



A Fate Worse Than Warming? Stratospheric Aerosol Injection and Global Catastrophic Risk

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Injecting particles into atmosphere to reflect sunlight, stratospheric aerosol injection (SAI), represents a potential technological solution to the threat of climate change. But could the cure be worse than the disease? Understanding low probability, yet plausible, high-impact cases is critical to prudent climate risk management and SAI deliberation. But analyses of such high impact outcomes are lacking in SAI research. This paper helps resolve this gap by investigating SAI's contributions to global catastrophic risk. We split SAI's contributions to catastrophic risk into four interrelated dimensions:

1. Acting as a direct catastrophic risk through potentially unforeseen ecological blowback.
2. Interacting with other globally catastrophic hazards like nuclear war.
3. Exacerbating systemic risk (risks that cascade and amplify across different systems);
4. Acting as a latent risk (risk that is dormant but can later be triggered).

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The potential for major unforeseen environmental consequences seems highly unlikely but is ultimately unknown. SAI plausibly interacts with other catastrophic calamities, most notably by potentially exacerbating the impacts of nuclear war or an extreme space weather event. SAI could contribute to systemic risk by introducing stressors into critical systems such as agriculture. SAI's systemic stressors, and risks of systemic cascades and synchronous failures, are highly understudied. SAI deployment more tightly couples different ecological, economic, and political systems. This creates a precarious condition of latent risk, the largest cause for concern. Thicker SAI masking extreme warming could create a planetary Sword of Damocles. That is, if SAI were removed but underlying greenhouse gas concentrations not reduced, there would be extreme warming in a very short timeframe. Sufficiently large global shocks could force SAI termination and trigger SAI's latent risk, compounding disasters and catastrophic risks. Across all these dimensions, the specific SAI deployment, and associated governance, is critical. A well-coordinated use of a small amount of SAI would incur negligible risks, but this is an optimistic scenario. Conversely, larger use of SAI used in an uncoordinated manner poses many potential dangers. We cannot equivocally determine whether SAI will be worse than warming. For now, a heavy reliance on SAI seems an imprudent policy response.

Keywords: climate engineering, stratospheric aerosol injection, global catastrophic risk, governance, systemic risk, latent risk, termination shock

HOTHOUSE EARTH OR SHITHOUSE EARTH?

Could the risks of large-scale solar geoengineering be worse than the dangers posed by climate change? Many concerns have been expressed over geoengineering the Earth's climate. These tend to centre on solar radiation management (SRM) methods, particularly stratospheric aerosol injection (SAI). These range from fears over negative unintended effects on ecology, political conflict, mitigation deterrence, to ethical objections. Given the breadth of objections, it is quite clear that SAI would be iatrogenic in some way. Like some medical interventions, SAI may have adverse side-effects and complications. The question is whether it could be worse than the problem it is seeking to remedy: climate change.

There is a wealth of information on the different risks posed by climate change (although notably little on high-end warming scenarios), yet few attempts to compare this to the potential damages of SAI. This is unsurprising since there have been limited attempts to systematically analyse the myriad of threats posed by SAI.

We address this gap by analyzing the severe downside risks of SAI. We do not directly compare the risks posed by SAI and climate change in this paper. Rather, we provide an analytical foundation for future comparative analyses. In this article we ask: *what are the plausible contributions of SAI to global catastrophic risk (GCR)?* To the best of our knowledge this is the first attempt to offer a novel, comprehensive framework for comprehending the contributions of SAI to GCR. As noted in section: *A Framework for Unraveling Global Catastrophe*, this is a useful and original step forward for the nascent field of studying GCRs. This is not just simply adding up SAI's potential negative impacts. It requires understanding how SAI could trigger or worsen other large-scale threats (such as nuclear warfare) or systemic risks. Understanding extreme downside risks can also help provide direction for policy and governance. The future may be hazy, yet avoiding the extreme downsides is a priority for risk management under uncertainty. To guide our investigation, we put forward a novel framework for understanding how SAI, or any other complex risk, contributes to GCR. We then use this to review and discuss the existing evidence on SAI's critical threats.

In **Table 1** we provide a brief set of definitions of the key terms we use throughout this paper.

