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Overview

An overview of the Earth system science of solar geoengineering

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Solar geoengineering has been proposed as a means to cool the Earth by increasing the reflection of sunlight back to space, for example, by injecting reflective aerosol particles (or their precursors) into the lower stratosphere. Such proposed techniques would not be able to substitute for mitigation of greenhouse gas (GHG) emissions as a response to the risks of climate change, as they would only mask some of the effects of global warming. They might, however, eventually be applied as a complementary approach to reduce climate risks. Thus, the Earth system consequences of solar geoengineering are central to understanding its potentials and risks. Here we review the state-of-the-art knowledge about stratospheric sulfate aerosol injection and an idealized proxy for this, 'sunshade geoengineering,' in which the intensity of incoming sunlight is directly reduced in models. Studies are consistent in suggesting that sunshade geoengineering and stratospheric aerosol injection would generally offset the climate effects of elevated GHG concentrations. However, it is clear that a solar geoengineered climate would be novel in some respects, one example being a notably reduced hydrological cycle intensity. Moreover, we provide an overview of nonclimatic aspects of the response to stratospheric aerosol injection, for example, its effect on ozone, and the uncertainties around its consequences. We also consider the issues raised by the partial control over the climate that solar geoengineering would allow. Finally, this overview highlights some key research gaps in need of being resolved to provide sound basis for guidance of future decisions around solar geoengineering.

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INTRODUCTION

Solar geoengineering has been proposed as a means of reducing some of the risks of climate change caused by rising greenhouse gas (GHG) concentrations. The aim of proposed solar geoengineering techniques is to increase the reflection of sunlight back to space by various means to cool the climate. Numerous climate modeling studies have shown that while no solar geoengineering technique can completely reverse the climate change caused by elevated atmospheric GHG concentrations, they may be able to offset a large fraction of the changes in several key climate variables, such as temperature and precipitation, thus potentially reducing climate risks.[1–3] Stratospheric aerosol injection (SAI) is widely discussed as a promising solar geoengineering proposal in terms of its potential to cool the Earth,[4] and its assumed technological feasibility.[5] The climate could be cooled as a result of

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injecting aerosol particles (in particular sulfate particles) into the stratosphere (a layer of the atmosphere that begins between 10 and 18 km above the surface). The particles would scatter and reflect solar radiation, increasing the planetary reflectivity (albedo), and cooling the climate.[6]

There are a number of other potentially effective solar geoengineering proposals that are not as well understood as SAI. Marine cloud brightening is a proposal to inject sea salt aerosols into the marine boundary layer to directly scatter light, and particularly to increase the albedo of low-lying clouds.[7] There are also proposals to increase the land surface albedo through the application of reflective materials in deserts or other areas, or through the enhancement of cropland albedo.[8,9] Cirrus cloud thinning is a proposal to inject aerosol particles to reduce the thickness and lifetime of cirrus clouds, allowing more thermal radiation to escape to space.[10] Though cirrus cloud thinning is not technically a 'solar' geoengineering proposal, it raises similar issues. Finally, the idea of solar geoengineering by placing an array of mirrors in space, so-called sunshade geoengineering, is occasionally discussed.[11] While the logistics involved render this idea unrealistic for implementation in the foreseeable future, it represents a very simple form of solar geoengineering to simulate with models, and the results of such modeling studies are considered in Section *Climate Response to Sunshade Geoengineering* of this article, before we proceed to considering the specific response to SAI in Section *Effects of Stratospheric Aerosol Injection Geoengineering*.

In its summary of SAI, the Intergovernmental Panel on Climate Change (IPCC) concluded that there is medium confidence that a radiative forcing of −4 W m^{-2}, approximately equivalent to reversing the radiative forcing effects of a doubling of the pre-industrial CO_2 concentration, could be achieved through the injection of 10 million tons of sulfur (S) annually into the stratosphere.[4] The injected aerosol particles would have a lifetime of approximately 1–3 years,[12] depending on their size, implying that if the injection of aerosols were terminated over a short period of time, there would be a rapid warming, a problem referred to as a 'termination shock' in the literature.[13–15]

In this article, we delve deeper into understanding the potential of SAI, discussing some of the expected climate effects of solar geoengineering as have been revealed in the peer-reviewed literature, as well as discussing several key research gaps:

1. Many climate model simulations of solar geoengineering have used the simple proxy representation of reducing total solar irradiance, here called sunshade geoengineering (Section *Climate Response to Sunshade Geoengineering*). This method is easy to implement in the models and represents some of the first-order climatic effects of SAI. Nevertheless, the differences between the relatively well-characterized simulations of sunshade geoengineering and simulations of SAI geoengineering are substantial (Section *Effects of Stratospheric Aerosol Injection Geoengineering*).
2. The models used to project Earth system changes in the coming century typically do not represent all the relevant processes for simulating stratospheric aerosols and so may not represent SAI well (Section *Effects of Stratospheric Aerosol Injection Geoengineering*). These modeling challenges are compounded by the limited sources of evidence available to validate the models' performance.
3. There is a potentially wide range of ways that solar geoengineering could be deployed and thus a wide range of possible consequences. This raises questions about what objectives would be pursued and how to evaluate their consequences, and, if a large-scale implementation of any form of solar geoengineering were to be pursued, how to design a deployment to best achieve specific objectives (Section *Solar Geoengineering as One Means of Limiting the Impacts of Climate Change*). Solar geoengineering is one option among others for addressing climate risks, which offers unique possibilities but also poses unique risks.

This overview does not address the many significant governance and ethical challenges posed by solar geoengineering. We suggest that the interested reader refer to, for example, the review of the ethical issues by Preston,[16] and the report of the European Transdisciplinary Assessment of Climate Engineering (EuTRACE) project.[17]

CLIMATE RESPONSE TO SUNSHADE GEOENGINEERING

This section summarizes the current state of knowledge about sunshade geoengineering as a proxy for SAI, with a focus on key climate variables, including changes in temperature, the hydrological cycle, sea level, vegetation, and the carbon cycle. We cover the range of topics that have been addressed in published material, but many aspects have yet to be investigated. Most of the results in the following section are based on findings from the idealized sunshade geoengineering experiment G1 of the Geoengineering Model Intercomparison Project (GeoMIP).[18] In this simulation, an instantaneous quadrupling of the CO_2 concentration (4xCO_2) relative to a preindustrial baseline case (piControl) is balanced by a reduction in incoming solar radiation (insolation) to maintain the same top-of-atmosphere radiative balance as in the piControl simulation. Consequently, global mean temperature in G1 remains about the same as its preindustrial value. To achieve this, insolation in each model was reduced by 3.5–5.0%, depending upon the model.[1] Despite being highly idealized, these experiments can provide useful information about the climate responses to scenarios with more realistic GHG forcing inputs, such as those based on the Representative Concentration Pathways (RCPs).[19] The sunshade geoengineering studies can also provide useful information about many aspects of what might be expected with an implementation of SAI, though there are some notable differences in the climatic response, as discussed in Section *Effects of Stratospheric Aerosol Injection Geoengineering*. Kravitz et al.[1] summarize the multi-model climate response to the G1 and 4xCO_2 experiments, providing several figures that illustrate the regional responses and may be used as a valuable supplement to the descriptions below.

