013]. However, the efficacy of solar geoengineering at offsetting the various consequences of elevated GHG concentrations can be quite different. Moreover, solar geoengineering produces a number of novel effects and does not directly affect the atmospheric CO_2 concentration (although it would have indirect effects on the carbon cycle, see section 1 of Appendix S1). Thus, while the overall *magnitude* of climate change, measured in terms of the deviations of various climate variables from some low-GHG baseline, might be reduced [*Boucher et al*., 2013], the *vector* of climate change would certainly be different from that of GHG-induced climate change, as the relative changes in these variables would differ [*Moreno-Cruz et al*., 2011; *Yu et al*., 2015]. While some climate impacts depend in a fairly straightforward manner on the state of the climate, for example, mortality in extreme heat conditions depends on changes in extreme temperatures, many climate impacts depend on changes in a number of different climate variables. For example, C4 grasses generally outperform C3 grasses in hot, dry, low-CO_2 conditions, and so it is unclear how the competition between these two types of vegetation will play out in scenarios with higher CO_2 concentrations, lower temperatures and an altered hydrological cycle [*Franks et al*., 2013]. Thus an evaluation of the effects of solar geoengineering on the full range of climate impacts will be needed.

Changes in the climate do not constitute risks and benefits on their own. Rather, the risks of climate change arise through the impacts of these changes in the climate on the systems and services we value and depend on, such as agriculture, health, and ecosystems. Impacts assessments must account for the *exposure* of natural and human systems to the *hazards* posed by a changing climate and the *vulnerability* of those systems to a modified climate. Vulnerability needs to be characterized both in terms of the susceptibility of the system to those changes and its adaptive capacity to cope with them (we use the definitions laid out in the IPCC WG2 glossary throughout [*Field et al*., 2014]). Deploying solar geoengineering would change the hazards posed by climate change, and while it would not directly affect the exposure and vulnerability of human populations to those hazards, these factors must be considered when evaluating the climate impacts of solar geoengineering (Figure 2).

To date, there has been little work into quantifying the climate impacts of any kinds of solar geoengineering. Here, we highlight progress that has been made toward understanding the potential climate impacts of scenarios of solar geoengineering deployment. These studies are summarized per sector below.

Among the few studies examining crop responses to solar geoengineering, *Pongratz et al*. [2012] found that a deployment of sunshade geoengineering would increase global crop yields compared to a scenario without sunshade geoengineering by reducing the heat stress associated with GHG warming. With a focus on China, *Xia et al*. [2014] found that sunshade geoengineering reduced rice yields and increased maize yields compared to a scenario of rising GHG concentrations without sunshade geoengineering, although compared to the preindustrial era, yields were increased in all cases due to the ongoing CO_2 fertilization effect. Both studies also found substantial regional variation that arises from regional differences in the climate response, particularly the precipitation response, and to the sensitivity of marginal regions to the sign of temperature change. *Parkes et al*. [2015] found that marine sky brightening geoengineering could increase crop yields and reduce the occurrence of crop failures in West Africa and Northern China, this response was partly due to the fertilization effect of atmospheric CO_2 and partly due to the increased precipitation in these regions, a response which may be unique to marine sky brightening.

Tropical coral reefs, and the rich biodiversity they support, are identified as very vulnerable to climate change [*IPCC*, 2014]. Coral bleaching, where corals eject their photosynthetic symbionts and which often results in colony mortality, is induced by anomalously elevated ocean temperatures but is also sensitive to aragonite saturation levels [*Anthony et al*., 2008]. A couple of studies have investigated the potential efficacy of sunshade geoengineering for protecting these shallow-water coastal ecosystems. Solar geoengineering was found to reduce sea surface temperatures and hence prevent a substantial fraction of current habitat from becoming unsuitable for coral reefs as compared to various GHG emission scenarios (Figure 3) [*Couce et al*., 2013]. However, in the case where solar geoengineering counters all forcing on a global scale, tropical regions become cooler with respect to the preindustrial period, causing a reduction

