18 Politically relevant solar geoengineering scenarios

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Abstract

Solar geoengineering, also known as Solar Radiation Modification (SRM), has been proposed to alter Earth's radiative balance to reduce the effects of anthropogenic climate change. SRM has been identified as a research priority, as it has been shown to effectively reduce surface temperatures, while substantial uncertainties remain around side effects and impacts. Global modeling studies of SRM have often relied on idealized scenarios to understand the physical processes of interventions and their widespread impacts. These extreme or idealized scenarios are not directly policy-relevant and are often physically implausible (such as imposing global solar reduction to counter the warming of an instantaneous quadrupling of CO_2). The climatic and ecological impacts of politically relevant and potentially plausible SRM approaches have rarely been modeled and assessed. Nevertheless, commentators and policymakers often falsely assume that idealized or extreme scenarios are proposed solutions to climate change. This paper proposes 18 scenarios that appear to be broadly plausible from political and Earth System perspectives and encompass futures that could be both warnings or perhaps desirable. We place these scenarios into four groups following broader strategic contexts: (1) Global Management; (2) Regional Emergencies; (3) Coordinated Regional Interventions; and (4) Reactive Global Interventions. For each scenario, relevant model experiments are proposed. Some may be performed with existing setups of global climate models, while others require further specification. Developing and performing these model experiments – and assessing likely resulting impacts on society and ecosystems – would be essential to inform public debate and policymakers on the real-world issues surrounding SRM.

Keywords
Geoengineering; scenarios; solar radiation modification; marine cloud brightening

1. Introduction

Anthropogenic climate change presents one of the world's greatest challenges today, with the crisis expected to intensify over the coming decades (IPCC, 2022). Adapting to climate change requires significant global effort and financial outlay (Stern, 2006) to resolve social, political, geophysical, scientific, and cultural issues. Progress on mitigation of greenhouse gas (GHG) emissions has so far been inadequate (UNEP, 2021), despite both hard-won international agreements (e.g., UN Paris Agreement) and many domestic and non-state initiatives. Drastic emission cuts are needed to restrain anticipated rises in global temperatures (United Nations, 2014), including

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no new oil, gas, or coal development if the world is to reach net-zero emissions by 2050 (IEA, 2021). Insufficient action on climate change has resulted in a revival of scientific and political consideration of Solar Radiation Modification (SRM) to supplement emissions reduction, Carbon Dioxide Removal (CDR), and adaptation to climate change.

In its modern usage, geoengineering (also ‘climate engineering’ or ‘climate intervention’) has meant the deliberate modification of the climate system (Shepherd, 2009) and has referred to two distinct categories, CDR and SRM. More recently, scholars have been careful to avoid conflating both approaches under a single term due to fundamental differences in function, the former reducing GHG concentrations and the latter addressing radiative forcing directly (Heyward, 2013). However, scholars also note that the extent of CDR usage could greatly influence how SRM fits into broader climate policy (Asayama & Hulme, 2019). As such, the scenarios proposed and discussed here focus on the role of SRM, acknowledging that assumptions about emissions reduction, CDR, and adaptation are also vital for contextualizing possible futures (McLaren & Corry, 2021).

The SRM scenarios presented here go beyond traditional climate modeling and lie within the broader scope of socio-environmental systems research. An SRM program would likely be instigated due to specific concerns related to human welfare, the economic impacts of a changing climate, and political stability. These social dimensions of potential SRM deployment have largely been neglected in the modeling literature – this paper aims to address this void by providing a qualitative description of 18 politically relevant SRM scenarios, across a range of technologies to orient future modeling work. The 18 scenarios presented here range from ostensibly desirable futures to others that ought to be avoided. We identify two scenario axes, regional – global and emergency – planned, to help provide an initial framework for organizing the scenarios. The term ‘politically relevant’ implies physically plausible scenarios with salience for policymaking over the next few decades.

2. Background

2.1 Solar radiation modification

SRM refers to a set of proposed technologies that modify the Earth’s radiation balance via reflecting a fraction of incoming sunlight. Various schemes have been suggested, such as Marine Cloud Brightening (MCB) and Stratospheric Aerosol Injection (SAI) (Caldeira et al., 2013). Natural analogs of these schemes include ship tracks over the oceans (caused by aerosols in ship exhaust increasing cloud reflectivity) and major volcanic eruptions (which result in a temporary aerosol layer in the stratosphere, reflecting some incoming solar radiation). The emergent technique of Cirrus Cloud Thinning (CCT) (Mitchell & Finnegan, 2009; Gasparini et al., 2020) works principally on the outgoing longwave radiation budget - but is typically grouped with SRM due to similarities across physics, engineering, and governance (National Academies of Sciences, Engineering, and Medicine, 2021).

Various classes of SRM are fundamentally different. SAI is more long-lasting than MCB and CCT as stratospheric aerosols remain aloft and impact temperatures for several years, even if injections stop. By contrast, MCB (Latham, 2002) is potentially more temporarily and spatially controllable, with aerosols often lasting mere days. The less studied CCT is more comparable to MCB than SAI in that it is short-lived and locally effective – notwithstanding potential teleconnections (Mitchell & Finnegan, 2009).

SRM does not fully counter the effect of GHG emissions. The effects of reducing shortwave radiation cannot directly counter the effects of increasing GHG concentrations, which act in the longwave. Based on previous highly idealized experiments, using globally uniform reductions in solar radiation (Kravitz et al., 2014), SRM is imperfect in uniformly reducing global surface temperatures of increased carbon dioxide (CO_2), with stronger cooling in the tropics and less cooling in high latitudes. Depending on levels of SAI deployed, the climate with SAI would either be drier or warmer than the pre-industrial climate (Tilmes et al., 2013). Furthermore, SRM does not directly lower CO_2 levels and therefore does not counter other effects of high CO_2 concentrations – such as ocean acidification. However, model experiments using targeted stratospheric sulfur dioxide (SO_2) injections, a precursor of sulfate aerosol, have been shown to be able to counter the greenhouse gas-induced surface warming more evenly, and therefore reducing some of the side effects of SAI identified by previous idealized simulations, such as overcooling of the tropics and undercooling of the poles, as well as shifts in precipitation pattern and other climatic changes (Tilmes et al., 2018).

Further modeling is needed to develop improved targeted interventions designed to reduce the expected side effects. Examples include optimizing deployment patterns to reduce uneven regional effects (Dai et al., 2018; Visioni et al., 2020; Lee et al., 2021) and alternate choices of aerosols to reduce impacts from deposition (Dykema et al., 2016). Presently, significant risks and controversies remain such as ozone depletion (Xia et al., 2017) and unexpected side effects (Kravitz & MacMartin, 2020). Such controversy has resulted in a situation where the treatment of SRM has been "at best selective and insufficient; at worst … misrepresented or ignored" (Parson, 2017). Along with a lack of adequate understanding of the full range of regional and ecological impacts, due in large part to insufficient modeling research (Kravitz & MacMartin, 2020), this has arguably made policymakers and the broader public reluctant to take SRM seriously.

2.2 Policy context for SRM

Traditional climate policy discussions tended to focus solely on emissions reduction and adaptation. More recently, however, both SRM and CDR have been prominent in discourse and debates on climate policy. CDR is now an essential element in major international agreements and considered as mitigation by IPCC; for example, all IPCC SR1.5°C pathways consistent with the Paris Agreement anticipate large-scale CDR deployment in the latter half of the 21st century to reach net-zero emissions (Lewis, 2015; Fuss et al., 2018; Nemet et al., 2018; IPCC, 2018). Furthermore, many Nationally Determined Contributions (NDCs) towards mid-century net-zero targets rely heavily on CDR (Mace et al., 2021).