One of the main lessons learned with the sunshade geoengineering simulations, as emphasized also by Boucher et al.,[4] is that simulations consistently suggest that a climate with elevated GHG concentrations and solar geoengineering (G1) would be more similar to that of a low-GHG climate (piControl) than a climate with elevated GHG concentrations alone (4xCO_2). However, neither sunshade geoengineering, nor any other form of solar geoengineering is capable of fully reversing the effects of elevated GHG concentrations; that is, there is a significant residual climate change when comparing the G1 and piControl simulations (G1–piControl).

Temperature and Extremes

A large reduction in incoming sunlight, as simulated in the G1 experiment, would reduce the global-mean temperature and surface temperatures everywhere compared to the temperatures in the 4xCO_2 simulation. However, differences between the solar and GHG forcing result in geographical and temporal temperature differences from piControl[4] (Figure 1). The greatest temperature reductions in these simulations occur in those regions which are expected to show the greatest warming under elevated GHG conditions, that is, at high-latitudes where strong positive feedbacks act on temperature changes.[1,20] In addition to mean temperature changes, the distribution of extreme temperature events shifts in the simulations; extreme hot event frequencies are reduced in G1 as compared to those of 4xCO_2, and extreme cold event frequencies are increased.[21] In experiment G1, simulations show an overcooling (relative to piControl) in tropical ocean regions and a residual temperature increase over high-latitude land regions and in polar regions (G1–piControl), although the magnitude of these changes is small compared with the avoided warming (4xCO_2–piControl).[1] Additionally, night-time temperatures are expected to rise more quickly than day-time temperatures under global warming; sunshade geoengineering would partially reverse this effect in most regions.[22]

Hydrological Cycle and Its Extremes

Global mean precipitation will increase with global warming, referred to as hydrological cycle intensification.[23] This response is composed of a 'slow' hydrological response to warming that increases the intensity of the hydrological cycle and a 'fast' response to the effects of GHGs on the atmospheric energy budget that suppresses the intensity of the hydrological cycle.[24] The net effect of anthropogenic emissions is an increase in the intensity of the hydrological cycle.[25] Solar forcing acts primarily on the surface, hence balancing GHG forcing by solar reduction, as in the G1 experiment, results in a more stable troposphere from the effects of GHG on the atmosphere, suppressing rising motion and hence reducing the intensity of the hydrological cycle. Tilmes et al.[26] showed that in experiment G1, which restores the global-mean temperature to the value in piControl (and hence cancels the 'slow' temperature-driven effect on the global-mean hydrological cycle), there is a reduction in the intensity of the hydrological cycle that is roughly equal to the 'fast' response to the elevated GHG concentration (Figure 2).

The regional hydrological response to global warming can be crudely summarized by noting that wet regions tend to get wetter and dry regions tend to get drier, largely due to a combination of changes in circulation and the equilibrium amount of water in the air at higher temperatures.[23,27] Regional hydrological conditions in G1 are more similar to piControl than those of 4xCO_2. However, there remain substantial regional hydrological cycle differences when comparing G1 against piControl (Figure 1). Global monsoon precipitation is

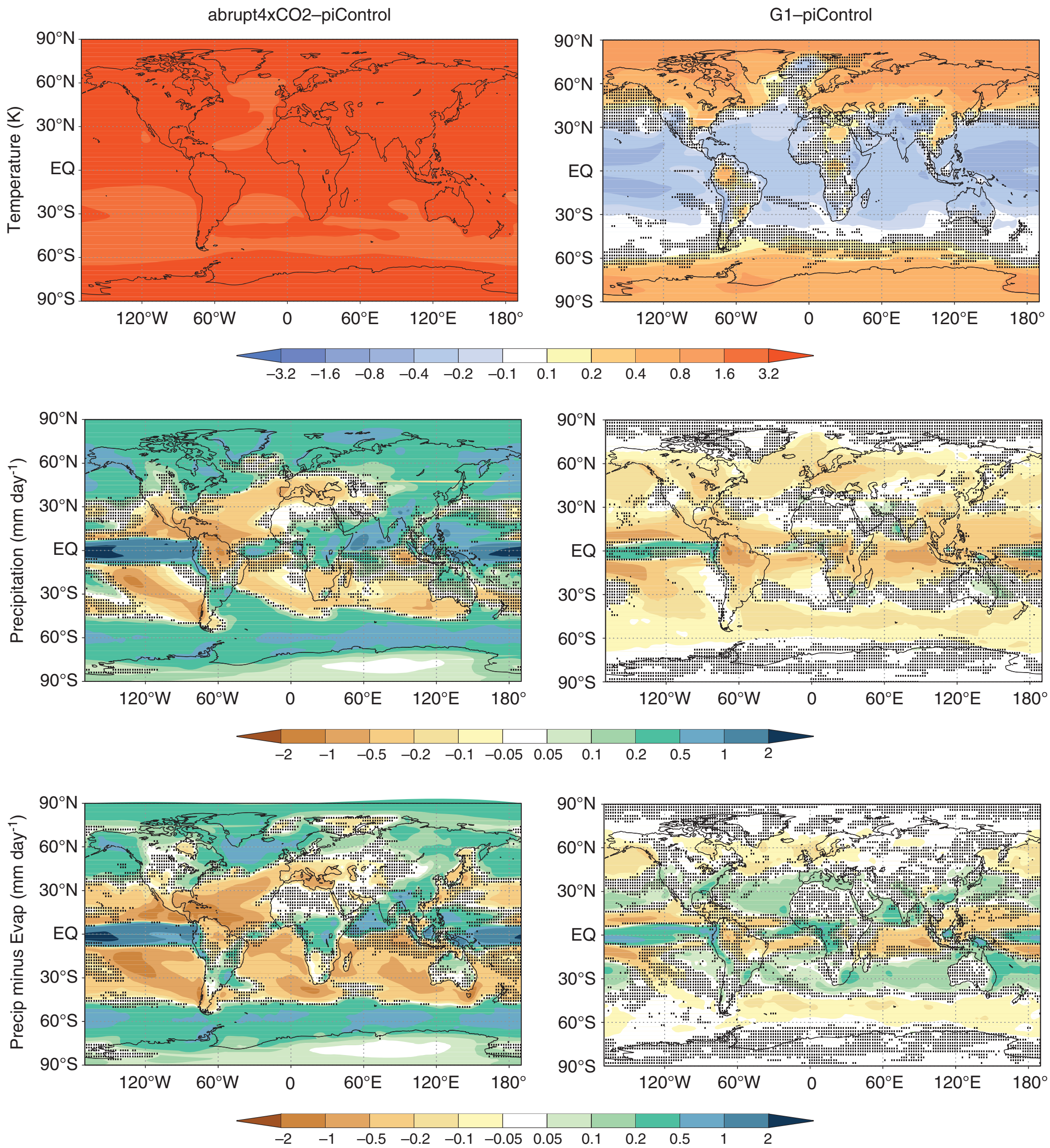

FIGURE 1 | Surface air temperature (K; top panels), precipitation (mm day^{-1}; middle panels), and precipitation minus-evaporation (mm day^{-1}; bottom panels) differences averaged over years 11–50 of simulation. Panels show an average of 12 models participating in the Geoengineering Model Intercomparison Project (GeoMIP) 15. Stippling indicates when fewer than 9 of 12 models agree on the sign of change. See Kravitz, et al.[1] for additional details.