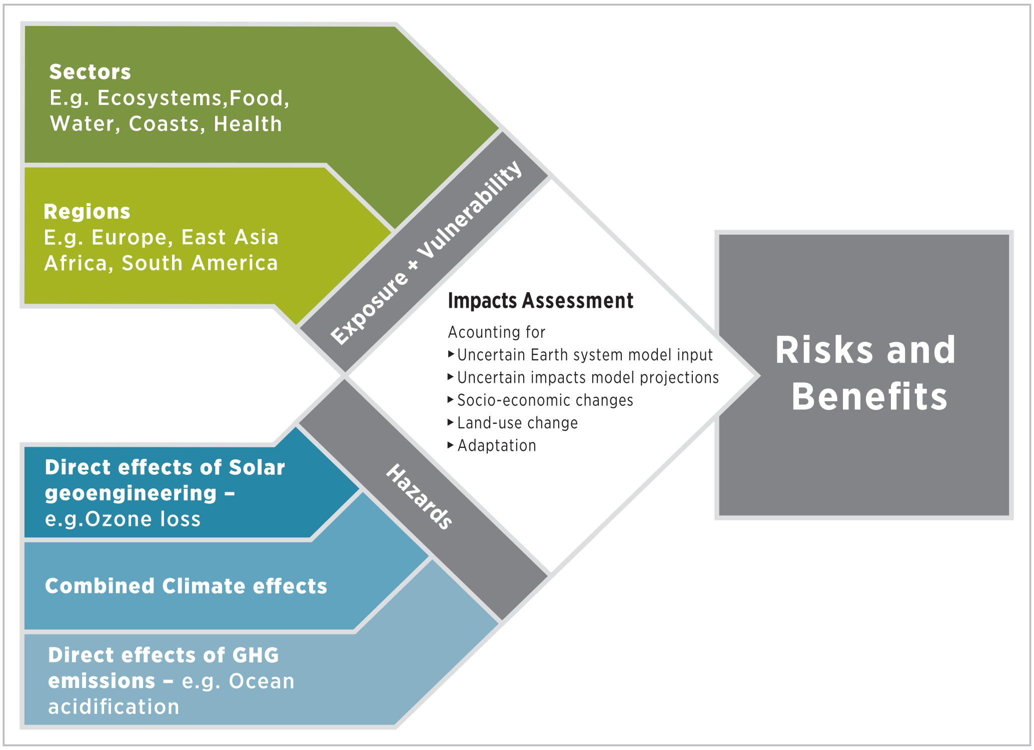

Figure 2. An assessment of the risks and benefits of scenarios of future climate change, including the deployment of solar geoengineering, must account for projected environmental hazards and the exposure and vulnerability of populations to those hazards. Some hazards will arise directly from anthropogenic GHG emissions, and others directly from the deployment of solar geoengineering, but the climate response will depend on both. Differences in exposure and vulnerability across sectors and regions must be considered when evaluating impacts. An impacts assessment of the potential benefits and risks of deploying solar geoengineering must consider many socioeconomic factors beyond solely the changes in the climate.

in habitat suitability (Figure 3). *Latham et al*. [2013] found that marine cloud brightening could reduce sea-surface temperatures and hence reduce the occurrence of the high temperature stress events, and *Kwiatkowski et al*. [2015] showed that these often fatal conditions were less likely to occur under the stratospheric aerosol injection geoengineering scenarios they investigated. In the studies that accounted for the effects of ocean acidification on corals, it was found to be of secondary importance relative to heat stress [*Couce et al*., 2013; *Kwiatkowski et al*., 2015], even though solar geoengineering would slightly enhance the solubility of CO_2 in ocean waters by lowering temperatures, increasing ocean acidification somewhat [*Matthews and Caldeira*, 2007; *Keller et al*., 2014]. Further studies on the impact of solar geoengineering on other marine and terrestrial ecosystems, and including community composition and biodiversity, are clearly needed.

