Uncertainty and the basis for confidence in solar geoengineering research

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Abstract | Solar geoengineering is an emerging topic in climate-change discussions. To support future decisions on the deployment of this technology, society requires better estimates of its environmental impacts and limitations. As solar geoengineering has never been deployed, conclusions about its climatic effects are primarily obtained through models and natural analogues. As such, our confidence in projections of solar geoengineering, the basis for that confidence and how our confidence can be improved is limited. In this Perspective, we review our current understanding of uncertainty and risk in solar geoengineering via stratospheric aerosols. Using a risk-register framework, we illustrate key uncertainties, such as sub-grid-scale mixing or effects of stratospheric heating, investigations of which should be prioritized to transition the field to a mission-driven research agenda. We conclude with recommendations for possible avenues of research, including targeted model intercomparisons and appropriately governed small-scale field experiments.

Solar geoengineering — which describes technologies that deliberately modify the Earth's climate — was recognized as a possible method of climate control as early as 1955 (REF.[1]). Since then, increasing confidence in the impacts and severity of anthropogenic warming has accelerated scientific research and public interest in geoengineering[2], which now encompasses a portfolio of proposals to offset the effects of anthropogenic climate change[3–5]. Among the numerous proposed methods[4,5], the most commonly discussed include stratospheric aerosols, brightening marine low clouds and thinning cirrus clouds. Stratospheric aerosol geoengineering (SAG) has received the most attention, largely as it is perceived to be more feasible than other methods. Inspired by the cooling seen after large volcanic eruptions[6], SAG involves placing reflective aerosols such as sulfate in the stratosphere, which would reflect incoming solar radiation and cool the surface[2,7] (BOX 1; FIG. 1).

SAG is virtually certain to reduce global mean temperature, offsetting, at least partially, changes associated with rising CO_2 concentrations. A wide range of modelled temperature reductions have been explored, including fully offsetting temperature change[8], partially offsetting temperature change[9], or slowing the rate of global warming[10]. Model-based evidence further indicates that SAG will alleviate many other impacts of climate change[8]: these include offsetting projected acceleration of the hydrologic cycle[11,12], ice melt[13,14], increased intensity or frequency of extreme events[15,16] and tropical cyclone intensity[9,17]. Indeed, under SAG, nearly all regions are predicted to experience a climate closer to the historical baseline[9,18]. However, there are almost certainly trade-offs, leading to concerns about winners and losers[18–20]; for example, no model results indicate that SAG can offset both temperature and precipitation changes in all regions of the globe.

Different SAG strategies are also known to produce different regional effects. SAG injection at higher latitudes, for example, preferentially cools the polar regions (with subsequent impacts on sea and land ice)[14,21], whereas injection in only one hemisphere preferentially cools that hemisphere (with concomitant shifts in tropical precipitation)[22]. SAG could also pose additional physical climate risks, such as depletion of stratospheric ozone and subsequent ultraviolet radiation changes[23,24], interactions with cirrus clouds and possible effects on the radiative balance[25], increased acid rain[26], changes to ecosystems[27], effects on the ocean[28], agricultural impacts[29,30] and the potential for climate rebound from the sudden termination of SAG[31,32]. FIGURE 1 summarizes some of the conclusions and risks involved in SAG, which have also been previously reviewed[4,5,33–39].

Despite numerous efforts to estimate the impacts of SAG, a systematic assessment of uncertainty (defined here as anything that is currently unknown) and confidence is absent; as such, there is little information to bound conclusions about the range and impacts of possible SAG effects. Thus, to support future decisions, there is a need to clearly articulate how confident the research community is in the potential effects of solar geoengineering, the basis for that confidence and what needs to be done to improve that confidence; the limits on what we can know also need to be determined.

In this Perspective, we do not attempt to address any of these questions directly but, rather, map out the processes by which these questions could be addressed. To allow for a more thorough discussion of uncertainty, we restrict our focus to SAG; other methods, such as marine cloud brightening, encompass fundamentally different uncertainties. We also restrict our attention to uncertainties in natural science, rather than also discussing those in the societal response; this is not to imply that any set of disciplines is more important than others, but some bounding of scope is necessary to make the subsequent discussions tractable. As the SAG method can influence which uncertainties matter, we first describe a design perspective for SAG, before introducing an SAG risk register as a basis for comparing and prioritizing different uncertainties. We then consider the epistemology and basis for confidence in our conclusions about SAG and discuss several specific categories of uncertainty. Finally, we discuss the implications of these uncertainties in supporting future decisions.

Box 1 | How SAG works

Stratospheric aerosol geoengineering (SAG) is conceptualized to mimic the global cooling effects observed after large volcanic eruptions[6]. Volcanoes eject, among other things, large amounts (megatons) of sulfur dioxide; in the atmosphere, this oxidizes to form highly reflective sulfate aerosols. If these aerosols are placed in the stratosphere (at approximately 20–30 km in altitude), they can persist for a few years, maintaining a layer that reflects a small portion of the incoming solar irradiance to space, cooling the planet. The stratospheric aerosols are transported by large-scale stratospheric winds, covering all longitudes within a matter of weeks and spreading to other latitudes over the course of months. SAG is designed to continually inject these aerosols (or their gaseous precursors, such as sulfur dioxide) in the stratosphere, maintaining cooling for as long as the injection is maintained[2]. This could be accomplished via numerous methods, but specially designed aircraft are likely to be most effective[156,157]. Although sulfate aerosols are the most commonly discussed because of the natural analogue of volcanic eruptions, other aerosols (such as calcite) have been proposed[75].

Scenario and strategy dependence

Before being able to assess confidence in the effects of SAG, the motivation of which is to inform future decisions, there needs to be increased understanding of where and why uncertainties arise. Here, using a few examples, we illustrate that the background climatic scenario and strategy in which SAG is deployed affect the relative importance of different risks and uncertainties.