approximately 5% higher than piControl under $4xCO_2$ and is approximately 5% lower than piControl under G1 (Tilmes et al.[26] provide a thorough discussion of regional precipitation effects and monsoonal precipitation changes). Over land, even though precipitation decreases in G1 relative to piControl, evaporation decreases are typically greater, resulting in a net increase in runoff (as measured by precipitation minus evaporation; Figure 1).[1]

The intensity of precipitation (i.e. the frequency of floods and droughts) is projected to increase due to anthropogenic emissions of GHGs and rising temperatures.[28] This general tendency would be reversed by sunshade geoengineering, with more low-intensity rainfall events and fewer, weaker extreme precipitation events.[21,26]

Large changes in the global hydrological cycle and its consequences at the regional level are often discussed as a potential risk of solar geoengineering.

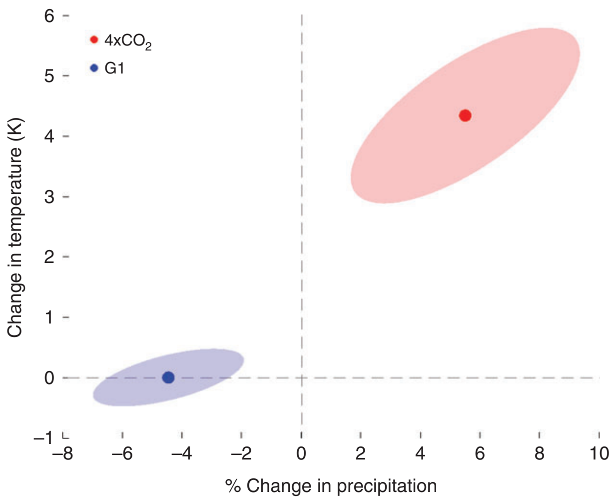

FIGURE 2 | Changes (from piControl) in global mean temperature (K; y-axis) and global mean precipitation (%; x-axis) for the 4xCO2 (red) and G1 (blue) simulations. Points represent a 12-model mean, and ellipses represent the range of model responses. All values are averaged over years 11–50 of simulation.

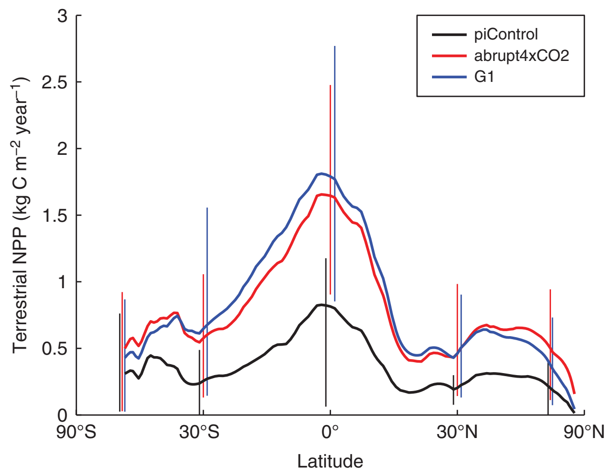

FIGURE 3 | Zonally averaged terrestrial net primary productivity (NPP) for piControl (black), 4xCO2 (red), and G1 (blue). x-axis is plotted as the sine of latitude to account for different areas of latitude bands. Thick lines indicate an 8-model average. Thin vertical lines indicate the range of model spread at five different latitudes. See Kravitz, et al.[1] and Glienke, et al.[29] for more details.

However, changes in the hydrological cycle are not straightforward to interpret. Simulations of solar geoengineering show that it would generally reduce precipitation on land, particularly in monsoon regions.[26] However, these reductions in precipitation are also accompanied by a reduction in evaporation that results in a net increase in runoff in many regions that show a decline in precipitation.[1,29] Vegetation plays an important role in the hydrological cycle and changes to the climate and to CO_2 concentrations will affect this important relationship.[29]

Vegetation Response

The response of vegetation has been argued to be a useful aggregator of changes in the climate as it can indicate whether or not growth is being hampered or promoted.[1,29,30] In both $4xCO_2$ and G1, the direct effect of CO_2 on plant growth accounted for nearly a doubling of net primary productivity (NPP; a measure of the total carbon flux from the atmosphere to the plants), with disagreement between models as to which experiment shows the highest NPP.[1,15,29] CO_2 fertilizes plant growth and also reduces transpiration and preserves water, increasing the water-use efficiency of plants; this mechanism is responsible for an observable greening of arid regions since the 1980s.[31,32] However, it has been found that the magnitude of this CO_2 fertilization effect is likely constrained by the availability of nitrogen and phosphorus, which is not represented in many global climate models.[33] Figure 3 compares the response of NPP in $4xCO_2$ and G1 and illustrates that the climate effects of sunshade geoengineering matter at the regional-scale. For G1–$4xCO_2$, a relative decrease in NPP at high latitudes for all models was found due to the reduced temperature increase, which would allow vegetation to grow in these cold regions.[29] There was also a relative increase in NPP in tropical regions for most models due to the reduced respiration at lower temperatures with sunshade geoengineering.[29] In addition, Glienke et al.[29] found that many regions which show an absolute decline in precipitation and P-E for G1–piControl, that is, those which have a drying trend, show an increase in NPP. The effect of sunshade geoengineering on crops is discussed in Section *Climate Impacts of Solar Geoengineering*; the crop response represents a special case as their environment is more-or-less controlled and different modeling tools are used to assess their response.

Vegetation productivity is also affected by a number of other factors including soil properties, the quality of light (the fraction of diffuse and direct light) and tropospheric chemistry. The effect of SAI geoengineering on tropospheric chemistry and the quality of light, and the implications of these changes on vegetation are discussed in Sections *Tropospheric Effects of Aerosol Deposition* and *Changes in Quality Of Light*, respectively.

Vegetation plays an important role in the hydrological cycle, with transpiration from vegetation responsible for a considerable fraction of total evapotranspiration on land.[34] CO_2 increases the water-use efficiency of vegetation, which causes a substantial reduction in transpiration and a substantial increase in runoff.[31,35] However, the fertilization effect of CO_2 on plants increases NPP which increases transpiration, somewhat offsetting this reduction in transpiration.[31] Irvine et al.[36] found that the very large uncertainty in the magnitude of NPP response for G1–piControl in the GeoMIP models (in some models NPP was more than twice as high as in others) was likely behind the large spread in tropical hydrological response due to the hydrological impact of NPP on transpiration.