Our approach makes use of a structured literature review and systems mapping exercise. We use our novel framework to structure a literature review covering studies relevant to the risks of SAI. For each area we highlight the level of evidence and uncertainty, and draw out some key implications. The nature of the risk will depend on the specifics of the geopolitical situation and the SAI intervention. We explore this through a causal-loop diagram (**Figure 1**) which plots out the connections between the level of risk, the amount of SAI loading, the level of international coordination and other key variables.

Note that for most of this paper we address SAI in the abstract. The exact potential damage imposed by SAI would vary the way it is deployed. In section: *Discussion: Building the*

Policy Boundaries for Climate Engineering, we discuss how the method of deployment creates different impacts. Throughout the paper we assume a “default” deployment method of SAI to be the continuous multi-decadal global use of planes with multiple injection locations, guided by a global cooperative endeavor led by states with private sector contributions, with an overall objective to respond to global warming. Deployment “thickness” (how much warming is masked) is a particularly important variable. We flag thickness throughout our analysis. Where we discuss the risks of other potential forms of deployment we directly state so.

We proceed by outlining our framework, before examining SAI's direct catastrophic risks, SAI's interaction with other catastrophic hazards, SAI's potential input to systemic risk, and finally SAI's influence on latent risk. We then discuss how different methods of deployment could lead to different risks and what the policy implications of our analysis are. To avoid the critical downside risks we consider throughout the paper, SAI governance would have to be near perfect for multiple decades.

A solution that is almost impossibly difficult to implement well, and that plausibly threatens catastrophe if implemented poorly, is not a good solution.

Whether this is preferable to climate change remains to be seen.

A FRAMEWORK FOR UNRAVELING GLOBAL CATASTROPHE

There is no agreed framework for understanding the contribution of different phenomena to GCR. Most studies and reports on GCRs rely on analyzing a set of large-scale “GCR-level” hazards (Bostrom and Cirkovic, 2008; Global Challenges Foundation, 2016). Usual suspects include anthropogenic risks such as nuclear weapons, climate change, and more speculatively, Artificial General Intelligence¹, biologically engineered pandemics, and natural risks such as super volcanoes and asteroids. While there have been some alternative frameworks for classifying GCRs (Avin et al., 2018; Liu et al., 2018; Baum and Barrett, 2019), these have yet to be widely adopted. They are also disconnected from relevant literature on systemic risk. Moreover, while they are helpful in classifying a given hazard, they do not act as aids in understanding how much a given event or system could contribute to overall levels of GCR or extinction risk.

There are several problems with the typical, hazard-centric approach. First, it is unclear how these hazards are decided on. Second, a risk is composed of hazards, vulnerabilities, and exposure, not just individual threats (IPCC, 2012; Avin et al., 2018; Currie and Ó hÉigearthaigh, 2018; Liu et al., 2018). Third, the different hazards are treated as disconnected when they frequently have similar institutional drivers. Fourth, it ignores

¹A single algorithmic system that can perform tasks at a level similar to humans across a broad range of cognitive domains.

TABLE 1 | Definitions.

Term	Definition
Climate engineering	Large-scale, deliberate interventions into the Earth system to mitigate the effects of negative impacts of climate change (The Royal Society, 2009).
Extinction risk	A risk that could plausibly cause human extinction.
Global Catastrophic Risk (GCR)	A risk that could plausibly cause a loss in global population of 10–25% (Atkinson, 1999; Global Challenges Foundation, 2016) and a disruption to one or more global critical systems.
Solar radiation management	Measures which impact the albedo of the Earth system in order to mitigate the impacts of climate change.
Stratospheric aerosol injection	The injection of light-reflecting chemical, such as sulfur dioxide, into the stratosphere.
Systemic risk	The ability for an individual disruption or failure to cascade into system-wide and cross-system failures (Centeno et al., 2015) due to structural conditions.
Latent risk	Risk that is dormant under one set of conditions but becomes active under another set of conditions.
Termination shock	A large and rapid increase in warming after the cessation of SRM measures.
Buffering	A period of roughly several months following the cessation of SAI where effects of termination shock do not occur. Redeployment of SAI during this period would ensure that termination shock does not occur (Parker and Irvine, 2018).