Conversely, SRM is not considered a major part of the current policy mix. Nevertheless, climate policies may yet broaden to include SRM, which could be rapidly (and potentially inexpensively) deployed after some modest development delay (McClellan et al., 2012; Smith & Wagner, 2018; Smith, 2020). The most recent estimates by Smith (2020) place SAI costs at as low as \$18B/year (USD) per degree Celsius of warming avoided. Technological development means that existing estimates could be reduced further – e.g., by electric propulsion, drones, automation of the supply chain, and self-lofting material (Gao et al., 2021). As GHG levels keep rising, more aggressive SRM interventions would be needed to reach desired temperature targets – unless rapid CDR deployment at scale occurs. Ultimately, the level of emission mitigation and CDR deployed will dictate how much SRM may be strategically desirable (Shepherd, 2009). However, SRM applications also have their limits and may not be used unlimited, for example when it comes to increasing impacts with injection amount (e.g., Tilmes et al., 2020) and increasing risks with termination (Parker & Irvine, 2018). Nevertheless, the near-term upper bound costs projection for moderate injection amounts has been suggested as between \$24.9B and \$68.5B (USD) over the first fifteen years of deployment, with higher-end estimates contingent on the extent of deployment (Smith & Wagner, 2018). Such estimates are subject to uncertainty in the cooling efficiency of SAI (Moriyama et al., 2017), and injection amounts can differ up to a factor of 2 for the same cooling scenario in different models (Visioni et al., 2021). Regardless of the considerable uncertainty in estimates, direct costs of SRM are likely on the order of tens of billions a year – and thus negligible compared to CDR (Hanna et al., 2021), direct health costs of climate change (Duncombe, 2021), or adaptation costs (Reynolds et al., 2016).

2.3 Scenario-relevant limitations of SRM

Current SRM research is characterized by a wide range of limitations in terms of the diversity of scenarios that have been performed (National Academies of Science, Engineering and Medicine, 2021). Without prioritizing, some major challenges relevant to the formulation of SRM scenarios are discussed here.

Modeling and empirical limitations

To date, SRM has primarily been investigated with physical climate simulations such as Earth System Models (ESMs). Most experts concur that SRM poses no insurmountable engineering complexities (Caldeira et al., 2013; Smith & Wagner 2018). However, some speculative forms (e.g., space mirrors) are prohibitively expensive at present (McInnes, 2010). Proposed outdoor experimentation for SRM technology have met with substantial governance challenges and controversy (Smith, 2018), so some empirical gaps may limit model agreement between ESMs. Some partial workarounds exist, such as utilizing data from observational proxies: volcanic eruptions for SAI (Proctor et al., 2018) and ship tracks for MCB (Robock et al., 2013). Nevertheless, scenario exercises using models uninformed by empirical data will require adequate methods for uncertainty management, such as sensitivity analysis (Elsawah, Hamilton et al., 2020) which can aid in checking the robustness of results given a specific model parametrization. Furthermore, to assess impacts from SRM scenarios, models will need additional capabilities that currently require development. For example, interactive aerosol formation and aerosol-cloud interactions should be included in models to improve future impact assessments. Significant uncertainties need to be overcome through further fundamental research on marine stratocumulus clouds to determine if MCB could indeed work (Latham et al., 2012; National Academies of Science, Engineering and Medicine, 2021).

Governance challenges

Much has been written in the popular and academic press about SRM and its governance (Mercer et al., 2011; Tingley & Wagner, 2017; Talberg et al., 2018; Reynolds, 2019; Gupta et al., 2020). Moreover, SRM is envisaged by various authors to be a controversial and challenging topic (Keith, 2013; Luokkanen et al., 2014; Parker & Geden, 2016). Existing authors primarily discuss SRM in the context of two potential deployment scenarios: orderly state provision and regulation (Ricke et al., 2013); or the rogue state or 'Greenfinger' philanthropist (Victor, 2008). Criticism of this limited scope, including consideration of alternative funding models, can be found in existing literature (Lockley, 2016a; Talberg et al., 2018). Because of the relatively low cost (McClellan et al. 2012; Moriyama et al., 2017; Smith and Wagner, 2018; Smith, 2020) and incremental nature of the intervention (i.e., not all-or-nothing), future deployment of SRM geoengineering could be initiated by commercial firms (Lockley, 2016b), decentralized non-state actors (Reynolds & Wagner, 2020) or by states and their proxies (e.g., oligarchs, client states, contractors) even without international coordination and consensus (Lockley, 2016a). Notably, private sector SRM is broadly neglected in the existing governance literature (Flegal et al., 2019; Reynolds, 2019).

Integrating with climate policy

If SRM were to be part of a broader climate policy portfolio which includes emissions mitigation, adaptation, and CDR to various degrees, policymakers would need to be cognizant of certain pitfalls. For example, relying on substantial SRM without ambitious mitigation and CDR increases the needed amount and duration of SRM application. Larger SRM interventions increase the risk of termination shock, i.e., an abrupt warming pulse, due to the interruption of sustained deployment (Matthews and Caldeira, 2007; McCusker et al., 2014). Abrupt termination of SRM is dangerous, as the rate of temperature rise would be much faster than from current CO_2 emissions, likely causing massive ecological damage as the biosphere would not adapt to such rapid changes (MacMartin et al., 2014; Trisos et al., 2018). Accordingly, integrating SRM into a climate policy portfolio would require orderly start and exit strategies (ramping aerosol loading up and down), which do not expose the climate to an otherwise avoidable risk of sudden cooling or warming (Parker & Irvine, 2018). These constraints for integrating SRM into a broader climate policy portfolio make scenario modeling helpful in examining possible strategies for combining SRM with mitigation and CDR (e.g., Global management scenarios).

There is an inextricable link between SRM, mitigation, and CDR. The requisite extent of SRM is partly determined by how much emissions abatement and carbon removal occur (Shepherd, 2009; Asayama & Hulme, 2019). Therefore, defining assumed emission baselines, how much CDR is deployed in future trajectories, and temperature targets, is essential for setting out SRM scenarios.

3. Methodology of proposing scenarios

Much scenario research (both quantitative and qualitative) has been conducted on climate change broadly, with key policy-relevant examples being the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) used for the IPCC assessment reports (van Vuuren et al., 2011; O'Neill et al., 2014; IPCC, 2018). However, relatively less work has been done for SRM scenarios, and the existing literature is dominated by quantitative climate science scenarios (Talberg et al., 2018), which are not explicitly formulated for policy relevance (Stilgoe, 2015). Recent large-scale modeling exercises such as the Geoengineering Model Intercomparison Project (GeoMIP) and the Geoengineering Large Ensemble (GLENS) used somewhat policy-relevant scenarios, e.g., reducing a high climate forcing scenario to a medium climate forcing scenario (Visioni et al., 2021), or reducing a high forcing scenario to 2020 surface temperature targets (Tilmes et al., 2018; Visioni et al., 2021). However, these scenarios are less desirable since they require continuously increasing SO_2 injections with time and do not include substantial mitigation and CDR efforts. Other SRM literature also implicitly considers scenarios such as in single model studies (Smith & Rasch, 2013; Tilmes et al., 2020), control theory formulations (MacMartin et al., 2014; Kravitz et al., 2016), integrated assessment modeling (Heutel et al., 2016, and proposed governance arrangements (Parson, 2014). Thus far, both large-scale modeling exercises and research with implicit scenarios are insufficient to cover the range of possible scenarios that are required for informing real-world policy.

In addition to existing large-scale modeling efforts, new scenarios are needed to inform the impact assessment community, governance practitioners, and the wider public. Politically relevant scenarios should offer feasible intervention trajectories and be supported by relevant modeling results. By considering additional, politically relevant scenarios and carefully designing associated model experiments, end-users will have modeling outputs more suitable for governance and policy decisions. Additional confidence can be provided using comprehensive modeling exercises through projects such as GeoMIP and GLENS.

The contribution of this paper is a qualitative set of SRM scenarios that aims to help fill the policy-relevant void in SRM literature. The approach here is in line with the burgeoning literature on exploratory scenarios commonly used in fields such as socio-environmental systems research (Maier et al., 2016; Elsawah, Hamilton et al., 2020), water management (van Vliet & Kok, 2015), energy transitions (Trutnevyte et al., 2014), and disaster risk management (Riddell et al., 2018).

Exploratory scenario methods address the question “What could happen?” in contrast to predictive scenarios (“What will happen?”) and normative scenarios (“What should happen?”). Although all three approaches are helpful for different purposes, exploratory scenario exercises are beneficial for tackling deep uncertainty (Maier 2016). Deep uncertainty is characterized by a situation in which there is disagreement over the appropriate models, probability distributions, and even the relative importance of outcomes for a given decision context (Lempert et al., 2003). The decision context for SRM research and deployment is rife with deep uncertainty due to pervasive unknowns and controversy across physical and social dimensions (Manoussi et al., 2018). Handling deep uncertainty entails an integrated treatment of modeling uncertainty, a problem that has recently been identified as one of the eight grand challenges for socio-environmental systems modeling (Elsawah, Filatova et al., 2020). Exploratory scenarios are particularly well suited for handling deep uncertainty and fit within the “story-and-simulation” approach for exploring the uncertainty space of SRM (Guivarch et al., 2017).