Air pollution is one of the leading causes of premature deaths in urban settings globally. Due to increased stagnation in hot regions and increased reaction rates with higher temperature, global warming is expected to lead to an increase in low layer ozone and other pollutants, an effect known as the “climate penalty” [*Rasmussen et al*., 2013]. *Nowack et al*. [2016] show that sunshade geoengineering could reduce ultraviolet radiation at the surface and increase surface ozone, which is harmful to human, animal, and plant health [*Silva et al*., 2013]. Stratospheric aerosol injection geoengineering would deposit the injected aerosols at the surface, posing an environmental risk that will depend on the aerosol material [*Effiong and Neitzel*, 2016], although most of the aerosol particles would be removed by wet deposition as they descend from the stratosphere and so the contributions to airborne particulate matter at the surface would likely be low [*Eastham*, 2015]. Stratospheric aerosol injection geoengineering would also change the chemistry of the stratosphere; if deployed soon, it could delay the recovery of the ozone hole by some decades [*Tilmes et al*., 2009; *Pitari et al*., 2014], though the effect will depend strongly on the injected type of aerosol [*Weisenstein et al*., 2015].

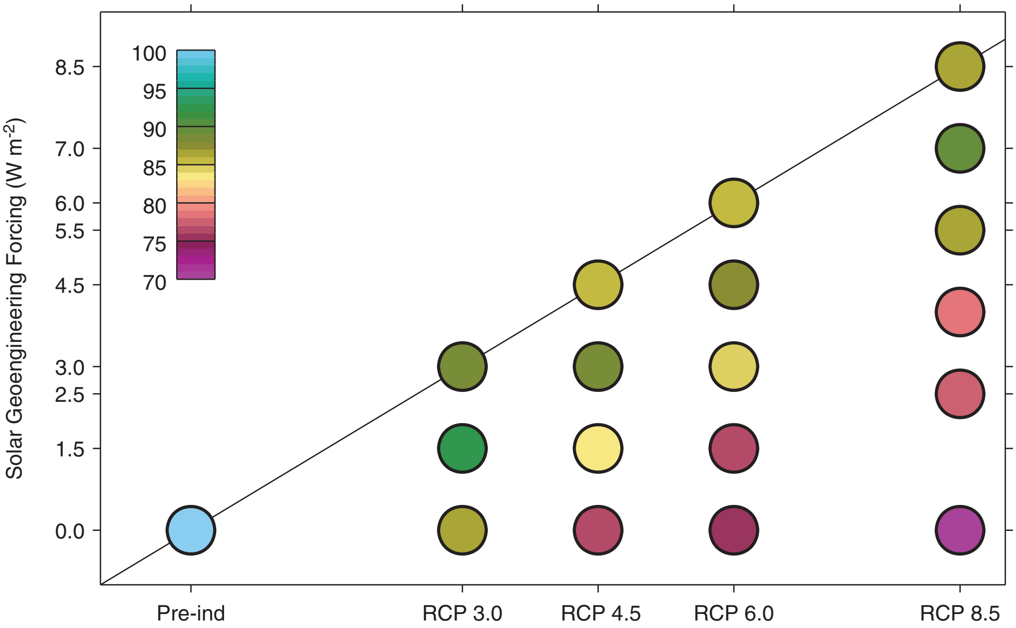

Figure 3. Shallow water tropical coral reef habitat suitability in 2070 (plotted as a percentage relative to preindustrial) under four representative concentration pathways (RCP; bottom row along *x*-axis) and various levels of sunshade geoengineering (*y*-axis). Habitat suitability is defined as the mean probability of a coral reef being present (as a single environmental niche, without resolving biodiversity or community composition) within a shallow water mask between 60°N and 60°S as predicted by bioclimatic envelope modeling. This figure is drawn from the Boosted Regression Trees results produced by *Couce et al*. [2013] who provide a more complete description of the experiments and analysis of these results.