The Carbon Cycle

The projected increases in NPP of vegetation would be expected to be reflected in the carbon cycle, though the exact effect will depend on the fate of the carbon that is taken up by the vegetation. Under scenarios of global warming, the land surface is projected to shift from a net sink to a net source of carbon as increases in soil respiration will liberate carbon stored in soils across the world.[37] Sunshade geoengineering would reduce this increase in temperature, so it will likely suppress soil respiration while potentially retaining most of the increases in vegetation productivity, leading to increased carbon storage on land and a potentially large reduction in atmospheric CO_2 concentrations.[13,29,38] However, recent attempts to include a nitrogen cycle in an Earth system model have resulted in a weaker terrestrial response than those earlier, simpler studies[39] In addition, sunshade geoengineering would reduce high latitude temperatures, which would reduce the rate of permafrost melting and possibly help prevent the release of sub-sea methane clathrate deposits, although this has yet to be evaluated.

Tjiputra et al.[39] found that the ocean absorbs 10% more carbon in the solar geoengineered scenario, similar to earlier findings with simpler models.[38,40] CO_2 is more soluble in colder seawater, so solar geoengineering increases inorganic carbon storage across most ocean areas. One exception is the Arctic, which stores less carbon because geoengineering encourages sea ice recovery, reducing the exposure of Arctic seawater to the atmosphere. Tjiputra et al.[39] also found that the so-called biological pump of carbon from the surface to depth (sinking biomass) is increased in the solar geoengineered case, as there is less stratification of surface waters (a projected effect of global warming) and increased upwelling of nutrient-rich waters to the surface, both of which boost the productivity of ocean surface waters. The strength of the meridional overturning circulation, which transports CO_2-rich Atlantic surface waters to depth, is projected to decline as the climate warms due to reduced sea-ice formation and increased fresh-water runoff, suppressing the formation of the cold, salty plumes of sinking water that drive this flow.[41] Tjiputra et al.[39] find that in their simulations, solar geoengineering maintains the strength of the meridional overturning circulation leading to a much greater transport of inorganic carbon to the interior of the Atlantic Ocean than in the reference case, contributing to the global reduction in atmospheric CO_2 concentrations but leading to a considerable acidification of these deep waters. Together these effects result in little change in surface pH in these simulations,[39] but the aragonite saturation level, important to the formation of the shells of certain calcifying organisms, would still decline, as this is reduced at lower temperatures.[40] However, studies of the impacts solar geoengineering on coral reefs suggest that the impacts of temperature change would be greater than those of reduced aragonite saturation level.[42,43]

Sea Level Response

Global sea-level rise can be driven either by an increase in the mass of water in the oceans, due to reduced storage of water on land primarily caused by the melting of ice, or by an increase in the volume of water, due to the thermal expansion of water (thermosteric sea-level rise). Sunshade geoengineering, or any form of solar geoengineering, would reduce the rate of thermosteric sea-level rise, as it would reduce the heat flow into the oceans.[14,44] The response of glaciers and ice-sheets is more complicated, as it depends upon the balance between accumulation of mass from precipitation and losses from melting and from the calving of icebergs into the oceans. While sunshade geoengineering would reduce precipitation (reduced accumulation) in most regions, idealized simulations of the response of the Greenland ice sheet to the G1 experiment suggest that the reduced temperatures (reduced loss) would have a greater influence in that region.[45] Simulations varying the reduction in insolation found that the Greenland ice-sheet could be stabilized by a deployment of sunshade geoengineering even if temperatures in that region are not restored fully to the pre-industrial value.[45] However, there is considerable uncertainty regarding the temperature rise sufficient to destabilize the ice-sheet.[46] Irvine et al.[14] found that sunshade geoengineering deployed early in the 21st Century could greatly reduce sea-level rise, though halting it would require offsetting all anthropogenic forcing (See Figure 4). While sunshade geoengineering could

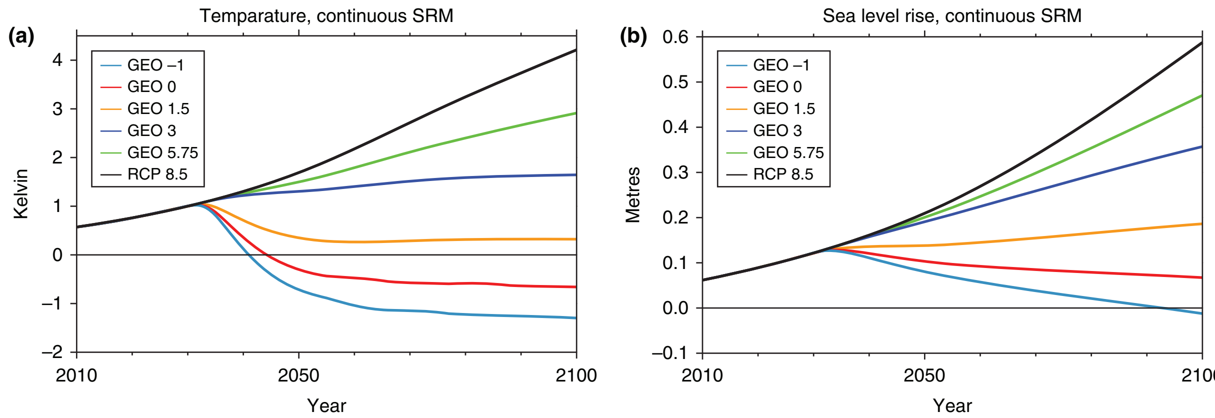

FIGURE 4 | Global mean temperature (a) and sea-level rise (b) response for the RCP 8.5 high GHG emissions scenario and a range of solar geoengineering scenarios. The different colored lines show scenarios of solar geoengineering deployment with background GHG emissions from RCP 8.5 that achieve different total radiative forcing values at year 2100, that is, GEO 1.5 (yellow line) has a net radiative forcing of +1.5 Wm^{-2} in 2100. The methods used to estimate the sea-level response to these scenarios is described in Irvine, et al..[14] (Reprinted with permission from Ref .[14] Copyright 2012 Nature Publishing Group)

reduce sea-level rise, simulations employing more sophisticated models suggest that hysteresis in the response of the Greenland and Antarctic ice sheets to climate change could mean that there may be a limited ability to reverse some of the contribution to sea-level rise from the ice-sheets if deployment of solar geoengineering is delayed.[47,48]

EFFECTS OF SAI GEOENGINEERING

While sunshade geoengineering is a useful first-order approximation to SAI, the effects of SAI will differ from that of sunshade geoengineering in important ways. Here we complement and extend the review of solar geoengineering by Robock,[49] highlighting the basic processes that shape the consequences of SAI and some of the broad differences between sunshade geoengineering and SAI. While we focus on sulfate aerosols throughout, we also note that alternative aerosol particles, such as aluminum oxide, titanium dioxide, or black carbon, would have qualitatively similar climate effects, though with important differences in the magnitude and distribution of those effects.[50–53]