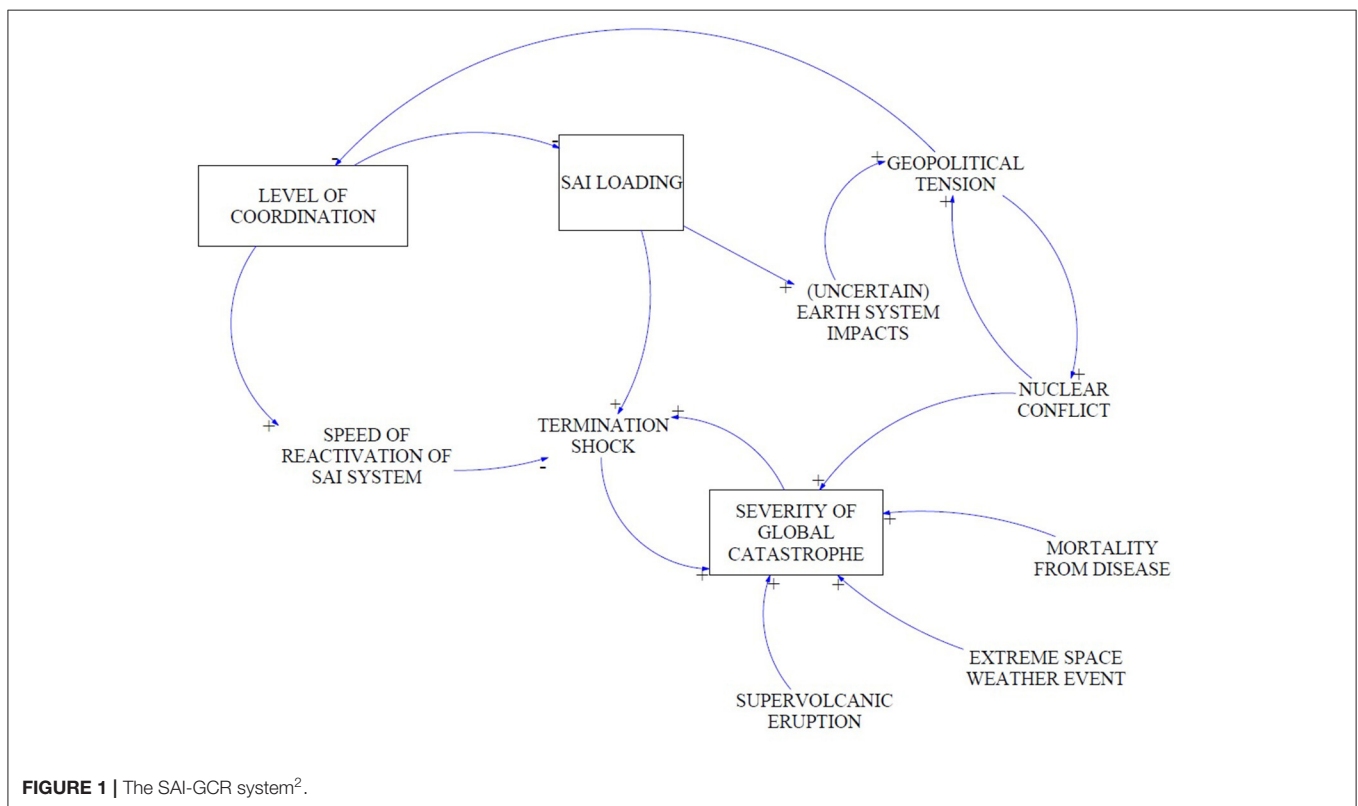


FIGURE 1 | The SAI-GCR system².

systemic risk, particularly the ability for a set of smaller,² diffuse risks to scale to a global and cataclysmic level due to the fragility and interconnectedness of critical systems. Risk is no longer just about hazards, vulnerabilities and exposures. Comprehensive risk assessment also needs to consider responses, as well as the

²This is a causal loop diagram. A positive polarity denotes an amplifying relationship (not necessarily positive in a normative sense) and a negative polarity denotes an inverse relationship (ie. as A increases, B decreases).

common drivers across these four risk determinants (Reisinger et al., 2021; Simpson et al., 2021).

We incorporate all of these aspects in a four-stream framework for understanding the contribution of a system or event to GCR. Hazards are directly assessed through the first two streams, while the focus on systemic risk analyses potential vulnerabilities. Latent risk explores the often neglected possibility of vulnerabilities that are hidden in the short-term. Exposure and responses are articulated throughout the analysis. The overall analysis informs a discussion on policy boundaries. Our analysis

rests not upon having a particular probability of occurring. Instead, we focus on what is plausible (rather than “merely possible”): consistent with our background knowledge of physical and social systems (Betz, 2016). Understanding risks which are plausible, high-impact, but low or unknown-probability is critical for robust decision making under uncertainty (Ord et al., 2010; Kunreuther et al., 2013; Wagner and Weitzman, 2015). For example, making decisions on the “better” worst case is central to the Maximin approach.