4. Research Gaps

Our review of the climate impacts research into solar geoengineering reveals substantial gaps in understanding. First, there have been few quantitative studies of the climate impacts of solar geoengineering. Almost all of these studies have focused on stratospheric aerosol injection geoengineering, or its proxy sunshade geoengineering, with only a couple of studies into marine sky brightening geoengineering and no studies into the climate impacts of other types of solar geoengineering. Critically, many climate impacts sectors are completely absent from the published literature to date, for example: water resources, flood risk, storm damage, terrestrial ecosystems, fisheries, and vector-borne diseases. Of the few sectors that have been studied (i.e., agriculture, ocean ecosystems, and air pollution; see above) there remains considerable work to constrain the potential climate impacts from solar geoengineering.

The gaps in understanding around the climate impacts of solar geoengineering go beyond simply the absence of studies addressing particular impacts, as solar geoengineering poses novel challenges for climate impacts research that will require novel approaches to address. We outline three key areas in which progress can be made: (1) The comprehensive, systematic assessment of the climate impacts of scenarios of solar geoengineering deployment, (2) the evaluation of the potential and limits of solar geoengineering deployment tailored to reduce climate risks, and (3) the development of objectives to evaluate solar geoengineering deployment scenarios.

Area 1 – Comprehensive, systematic assessment of the climate impacts of scenarios of solar geoengineering deployment.

Evaluating the climate impacts of particular scenarios of solar geoengineering deployment poses many of the same challenges that have been faced in evaluating the climate impacts of scenarios of future GHG emissions. The future development of demography, economy, land-use, and other factors are critical for shaping the exposure and vulnerability of societies and ecosystems to the risks of climate change, and these factors will also need to be accounted for in climate impacts assessments of solar geoengineering by considering a range of future socioeconomic pathways [*O'Neill et al*., 2014]. It will also be critical to account for uncertainties in and among the different impacts models (e.g., the response of systems to climate conditions that are novel), Earth system models (e.g., climate feedbacks and the parameterization of subgrid scale processes), and socioeconomic projections to make a thorough evaluation of risks. Additionally, the linkages between different hazards and different sectors need to be assessed; for example, changes in water availability affect crop yields through effects on irrigation, with cascading impacts on food security, and in turn human health. The climate impacts community is currently working to integrate uncertainty in the socioeconomic projections and interactions between sectors and regions into projections of climate risk, but this work is still at an early stage [*Hallegatte et al*., 2016].

Area 2 – The evaluation of the potential and limits of solar geoengineering deployment tailored to reduce climate risks

In addition to these familiar challenges with impacts assessment modeling, solar geoengineering poses a novel challenge for climate impacts research. GHG emissions policy permits some influence over the future evolution of the climate state; however, there are strong constraints, for example, the economic costs and infrastructural lifetimes, which effectively limit this influence to reducing the magnitude of future warming. On the other hand, the climate consequences of solar geoengineering would depend on how it is *chosen* to be deployed and feasible forms of solar geoengineering present a wide range of options for deployment. For example, the altitude, latitude, season, and rate of release of stratospheric aerosols would be a matter of choice and the consequences of different patterns and rates of release would differ in important ways [*Niemeier et al*., 2011]. Any deployment of solar geoengineering whether in climate models or in the real world, would need to be defined in terms of its inputs, outcomes, or both. For example, GeoMIP includes a stratospheric aerosol injection experiment with a specific, fixed release rate of SO_2 into the tropical lower stratosphere, that is, it is defined only in terms of its inputs, and also a similar experiment where the rate of release is adjusted to halt the increase in radiative forcing due to rising GHG concentrations, that is, it is defined both in terms of its inputs and its outcomes [*Kravitz et al*., 2011]. Focusing solely on the outcomes would be to adopt a design perspective, where the particulars of a solar geoengineering deployment would be chosen specifically to pursue certain objectives such as reducing the impacts of climate change [*Kravitz et al*., 2016].