The scenario formulation in this paper took an exploratory and bricolage-style approach. The term “bricolage” describes how the overall methodology pragmatically drew from various methods and practices, which Fu et al. (2020) advocated for exploratory scenario exercises. The scenarios were informed by an informal literature review, guided by the authors’ wide-ranging research expertise on SRM and workshop-style brainstorming discussions. These scenarios were then presented according to the two scenarios dimensions introduced in the next section: the spatial scale of the intervention, versus how planned or reactive the strategy is. This approach is similar to the scenario-axes technique, which is common in scenario modeling. (van’t Klooster & van Asselt, 2006). This expert-driven approach enabled consideration of plausible but undesirable scenarios. The approach offered is distinct from participatory scenario processes (Van den Belt, 2004), which aim to include stakeholder engagement as part of scenario formulation. The politically relevant scenarios described here could, however, serve as a basis for further analysis by political and social scientists, informing participatory scenario research (Sugiyama et al., 2018).

4. Scenario Dimensions

Two dimensions were identified which characterize the SRM scenario space; political (planned vs. emergency) and spatial (regional vs. global). CDR was taken into explicit consideration for scenarios that align with global & planned aspects. Although these two axes do not distinguish all relevant differences, they provide a helpful framework for considering politically relevant interventions. These scenario dimensions are summarized in Figure 1.

In principle, any scenario proposed here fits into one of the four quadrants in Figure 1. In reality, most scenarios span multiple categories depending on implementation, so these are differences more of degree than kind. Planned and global scenarios assume a peaceful world that can perform well-designed, targeted deployment with globally optimized impacts. However, history has shown that unexpected social, political, and natural events may induce sudden societal changes; scenarios which fall into “geoengineering emergencies” explore this possibility. Additionally, some geoengineering strategies may be considered on a more regional or local level. These could be easily performed by single nations or companies (regardless of the international consensus) but may have global consequences. Finally, some long-term scenarios describe reactive and extensive use of SRM to address large-scale issues, such as sea-level rise or continued use of fossil fuels. Many scenarios have overlaps or similarities with others, so the grouping presented here is only a loose, preliminary one. Future modeling efforts may potentially benefit from considering several scenarios contemporaneously. Table 1 provides a detailed summary of all 18 scenarios.

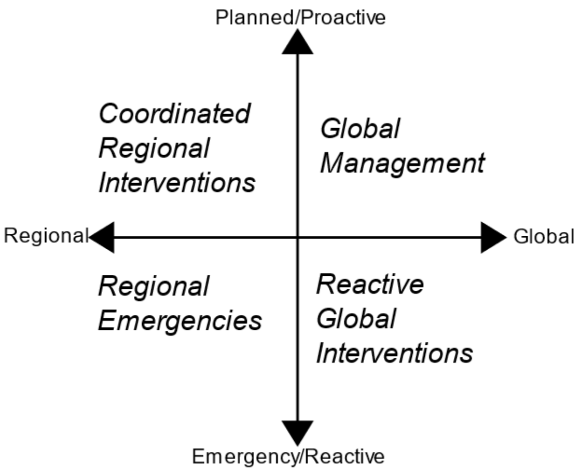

Figure 1: SRM scenario space. The vertical axis represents political coordination, whilst the horizontal axis defines the relevant spatial scale of the intervention.

Table 1: Summary of proposed scenarios. References to the literature on similar scenario(s) are provided where possible.

Scenario	Description	Global/ Regional	Planned/ Reactive
1a) Napkin Diagram	Combined mitigation with temporary phase-in of SRM, using CDR to ramp down deployment (Long & Shepherd, 2014; Tilmes et al., 2020)	G	P
1b) Slowing Warming	Temporary SRM only to reduce the rate of warming, CDR unavailable (Keith & MacMartin, 2015)	G	P
1c) Temperature-optimized SRM	Use of SRM to reach and maintain specific global temperature (Kravitz et al., 2017; Visioni et al., 2019)	G/Reg	P
1d) Impact-optimized SRM	Optimized SRM use for climate impacts such as water availability, crop production, or heat stress (e.g., Fan et al., 2021 on crop yields)	G/Reg	P
1e) Cocktail Geoengineering	Combined deployment of SRM technologies, such as SAI + MCB (Boucher et al., 2017; Cao et al., 2017)	G	P
2a) Response to Tipping Points	SRM deployment to counter abrupt warming from climate tipping points	G/Reg	Reac
2b) Response to Volcanic Eruptions	Adjusting already deployed SRM to abrupt cooling from volcanic eruptions	G/Reg	Reac
2c) Counter-Geoengineering	“Arms Race” responses to undesired SRM deployment (Parker et al., 2018)	Reg	Reac
2d) Temporary Termination	Temporary interruption (< 10 years) of SRM deployment and subsequent restart (Parker & Irvine, 2018)	G	Reac
2e) Technology Switch	Switchover from one SRM technology to another, such as SAI to MCB	G/Reg	Reac
3a) MCB over ocean regions	Regional and temporary deployment of MCB for specific applications such as protecting coral reefs and weakening hurricanes (Latham et al., 2013)	Reg	P
3b) Tropospheric aerosols over land regions	Short term release of aerosols in the troposphere to reduce impacts of heatwaves in populated regions (Bernstein et al., 2013)	Reg	P/Reac
3c) Single nation SAI	Unilateral deployment of SAI from a single region (Michaelowa, 2021)	Reg	P/Reac
3d) Polar SRM	SRM deployment limited to high latitudes to protect Arctic sea ice (Lee et al., 2021)	Reg	P/Reac
3e) Polar albedo enhancement	Surface brightening of Arctic sea ice using hollow glass microspheres (Field et al., 2018)	Reg	P/Reac
4a) Overcooling below pre-industrial	Deploying SRM to cool global temperatures below pre-industrial average (Harding et al., 2020)	G	P
4b) Curbing or reversing sea-level rise	Extreme and long-term SRM deployment to slow or reverse sea-level rise (Lockley et al., 2020)	G	P
4c) Continued fossil fuel use with SRM	Insufficient progress on mitigation in conjunction with (or enabled by) SRM policy (Sovacool, 2021)	G	Reac

These scenarios reflect a wide range of feasible deployment approaches, governance arrangements, and technologies - encompassing various strands of SRM. Furthermore, the proposed scenarios seek to place SRM, particularly SAI, in a future world in which climate policy includes varying levels of CDR and mitigation.

4.1 Global Management

Current and planned mitigation efforts are likely insufficient to reach important climate targets and prevent severe climate impacts (IPCC, 2018). This group describes SRM scenarios designed to reach specified climate targets and likely require international deployment agreements. Furthermore, modeling these scenarios would likely require use of sophisticated control-theoretic algorithms to maintain optimal deployment for a given climate target (MacMartin et al., 2014; MacMartin & Kravitz, 2019).

1a) Napkin diagram - Combined mitigation, CDR and SRM [Global, Planned]

Long and Shepherd have considered how different climate intervention approaches may be combined with the “Napkin Diagram” (Long & Shepherd, 2014). Those scenarios include considerations of the strengths, weaknesses, and impacts of different approaches – in terms of timing (i.e., the slower effects of CDR) and combined effectiveness. They suggested a limited application of SRM until mitigation and CDR efforts have been ramped up sufficiently.

SRM scenarios do not currently implement the Napkin Diagram, although parallels exist in other work (Kravitz et al., 2015; MacMartin et al., 2018; Moreno-Cruz et al., 2017). The modeling for such scenarios would require careful implementation of relevant CDR technologies, ensuring that scenarios are based on realistic rates of CDR deployment (Hanna et al., 2021). A combined SRM and CDR scenario could, for example, involve a logistic curve ramp-up and ramp-down of SRM deployment, optimized to meet a given temperature target (Chen et al., 2021).

The use of SRM in overshoot scenarios has previously been suggested (Wigley, 2006; Tilmes et al., 2020) based on the CMIP6 overshoot scenario, which assumes somewhat unrealistic amounts of CDR (O’Neill et al., 2016; Fuss, 2018). Overshoot and cooling using SAI would entail ramp-up and ramp-down deployment until at least 2100 to keep surface temperatures from breaching 1.5°C or 2.0°C. This scenario is well-defined and could be readily performed using ensembles of ESMs.