Generating a Stratospheric Sulfate Aerosol Cloud

The most commonly discussed approach to generate a stratospheric sulfate aerosol layer would be to release a gaseous sulfate aerosol precursor such as SO_2 in the stratosphere. This gas then oxidizes over a period of weeks to form sulfuric acid, which condenses to form aerosol particles.[54] Once the aerosols are formed, particles begin to coagulate, and gaseous precursors condense onto existing aerosol particles, resulting in larger aerosol sizes. For higher rates of injection, these processes have larger aggregate effects, shifting the aerosol size distribution toward larger, less reflective particles, resulting in diminishing returns.[54,55] The size of the aerosol particles in the cloud is critical as it determines: (1) how well light is scattered, with a diameter of around 0.1 micron being most effective;[56] (2) the lifetime of the aerosols, as larger particles sediment more rapidly;[55] and (3) the amount of stratospheric heating by the aerosols, which undermines the scattering effect to some extent.[12,56]

It could also be possible to gain more direct control over the aerosol particle size distribution by either releasing sulfuric acid (H_2SO_4) directly, or by injecting pre-formed particles of some other composition such as TiO_2.[50] Any of these possibilities would have the challenge of more difficult logistics, as well as additional degrees of uncertainty in the technological feasibility (e.g., nozzle technologies which would produce particles of appropriate sizes under the flight conditions). Focusing particularly on the case of emitting H_2SO_4 instead of SO_2, simulations suggest that the H_2SO_4 would condense rapidly in the release plume, and that this would allow more control over the aerosol size distribution,[56] potentially avoiding some of the scaling problems seen for SO_2 release.[55,56] However, more research is needed to determine whether the desired aerosol particle distribution could be achieved. In particular, models that can represent in-plume processing may be critical; English et al.[57] simulated release of H_2SO_4 over a large volume but did not consider in-plume dynamics, and so they did not replicate the methods or results of Pierce et al.[56]

The injection strategy for SAI would be critically important in determining the efficacy and consequences of the deployment. Injecting SO_2 or H_2SO_4 in the equatorial stratosphere would be effective for achieving a global aerosol layer, as the Brewer–Dobson circulation, which rises in the tropical stratosphere and descends at higher latitudes, would help to distribute the aerosols to produce a global coverage.[58] Any release of aerosols from a point source into the stratosphere would quickly become distributed zonally due to the strong zonal flows in the stratosphere and would also tend to be transported poleward, albeit at a slower rate.[12,59] The height of the aerosol release is also critical, with aerosols released at higher altitude tending to have a longer lifetime.[12,55] The technical feasibility of SAI geoengineering is discussed in Box 1.

In the rest of this section, the discussion focuses on the consequences of releasing SO_2 into the tropical lower stratosphere to produce a global sulfate aerosol layer, as this is the most commonly simulated experiment.

BOX 1

THE TECHNICAL FEASIBILITY OF SAI GEOENGINEERING

There have been a number of assessments into the feasibility and costs of annually lifting the millions of tons of material to the stratosphere that would be required to implement SAI.[5,60,61] While a wide range of options have been considered, ranging from rigid towers to artillery, only two options seem both feasible and relatively cheap: high-altitude aircraft or tethered balloons.[5,60] All assessments agree that aircraft have the potential to deliver millions of tons of material to the lower stratosphere (~20 km or 60 hPa) at a cost on the order of 1–10 billion US dollars per mega-ton of material per year.[5,60,61] Tethered balloons offer a potentially cheaper alternative, especially for large injection amounts, with estimated costs ranging from an order of magnitude less to an order of magnitude more than delivery by aircraft;[60] balloon-borne injections would rely on less certain technologies, and as such, assessments disagree on its potential feasibility.[5,60] However, getting the material to the stratosphere is a necessary but not sufficient condition to produce a cooling effect, as the aerosols or aerosol precursors must then form an effective aerosol layer with the appropriate optical properties.[49] The direct costs of SAI might therefore be small relative to the costs of mitigating emissions of GHGs or adapting to climate change. However, cost estimates so far have assumed a perfectly efficient formation of an aerosol layer, so they should be interpreted as likely providing a lower bound on the costs.[49,62]

Effects of Atmospheric Heating by Aerosols

Sulfate aerosols are excellent at scattering radiation in the visible band, but they also absorb some solar and thermal radiation, which results in heating by the aerosols.[63] The amount of heating would depends on the total amount of aerosol and the aerosol size with larger particles absorbing more radiation.[12] As an example, the 1991 eruption of Mt. Pinatubo placed approximately 20 Tg of SO_2 in the troposphere and lower stratosphere, which caused a peak stratospheric warming of approximately 3.5°C.[64]

One effect is that stratospheric heating changes the total column energy budget, leading to greater imbalances between the surface and the atmosphere than would occur under an equivalent amount of sunshade geoengineering radiative forcing. Because the hydrological cycle responds to the total column energy budget,[65] there ends up being a greater hydrological cycle response to SAI than to sunshade geoengineering.[2,66] However, the degree to which the two methods differ depends on the injection strategy, and studies disagree on the magnitude of this difference.[67]

Furthermore, the stratospheric heating would cause circulation changes. Aquila et al.[68] found that the quasi-biennial oscillation (QBO, an approximately two-year cycle in the direction of stratospheric winds) has a longer westerly phase in response to stratospheric heating. With sufficient warming, this oscillation 'locks' in a permanent westerly phase. The QBO also modulates the Arctic Oscillation and the jet stream, and hence can affect surface climate.[69] Ferraro et al.[70] found that SAI reduces tropical convection strength, although these simulations were conducted using a model that lacks the full complexity of a general circulation model, including radiative feedbacks on dynamical circulation patterns, so further investigation is needed.

Stratospheric Chemistry Changes

The stratosphere is home to the ozone layer, which protects the surface of the Earth from the full intensity of ultraviolet (UV) radiation from the Sun. The reactions that determine the ozone concentration are sensitive to the quantity of UV, temperature, and humidity, as well as the presence of various reactive gases.[71,72] After the 1991 eruption of Mt. Pinatubo, there was an observed reduction in total column ozone,[73] and simulations of SAI have shown similar effects.[74] SAI would provide more surface area on which ozone-destroying reactions could occur.[75,76] However, the stratospheric warming that would result from SAI would suppress another ozone destroying chemical reaction: the NOx (mono-Nitrogen Oxides) cycle.[76] Local warming would produce greater upwelling which could potentially increase the quantity of water vapor that penetrates into the very dry stratosphere with further consequences for stratospheric chemistry.[12,77]

There are major uncertainties in the effects of SAI geoengineering on stratospheric ozone chemistry, but despite these uncertainties in modeling studies to date, the projections of its effects are fairly consistent. In the earlier decades of the 21st century when ozone-destroying chlorofluorocarbon (CFC) concentrations will still be high, SAI would be expected to reduce global-mean stratospheric ozone concentrations, delaying the recovery of the ozone hole for many decades.[75,78] But due to the declining concentrations of CFCs and the suppression of the NOx cycle, SAI would be expected to increase ozone concentrations in the second half of the 21st century.[76,78] Additionally, as the aerosols would scatter light, including UV, it would prevent some of the UV from reaching the Earth's surface, which would reduce UV exposure if there were no changes in ozone.[76] Some regions may experience increases in UV exposure in the spring and early summer seasons, but this is restricted to polar regions and is a smaller effect than the existing ozone hole.[76] There are a number of uncertainties around the effects of SAI on ozone, but these studies suggest that it is a relatively small effect that would not pose substantial risks, perhaps with the exception of regions already affected by the ozone hole.