While solar geoengineering could be tailored with the *aim* of pursuing certain objectives, the large natural variability in the climate and the substantial uncertainty about the climate response to solar geoengineering would limit what could be achieved. Simulation studies have demonstrated that solar geoengineering could be deployed to maintain global mean temperatures at some constant level, or alternatively to slow the rate of change, in the presence of rising GHG concentrations and substantial natural variability [*MacMartin et al*., 2013b, 2014; *Kravitz et al*., 2014b]. In these studies, the global mean temperature was kept close to the target value using simple negative feedback from observations, that is, increasing the amount of light reflected when the planet is observed to be above the target temperature and vice versa. Beyond affecting global mean temperature, solar geoengineering deployment could be tailored in a number of ways to affect regional climate outcomes. Idealized studies have demonstrated that it is in theory possible to "optimize" solar geoengineering deployment to more closely offset the effects of elevated GHG concentrations in terms of regional mean temperature or precipitation, by modifying the latitudinal and seasonal distribution of solar forcing [e.g., *Ban-Weiss and Caldeira*, 2010; *MacMartin et al*., 2013a]. In a climate model study, *Kravitz et al*. [2016] demonstrated a crude version of such regional optimization on an ongoing deployment of solar geoengineering using the same kind of feedback described above.

Nevertheless, no past study has attempted to tailor solar geoengineering deployment to alleviate the *impacts* of climate change. Given that solar geoengineering is being considered as a means to reduce the risks and impacts of climate change this begs the question: What potential deployments of geoengineering could best reduce these risks? To provide robust answers to this question would require surveying the climate impacts of a much broader range of scenarios than have been assessed to date and making quantitative comparisons between alternative outcomes. The degree of certainty to which these outcomes could be attributed to the particular deployment of solar geoengineering in a still poorly understood and noisy climate system would also need to be evaluated.

Area 3 – The development of objectives to evaluate solar geoengineering deployment scenarios.

Policymakers faced with the choice of whether and how to deploy solar geoengineering would want to know how it affects the stakeholders they represent. Clear climate objectives which address the effects of policies on the impacts of climate change would therefore be of great value. An example of this is the high-level objective agreed at the Paris COP21 to limit the global-mean temperature increase, as a proxy for aggregate climate risks, which is being used to guide national emissions policies. While solar geoengineering deployed along with emissions cuts could make it possible to reach the 2.0 or even 1.5°C global-mean temperature targets, the climate impacts of limiting the global mean temperature by stringent emissions cuts would be different from those of achieving the same target by moderate emissions cuts supplemented by cooling from solar geoengineering [*Tilmes et al*., 2016]. This means that global mean temperature would not be a good proxy for aggregate climate risks if solar geoengineering were to be deployed. To inform decisions on whether and how to include solar geoengineering as part of a portfolio of climate policies an objective (or objectives) which appropriately captures the climate risks of these different choices would be valuable.

An appropriately defined climate objective, that is, one which can serve as a reasonable proxy for overall climate risks, might also be a useful target for the tailoring of solar geoengineering deployment. To date, studies which have defined an objective for solar geoengineering deployment have typically formulated it in terms of restoring mean temperature and precipitation conditions of some baseline climate [*Ban-Weiss and Caldeira*, 2010; *Moreno-Cruz et al*., 2011; *Kravitz et al*., 2014a, 2016]. However, it will be important in future work to address the effects of solar geoengineering on the full range of different climate impacts. Initial studies have illustrated a number of trade-offs that would need to be addressed in defining an objective (or objectives) for solar geoengineering deployment. For example, the goals of restoring precipitation patterns and restoring Arctic sea-ice cover to a low-GHG state would be best achieved by different deployments of solar geoengineering [*MacMartin et al*., 2013a]. In addition, due to regional differences in the climate response to solar geoengineering the deployment which best achieves an objective in one region is not going to be the same as that to achieve it in all others [*Kravitz et al*., 2014a]. Formulating objectives to aid decision-making on whether and how to deploy solar geoengineering will thus be a major challenge and one in which climate impacts research will have an important role.