The scenario — which describes the severity of background climate change — exerts a strong control on SAG risks. Under climate change, uncertainty in surface-climate effects increases with time, in part due to temperature-dependent climate feedbacks[40,41]. Under solar geoengineering, temperature rise and, hence, feedback strength are suppressed, leading to reduced model spread in projections of future change[12,42,43]. As another example, ozone depletion is a modelled effect of SAG deployment[23], attributed to an increase in aerosol surfaces where chemical reactions involving chlorofluorocarbons (CFCs) can occur[44,45], as observed after large volcanic eruptions. The concentration of atmospheric CFCs, however, has declined since the 1990s and will continue to do so. Thus, if SAG were to be deployed late in the 21st century instead of in the near future, lower CFC concentrations would result in substantially smaller stratospheric ozone depletion[46]. Similarly, the severity of potential climate rebound following rapid termination of SAG is dependent on the level of background greenhouse gas (GHG) emissions and the magnitude of SAG deployment; for instance, a high GHG scenario coupled with strong cooling achieved through SAG would increase the consequences of a pronounced rebound effect. Many of the conclusions about scenario dependence are based on representing solar geoengineering via solar reduction, and they have not yet been comprehensively explored for SAG. It may be expected that stratospheric circulation and surface-climate responses will be different for SAG[47], but changes in the net terrestrial carbon cycle may be similar between the two representations, despite the enhanced diffuse radiative flux under SAG[48].

The effects of SAG, as well as the risks and uncertainties, are further dependent upon the deployment strategy, including: the objectives (what SAG is trying to achieve) and the way in which SAG is deployed (latitude, altitude, magnitude and time of year of injection, as well as aerosol or precursor composition)[49]. A similar list could be made for other solar geoengineering methods; for example, for marine cloud brightening, the effects might depend upon the location and timing of injection, marine boundary-layer stability, particle composition and particle size[50–52]. We illustrate different risks associated with different deployment strategies through a case study of the quasi-biennial oscillation (QBO), a mode of stratospheric variability that describes the equatorial zonal winds as being easterly or westerly, impacting the spread of injected aerosols and, thereby, surface impacts[53]. Under tropical SAG injection, the QBO transitions to a persistent westerly phase (FIG. 2), with dynamical effects that can alter tropospheric winds and precipitation patterns[54–57]. However, for off-equatorial injection that still results in similar levels of global mean cooling, the phase and magnitude of the QBO remain relatively unchanged (FIG. 2), and some of the side effects experienced under equatorial injection do not materialize[58].

By modifying several of these degrees of freedom — that is, factors related to the deployment strategy — it may be possible to design SAG to achieve climate outcomes beyond solely reducing global mean temperature[19,38,49,59]. For example, if SAG was to be deployed only in the equatorial regions, this would prevent the rise in global mean temperature[58] but have the side effect of residual polar warming[8] (FIG. 3). However, by injecting SO_2 in four independent locations, it is possible to meet simultaneous temperature objectives (such as offsetting changes in global mean temperature, the interhemispheric temperature gradient and the equator-to-pole temperature gradient; FIG. 3)[21,60]. By considering the design of SAG, it may be possible to further predictably modify related climate features, such as the position of the intertropical convergence zone or Arctic sea ice extent[49].

In addition to choosing the injection strategy based on the projected response, the deployment strategy can be selected to reduce uncertainty. Off-equatorial injection, for example, could be chosen to reduce dependence on unclear aerosol-coagulation rates (so aerosols are quickly transported away from the injection site)[61] or sulfate aerosols may be chosen over calcite, despite projected detrimental ozone effects, to avoid poorly bounded uncertainties[39].

However, there are fundamental trade-offs in the climate system and, hence, in what SAG can achieve. For example, solar geoengineering cannot completely offset simultaneous CO_2-related changes in global mean temperature and global mean precipitation[11]. Other trade-offs need to be further understood; even though sea level would continue to rise if global mean temperature change was arrested by solar geoengineering[62], conclusions about the amount of resulting sea level rise should be revisited[63]. There is still substantial uncertainty in the range of climate features that can be effectively managed with SAG[38] and whether that space can be expanded by complementing SAG with, for example, marine cloud brightening or cirrus thinning[64,65]. In the absence of complete knowledge, the climate community has adopted proxies that encapsulate many different climate objectives, typified by the 1.5 °C or 2 °C warming targets to prevent dangerous anthropogenic interference in the climate system[66]. Similar high-level heuristics for solar geoengineering may also be useful for encompassing a wide range of effects; as described in the following section, a risk register could offer a path towards developing such heuristics for comparing risks under a range of possible future scenarios and strategies.

Prioritizing uncertainties

Although there have been attempts to articulate physical-science uncertainties in SAG[39], there has not yet been the prioritization that is necessary for a transition to mission-driven research[67], that is, research aimed at identifying and