Further refinements of this scenario could include earlier mitigation efforts and more realistic implementations of CDR using historical diffusion pathways to constrain technology growth (Realmonte et al., 2019). It may also be sensible to model a continuation of SRM towards and perhaps beyond 2100, terminating in an orderly, non-abrupt disengagement. The design process would require a coordinated effort between scenario design and Integrated Assessment Modeling groups.

Sub-scenarios may be advisable. For example, CDR deployment may start later than anticipated but running well beyond 2100. The risk of over-reliance on SRM in delayed CDR scenarios is important to consider. While the potential use of SAI is hopefully brief, the duration of deployment is constrained by the maximum CDR rate (Ricke et al., 2017; Fuss et al., 2018; Asayama & Hulme, 2019).

1b) SRM for reducing the rate of warming [Global, Planned]

If carbon removal is unavailable for political, economic, or technical reasons, then SRM could be used only to reduce the rate of warming, as previous authors have suggested (Kosugi, 2013; Keith & MacMartin, 2015; Irvine & Keith, 2020). This scenario may come about due to CDR failing to scale adequately or political deliberation around the acceptability of prolonged SRM use. If gigaton-scale CDR is infeasible, and side-effects such as termination shock risk from indefinite SRM deployment deemed unpalatable, then a moderate and temporary use of SRM only to limit the rate of warming could be politically justified.

Multi-model investigations replicating this “temporary, moderate, responsive” deployment (Keith & MacMartin, 2015) could help to estimate effectiveness and impacts. It could be valuable to compare the benefits and impacts of alternate SRM schemes; moderate SRM for rate-limiting warming vs. heavy use of SRM for holding temperatures constant. Thus far, there is insufficient modeling data to determine whether slowing warming via moderate SRM would ultimately be beneficial to “buy time” for societies and ecosystems to adapt to climate change.

1c) Optimizing SRM deployment at various scales for specific temperature targets [Global/Regional, Planned]

Well-designed climate intervention strategies must be informed by scenarios that simultaneously target specific temperature goals and minimize risks and impacts. Besides global average surface temperature, other significant climatic variables include the interhemispheric surface temperature gradient and equator-to-pole surface temperature gradient. Preliminary work by Kravitz et al. (2017) and Tilmes et al. (2018) demonstrated that SAI could achieve both the primary climate objective of reducing global average temperatures while minimizing impacts on hemispheric and equator-to-pole gradients. However, these initial studies also show that annual injections with fixed-latitude injections may not be optimal. Seasonal variability of stratospheric aerosol forcing could result in relatively warmer winters and cooler summers compared to the present day, especially over the North Atlantic and Northern Europe (Jiang et al., 2019). These changes are influenced by stratospheric heating and acceleration of the Atlantic Meridional Overturning Circulation (AMOC) due to SAI; however, significant model uncertainties remain (Fasullo et al., 2018).

Current SAI modeling has looked at further optimizing deployment. For example, Visioni et al. (2019) and Lee et al. (2021) performed simulations that include seasonally and spatially adjusted injections by injecting aerosols at high latitudes during the Northern Hemisphere spring. They found that seasonally optimized SAI reduces the required amount of material injected, reducing costs, side effects, and environmental risk. In addition, Lee et al. (2021) found that Spring-only injection could restore twice as much sea ice and achieve a 50% greater reduction in global average temperatures than year-round SAI deployment for the same volume of SO_2 injected.

The potential for SAI to modulate seasonal and regional temperature patterns has its limitations (Visioni et al., 2019). Due to the long lifetime of stratospheric aerosols and the specifics of stratospheric dynamics, aerosol distributions cannot be substantially changed through seasonal injection adjustment. Large-scale stratospheric circulations largely dictate aerosol distribution, so the capacity to control artificial aerosol layers is limited. Much more optimization and scenario modeling is needed to explore the possibilities of achieving a more balanced modification of seasonal and regional surface temperature patterns via intermittent SAI deployment.

Optimizing SAI for reaching a given temperature target, potentially combined with Scenarios 1a or 1b, could be explored using ESMs to identify potential climate benefits and verify existing results. Regional temperature adjustments may also be performed by combined approaches, as described below in Regional Intervention scenarios.

1d) Optimizing SRM for more impact-relevant targets [Global/Regional, Planned]

Instead of controlling for surface temperature (Scenario 1c), other impact-relevant measures may be more politically salient, such as food and water availability, air quality, and other environmental risks. For example, many increasing risks from climate change are typically concentrated in the summer months, such as wildfires, droughts, and heatwaves. There may therefore be more public pressure for cooling summers than winters – particularly bearing in mind that places with frequent but limited winter snow and ice can suffer significant economic losses from increasingly frequent or severe snow events. Although research on SRM is inconclusive regarding changes to cold extremes, public perception may galvanize regardless and influence policy. Alternatively, preventing Arctic sea-ice loss, permafrost degradation, and concomitant disruption to weather patterns in the Northern Hemisphere (Francis et al., 2017) could take priority, possibly leading to SAI deployment optimized for high latitude cooling (Lee et al., 2021). Recent modeling work has also shown that SAI could increase crop yields (Kravitz, 2021; Fan et al., 2021), providing another critical variable which decision-makers may wish to optimize.

Restoring historical precipitation patterns could be an alternative target. Surface flooding and droughts are some of the impactful weather extremes influenced by climate change. Not only do they have immediate impacts, but flooding and drought also cause measurable loss and harm. Urban floods, such as those frequently experienced in the Houston area in recent years (Randall, 2018), and extreme drought in southeastern Australia (King et al., 2020) may stimulate political impetus for SRM programs. Such a scenario is highly contingent on whether research can confidently ascertain the influence of SRM on climate variability. Accordingly, it is conceivable that demand may arise to restore precipitation extremes to a pre-industrial climate (or other baselines). However, extreme precipitation events and phenomena like atmospheric rivers (Leung & Qian, 2009) are often not investigated in the context of SRM. Restoring historic conditions across the entire globe may be difficult, but there is potential to lower the likelihood of costly or damaging extremes with SRM. One example could involve leaving residual warming using only moderate SAI, limiting the intensification of the hydrological cycle, and maintaining current soil moisture conditions (Cheng et al., 2019).

Regional hydroclimate impacts from climate change and SRM could be further assessed using downscaled general circulation model (GCM) data as inputs to catchment models (Teutschbein et al., 2011) and with regional climate models (RCMs) (Teutschbein & Seibert, 2012). However, there are significant challenges in addressing the ambitions of impact-optimized SRM. Firstly, relevant climate impacts may be poorly resolved in climate models, and extensive statistical downscaling may be required (Chokkavarapu & Mandla, 2019). A further difficulty comes from ensuring that models can accurately simulate regional-scale hydrological responses (surface flows, storm surge, runoff, etc.) to climate forcing. Secondly, impacts on sectors such as agriculture and water management may require integrating ESMs with other sectoral models (McDermid et al., 2017), leading to discrepancies in spatial and temporal scale (Iwanaga et al., 2021). Thirdly, small changes in inputs and parameters can result in erratic model output, differing widely across different models. Checking model robustness and comparing other implementations can be done using sensitivity analysis (Saltelli & Annoni, 2010; Saltelli et al., 2019) and model intercomparison ensembles (Challinor et al., 2014) to reduce uncertainty. Moreover, while feedback and control algorithms have been explored for temperature targets (MacMartin et al., 2014), similar approaches for hydrological targets could be vastly more complex. Although defining a hydrological target would be challenging both scientifically and politically, such a modeling exercise could be substantially informative and justifies further exploration.

1e) Cocktail geoengineering [Global, Planned]

Cocktail geoengineering involves layering different SRM techniques on top of each other (Aswathy et al., 2015; Boucher et al., 2017; Cao et al., 2017; Muri et al., 2018). SAI deployments are hemispheric, spreading rapidly on zonal winds (Brühl et al., 2015) and more slowly poleward by the Brewer-Dobson circulation (Keith, 2010; Tilmes et al., 2017). The radiative forcing from MCB and CCT is more localized than SAI – but climatic teleconnections preclude a cleanly isolated effect (Hill & Ming, 2012). Furthermore, SAI and MCB are expected to have differing effects on precipitation, contingent on the precise injection pattern (Jones et al., 2011). Because of these distinct features, Boucher et al. (2017) suggest possible complementary effects when SAI and MCB are used simultaneously.