5. Ways Forward

Here we provide some recommendations on how the field might make significant headway in providing a comprehensive understanding of the impacts of solar geoengineering. These recommendations ultimately require that the field moves from a curiosity-driven approach to one that is more strategic about addressing key scientific uncertainties.

Recommendation 1 – Drive impacts models with standardized solar geoengineering scenarios and prioritize the most pressing analyses.

While a comprehensive climate impacts assessment of scenarios of solar geoengineering deployment will be challenging, many of the tools and much of the expertise needed have already been developed. For example, the Inter-Sectoral Impacts Modelling Intercomparison Project (ISIMIP) has developed a framework for meeting the same basic challenges in assessing the risks of climate change [*Warszawski et al*., 2014]. ISIMIP has drawn together previously independent efforts to evaluate climate change impacts on various sectors and at different temporal and spatial scales. It has produced ensemble-based, cross-sectoral and quantitative projections by developing a consistent approach to climate data processing and bias correction, and employing shared socioeconomic projections [*Hempel et al*., 2013; *Warszawski et al*., 2014].

The Geoengineering Model Intercomparison Project (GeoMIP) [*Kravitz et al*., 2011] has been developing and analyzing a set of solar geoengineering experiments that could be used as input for future climate impacts studies. Its outputs can be used in the same way as the RCP scenario simulations from the Coupled Model Intercomparison Project 5 (CMIP5) are used in efforts to project the impacts of global warming (such as in ISIMIP). These GeoMIP results are archived in the same databases and to the same standards as the CMIP5 results and are publically available through the Earth System Grid Federation network (http://esgf.llnl.gov/). The next round of GeoMIP simulations will include a small number of core experiments addressing various forms of solar geoengineering including, for example, the G6 experiment where sulfate aerosol injection (and alternatively sunshade) geoengineering is deployed against a backdrop of a high-emissions scenario to reproduce the radiative forcing of a moderate-emissions scenario, as well as a number of idealized experiments. These simulations are being produced on the same schedule as the CMIP6 simulations with results expected through 2017 [*Kravitz et al*., 2015]. Thus, a timely opportunity exists to combine the ISIMIP framework with state-of-the-art projections from Earth system models run under specific solar geoengineering scenarios.

Given the wide range of possible scenarios of solar geoengineering deployment, climate impacts sectors, and regions to analyze we recommend a number of priorities for this research. We recommend that those forms of solar geoengineering in which there is the greatest confidence that they are technically feasible be given the highest priority, that is, stratospheric sulfate aerosol injection or marine cloud brightening geoengineering [*Boucher et al*., 2013]. That said solar dimming experiments are useful learning tools as they eliminate some of the complications and uncertainties posed by the other forms of solar geoengineering. Furthermore, there should be a systematic approach to address the knowledge gaps, with impacts that have not received a great deal of attention previously, such as water resources, terrestrial ecosystems, and human health, being given the highest priority. It may be useful to consider a number of regional "test cases" to explore interdependencies of risks and to aid in accounting for the specifics of different regional exposures and vulnerabilities to the range of risks that climate change poses and that solar geoengineering would affect. A number of priority regions have been identified for climate impacts research, which, for the purpose of synergy, would be useful to choose here [*Warszawski et al*., 2014].

Recommendation 2 – Make a structured comparison of the climate impacts of a wide range of scenarios of future GHG forcing and possible deployments of solar geoengineering using emulators of more complex models.