Tropospheric Effects of Aerosol Deposition

Deposition of the sulfate aerosols, which will generally make precipitation more acidic, is known to be a potential source of significant damage to ecosystems if the sulfate is sufficiently concentrated.[79] Kravitz et al.[80] found that only the most poorly buffered ecosystems would be susceptible to the additional acid deposition from an SO_2 injection rate of 5 Tg per year (about a fourth the amount of the injection by the 1991 Mt. Pinatubo volcano eruption); the amount of global sulfur pollution due to industrial activities is over an order of magnitude greater.[81] However, this conclusion may need to be revisited if larger sulfate aerosol injection amounts were to be considered.

Preliminary analysis of stratospheric sulfate aerosol injection using a chemical transport model have suggested that SAI could result in 26,000 premature deaths per year (per degree of cooling),[82] a small fraction of the more than three million premature deaths associated with existing air pollution.[83] This total is highly uncertain as it depends on the cancelation of two large and highly uncertain contributions, an increase in harmful particulate matter and a decrease in tropospheric ozone, and includes a smaller contribution from increased UV exposure (4500 premature deaths per year per degree of cooling). These results need further confirmation, as a large portion of the variance in these estimates is due to uncertainties in the relationships between exposure and mortality. Importantly the study found that the descending stratospheric aerosol itself would be almost entirely removed by wet deposition so the direct contribution of the sulfate aerosols themselves to particulate matter burden at the surface would likely be very low.

Of additional concern are aerosol–cloud interactions as the aerosols sediment out of the stratosphere and through the troposphere. Aerosol–cloud interactions are some of the leading sources of uncertainty in understanding climate change.[4] In the context of SAI, these sorts of interactions are not well understood. Kuebbeler et al.[84] and Cirisan et al.[85] found an enhancement of cooling from SAI due to depletion of cirrus clouds by the falling aerosols, but their results strongly depend upon the cloud and aerosol microphysics treatment used in their simplified studies. The strong mixing events that occur through folds in the tropopause might pose a particular concern for SAI; the stratospheric air can be transported deep into the troposphere and even reach the surface, possibly leading to strong deposition events.[86] Evidence was also found of effects on cirrus clouds due to the fallout from the 1991 Mt. Pinatubo eruption,[87] but this was shown to be very difficult to quantify and does not provide quantitative information of what would be anticipated for SAI.

Changes in Quality of Light

SAI would change the balance of direct and diffuse radiation, whereas sunshade geoengineering would not affect this balance. For every 1 W m^{-2} of sunlight reflected to space by SAI, approximately 4 W m^{-2} is scattered downward as diffuse light.[88] Simulations suggest that this would not significantly change the hue of the sky, except during sunrise and sunset, but would whiten it noticeably (reduced color saturation), shifting its appearance toward that of urban skies.[88] The reduced intensity of direct sunlight would reduce the ability of concentrating solar power plants to generate power.[89] The increase in diffuse light is expected to boost plant productivity, as diffuse light can penetrate through the canopy to the shaded leaves below.[90] Xia et al.[91] found an increase in the rate of photosynthesis in a study of the effects of SAI geoengineering but did not isolate the effects of diffuse light from the other effects of SAI. Kalidindi et al. compared the effects of SAI geoengineering and sunshade geoengineering, finding that the increase in the rate of photosynthesis of the shaded leaves from the increased diffuse light was offset by the decrease in productivity of the sunlit leaves due to the decreased direct light.[67] More work is needed to determine the magnitude of the diffuse light effect from SAI geoengineering on photosynthesis.

Model Uncertainty in the Response to SAI Geoengineering

To simulate the effects of SAI requires a model that has a thorough treatment not only of climate processes and feedbacks, but also of stratospheric chemistry and aerosol microphysics, with an upper model boundary that is sufficiently high to completely resolve the stratospheric circulation.[92] Sophisticated representations of stratospheric chemistry and dynamical processes are not yet included in most climate models, and observational-based validation of these models that do include such processes is limited.[93] Moreover, comparisons with the observed climate response to volcanic eruptions suggest that Earth system and climate models do indeed fall short of representing all the relevant processes. For example, after large volcanic eruptions a warming at high latitudes in the winter is observed but is not reproduced by many of the current models.[94] Thus, simulations to date of the consequences of SAI have been made with models with a number of significant shortcomings resulting in significant uncertainty in some aspects of the response.

One measure of this uncertainty can be found by comparing the range of model responses to a prescribed release of SO_2 in the stratosphere. Figure 5 shows the distribution of sulfate aerosols from three models participating in the GeoMIP experiment G4, in which 5 Tg of SO_2 is injected into the lower stratosphere each year.[18] The GISS-E2-R and HadGEM2-ES models both used interactive treatments of sulfate aerosols, including conversion of SO_2 gas into aerosols, transport of the aerosols, and subsequent stratospheric removal. MIROC-ESM prescribed aerosol distributions based on scaling the distribution for the 1991 eruption of Mount Pinatubo. It is clear from Figure 5 that the models are producing very different aerosol clouds for the same deployment of SAI, which will of course affect the climate outcomes.

Figure 6 shows the broad multi-model spread in global mean temperature response to the G4 experiment, that is, the global cooling effect of the same release of SO_2 is very different in the various models. The figure also shows results for the G3 experiment in which all models are prescribed to produce the same global mean radiative forcing. Despite

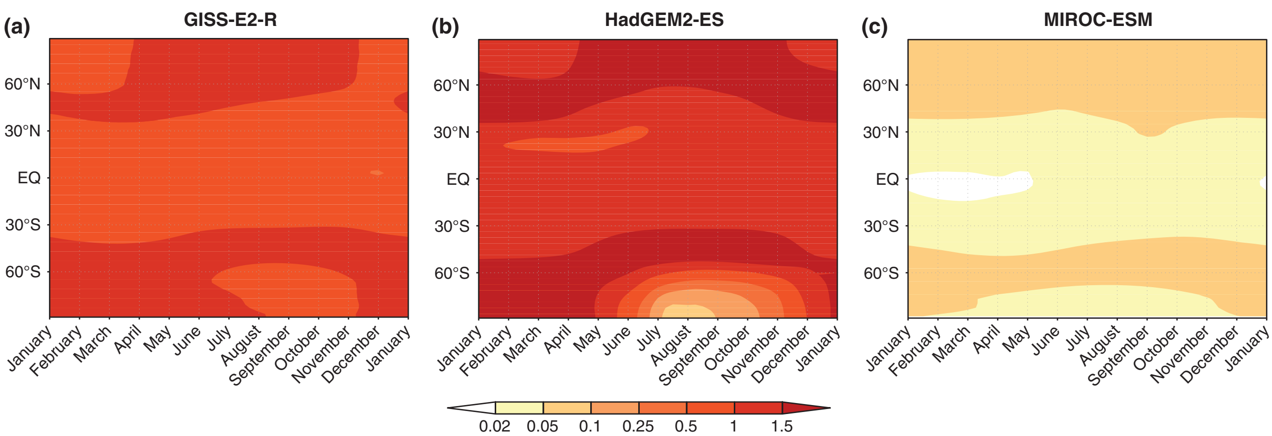

FIGURE 5 | Zonally averaged stratospheric sulfate aerosol total column burden (kg m^{-2}) above 200 mb for three models participating in GeoMIP experiment G4. This experiment involves a sustained injection rate amounting to 5 Tg SO_2 (~10 Tg H_2SO_4) per year. (a) GISS-E2-R, (b) HadGEM2-ES and (c) MIROC-ESM