For example, SAI may be layered with MCB. A combined approach may have several potential advantages. Firstly, controllability may be increased by having additional degrees of freedom. The design space for SAI has previously been modeled with three deployment variables; the amount of aerosol, hemispheric imbalance, and hemisphere-pole gradient (Ban-Weiss & Caldeira, 2010; Lee et al., 2020). In contrast, MCB is tunable to sub-regional scales and has received limited modeling research regarding controllability (Parkes, 2012).

There could be several benefits in combining SRM technologies. Some authors stipulate that regional precipitation changes from SAI may be reduced by combining it with another technique such as MCB (Boucher et al., 2017). Secondly, using multiple techniques may shield society from the risk of either system failure or a forced cessation due to unforeseen environmental consequences. Thirdly, the ecological impacts of an SRM program in totality could be mitigated by capping the extent of any one type of intervention. Although significant uncertainty remains around the ecological impacts of SRM (Zarnetske et al., 2021), further work may elucidate to what degree these could be mitigated by optimally combining several SRM techniques. Moreover, cocktail geoengineering would require the radiative forcing from both systems to be approximately fungible and deployable at comparable scales.

Accordingly, cocktail geoengineering scenarios would be politically relevant. Moreover, large-scale modeling of cocktail geoengineering through model intercomparison and ensemble studies could be scientifically informative. Such modeling could reduce uncertainty in climate dynamics such as regional changes in temperature and precipitation and improve understanding of microphysical processes such as aerosol-cloud interactions. As GeoMIP6 (Geoengineering Model Intercomparison Project) already includes a simplified MCB experiment, extending existing modeling work to combine SAI and MCB would be relatively straightforward. Control-theoretic work has considered SAI optimization – but MCB has substantially more degrees of freedom and requires further work (MacMartin & Kravitz, 2019). Accurately simulating cocktail geoengineering would be a significant scenario modeling exercise, layering the complexity of different SRM techniques. A sophisticated approach would model all relevant sub-grid scale processes such as stratospheric aerosol microphysics and cloud physics, as interactions between techniques may not be apparent from static parametrizations. Nevertheless, efforts in this direction could ultimately be highly politically relevant for designing an optimal geoengineering policy.

4.2 Geoengineering Emergencies

Limited knowledge and foresight of Earth System processes may hinder capacity for ideal decision-making on SRM, which could last decades or even centuries. Accordingly, modeling scenarios exploring potential surprises that could instigate or disrupt an SRM program is a politically relevant exercise.

2a) Response to crossing Carbon cycle tipping points [Global/Regional, Reactive]

Currently, significant uncertainties exist in the carbon cycle response to global warming (Holden et al., 2018). Conceivably, large releases of carbon dioxide or methane may occur due to crossing one or more so-called “tipping points.” Examples include biome shifts in Boreal forests, die-back of Amazon rainforest, the breakdown of Arctic permafrost, and collapse of AMOC (Lenton et al., 2008; Lenton, 2012; Steffen et al., 2018). Given that the delay between the emission of CO_2 and associated peak warming is about ten years (Ricke & Caldeira, 2014), the fast-acting nature of SAI could make it particularly well-suited for responding to unexpected carbon cycle tipping points.

Although not directly related to the natural carbon cycle, leakage of artificial CO_2 storage reservoirs may be possible if large amounts of CO_2 have been removed through CDR processes during the 21st Century (Shaffer, 2010). Additionally, some countries may not phase out some greenhouse gases instead of expanding their production and emissions (see Scenario 4c). Such GHG fluxes – and their timing and magnitude – are necessarily speculative. However, it is certainly conceivable that an unanticipated and sustained release of CO_2 or methane may occur. The unexpected release of GHGs could be on a scale of tens of gigatons CO_2 equivalent per year (comparable to current global annual emissions) and may last for decades. Such a large and unexpected carbon flux may require urgent intervention. An SRM scenario that considers additional compensatory cooling could be useful for risk management and policy planning. Modeling this scenario could include a large pulse of CO_2 or methane as an exogenous, generic perturbation, or consider modeling worst-case transgression of carbon-cycle tipping points to consider the emergency response context. Such a scenario exercise would then explore possible strategies for countering the resulting warming with further strengthened SAI or MCB.

In general, carbon cycle model intercomparisons are challenging, as models adopt radically different representations of the carbon cycle (Arora et al., 2020). Accordingly, an alternative approach might be to standardize consideration of carbon cycle effects – such as by seeking to prevent a given amount of permafrost warming or drying of the Amazon. Harmonization of model inputs and carbon-cycle parameters would be necessary for future model intercomparison of this scenario.

2b) Response to large volcanic eruptions [Global/Regional, Emergency, Reactive]

The timing of future large volcanic eruptions is unpredictable, but they are inevitable over long timescales. Their impact on SRM is significant and has previously been investigated (Laakso et al., 2016). Simulating a variety of eruptions at different magnitudes and locations would be helpful to understand climate responses to a combination of SRM and volcanic eruptions.

This scenario would be an opportunity to stress-test control algorithms and evaluate how to effectively adjust SAI in the aftermath of a large eruption (such as Mt Pinatubo in 1991). After eruptions that injected large amounts of sulfur, mostly into one hemisphere, large shifts in precipitation have been observed (Robock, 2000). SAI adjustment or commencement may mitigate asymmetry by injecting into the other hemisphere (Haywood et al., 2016; MacMartin & Kravitz 2019). In addition, a reduction in the pre-planned strength of SRM intervention in the affected hemisphere may be required, as determined by control algorithms.

2c) Counter-geoengineering [Regional, Emergency, Reactive]

Counter-geoengineering (Parker et al., 2018; Heyen et al., 2019) is a postulated response to SRM. It involves the deliberate release of short-lived warming agents (e.g., methane, black carbon, halocarbons, etc.) to suppress the net effect of undesirable SRM interventions – as an alternative to diplomatic or military action (Lockley, 2019). An illustrative scenario could involve SRM deployed to halt additional global warming from 2030, but a counter-geoengineering intervention deployed to offset the cooling shortly after.

Counter-geoengineering scenarios divide into two broad classes. Firstly, SRM may be partly or completely suppressed – although there may be large regional variations in net effect. Secondly, an "Arms Race" scenario may emerge, where states deploy ever-increasing amounts of SRM and counter-geoengineering (Parker et al., 2018). "Arms Race" scenario modeling could consider both the speed of response and efficacy of interventions in countering cooling.

Both scenarios are interesting from a political and climate modeling perspective. These examples have important implications for international security (Bas & Mahajan, 2020). As the level of short-lived climate forcers (e.g., the global methane concentration or spatially resolved concentration of black carbon) can be prescribed as an input to many climate models, only limited modeling workload is necessary.

2d) Temporary termination [Global, Emergency, Reactive, Short Term]

Abrupt warming from interrupted deployment is frequently discussed as a major risk of SRM (Parker et al., 2018). However, previous modeling of "termination shock" has generally only considered complete and permanent termination, leading to severe climate impacts with abrupt warming in the years immediately following SAI termination (Crook et al., 2015).

In a real-world scenario - where termination shock is known to have adverse effects, and the technology to reverse termination is available - it seems implausible that no attempts by other parties to restart the SRM program would be made (Parker & Irvine, 2018; Halstead 2018). However, it is feasible that unexpected events can temporarily disrupt future SRM applications. For example, such disruption could originate from environmental or public health catastrophes, political change opposing SRM, economic recession, or war.

More realistic termination shock situations could be explored by applying shorter (1 to 10 years) interruptions to ongoing SRM (Parker & Irvine, 2018). Temporary termination scenarios could be explored using existing models, requiring minimal further model development. However, a large model ensemble may be necessary to detect temporary termination shock. Modeling around a 1-10 year interruption should be long enough to accommodate many conceivable disruptions (e.g., the onset of a financial crisis) without assuming the instigating cause. Temporary termination could also test the climate response to short perturbations in radiative forcing. Additionally, such a modeling exercise should explore how SRM would optimally be restarted, comparing strategies such as ramping up vs. step responses.