The handful of scenarios produced by GeoMIP can neither span the full range of possible combinations of GHG and solar geoengineering scenarios nor capture the ways in which solar geoengineering could be tailored. As an example, conducting the analyses shown in Figure 3 using fully complex Earth System Models and climate impacts models to investigate the full range of plausible scenarios would be computationally prohibitively expensive. Instead, reference scenarios, such as the GeoMIP G6 experiment [*Kravitz et al*., 2015], could be used to develop computationally efficient emulators of the effects of solar geoengineering so a wider range of scenarios could be explored [*Cao et al*., 2015]. Simplified methods, such as linear scaling [e.g., *Irvine et al*., 2010, *Ricke et al*., 2010; *Kravitz et al*., 2014a) or climate emulation (also called pattern scaling, e.g., *Rougier and Sexton* [2007], *Sanderson et al*. [2008], and *Osborn et al*. [2014]) which has already been applied to climate impacts studies, for example *Gerten et al*. [2013] and [*Arnell et al*., 2016], may show particular promise for exploring the range of climate model responses to geoengineering in a cheaper, computationally efficient way.

Ultimately, these simulations could be used to address tradeoffs between solar geoengineering and emissions cuts as means for achieving particular temperature targets. There has already been substantial work to describe and quantify the impacts of different levels of mean global warming under different GHG emissions scenarios [*Arnell et al*., 2016; *Schewe et al*., 2014]. This could be extended by investigating the climate impacts of cases which achieve a certain temperature target with different scenarios of GHG emissions and solar geoengineering deployment, as was done for Figure 3. In addition, different manners of deploying solar geoengineering, different methods, or combinations thereof could be compared within such a framework to ascertain which deployments might be more optimal for particular impacts. However, the substantial uncertainties in the climate response to GHG forcing and solar geoengineering will need to be accounted for and would limit the confidence in such projections.

Recommendation 3 - Apply the concept of dangerous climate change to develop quantifiable objectives for the evaluation of solar geoengineering.

We recommend that the climate research community apply the concept of dangerous climate change to scenarios including solar geoengineering. The concept of dangerous climate change has helped to focus discussions and clarify issues in climate change and, appropriately modified, it may serve the same function in the discussion of solar geoengineering. Five "reasons for concern" were first elaborated in the IPCC's third assessment report as a means to inform the declared intention of the UNFCCC to avoid "dangerous climate change" [*McCarthy*, 2001]: risks to unique and threatened systems, extreme weather events, the distribution of impacts, global aggregate impacts, and large-scale singular events. These same reasons for concern could help provide a framework for understanding the complex mix of potential benefits and risks of different scenarios of GHG emissions and solar geoengineering deployment (we briefly review the potential effects of solar geoengineering on each of these reasons for concern in section 3 of Appendix S1). However, it may be necessary to complement such a framework by incorporating novel concerns such as the risk of rapid warming that would follow if solar geoengineering deployment were to be terminated at a point when a large cooling effect was being exerted [*Matthews and Caldeira*, 2007].

Just as there has been a demand for quantifiable objectives for climate policy, for example, global-mean temperature targets and carbon budgets, there may be a demand for similar objectives to guide possible solar geoengineering deployment. Such objectives will be of value for evaluating the different ways that solar geoengineering could be deployed [*Kravitz et al*., 2016]. Evaluating climate impacts and summarizing these results in terms of the reasons for concern outlined above supported the assessment of what would constitute dangerous climate change, that is, in setting temperature targets, and hence served to guide the formulation of climate policy goals. In the same manner, evaluating the climate impacts of solar geoengineering and evaluating the effects on these reasons for concern could provide the basis for quantifiable objectives for solar geoengineering deployment and thereby inform the debate as to whether solar geoengineering could be a serious option to be considered along with GHG emissions mitigation.

6. Conclusions

We have described the current state of knowledge about the climate impacts of solar geoengineering on natural and human systems and revealed substantial research gaps. First, we noted that the climate response to the various forms of solar geoengineering is markedly different from that to GHG-induced warming. Until now there have been very few studies on the climate impacts of solar engineering, covering only a limited number of sectors (agriculture, coral reefs, and air pollution). For example, the absence of studies into the effect on water resources seems a glaring omission given that climate model results robustly indicate systematic differences in the hydrological responses to GHG forcing and solar geoengineering. We therefore conclude that a thorough climate impacts assessment is needed to provide input to the question of whether and how to deploy solar geoengineering.