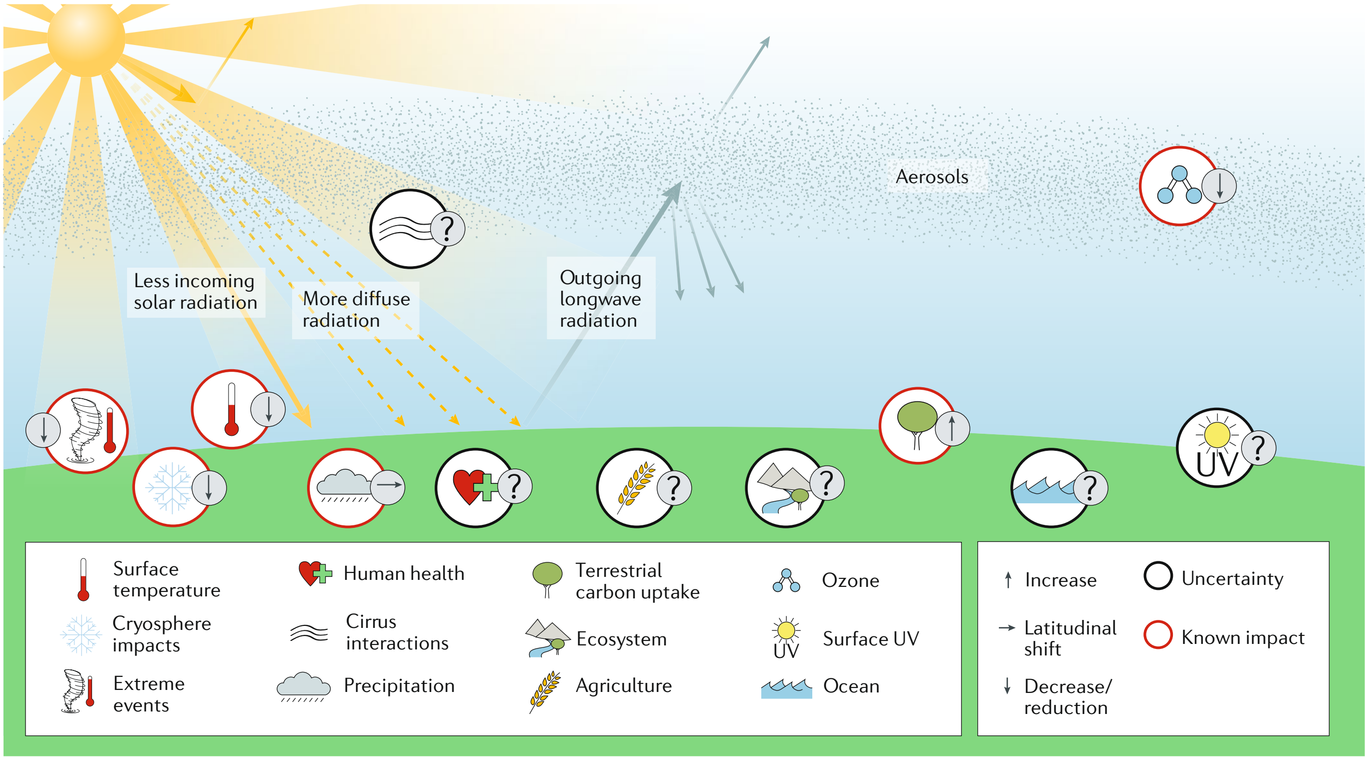

Fig. 1 | **Climatic effects and uncertainties associated with SAG.** Schematic of some of the conclusions and risks involved in stratospheric aerosol engineering. SAG, stratospheric aerosol geoengineering; UV, ultraviolet.

reducing the most important uncertainties. One method of accomplishing this is a risk register[68] (FIG. 4). In a risk register, each uncertainty, such as what effect would termination have or how does stratospheric transport influence SAG, is assessed on two axes, representing probability (of occurrence or of being wrong) and consequences. The combination of these parameters describes the overall risk associated with that uncertainty, categorized as low, low–medium, medium, medium–high or high risk. Some uncertainties might never have any basis for assigning an objective likelihood[69] or an absolute ranking of all uncertainties, yet some qualitative and subjective assessment may still be possible. Any item that sits in the top-right corner of a risk register immediately becomes a high research priority; actions might aim to reduce the likelihood or degree of uncertainty (through additional observations or experiments) or to find ways to reduce the consequences (choosing strategies that are less dependent on knowledge of a particular parameter or process). However, prioritizing uncertainties is independent of efforts to address them. Research is a primary means of reducing uncertainty but some uncertainties are empirically or practically irreducible, regardless of priority; for example, precise prediction of regional temperature and precipitation outcomes for any given solar geoengineering strategy.

The risk register is not intended for quantitative accuracy or to replace human judgment. Indeed, positioning on a risk register is a somewhat subjective process shaped by expert opinion and is dependent on scenario and strategy. Using the previous example of the QBO, the consequences (the y-axis of the risk register) are much lower for off-equatorial injection than equatorial injection[58], so the probability of being wrong about the QBO (an appropriate interpretation of the x-axis in this case) is low. Instead, a risk register serves as a means for ensuring a conscious, explicit conversation about relative priorities and the basis for that prioritization, as well as a way to track progress on reducing risk over time. Since the purpose of a risk register is comparability, the scope of any risk register needs to be carefully chosen and any major project (such as global-scale SAG) would likely have numerous risk registers that cover different aspects of the problem; for example, the risk of technological lock-in due to private financial interests in maintaining a solar geoengineering programme[70] is not directly comparable to uncertainties in climate effects due to aerosol coagulation[53], so those two risks are unlikely to appear on the same risk register. However, uncertainties in stratospheric water vapour changes and stratospheric ozone chemical effects[71] due to SAG are likely to appear on the same register. The overall project would also involve a high-level synthesis, where all of the risk registers are evaluated simultaneously to look for overlaps, blind spots and potentially compounding risks.

Basis for confidence

Positioning on a risk register becomes less subjective with more confidence in conclusions about the effects of SAG, which, in turn, requires reducing (or at least bounding) uncertainties. Sources of evidence available to reduce geoengineering uncertainties are few and, as such, there is a limited basis for confidence in any conclusions.

Since geoengineering has never been deployed, bounds on potential uncertainties are reliant on information from natural analogues, such as large volcanic eruptions. These analogues, however, often provide limited information[72]; differences in aerosol microphysics[73] and climate responses[74], for example, will vary markedly when comparing pulse volcanic eruptions and sustained injections through SAG. In addition, there is sometimes no natural analogue that can be used. Calcite, for instance, has been proposed as a potential SAG aerosol, as it is hypothesized to be less harmful to stratospheric ozone than sulfate[75]. However, as there has never been a large amount of calcite in the stratosphere, the risks of 'unknown unknowns' are higher.

Given the limitations of observing natural analogues, experiments to reduce uncertainties have been proposed. Observational experiments, such as aircraft measurements of the next major volcanic eruption, could provide process-level information about aerosol microphysical growth or stratospheric transport[76]. Laboratory experiments are constrained in the types of problems to which they can be applied but can be useful in narrowing down specific uncertainties, such as highly accurate measurements of aerosol refractive indices[77]. Similarly, limited-scope field experiments — either observational campaigns or perturbation experiments — may provide insight into particular processes[78,79]. For example, the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) deliberately introduced aerosols into marine clouds to learn how cloud properties changed[80], providing information relevant to marine cloud brightening. Similarly, small experiments have been proposed for measuring chemistry in the stratosphere[78], while other uncertainties, such as local surface-climate effects, may not be possible to directly validate, even after deployment has started[67]. In all instances, experiments would require appropriate governance mechanisms to assess whether the science justifies any environmental risk, as could be informed through the risk register.

To date, models have been the primary source of natural science evidence regarding solar geoengineering[81], allowing a variety of situations and uncertainties to be explored with minimal environmental impact. Process-level studies can reveal mechanistic understanding; for example, simulations that prescribe or turn off longwave radiative heating[47,82] can explore the effects of stratospheric heating on surface climate, revealing and isolating mechanisms of change. Idealized simulations investigating how the altitude of injection influences stratospheric heating may further inform the importance of these effects[83]. Model intercomparisons (for example, the Geoengineering Model Intercomparison Project (GeoMIP)[84]) also offer useful insight, particularly with understanding the similarities and differences between responses to standardized modelling experiments. Furthermore, large ensembles of simulations with slightly different initial conditions, such as the Community Earth System Model (CESM) large ensemble[85] or the Geoengineering Large Ensemble (GLENS)[86] can reveal the influence of internal variability; while these large ensembles can be computationally expensive, emulators offer a useful compromise, generating numerous ensemble members cheaply but at reduced fidelity or granularity[87].