Our four-stream framework is as follows:

1. The first stream focuses on directly catastrophic impacts. A direct contribution refers to ways in which the impacts caused by SAI could alone plausibly cause sufficient mortality and morbidity without considering wider knock-on effects.
2. The second stream examines how SAI could interact with other high-impact hazards such as nuclear war.
3. The third investigates how SAI could contribute to and be affected by systemic risk. Systemic risk focuses on how structural conditions and multiple small stressors can lead to widespread collapse or synchronous, reinforcing failures (Homer-Dixon et al., 2015). Indeed, complex systems can undergo rapid degeneration even without large shocks. They frequently organize into critical states in which small perturbations quickly cascade into calamity (Homer-Dixon, 2008; Helbing, 2013).
4. The final stream focuses on SAI’s latent risk. Latent risk focuses on deciphering how SAI could pose threats that manifest under post-catastrophe conditions, such as in the aftermath of societal collapse.

Together, these different factors provide a comprehensive framework for comprehending how SAI could raise or lower overall levels of GCR in the world. The framework is intended to be a first step to risk comparison, in this case climate change and SAI.

Historically, comparison between the two have been a rhetorical device to justify SAI. This is by no means a straightforward juxtaposition since the two interact [for example, through mitigation deterrence: actors may be less open to ambitious emissions reduction if there is a “technofix” on the horizon (McLaren, 2016)] and any analysis hinges on subjective judgements about climate sensitivity, tipping points, adaptive capacity, and the likelihood of international cooperation. There is also the issue of which precise baselines should be used for comparison (McLaren, 2018): what should climate change or SAI be specifically compared against? In addition, how should the two be compared? Given the high uncertainties for both climate change and SAI, is a Maximin analysis of the “better” worst case a prudent or viable approach? Given these difficulties, we do not look to provide a definitive answer or quantitative analysis. Ultimately, we are not just comparing two different sets of risks, but two separate Earth system states (Jebari et al., 2021) with different winners and losers. Navigating these entangled risk analyses is an area for future analysis, but analysis that this paper can hopefully inform.

Nonetheless, any public deliberation and democratic decisions need to rest on comparable evidence and information. Any action is bettered by risk assessment, even if it is always mired in uncertainty. This article provides an initial and incomplete basis for informing such discussions. Imperfectly mapping out risk trade-offs is preferable to sleepwalking (McKinnon, 2018) into a dangerous future.

DIRECTLY CATASTROPHIC IMPACTS: ECOLOGICAL BLOWBACK?

Could SAI lead to directly³ catastrophic ecological impacts? Existing studies highlight a raft of potential negative consequences. But the specific nature of these impacts, and their contributions to catastrophic outcomes, depends on the specific SAI implementation. This is an issue of high uncertainty, particularly regionally.

The projected local ecological effects of SAI are mixed and uncertain, depending on the specific analytical approach and specific SAI deployment. Monsoon areas would likely face a drop in precipitation under large scale SRM (Tilmes et al., 2013; Reynolds et al., 2016), but this focuses on SRM in the abstract and may not be fully applicable to SAI. Many regions could face a seasonal under- or over-compensation in rainfall (compared to a high warming average (RCP8.5) from 2010 to 2030, and assuming SAI is implemented to mask 5 degrees of warming) (Jiang et al., 2019). Effects on hydrological systems would be regionally diverse and uncertain due to potential changes in non-linear variables including surface runoff, evapotranspiration, rainfall levels, and distribution (Dagon and Schrag, 2016, 2019). These fine-grained changes in weather could then affect vegetation. Plant communities could transform their structure, traits, and geographical range, particularly under larger swifter SAI deployments (Zarnetske et al., 2021). While SAI might offer salvation to climate vulnerable vegetation it will depend on deployment timing. Some communities may already be committed to at least local extinctions before SAI is deployed. SAI would likely result in ecological trade-offs with some communities benefitting and others suffering. The exact nature of these trade-offs is uncertain and needs further study (Zarnetske et al., 2021). The key theme here is that SAI would likely have a range of impacts on many ecological systems. But how these would play out is highly uncertain, particularly at regional scales. Impacts hinge on the inherent uncertainties within complex ecological systems, varied comparative baselines, and the specific SAI deployment.