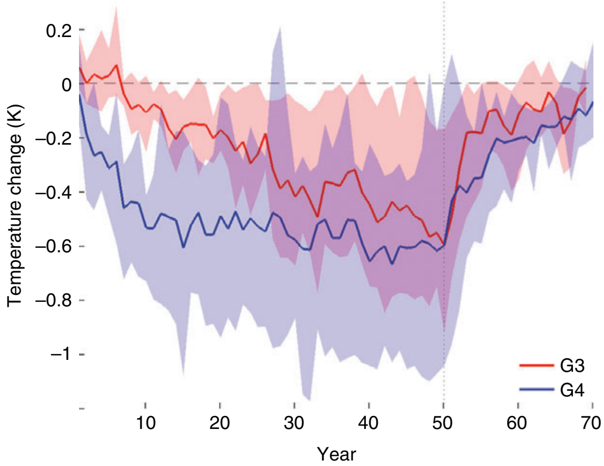

FIGURE 6 | Range of global mean temperature response to two different SAI scenarios, as described by the Geoengineering Model Intercomparison Project (GeoMIP).[18] Solid lines show the model mean, and shading shows the model spread for each experiment. Results for G3 include three models, while G4 include six models.

this imposed conformity, temperature differences for both experiments span nearly 1°C, which is double the amount of cooling produced in the all-model mean.

Climate Differences between SAI Geoengineering and Sunshade Geoengineering

The current generation of climate models are not capable of modeling all relevant aspects of the response to SAI, so there are considerable uncertainties in the response to SAI, as shown above. This uncertainty, combined with a paucity of model studies, means that the regional climate response projections produced so far are not robust enough to describe in detail. Instead, we provide a broad-brush description of the key differences between the climate response to SAI and sunshade geoengineering.

The effects of SAI on the Earth system differ from those of sunshade geoengineering in a number of important ways described above and some of these will give rise to distinct climate consequences. A key difference between SAI and sunshade geoengineering is that the absorption of solar and thermal radiation by a stratospheric aerosol layer would increase downwelling thermal radiation that would warm the troposphere which would need to be balanced by a greater reduction in downwelling sunlight than would be required for sunshade geoengineering. The combination of these two forcings would result in the increased stability of troposphere that would lead to less precipitation.[66,95] This effect means that SAI would result in a greater reduction in the hydrological cycle than sunshade geoengineering for a similar reduction in global temperatures.[2] Another effect of this warming would be changes to stratospheric circulation, which would have impacts on the surface.[47,68] Unlike sunshade geoengineering, in which incoming sunlight is reduced uniformly, SAI would produce a non-uniform forcing because the aerosol cloud would not be evenly distributed across the world (see Figure 5). Studies of the combined effects of these differences find that for the same global mean temperature reduction, SAI produced a greater change in the hydrological cycle than sunshade geoengineering and gave rise to greater regional change in climate, particularly in the tropics.[2,67,96]

Despite these differences, there are important lessons about SAI that can be learned from sunshade geoengineering. A substantial portion of the climate system response to radiative forcing is due to temperature-related feedbacks and is relatively independent of the particular forcing agent.[97] In the case of SAI, the latitudinal distribution of radiative forcing from SAI deployed in the tropical lower stratosphere will likely be qualitatively similar to that of solar irradiance reduction.[2] As such, the climate effects of offsetting CO_2 via shortwave radiative flux reduction are likely to have some fundamental commonalities regardless of the method by which shortwave irradiance is reduced.[98]

SOLAR GEOENGINEERING AS ONE MEANS OF LIMITING THE IMPACTS OF CLIMATE CHANGE

Solar geoengineering is one option, among others, that could help to limit the impacts of climate change. Thus to understand the role, or roles, that solar geoengineering could play, it is important to understand what would be possible with solar geoengineering, how these choices would affect various climate-related objectives, and how the potentials and limits of solar geoengineering compare against those of other options. This is obviously a substantial challenge, and the available literature is still limited. Here we provide a brief overview of some of the key issues.

Shifting to a Design Perspective for Solar Geoengineering

There are many choices involved in how any form of solar geoengineering might be implemented;[99] two key parameters determining the effects of SAI are the amount and location(s) of injection. Strong stratospheric winds would quickly spread out a stratospheric aerosol cloud zonally, preventing a regionalization of the forcing. However, as the net transport in the stratosphere is poleward it would be possible to concentrate a stratospheric aerosol cloud in one hemisphere or at high latitudes. Robock et al.[59] and Haywood et al.[100] found starkly different climate effects for SAI restricted to one hemisphere as opposed to global SAI. In addition, alternative aerosol particles could be injected which would have different radiative, microphysical and chemical properties, and hence would produce different climate outcomes.[50,53]

In many previous studies, including all the GeoMIP studies, the central question has been to understand the climate effects of prescribed geoengineering scenarios. Instead, one could ask the converse question: given a set of climate-related objectives, what geoengineering strategy would best achieve these? In idealized simulations that are suggestive of the types of degrees of freedom that may be available through SAI, Ban-Weiss and Caldeira[101] and MacMartin et al.[102] found that altering the spatial and seasonal patterns of solar forcing in a high-CO_2 scenario could better achieve a range of objectives, such as more closely restoring pre-industrial precipitation conditions or restoring Arctic sea-ice coverage. It is unclear, however, how one could technically achieve such forcing patterns in real injection scenarios. Studies exploring the challenge of meeting specified objectives interactively in the presence of uncertainty, that is, using only the observations that would be available at the time, have found that certain simple climate objectives could be met. This is if it were possible to develop the additional monitoring and deployment infrastructure needed to use feedback from observations to guide the deployment of solar geoengineering.[99,103,104] However, there are limits to what could be achieved, even with idealized interventions. For example, starting from a scenario of elevated CO_2 concentrations, it is not possible to simultaneously restore both global mean precipitation and temperature to the values of a lower CO_2 scenario using any pattern of solar forcing alone (see Section *Climate Response to Sunshade Geoengineering*).[101] Solar geoengineering thus cannot be seen as a panacea for avoiding climate change, and any potential decision of whether and how to deploy it would involve trade-offs between various objectives.

Climate Impacts of Solar Geoengineering

Most of the work to date on solar geoengineering has focused on changes to the physical environment, such as temperature and precipitation. However, the impacts of climate change on natural and human systems, such as agriculture and ecosystems, are the fundamental motivation for mitigation and adaptation and for considering solar geoengineering. Thus, a clear understanding of how solar geoengineering would affect climate impacts will be critical to making decisions on whether and how to deploy it (see Box 2).