2e) Technology switch - e.g., SAI to MCB [Global/Regional, Reactive]

SRM involves a variety of risks – both known and unknown. One SRM program could be phased out in favor of a different type, which is perceived as cheaper or safer. There are already scenarios for comparing outcomes of SAI and MCB (Boucher et al., 2017; Muri et al., 2018). One could create a modeling scenario involving a switch between these two scenarios during deployment. The two technologies may have different degrees of persistence, different regional effects, and may have interactions (e.g., aerosol deposition from SAI may influence MCB) during switchover. A switch may also include additional cocktail techniques, such as adding cirrus cloud thinning (CCT), during SAI deployment. This scenario exercise could explore the switchover period, strategies for phase-in/out between interventions, control algorithms, and climate response.

A simple program switch would assume that MCB and/or CCT could have the same ultimate cooling potential as SAI, although this is currently unclear. MCB and CCT are expected to cause different regional temperature and precipitation patterns, which modeling would quantify. The transition between different geoengineered climates and the resulting persistent regional differences would be crucial to characterize. Furthermore, feedback and control algorithms for MCB and/or CCT do not currently exist (MacMartin & Kravitz, 2019), and these would have to be developed to model a safe transition.

A second option may be to switch to space-based methods, perhaps much later this century. This could utilize reflective mirrors or dust at the L1 Lagrangian point between the Sun and Earth (McInnes, 2010). Space-based SRM avoids SAI side effects, such as stratospheric heating, ozone loss, and particulate matter-related health impacts (Nowack et al., 2016; Xia et al., 2017; Eastham et al., 2018). Scarce research currently exists on space-based SRM, so side-effects from such an intervention are unknown – and pollution from rocket launches is nontrivial (Dallas et al., 2020). Space-based SRM may be prohibitively expensive now, but costs will fall due to developments such as reusable rockets. In the meantime, modeling a transition from SAI to space technologies could easily be approximated with current ESMs.

Duration of switchover is significant and could take a gradual or abrupt character. A gradual shift is akin to temporary cocktail geoengineering (Scenario 1e). The first intervention would be ramped down, over perhaps 5 to 20 years - and the replacement technology ramped up. Switchover could use linear or logistic functions to combine radiative forcing. Alternatively, an abrupt switch between technologies could be akin to termination shock (Scenario 2d). In this instance, the first intervention would be abruptly halted, perhaps with perhaps a short break of 1-5 years, before the replacing SRM technique would be put in place. This scenario would model a "nasty surprise," such as discovering unanticipated health or ecosystem damage (Bodansky, 2013). In any case, SRM technology switchover is a politically relevant possibility, which should be investigated in future modeling studies.

4.3 Regional Interventions

Approaches such as MCB may be deployed on regional scales, albeit with global impacts. Depending on the implementation, some regional geoengineering scenarios will still require global coordination to some extent (see polar interventions). Other scenarios exploring SRM at small scales may be useful for nations weighing up policies to address local climate impacts.

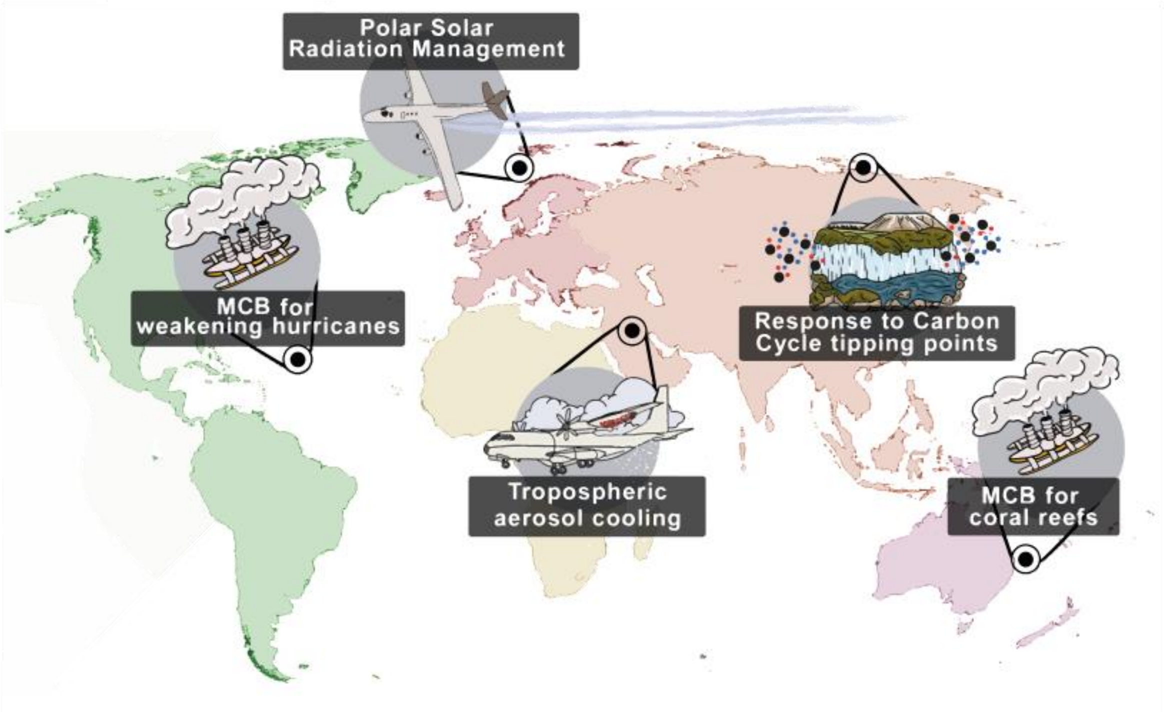

Figure 2: Illustrative map of regional SRM strategies

3a) MCB over specific oceanic regions [Regional, Planned]

MCB has the advantage of being deployable regionally and could temporarily mitigate local impacts from climate change. Two proposed examples where a local and urgent MCB intervention may be used include cooling during marine heatwaves to protect coral reefs (Latham et al., 2013; Harrison, 2018) and localized suppression of hurricanes (Latham et al., 2012; 2014). This type of temporary, local, and crisis-driven response represents a plausible scenario for early deployment – particularly given recent outdoor MCB experiments on the Australian Great Barrier Reef (McDonald et al., 2019). Therefore, modeling such scenarios will likely be relevant to scholars in a broad range of disciplines.

Note that the current representation of MCB within GeoMIP is simplified, using a modification of ocean albedo (Hill & Ming, 2012) or changes in CCNs and sea salt (Ahlm et al., 2017; Kravitz et al., 2018; Stjern et al., 2018). These modeling techniques are not designed to produce accurate results for interventions at regional scales. Nevertheless, crude modeling offers a computationally inexpensive way to test various local interventions. More realistic treatment of MCB could range from including turbulent mixing and hurricane formation to teleconnections and climate system feedbacks (Latham et al., 2014; MacMartin & Kravitz, 2019). Further work will need to improve ESMs, developing a hierarchy of models to resolve the cross-scale effects of MCB.

Teleconnections between regional climates imply that localized MCB deployment is unconfined, regardless of intent (Parkes, 2012). Modeling targeted MCB along with its broader impacts could guide actors and those affected – including in regions far removed from the intended interventions (National Academies of Science, Engineering and Medicine, 2021).

3b) Tropospheric aerosol intervention over specific land regions [Regional, Planned/Reactive, Short Term]

Similar to flooding (see Scenario 1d), heatwaves are another poster child of climate change – bringing substantial economic, air quality, and health consequences (e.g., Xu et al., 2020). High death tolls can be associated with present-day heatwaves – though these are much less severe than may be expected later in the century (Lin et al., 2018). One postulated SRM scenario is the use of tropospheric aerosols (Bernstein et al., 2013), as opposed to stratospheric aerosols. Tropospheric aerosol injection could be more accurately targeted by time and location, such as responding to one month of 45°C daytime peak heatwave over Southern Europe or the Middle East. Short tropospheric aerosol lifetimes and wind dispersal would mandate a distribution program that is localized and intense to maintain a sufficient aerosol layer. Potential benefits of tropospheric cooling would need to be weighed against side effects, such as increased air pollution and environmental impacts. Alternative interventions may be considered, such as deployment over adjacent oceans.