However, models have uncertainties, presenting their own challenges when assessing confidence in SAG. As described, model intercomparisons may be useful when diagnosing responses to standardized experiments, but as many of these models are related[88,89], spread may provide a biased estimate of uncertainty. Moreover, no single model can span all relevant scales, meaning that any behaviour on sub-grid scales is parameterized. Models may further have incomplete representations of reality, often due to poor understanding of real-world behaviour.

Our understanding of the underlying mechanisms and projected effects of climate change is now well supported by models, observational platforms and underlying theory, providing robustness and confidence in our estimates of corresponding uncertainty[90]. However, solar geoengineering thus far lacks diversity in its sources of evidence, leading to an incomplete picture of uncertainty; model uncertainty is not a good proxy for all other sources of uncertainty. As such, it is presently difficult to determine the level of confidence in our conclusions about SAG, let alone build a high degree of confidence or how present confidence levels[90] will change after further research.

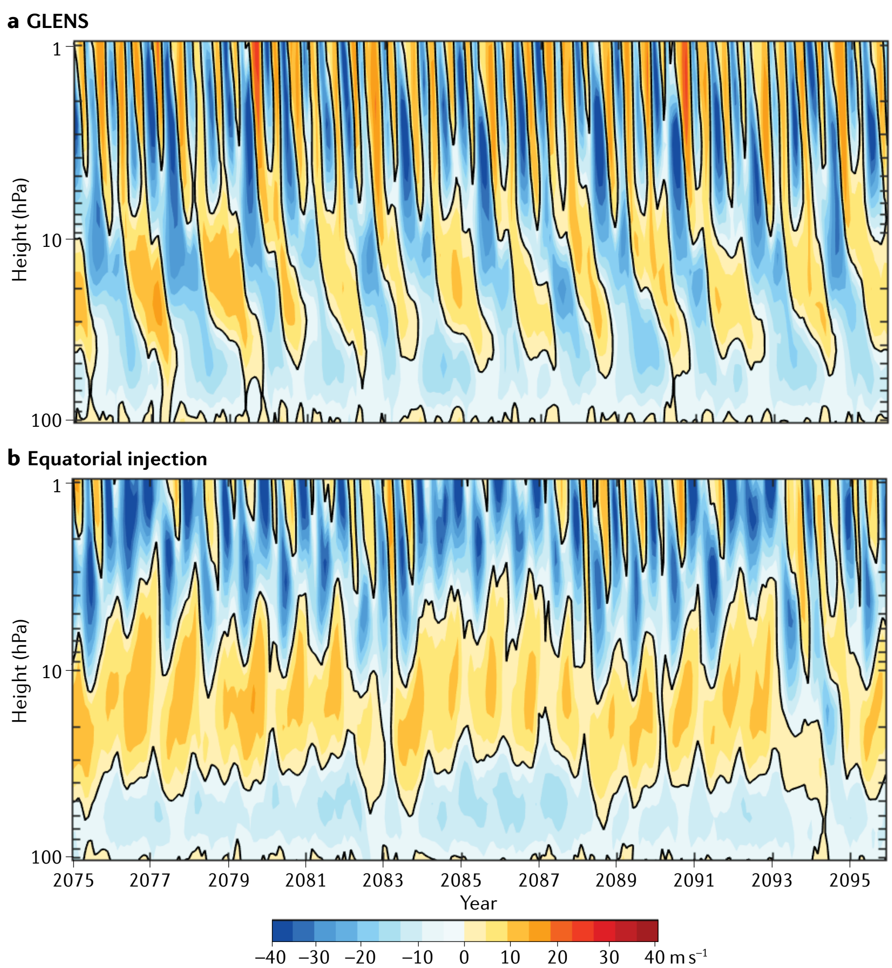

Fig. 2 | **Contrast between QBO strength for SAG via equatorial SO_2 injection and GLENS.** Stratospheric zonal mean wind speed (m s^{-1}) averaged over 2°S–2°N in Geoengineering Large Ensemble (GLENS)[86], where SO_2 is injected at four off-equatorial locations (30°N, 30°S, 15°N and 30°S) (part **a**), and equatorial stratospheric aerosol engineering (part **b**). Positive wind values indicate a westerly phase of the quasi-biennial oscillation (QBO) and negative values an easterly phase of the QBO. SAG, stratospheric aerosol geoengineering. Adapted with permission from REF.[58], Wiley-VCH.

Key uncertainties

Here, building on previous efforts[39], we review key uncertainties in SAG in the context of the risk-register formulation (that is, probability and consequence), focusing on discussions around stratospheric processes (many of which determine the radiative forcing associated with the aerosols), the resulting climate response and their impacts. We also provide our personal assessment of where each uncertainty falls on the risk register, recognizing that there is not yet an adequate basis for objectivity and that the process will constantly evolve with new information (TABLE 1). TABLE 1 is not exhaustive and other potential uncertainties could include impacts on extreme events[15], methane chemistry[71], the carbon cycle[91,92], water cycling[93], vegetation[94], agriculture[29,30], human health[95] and the cryosphere[13,14]. Nevertheless, TABLE 1 is a useful starting point to identify, prioritize and reduce uncertainties in SAG, as well as motivate discussion on how to reduce or manage these uncertainties.

Stratospheric processes

Based on what occurs with a volcanic eruption, a typical assumption for SAG is that SO_2 gas would be injected into the stratosphere and undergo transport and oxidation to sulfate aerosols. The direct condensation of H_2SO_4 into droplets[96], or the use of calcite[75], would bypass the oxidation step. Sulfate aerosols would then grow due to condensation onto existing particles and coagulation between particles[97]. Larger particles lead to decreased shortwave scattering efficiency, increased longwave absorption (and, hence, stratospheric heating) and increased sedimentation rate (and, thus, shorter lifetime)[96]. As the aerosols fall, they will likely interact with cirrus clouds; cirrus would also be affected by changes in ice-crystal size distribution[98] and altered vertical velocities resulting from stratospheric heating[99]. Heating will also lead to increased stratospheric water vapour[46,100]. Each of these processes has uncertainties that would affect the necessary injection amount needed to meet the chosen objectives[53], the spatial distribution of the effects and the severity of the side effects induced by stratospheric heating.