The potential for solar geoengineering to lower global temperatures and offset various climate trends provides an indication that it could reduce climate impacts. However, to gain confidence, the climate impact response to solar geoengineering scenarios needs to be evaluated in depth. Only two domains of climate impacts have received any attention to date:

BOX 2

CONSIDERING THE BROADER IMPLICATIONS OF SOLAR GEOENGINEERING

The Earth system response to solar geoengineering described in this overview is relevant to the broader discussion on solar geoengineering, as the answers to many questions depend, at least in part, on the distribution of the benefits and risks. As we note in Section *Solar Geoengineering as One Means of Limiting the Impacts of Climate Change*, there has yet to be a thorough assessment of the impacts of solar geoengineering on agriculture and a host of other sectors of great concern. This has meant that most studies to date have had to employ 'damage functions' developed for climate change or develop novel heuristics. The wide range of heuristics employed has led to wildly differing conclusions from studies employing similar climate data.[105–107] Without a solid basis for choosing one heuristic over another the inferences drawn from such studies may in effect be arbitrary, that is, functions of the choice of heuristic rather than a true reflection of the implications of solar geoengineering. Thus, it is critical to develop a clearer picture of the impacts and to develop ways to represent these fairly in higher-level studies of its implications to answer some of the most pressing questions regarding solar geoengineering. For example, would the impacts be distributed in a just manner? And what would the geo-political implications of solar geoengineering be?

the effect of solar geoengineering on coral reefs and crop yields. Couce et al.[43] found that solar geoengineering could help maintain the suitability of coral reef habitat in the face of increasing ocean acidification, and Kwiatkowski et al.[42] found that solar geoengineering could reduce future occurrence of coral bleaching events. Pongratz et al.[108] and Parkes et al.[109] suggest that solar geoengineering could reduce some of the detrimental effects of climate change on crop yields, while Xia et al.[110] found that a future with high CO_2 and solar geoengineering might have increased crop yields regionally.

The field of solar geoengineering research has recently reached a critical juncture. The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP),[111] an approach to evaluate the impacts of climate change in a rigorous and consistent manner, has reached a stage of maturity where it now may draw upon the output from GeoMIP to begin a critical evaluation of the potential impacts of solar geoengineering. However, this will be a major challenge given the wide range of potential outcomes and the fact that solar geoengineering could be designed to achieve a variety specific climate objectives.

Mitigation, Adaptation and Solar Geoengineering

Solar geoengineering is of course only one potential option for addressing some of the impacts of climate change. Mitigation, adaptation, GHG removal, and solar geoengineering all carry (or would carry) direct costs, have a range of consequences for climate and beyond, and raise broader social, economic, political and other issues. For example, while SAI geoengineering is estimated to be relatively inexpensive as compared to other methods (See Box 1) and would act relatively quickly, it would not offset all effects of high GHG concentrations (e.g., Figures 1 and 2). Mitigation directly addresses the physical cause of climate change, but due to the very long lifetime of CO_2 in the climate system[112] and the thermal inertia that implies the current warming is less than the committed warming for the amount of CO_2 in the atmosphere, even reducing emissions to zero immediately would not offset many of the risks of climate change already present. Carbon dioxide removal could potentially draw CO_2 levels down much more rapidly than would occur naturally by enhancing natural sinks or developing artificial ones. However, the rate of draw-down would be limited, as it would be both expensive and energy or land intensive.[17] Adaptation can build the robustness and resilience of societies to climate impacts, but for certain impacts, such as changes to ecosystems, there will be little that can be done to reduce their damage.

Solar geoengineering would only mask the warming effect of GHGs. One of the concerns that has been brought out in previous studies is that, given the relatively short lifetime of the various proposed forcing agents, a rapid warming, dubbed a 'termination shock,' would follow any sudden cessation of a solar geoengineering deployment that was exerting a substantial cooling.[13] To avoid the risk of such a rapid warming, large-scale solar geoengineering deployments would need to be phased out gradually on a timescale of decades.[14] Even slowly phasing out solar geoengineering would mean that the warming that had been offset by solar geoengineering would occur as a substantial fraction of emitted CO_2 will remain in the atmosphere on a timescale of millennia.[113,114] This has led to suggestions that solar geoengineering be used in combination with large-scale deployments of carbon dioxide removal geoengineering to actively bring CO_2 concentrations down, in so-called peak-shaving scenarios.[115] Were solar geoengineering to be exerting a large cooling there is the potential for an unplanned interruption to the deployment to cause disaster,[116,117] though given the gravity of such a failure it would seem as if there would be strong incentives for most actors to make efforts to ensure the redundant and backup capability were in place to allow the deployment to be maintained.[118]

Evaluating different combinations of mitigation, adaptation and solar geoengineering policies is challenging and involves trade-offs between various objectives on different time-scales and for different regions. Currently, no consistent picture emerges from efforts to investigate these issues.[105–107] The potential role of solar geoengineering among other climate policies thus remains a difficult open research question.

CONCLUSION

Solar geoengineering is a novel proposal to reduce the risks of climate change by increasing the reflection of sunlight back to space to lower global surface temperatures. SAI has attracted particular attention and is the focus of this overview, as numerous studies suggest that it should be technically feasible. Although current technical readiness is at a relatively low level (see Box 1), the mechanism by which it cools the climate is simple, and there is a natural analogue in the cooling effect of large volcanic eruptions. However, there are many uncertainties in its expected effects as projected by climate models and there are a number of broader consequences that could result from the deployment of SAI. Further understanding of the effects of SAI can be developed through analysis of sunshade geoengineering or natural analogues (like volcanic eruptions); however, differences between these proxies and SAI are significant enough that they cannot be relied upon alone. Moreover, because there are no observations of SAI, any conclusions about its effects or effectiveness are inherently uncertain due to a lack of confirmation by different types of evidence.

In general, many of the uncertainties in geoengineering research, or model representations of SAI, are also present in fundamental climate science.[4,119] For example, large volcanic eruptions are excellent tests of our understanding of the climate system. To accurately represent the effects of volcanic eruptions, there needs to be a synergy between models and observations to improve understanding of sulfate aerosol microphysics, stratospheric transport of the aerosols, interactions with radiation and dynamics (e.g., the effects of stratospheric heating), removal of the aerosols from the stratosphere, interactions between the aerosols and clouds, and effects on the climate at the Earth's surface. These concerns are identical to some of the key concerns with respect to SAI. There are many mutual benefits between climate science research and SAI research, and in many cases, the research needs of the two areas are indistinguishable.

Solar geoengineering introduces one particular issue that is novel to climate change research and climate policy measures, in that it has the potential to be designed to meet specific objectives. For SAI, the location, altitude, and amount of injection can be varied to attempt to address various aspects of climate change, potentially including climate impacts. This in turn raises questions about how to manage trade-offs between different goals and the possible role(s) of solar geoengineering as an option in addressing climate change, alongside mitigation and adaptation. Understanding the range of climate states made possible through solar geoengineering, as well as the relationships between those climates and their impacts, are some of the most important open questions in solar geoengineering research.

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