Modeling challenges may potentially exist. For example, SAI models may not reliably resolve tropospheric aerosols. Also, heatwaves are spontaneous in climate models, making it hard to pre-determine the timing and location of deployment. Nevertheless, despite technical challenges, modeling tropospheric aerosol cooling could be useful. The urgent, regional, and temporary nature implies increased plausibility. This scenario also has similarities with Scenario 3a – but it can also be applied over land or ocean without cloud cover.

3c) Single nation SAI [Regional, Planned/Reactive]

SAI applications are not homogenous in space and time; one kilogram of SO_2 injected is not necessarily equivalent to others. Time, season, and injection latitude can all impact distribution, particle size, lifetime, climate impacts, and atmospheric chemistry (Dai et al., 2018; Visioni et al., 2020). According to the locus of injection, SAI broadly remains within the Northern or Southern Hemisphere (Haywood et al., 2013). Hemispheric imbalances in deployment could cause shifting of the Inter-Tropical Convergence Zone (ITCZ) - possibly disrupting climate and precipitation patterns of the tropics (Jones et al., 2017). As such, single-location SAI would be risky.

Nevertheless, due to its lower cost, it may represent a possible scenario. A selfish actor, or one disgruntled by inaction on climate policy, may undertake a single-location injection. A plausible fictional scenario is SAI unilaterally deployed by India after a deadly heatwave kills millions (Robinson, 2020). Alternatively, an authoritarian government may take it upon itself to “solve” global climate change, taking SAI deployment into its own hands (Michaelowa, 2021). Although SAI is usually conceptualized as deployed by aircraft, unilateral deployment could instead use tethered balloons to avoid conflict. Some scholars dispute the plausibility of unilateral SAI deployment (Horton, 2010; Surprise, 2020). Regardless, some countries may find unilateral SAI scenarios of relevance to national security, and a single-location injection would be a relatively simple modeling exercise. This scenario could demonstrate what undesirable SRM could look like and provide modeling evidence to encourage cooperative governance.

3d) Polar SRM [Regional, Planned/Emergency]

SRM in polar regions has been previously modeled as a possible targeted intervention (Caldeira & Wood, 2008; Robock et al., 2008; MacCracken et al., 2013; Lee et al., 2021). The geophysical impact of climate change is concentrated in polar regions due to polar amplification of warming and the temperature sensitivity of polar ecosystems, permafrost, and sea ice (IPCC, 2019). Carbon from permafrost loss in Siberia and northern Canada threatens major consequences for the global climate system (see Scenario 2a). Consensus on SRM deployment for addressing an emergency of lost Arctic summer sea ice may be more plausible than global deployment (Corbett, 2021), particularly as direct health and air quality impacts would be limited to less-populated regions. As in Scenario 1c, modeling by Lee et al. (2021) demonstrated that spring-season SAI could be more effective than year-round SAI, making a polar intervention less intrusive than global deployment. These properties make polar-specific SAI deployment arguably more politically palatable and its modeling particularly relevant.

Additionally, the lower polar tropopause means existing aircraft could suffice for SAI, greatly reducing development costs. Moreover, ITCZ shifts due to hemispheric imbalance (Haywood et al., 2013) could be ameliorated by injecting at both poles (Kravitz et al., 2016). Polar experiments in any model with stratospheric aerosol handling will be relatively easy; it does not require modification beyond their traditional bounds. Tilmes et al. (2014) showed that dimming the Arctic to retain sea ice requires very large changes in radiative forcing, due to low polar solar insolation. Furthermore, aerosols are quickly removed from the lower stratosphere and require larger or more frequent injections. Further modeling work of polar-specific SAI deployment scenarios, building from recent studies (Jackson et al., 2015; Visioni et al., 2020; Lee et al., 2021), should be high on the research agenda. This work could further investigate balancing hemispheric gradients (to prevent ITCZ shifts), seasonal modulation, and impacts on permafrost and Arctic methane emissions.

3e) Polar albedo enhancement [Regional, Planned/Emergency]

A speculative SRM technique is the application of albedo enhancing surface treatments to polar land and sea ice using hollow glass microspheres, an approach currently researched by the Arctic Ice Project (Field et al., 2018). Despite concerns about feasibility and environmental impacts, it is a form of SRM that should be included in scenario modeling studies.

Climate models routinely consider albedo of sea and land surfaces around the poles (IPCC, 2019), but limited studies have investigated surface albedo modification directly. Cvijanovic et al. (2015) previously modeled the climate response in a 4xCO_2 scenario to Arctic albedo whitening, finding mixed results. Given limited model evidence for the relative efficacy of polar surface whiting, further work is merited. Modifying existing models such as the Community Earth System Model (CESM) – used by Cvijanovic et al. (2015) – could provide a straightforward means to assess the Arctic Ice Project concept. From a scenario formulation standpoint, this should also consider the timing, extent, and duration of albedo interventions within politically realistic bounds. More complex models which include ecosystem-climate coupling dynamics would be necessary for identifying impacts on terrestrial and marine ecosystems in the Arctic. Further exploration of changes to mid-latitude precipitation due to climate teleconnections would be vital.

4.4 Long Term Scenarios

Globally, society may decide to use SRM in a much more reactive manner, leading to higher SRM use for much longer time periods than is usually considered. Most model experiments of climate change and SRM run until 2100. However, decisions made today on mitigation and SRM will have far longer-term impacts. This section considers globally reactive scenarios which are much longer-term and use higher amounts of SRM than typically considered. Modeling such pathways could help contextualize the risks of following unsustainable trajectories.

4a) Overcooling to below pre-industrial temperatures [Global, Planned, Long Term]

Much of the world's population lives in societies where temperatures are higher than optimal for comfort and economic activity. While speculative, there may be substantial demand for generalized cooling (Irvine et al., 2010; Harding et al., 2020). Although less realistic than other scenarios, over-cooling could be an interesting modeling exercise from climate and economic development standpoints. Economic cost-benefit evaluation of overcooling could be performed using integrated assessment models (IAMs), but considering the economic effects of average regional temperature change would be necessary. Cooling below pre-industrial may also curtail or reverse sea-level rise (see Scenario 4b).

From a climate modeling perspective, this scenario would stress-test the models in an unorthodox manner. Overwhelmingly, models are run with increasing temperature – allowing feedback between observed warming and model calibration. By contrast, over-cooling may reveal disagreement between models, helping to correct the implementation of processes such as temperature-carbon feedbacks. Economically relevant changes to vector-borne disease spread, agricultural productivity, and heat-related health effects could be examined using model results from GCMs as inputs into a sufficiently detailed process IAM.

4b) Curbing or reversing sea-level rise [Global, Long Term]

Ordinarily, SRM experiments target global average temperatures. By contrast, sea-level rise (SLR) is arguably the most impactful and inescapable effect of climate change (Jevrejeva et al., 2018; Hinkel et al., 2018; Nishiura et al., 2020) almost certainly bringing very large-scale disruption to civilization. Many of the world's major coastal cities will be placed in danger of significant flooding and storm surges, with some areas expected to have hundred-year events occurring annually (IPCC, 2019). Some low-lying island nations and coastal regions may be uninhabitable in high emissions pathways, leading to millions of displaced people (IPCC, 2018). Due to the accelerating rise in sea levels, coastal ecosystems (such as marshes and mangroves) could be lost, exacerbating climate damages. Thus, humanity's primary goal in deploying SRM may not be stabilizing temperatures but holding back the sea (Irvine et al., 2012; Zhao et al., 2017; Wolovick & Moore, 2018; Li et al., 2020; Lockley et al., 2020).

Major cities will be threatened as SLR accelerates. Some, such as London, have existed for millennia. There will likely be a strong political impetus to defend coastal cities for national identity and human welfare. Dense populations and concentrations of economic value in coastal property will bolster economic and political pressure to act (Xia, 2020). SLR will continue apace well into the 22nd century – endangering long-term national interests. Accordingly, modeling of SLR and possible SRM responses is highly politically relevant.

SLR originates mainly from the melting of glaciers, ice caps, and ice sheets (Rignot et al., 2011); and the thermal expansion of seawater (Albritton et al., 2001). Although SRM could reduce the melting of inland glaciers and the Greenland ice sheet (Tilmes et al., 2020) and slow thermal ocean expansion; however, little is known about the effects of temperature changes over Antarctica due to non-linear ice dynamics and uncertain response times (Pattyn & Morlighem, 2020). Thus, neither moderate SRM (Irvine & Keith, 2020) nor Paris Agreement emissions cuts will reverse Antarctic ice sheet loss on policy-relevant timescales.