The mean modelled radiative forcing from equatorial injection of sulfate for SAG is approximately $-0.23 \pm 0.07\ \mathrm{W\,m^{-2}}$ per Tg SO_2 $\mathrm{year^{-1}}$, with the range across models being -0.11 to $-0.31\ \mathrm{W\,m^{-2}}$ per Tg[53]. There have not yet been sufficient inter-model studies to quantify a range of uncertainty for off-equatorial injection or geoengineering during only part of the year. Models can reproduce observed properties of the aerosol layer (for example, thickness and aerosol radius) after volcanic eruptions[101], but these observations are insufficient to constrain aerosol microphysical uncertainties for SAG because of different aerosol growth rates between pulse and sustained injections, as well as uncertainties in eruption observations[102,103]. Changes in stratospheric water vapour are difficult to quantify on sub-decadal timescales[104–106], so, although stratospheric aerosol loading is a known source of stratospheric water vapour[100,107], it is difficult to quantitatively validate how well models reproduce this feature. The amount of ozone destruction from stratospheric aerosols depends strongly on the location and size of the aerosols[108], as well as changes in stratospheric heating[109–111]. Moreover, models have trouble reproducing both the baseline and the perturbed state of the stratosphere[112–114], a fact that is complicated by predicted but unknown changes in large-scale atmospheric flow under climate change[61]. Interactions of stratospheric sulfate aerosols with cirrus are poorly understood both in observations of volcanic eruptions[115,116] and in model simulations of SAG[25]. Furthermore, many of the aerosol and transport processes happen on the sub-grid scale, which is subject to additional uncertainties.

There are ongoing activities to reduce several of these uncertainties. The Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP) is aimed at validating modelled representations of volcanic eruptions by minimizing differences in the applied volcanic forcing[117]. The Interactive Stratospheric Aerosol Model Intercomparison Project (ISA-MIP) aims to understand the range of modelled stratospheric responses to quiescent and changing conditions over measured history, with the purpose of improving and validating models[118]. This project also includes a protocol to explicitly quantify the impact of aerosol microphysical uncertainties on climate outcomes under geoengineering. Preparing an observation platform that could be rapidly deployed during the next volcanic eruption would substantially improve our understanding of aerosol formation and microphysical growth[76]. In addition, during a hypothetical deployment, aerosol optical depth and surface air temperature could be measured regularly to adjust the injection amounts[119], compensating for uncertainty in the injection required to achieve the

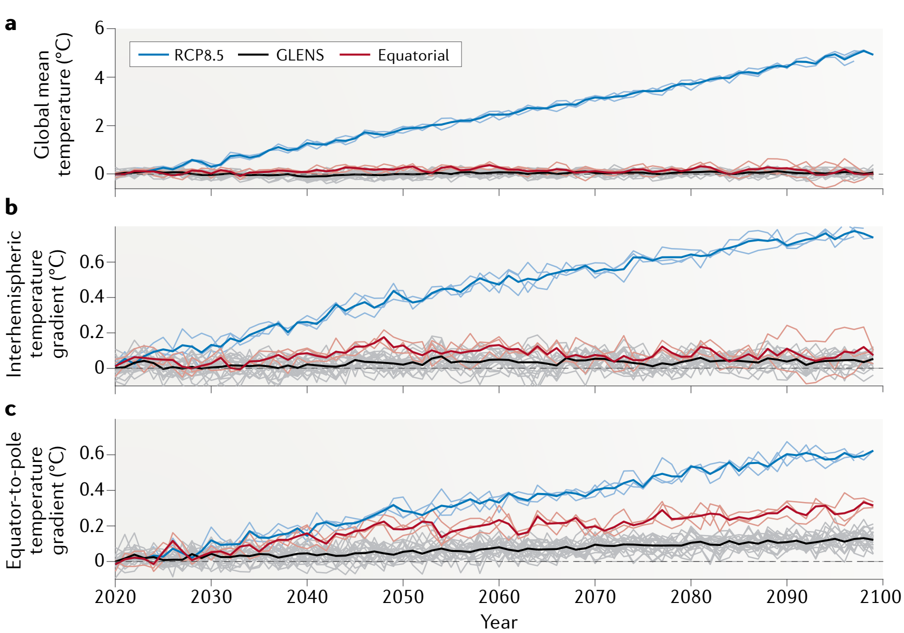

Fig. 3 | **Effectiveness of SAG strategies in achieving temperature targets.** Comparison of stratospheric aerosol engineering strategy on various temperature metrics[49]: global mean temperature (part **a**), the interhemispheric temperature gradient (part **b**) and the equator-to-pole temperature gradient (part **c**). The blue lines show Representative Concentration Pathway 8.5 (RCP8.5), the background against which stratospheric aerosol engineering is being performed, the black lines show results for Geoengineering Large Ensemble (GLENS)[86] and the orange lines show results for equatorial-only injection of SO_2 (REF.[58]). The faint lines show different simulation ensemble members and the darker lines show the ensemble mean. The dashed grey zero line shows the objective (no change from 2020 values). SAG, stratospheric aerosol geoengineering. Adapted with permission from REF.[58], Wiley-VCH.

desired cooling, even in the presence of uncertainties in size distribution, deposition and stratospheric heating.

Climate response

Due to temperature-dependent feedbacks, many of the uncertainties in the response to SAG are also uncertainties in the response to CO_2 (REF.[43]). Focusing only on how the two forcings affect the climate differently[120] thus simplifies the assessment of uncertainty. Whereas many broad features of the different climate responses to CO_2 and SAG are robust across models[121], details of regional changes can differ substantially between models. For example, all models predict that some locations may see increased departures from preindustrial precipitation due to solar dimming, but there is little agreement between models on where this might occur[18,122].