The overall direct impacts of SAI, while uncertain, do not currently seem to constitute a catastrophic threat. Whether SAI would cause greater risks in terrestrial, freshwater, marine systems than climate change is unclear and depends on

³This section studies the potential *direct* catastrophic impact of SAI, not the impacts of termination shock [which are almost guaranteed to be catastrophic if used to mask high levels of warming and if SAI undergoes a indefinite suspension (Trisos et al., 2018)]. By directly we refer to clear causal relationships with less than two degrees of separation.

SAI's specific deployment configuration. Higher levels and swifter deployment of SAI would mean greater potential for disastrous impacts (Trisos et al., 2018; Zarnetske et al., 2021). Additional considerations like seasonal (Lee et al., 2021) or hemispheric (MacMartin et al., 2017) deployment further affect potential impacts.

There is a paucity of research on SAI impacts (Irvine et al., 2016, 2017; MacMartin et al., 2016; McCormack et al., 2016; but see Schäfer et al., 2015 for an exception), particularly so for catastrophic or worst-case impacts. This has been the case for climate modeling literature in the past as well (Brysse et al., 2013). Climate modeling is often an exercise in "betting on the best case" (Geden, 2015; Jehn et al., 2021). Others have noted this idealistic tendency for SAI modeling (Low and Honegger, 2020), for example limiting SAI use to only halving warming (Irvine et al., 2019) or limiting SAI deployment to spring (Lee et al., 2021). These idealized approaches in theory could reduce negative impacts associated with SAI. Yet their likelihood is questionable due to optimistic assumptions of multi-decadal international cooperation (see section: *Politics*).

The possibility of dangerous ecological tail-risks depends on the level of cooling. Initial game theoretic research indicates the possibility of overcooling if SAI is pursued by uncoordinated actors (Abatayo et al., 2020). Negative impacts which are projected to be relatively minor in existing studies, for example sulfate deposition impacts on terrestrial ecosystems (Kravitz et al., 2009; Vioni et al., 2020b), may become major ecological issues if SAI is deployed to far more of an extent than envisioned. Similarly, a poor choice⁴ of aerosols could result in large-scale ozone depletion (Heckendorn et al., 2009; Keith et al., 2016). It is unclear whether, in these extreme cases, biophysical impacts would revert to their pre-SAI state once SAI is removed. Modeling on "worst" cases is thus critical in informing SAI's desirability. Exploring uncoordinated scenarios with the (simultaneous) use of different aerosols, different desired extents of cooling, and implementation by a small club, would all be helpful complements to existing idealized modeling scenarios.

Regardless of how developed our understanding on SAI impacts become, there will always be inherent uncertainty. When dealing with a complex system like the climate there is always the chance that a black swan is lurking in the dark.

Some commentators have downplayed the potential of unknown impacts due to the availability of historical analogs, namely historically severe volcanic eruptions (Halstead, 2018). Improvements in modeling, a gradual implementation, and a cessation if unacceptable negative impacts are found could also lessen the likelihood of an unforeseen catastrophic tipping point.

None of these reasons are causes for comfort. Modeling, regardless of improvements, may simply be incapable of capturing rare tipping-points and is not intended to accurately predict or foresee non-rational political dynamics (Elsawah et al., 2020). In addition, a gradual rational phase-in and phase-out relies on optimal governance conditions. Overly rapid

deployment due to "free-driving"⁵, (Weitzman, 2015) or overly slow phase-out due to technological or infrastructural lock-in (Seto et al., 2016) are entirely plausible. Moreover, SAI impacts may also not follow the pathway of historical analogs. The core rationale of SAI is to manufacture the cooling effect of a volcanic eruption in a "safe" manner, not replicate volcanic processes. Deviance from historical analogs is especially a possibility if the choice or mix of aerosol is radically different. This is particularly the case since climate change and human-pressures are already pushing ecological systems into novel states (Williams and Jackson, 2007; Williams et al., 2021). SAI would push systems into further novel states that make unseen ecological responses likely (McKinnon, 2018).

Our understanding of both Earth systems and the likely contours of deployment are too weak for us to rule-out a potentially catastrophic form of ecological blow-back. For now, the literature points to SAI having numerous impacts. But none seem remotely capable of being a GCR, particularly if SAI deployment were limited. Nonetheless, the Specter of an unforeseen tipping point in the Earth's climatic system remains.