This scenario may require prolonged overcooling (below pre-industrial) due to hysteresis effects of ice sheet loss (Garbe et al., 2020). SRM overcooling is challenging to model, requiring both century-long simulations and complex ice-sheet modeling (Vaughan & Arthern, 2007), absent from many state-of-the-art global climate models. Knowledge gaps exist particularly regarding the flow of ice sheets (via glaciers), stability of buttressing ice shelves as seas warm underneath, and the effects on the cryosphere of surface melting and consequential infiltration (IPCC, 2019). These knowledge and modeling gaps imply large uncertainties when dealing with non-linear processes and century-long timescales. While modeling sea level rise is important, it presents a substantial challenge for the capacity of current models. Such exercises would thus need to be interdisciplinary collaborations with SRM and cryosphere experts (Irvine et al., 2018). Nevertheless, the threat SLR poses to civilization suggests a concerted effort to improve model capability and reduce uncertainty is warranted.

An alternative modeling approach would be to empirically estimate SLR as a function of global temperature change in simple climate models (Vermeer & Rahmstorf 2009; Hu et al., 2013), without explicitly simulating the physical processes contributing to it. Simplified empirical approaches could make a pre-emptive assessment of SRM use for preventing SLR far more tractable. However, neglecting nonlinear physical processes, feedbacks, and threshold behavior could lead to biased conclusions based on statistical fits, which assume stationarity. Nevertheless, statistical modeling of SLR could give cursory yet useful insights into whether SRM is even suitable for such a purpose, despite land ice and shelf dynamics not being fully represented.

Importantly, although slowing SLR is still within current climate modeling paradigms, any attempts to rapidly halt or even reverse SLR will take models well beyond their traditional operating space. To reverse SLR, substantial regrowth of ice sheets will be necessary. SLR reversal may require long-term overcooling, perhaps accompanied by targeted interventions to directly manipulate either ice sheets or input precipitation (Lockley et al., 2020). Due to current knowledge gaps in ice sheet dynamics, the speed and extent of possible ice sheet regrowth simulated by models would be highly uncertain. Moreover, recovering ice sheets through SRM intervention could likely involve cooling below pre-industrial temperatures for centuries due to ocean thermal inertia. If modeling determines that reversing SLR using SRM is not practically possible, this could have existential ramifications for adaptation planning.

4c) Continued fossil fuel use with SRM [Global, Reactive, Long Term]

Some research suggests we could transition to a 100% renewable energy-based economy in the near term (Hansen et al., 2019; Jacobson et al., 2020). However, phase-out of fossil fuels may stall or reverse – particularly if SRM acts as a deterrent to mitigation (McLaren, 2016). Although extreme, one could imagine a future in which the availability of an SRM "techno-fix" disincentivizes national net-zero commitments – particularly if substantial challenges arise in decarbonizing sectors such as transportation, industry, and agriculture. Such a scenario is like the GLENS scenario, which requires injections of an equivalent of over 4 times the amount of Mt Pinatubo per year (Tilmes et al., 2018).

Additionally, renewable energy could run into resource constraints over rare earth elements with fragile supply chains (Pitron & Jacobsohn, 2020). In such a scenario, some lackluster mitigation would nonetheless continue, but perhaps one-third to half of the global economy might resist further decarbonization, leading to a reliance on SRM to avoid catastrophic warming. Furthermore, developing nations may not progress with a green growth paradigm if developed countries fail to lead on decarbonization. Economic development akin to business-as-usual would result in more exploitation of fossil fuel reserves to keep up with population and economic growth. This scenario is plausible if energy use per capita grows beyond current expectations (van Ruijven et al., 2019) and if population growth exceeds projections.

Modeling such a pathway would likely be a contentious exercise, given long-standing disagreements over whether SRM would displace or discourage mitigation efforts (Raimi et al., 2019; Gunderson et al., 2019; Aldy & Zeckhauser 2020; Smith & Henly, 2021; Sovacool, 2021). Note that Lockley & Coffman (2016) distinguish different ways SRM could decrease mitigation: moral hazard (malfeasance leading to displaced mitigation); and morale hazard (recklessness leading to decreased motivation for mitigation). Either or both effects could be investigated through this type of scenario, illustrating the dangers of relying on SRM. Exploring this scenario with different assumptions for development, mitigation, and SRM policy trajectories could be performed using existing IAMs (Heutel et al., 2016) within the SSP framework (O'Neill et al., 2014). This scenario could be particularly interesting to explore in conjunction with termination shock; over-reliance on SRM may lead to systemic fragility, with rapid and intense warming rebound. Such a cautionary scenario could be politically relevant in motivating increasing ambitions for decarbonization and illustrating how SRM policy ought not to proceed.

5. Discussion

The scenarios presented here span multiple dimensions in technologies, and spatial & temporal scales. This exercise illustrates the wide array of possibilities that future solar geoengineering strategies may present, indicating a significant challenge for future modelers and policymakers. The scenario formulation and descriptive process here is useful in exploring the different edges of the solar geoengineering possibility landscape, with some such as tropospheric aerosols being extremely short term and regional, whilst others such as reversing sea level rise being excessively long term and global in nature. This also points to a need for a wide range of models for future geoengineering research, including GCMs and IAMs across various spatial scales.

In terms of future research directions, the work here suggests a few specific advances necessary for near term policy-relevant research. Firstly, whilst much of solar geoengineering modeling research thus far has sought to explore optimal scenario cases, the exploration here points to a wide variety of sub-optimal yet still politically salient scenarios whose impact have yet to be quantified. It therefore seems reasonable to suggest future geoengineering modeling focus more efforts towards "emergency/reactive" type scenarios, such as responding to carbon cycle tipping points, counter-geoengineering or temporary termination shock. In particular, understanding the plausible efficacy or non-efficacy of emergency response SRM would help elucidate edge cases and risks of solar geoengineering for decision makers.

Various regional geoengineering interventions described here may have particularly relevant impacts for vulnerable populations and depending on implementation may result in a "winners and losers" paradigm. Some may induce particularly regional complications. For example, MCB in one region may alter precipitation patterns in another (Stjern et al., 2018). Tropospheric aerosol deployment may be a particularly relevant geoengineering strategy in heatwave-prone, primarily poor countries in the tropics. Arctic-focused deployment may require geopolitical coordination of Arctic coastal states, which may be legally and politically challenging (Bodansky & Hunt, 2020). Further research could investigate the impacts and implications of such regional strategies.

Furthermore, whilst the scenario exercise here presents some first steps in illustrating a wider range of solar geoengineering scenarios that ought to be explored, further work will need to elaborate on a more comprehensive framework to standardize modeling results. Whilst earlier GeoMIP experiments have aided greatly in fundamental scientific understanding of how solar geoengineering would theoretically operate, new scenarios with the same policy relevance as, for example, the SSP-RCP framework are needed. The descriptive dimensions of "local – global" and "emergency – planned" provided could be the first part of a broader geoengineering scenario scaffold which is fit for policy-relevant work.

6. Conclusions

The 18 scenarios proposed here represent a range of future possibilities. While some are more plausible than others, it is difficult to establish a rank order of scenarios most appropriate for future modeling work. Nevertheless, exploring such politically relevant scenarios for SRM will ultimately be necessary for future work. By providing a wide range of scenarios, some perhaps desirable and others cautionary, the authors seek to inform public and academic debate, and offer suggestions for the modeling community to explore a range of politically relevant experiments. Any such bricolage will inevitably be both flawed and incomplete; most scenarios offered require refinement and all require further numerical detailing – in itself a challenging process. Some scenarios described here, such as optimizing deployment for temperature targets, are already well in line with the direction of current research work, while others highlight the need for exploring under-researched possibilities, such as preventing a further sea-level rise. This work nevertheless extends and deepens the range of possible scenarios. It thus represents an improvement to the current range of highly idealized scenarios used commonly by the modeling community.

This paper further points to the need for a much wider research program, including developing scenario model experiments (using a mix of ESMs/GCMs, IAMs, and sector-specific models) to explore the possibility space for SRM policy. Such experiments could guide future generations of large-scale modeling exercises such as GeoMIP and GLENS. As such, the scenarios listed here should be promptly investigated, with results widely shared with the research community. Results and insights from scenario studies should serve as a basis for further stakeholder and public engagement.

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