It is useful to explicitly separate differential climate responses from SAG and CO_2 into categories arising from shortwave versus longwave forcing, the spatial and seasonal pattern of forcing and processes unique to stratospheric aerosols, particularly those owing to stratospheric heating or ozone depletion. This subdivision illustrates the appropriate level of granularity in constructing a risk register. Also, because each of these categories is associated with their own uncertainties, subdividing indicates how to design dedicated simulations to isolate individual mechanisms. For example, offsetting CO_2-induced global mean temperature change with reduction in the solar constants of models overcools the tropics and undercools the poles[8,123]. This differential latitudinal cooling is due in large part to different spatial patterns of forcing between CO_2 and insolation and differences in shortwave versus longwave forcing[124]. Furthermore, geographically varying patterns of solar reduction result in different surface-temperature patterns[49]. Finally, regardless of the spatial pattern of forcing, offsetting increased GHG forcing with a reduction in shortwave radiation will reduce the strength of the hydrological cycle, as the shortwave reduction compensates for the temperature-dependent precipitation response but not for the 'fast' response to increased CO_2, which is a radiative effect that acts to reduce evaporation and, hence, upward moisture flux into the free troposphere[125]. To determine which of these responses is most important for understanding the latitudinal distribution of cooling, one could design simulations with different spatial patterns of solar geoengineering and different characters (longwave versus shortwave) of forcing[47,49,124].

The sources of uncertainty for differential regional responses to SAG are not yet fully understood. Many of the surface-climate effects are tied to changes in large-scale circulation[61,126], which often have poorly represented processes in Earth system models[127], leading to model spread. For example, FIG. 5 shows the maximum and minimum (on a grid-cell level) across models of regional responses to offsetting high CO_2 with solar dimming; not even the sign of the regional changes is consistent across all models in most places. Similar results do not yet exist for simulations of SAG as there are not yet any inter-model comparisons using models that can simultaneously include enough of the relevant aerosol processes. However, the uncertainty in the surface response to SAG would presumably be even larger, as it would include both the uncertainties associated with compensating increased CO_2 with a solar reduction, as well as further uncertainties associated with the stratospheric aerosol processes, including the effects of stratospheric heating on the surface climate. Moreover, different models have different representations of CO_2 fertilization to accelerate plant growth, as well as different nutrient-limitation cycles, leading to different magnitudes of change in surface fluxes, temperature changes and hydrological responses[32,128]. A common approach to reducing spread or selecting models that accurately reproduce real-world phenomena is through observational constraints[129], but such information is lacking for solar geoengineering. SAG field experiments directly aimed at eliciting a climate-system response are effectively deployment-scale[130–132] and are best categorized as operational 'pre-deployment' activities[67], rather than tools to reduce uncertainty in climate response.

Impacts

Solar geoengineering has maintained interest due to its potential to alleviate many of the consequences of climate change[4]. While direct model outputs allow quantification of SAG-induced changes in climate-related variables such as temperature, precipitation and sea ice[133], synthesizing these into corresponding impacts on food and water security, health, ecosystem services and sea-level rise is more difficult and uncertain[134]. Gaining consensus on how SAG influences these aspects from impact modelling is difficult

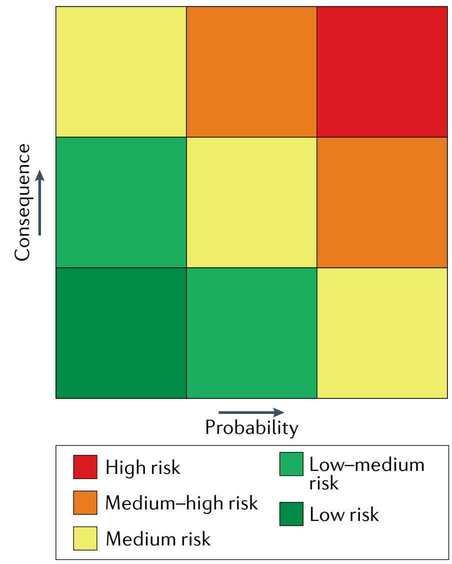

Fig. 4 | **Schematic of a risk register.** Risks are placed in terms of their probability of occurrence (*x*-axis), for example, being wrong about some process or parameter, and the consequence (*y*-axis). The risk register serves as a heuristic for comparing risks and identifying the highest priorities (items towards the top-right of the register). Adapted with permission from REF.[67], PNAS.

due to the diversity of model representations of scale and processes, even in the same sector[135]. In addition to assessing impacts associated with novel SAG-induced climate regimes, it will be important to assess the direct impact of the aerosols on health (from particulates[95], acid rain[26] or ultraviolet radiation due to ozone loss[24,136,137]) and on ecosystems and agriculture (owing to the small reduction in overall sunlight and the increase in diffuse light)[138,139].

The incomplete and indirect relevance of available datasets may limit efforts to constrain the impacts of SAG (for example, on agriculture) using volcanic analogues[30]. Moreover, the impacts of SAG are highly dependent on societal decisions; for example, the potential detrimental effects of SAG on agriculture could be compensated for by changes in fertilizer use[29]. Coordination between the SAG research community and impact-assessment modellers is essential to reduce uncertainty and improve confidence in our understanding of whether SAG is effective at reducing the impacts of climate change and, if so, where[140].

The impacts of climate change typically increase monotonically with increased GHG concentrations. However, solar geoengineering would not decrease all impacts proportionally; known correlations between variables for climate change can be different for solar geoengineering[141]. As such, single-objective targets may not be appropriate for managing trade-offs in hypothetical deployments. An important component of investigations to create a holistic understanding of the potentials and limitations of solar geoengineering is effective scenario generation[142] to capture relatively unexplored issues in climate models, such as distributional justice and multiple stakeholder perspectives[143,144].

Conclusions and next steps

Ultimately, the goal of quantifying uncertainty in SAG is to decide what to do about it, of which there are many courses of action. Reducing uncertainty requires research and, implicitly, a prioritization of that research. Managing uncertainty can be accomplished through adaptive methods (such as feedback)[21,49,119,145], where geoengineering is adjusted regularly to ensure that the objectives are being met[38]. Avoiding uncertainty can be accomplished by pursuing methods where SAG is needed less or not at all, such as more aggressive mitigation[122], or by choosing strategies