Unlike efforts to cut emissions, solar geoengineering deployment has the potential to be tailored to some extent to pursue particular objectives by, for example, modifying the latitude, altitude, and rate of injection of aerosols into the stratosphere. This possibility poses a novel challenge for climate impacts research as a small number of standard scenarios will be insufficient to adequately capture the full range of possible deployment choices and so to provide answers for the range of questions that will arise. To address this issue we recommend the use of emulation of the results of standard scenarios of solar geoengineering deployment as a means to broaden the range of cases that can be studied. However, we caution that the substantial uncertainties in the climate response to solar geoengineering will limit the extent to which solar geoengineering deployment could be tailored.

No form of solar geoengineering could simply reverse the effects of climate change; rather, it may reduce some environmental changes (e.g., temperature rise and sea level rise), leave others largely unaffected (e.g., ocean acidification), and introduce novel environmental changes (e.g., ozone loss in the case of stratospheric aerosol injection geoengineering). Therefore, if solar geoengineering is deployed, global mean temperature would no longer be a reasonable measure of the level of danger posed by climate change. Accordingly, we suggest that the concept of dangerous climate change be applied to solar geoengineering, whereby evaluating the effect of solar geoengineering on the five “reasons for concern” may be a useful first step. Though not the focus of this paper, it is important to note that there are also many issues beyond climate impacts, including ethics, engineering, economics, and international law, which need to be considered before a knowledgeable decision could be made about the deployment of any form of solar geoengineering.

To provide a reasonable answer to the question of whether, and if so, how, solar geoengineering should be deployed will require understanding whether it could reduce climate risks overall and how it would redistribute the burden of those risks. The engagement of the climate impacts modeling community with this challenging emerging issue will therefore be critical in the coming years.

Appendix A: References for Supplementary Review

The Supporting information contains an extensive review of the climate response to solar geoengineering and cites the following papers [*McCarthy*, 2001; *Weaver et al*., 2001; *Cox et al*., 2004; *Wigley*, 2006; *IPCC*, 2007, 2014; *Matthews and Caldeira*, 2007; *Lunt et al*., 2008; *Tilmes et al*., 2008, 2009; *Irvine et al*., 2009, 2010, 2011, 2012, 2014a, 2014b, 2016; *Kravitz et al*., 2009, 2013, 2014a; *Mercado et al*., 2009; *Murphy*, 2009; *Ridgwell et al*., 2009; *Bala et al*., 2010; *Moore et al*., 2010, 2015; *Meinshausen et al*., 2011; *Trenberth*, 2011; *Vaughan and Lenton*, 2011; *Jones and Haywood*, 2012; *Lau and Kim*, 2012; *Partanen et al*., 2012; *Schmidt et al*., 2012; *Seneviratne et al*., 2012; *Alterskjær et al*., 2013; *Boos and Hurley*, 2013; *Camargo*, 2013; *Cheng et al*., 2013; *Collins et al*., 2013; *Couce et al*., 2013; *Cziczo et al*., 2013; *Jones et al*., 2013; *Niemeier et al*., 2013; *Schuur et al*., 2013; *Sillmann et al*., 2013a, 2013b; *Curry et al*., 2014; *Davin et al*., 2014; *Joughin et al*., 2014; *Kalidindi et al*., 2014; *MacMartin et al*., 2014, 2015; *Pitari et al*., 2014; *Storelvmo et al*., 2014; *Applegate and Keller*, 2015; *Crook et al*., 2015; *Gabriel and Robock*, 2015; *Glienke et al*., 2015; *Kristjánsson et al*., 2015; *Kwiatkowski et al*., 2015; *McCusker et al*., 2015; *Mengis et al*., 2015; *Muri et al*., 2015; *Dagon and Schrag*, 2016; *Ferraro and Griffiths*, 2016].

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