Table 1 | **Summary of key risks and uncertainties associated with SAG**

Uncertainty	Probability	Consequence	Overall assessment
Process			
Aerosol microphysics	High; inadequately constrained by volcanic analogue[102,103]	High; size distribution affects total forcing[53], sedimentation rate[26], stratospheric heating[126] and stratospheric water vapour[46,100]	High
Sub-grid-scale mixing	High; model assumptions regarding aerosol distribution and coagulation untested on sub-grid scales[73]	High; could substantially affect aerosol microphysics and resulting size and spatial distributions	High
Stratospheric transport	High; moderate inconsistency between models[113,158], inadequate fidelity to observations[112]	Medium; affects aerosol spatial distribution and lifetime[53]	Medium–high
Stratospheric water vapour	High; mixed ability of models to represent stratospheric water vapour changes[159,160], uncertain observations of stratospheric water vapour[104–106]	Medium; stratospheric water vapour amplifies surface and stratospheric warming[161], affects chemistry rates[71]	Medium–high
Impact on cirrus	High; aerosol–cloud interactions are highly uncertain for cirrus[25,115,116], poor representation of upper-tropospheric ice water path and vertical velocities in models[162], poor observational constraints on cirrus[163]	Low; cirrus changes from SAG constitute O (10%) radiative forcing, less than stratospheric water vapour[25]	Medium
Ozone chemistry	Low; dependence on uncertain radical concentrations[164,165] but generally well constrained for adequate particle-size distribution and stratospheric-heating information[45]	Medium; ozone has surface climate effects[166,167] and impacts on ultraviolet radiation[24,136,137]	Low–medium
Response			
Impact of stratospheric heating on tropospheric and surface climate	High for certain aerosol choices, such as sulfate; stratospheric-heating effects on tropospheric and surface climate are known but uncertainties regarding magnitude of responses and robustness across models[6,47,168]	High; stratospheric heating may be responsible for many of the surface-climate side effects of SAG[47]	High
Differences in CO_2 and SAG climate responses	Medium; SAG offsets many features of climate change due to CO_2 but residuals remain[20,21,36]; consequences due to spatial and seasonal differences in forcing are well understood (for example, tropical overcooling and polar undercooling)[121] but outcomes are scenario dependent[19,49]; limited ability to decouple the differential shortwave and longwave effects[122]	Medium; differences in how CO_2 and SAG affect the climate differently account for most of the uncertainty in projected changes in regional precipitation[43]	Medium
Termination effect	Low; termination is a well-established risk[31]	High; impacts of sudden termination of SAG are likely to be severe[32,169]	Medium
Impacts			
Ecosystem response	High; limited studies[27,170]	High; ecosystem services constitute the entire food chain and a sizable portion of the world's economy[171]	High
Partitioning of direct and diffuse light on ecosystems and agriculture	High; limited geoengineering modelling studies[138] and applicability of natural analogues[30]	Low; compared with CO_2 fertilization and reduction of heat stress under SAG, partitioning of diffuse and direct light has a lower order effect[139]	Medium
Stratospheric aerosol delivery cost	Medium; some uncertainty in estimates[156,157,172,173]	Low; the costs are lower than any other method of addressing climate change	Low–medium

Risk is discussed in the context of the two axes of the risk register described in this article: the probability of occurrence (if known) or of being wrong and consequence. Uncertainties shown are non-exhaustive and are exclusively derived from natural science. SAG, stratospheric aerosol geoengineering.

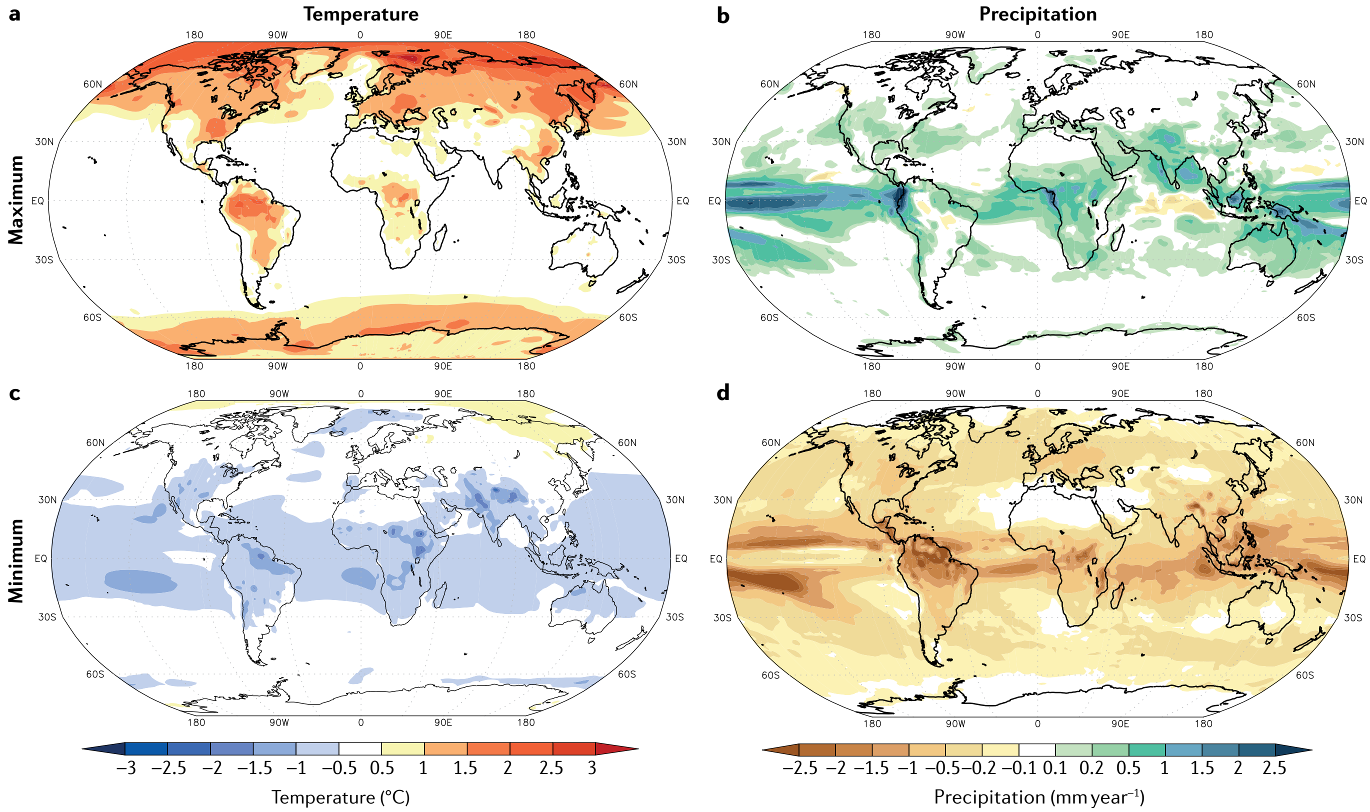

Fig. 5 | **Uncertainty in climate responses to SAG.** Model spread from 12 models in which the solar reduction fully offsets the global mean temperature increase from abrupt4xCO_2, using data from the Geoengineering Model Intercomparison Project G1 experiment[84]. Shown are: maximum temperature (part **a**), minimum temperature (part **b**), maximum precipitation (part **c**) and minimum precipitation (part **d**), all computed for each grid cell. SAG, stratospheric aerosol geoengineering.

for deployment that are less sensitive to particular uncertainties (for example, off-equatorial injection to minimize effects on the QBO)[58]. Finally, some uncertainties may be irreducible but they can still be quantified and prioritized so that their risks are understood.

The focus here has been to define a path towards quantifying the effects of uncertainty in SAG, following which there may be a diversity of responses in research. In one extreme, there may be a non-zero probability that climate change is catastrophic, providing strong motivation for solar geoengineering research[146]. Conversely, the probability of showstoppers (that is, catastrophic risks from deployment) may be non-zero, meaning that no further effort should be spent on solar geoengineering research[147]. However, justifying these two extreme responses, and all responses in between, does not necessitate the complete quantification of all uncertainties; it can be argued that there is insufficient knowledge to support decision making, but decisions can be made in light of uncertainty[148]. Any decision regarding SAG deployment will involve a risk–risk trade-off[149]: how do the risks of deploying, including risks introduced by uncertainty, weigh against the risks of not deploying solar geoengineering? Ultimately, this is a question of governance[150], and determining what objectives solar geoengineering can and cannot achieve is crucial for understanding what governance mechanisms require further development and expansion[151], as well as what observations are needed to inform those governance mechanisms[152].

Research recommendations

Based on our current assessment of the state of uncertainty in solar geoengineering, we provide recommendations on several high-priority research directions in an effort to gain greater confidence in present and future conclusions regarding SAG. In doing so, we offer a pathway whereby similar explorations may be applied to other solar geoengineering methods (such as marine cloud brightening).

Recommendations on prioritization. We have described a risk register for prioritizing uncertainties and, thereby, areas of future research. In TABLE 1, we have identified several research questions that we deem high priority (such as aerosol microphysical growth, sub-grid-scale mixing and ecosystem response), but these are based on our opinions. A more comprehensive effort to thoroughly explore a wider range of uncertainties (including those that fall outside of the realm of natural science), combined with a more objective way of assessing their risks, would be highly informative for building a coordinated, large-scale research agenda.

Recommendations on model intercomparisons. Although model intercomparisons can reveal substantial knowledge about uncertainty through analysing model similarities and differences, most multi-model studies have focused on where models agree on SAG than where they disagree[134]. Pitari et al.[24], by contrast, evaluated differences in ozone changes in different models with different processes, revealing the importance of including specific chemical processes in models[24]. Studies like this are excellent examples of how model intercomparisons can inform prioritization of uncertainties, and we argue that more studies exploring model differences (for example, simulations with different representations of aerosol microphysics) or looking at a diversity of model responses across high-priority areas (for example, ecosystems) are needed. These may include further analysis of existing model experiments, such as those produced under GeoMIP, as well as carefully constructed simulations to isolate different physical mechanisms, for example, constraining the role of stratospheric heating by introducing specified stratospheric heating rates without the aerosols[47] or conducting simulations with idealized aerosols without any heating. In addition, model comparisons can increase robustness in conclusions, for example, repeating GLENS in other, independently developed models that include the relevant processes.

Recommendations on field experiments. In the future, there may be a role for SAG field experiments to reduce critical uncertainties. The planned Stratospheric Controlled Perturbation Experiment (SCoPEx)[78], for example, is aimed at understanding aerosol-nucleation processes and stratospheric chemical perturbations associated with calcite injections. As another example, in situ observations of aerosol–cloud interactions in cirrus could address critical uncertainties in solar geoengineering (TABLE 1) and climate science more generally. The societal acceptability and potential risk of harm are greater for field experiments than for modelling or laboratory experiments and, as such, determining the roles of field experiments and whether they should go forward is a matter of governance[150]. We suggest two potential components of a cost–benefit analysis that could judge whether field experiments proceed: ensuring that the information cannot be obtained by another, less intrusive way and specifying that the field experiments are truly mission driven, aimed at addressing high-priority uncertainties.

Recommendations on natural analogues and observations. The role of natural analogues in bounding risk needs to be understood, especially about unknown unknowns. As an example in SAG, there is not yet a way to compare confidence in the deployment of sulfate (which multiple sources of evidence say are likely to have detrimental side effects) with the deployment of calcite (which may have substantially fewer side effects), and any such conclusions are based on a limited set of modelling studies. Although the usefulness of volcanoes as analogues for SAG is limited, observing future large volcanic eruptions could provide key information on aerosol microphysical growth or stratospheric transport that would help validate model representations of SAG[76].

Recommendations on research-capacity building. Research on solar geoengineering has been dominated by developed countries with climate-modelling capacity, which insufficiently captures the breadth of populations who would be affected by any potential deployment[149]. The lack of a broader geographical diversity of researchers and cultural perspectives may be detrimental to gaining a full appreciation of all sources of uncertainty. Ongoing research activities, such as GeoMIP and the Climate Engineering Conference series, have actively encouraged increased participation from developing countries[153,154]. Recently, through small research grants, the Developing Country Impacts Modelling Analysis for SRM (DECIMALS) fund has catalysed research into modelled SAG effects on developing countries[155], which is an important step towards increasing the diversity of well-informed perspectives in solar geoengineering discussions. Increased diversity in solar geoengineering research will improve confidence that as many uncertainties in solar geoengineering are identified as possible and that the prioritization process will be performed more equitably.

Much of the discussion surrounding new results in solar geoengineering raises questions about their accuracy and relevance to reality. Unfortunately, this reflects how little confidence there is in many of the results. This lack of confidence is inadequate as a basis for climate policy. Although nearly all global-scale decisions are made in the presence of some amount of uncertainty, in the case of solar geoengineering, there is presently not enough confidence in any of the conclusions to design a deployment strategy with the expectation that it will behave as intended. Eventually, with enough research, there may be sufficient confidence in the risks of solar geoengineering that enable well-informed discussions about its role (alongside mitigation and adaptation strategies, and carbon-dioxide removal) in addressing climate change to proceed. Solar geoengineering sits at the frontier of climate science research, with all of the discovery and pitfalls therein; addressing uncertainty in a systematic way will move the field forward and improve its relevance in policy discussions.

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