INTERACTIONS WITH OTHER GLOBAL CATASTROPHIC HAZARDS

The impacts of SAI, or any other catastrophic risk, should not be assessed in isolation (Baum et al., 2013). Different catastrophic hazards⁶ have interactions. One could potentially trigger another and/or worsen its effects. Climate hazards for example have been shown to compromise governments' ability to provide effective responses to COVID-19 (Phillips et al., 2020). The potential for one global shock to ignite and amplify another has previously been dubbed "double-catastrophes." Baum et al. (2013) suggest that this could be the case if nuclear war or a pandemic were to disrupt an SAI system, leading to abrupt termination shock. GCHs which are simply a matter of probability, like extreme space weather or a volcanic eruption, may also coincide through pure bad luck.

In this section we consider both a broader array of hazards and how SAI could trigger and interact with them. This will not be an exhaustive comparative analysis of all possible GCHs. Instead, we focus on hazards that have clearly established causal relationships, relatively well-developed literatures, and some empirical track record of their impacts. Our analysis suggests that the possibility of SAI sparking other GCHs are tenuous. SAI could only plausibly contribute to large-scale conflict and potentially nuclear war. The possibilities of SAI exacerbating other GCHs are more concerning. SAI has the worrying ability

⁴Commonly proposed coolant agents could be benign or even increase ozone thickness (Pitari et al., 2014; Irvine et al., 2016) (though this is a relatively recent shift).

⁵A 'free-driver' problem (or 'forced rider') is where a single or limited number of actors' actions create negative consequences that the rest of the system must endure. In this case, a limited number of actors could implement SAI, and the rest of the world's economic and political systems would have to deal with the consequences. This can be seen as the 'opposite' to a conventional 'free rider' problem where benefits flow onto non-cooperative third parties.

⁶Instead of Global Catastrophic Risks, this section focuses on Global Catastrophic Hazards. Risks include vulnerability and exposure. Instead, this section focuses on the interactions between different specific hazards and SAI.

to significantly heighten the impacts and mortality of any global catastrophe due to termination shock.

Volcanic Eruption

A large volcanic eruption would demand rapid SAI adjustments. While severe overcooling seems unlikely [the cooling of SAI and volcanic winter are not additive (Laakso et al., 2016)], SAI should be rapidly scaled down in a matter of weeks (MacMartin et al., 2019). Laakso et al. (2016) assume a relatively thick SAI injection (offsetting roughly a doubling of carbon dioxide from preindustrial levels). The prudent course of action for thinner SAI is unclear. However, the SAI adjustment in a volcanic future is not simply one of scale down. SAI injection may need to increase in the opposite hemisphere to the volcanic eruption to ensure a more uniform global temperature (MacMartin et al., 2019) (a high temperature variance across hemispheres can have severe adverse impacts on precipitation and drought dynamics).

Adjusting the SAI level may seem straight-forward but depends on an informed, rapid political response. There are reasons to doubt this would be forthcoming. First, the technical demands may prove too much for cumbersome domestic and multilateral politics. These includes potentially politically vexing dilemmas over the balance between scaling SAI up and down on different hemispheres, whether to inject SAI at new locations or “thicken” existing deployments (MacMartin et al., 2019), or whether SAI should be scaled down at all. A second and novel addition is that a volcanic eruption would not solely affect temperature. Many pinch points of global supply systems are near active volcanic areas. Even modest volcanic eruptions could lead to disruption and catastrophic economic system collapse (Mani et al., 2021). The difficulty of coordinating regional SAI adjustments would be compounded by sub-optimally functioning supply systems and general economic and political chaos.

While the interactions between a volcanic eruption and SAI currently seem to have only modest direct contributions to catastrophic risk, the highly political decisions of a volcanic-SAI world may lead to political ruptures and ineffective SAI governance.

Space Weather

Solar flares, coronal mass ejections, and associated solar radiation and geomagnetic storms, can lead to widespread damage to terrestrial, avionic, and space infrastructure. The fear for SAI is that a “black sky” event could disrupt and knock-out critical SAI infrastructure. Yet there have been no attempts thus far to investigate SAI-space weather interactions. We examine SAI interactions with an Earth-bound space weather event roughly on par or worse than the 1859 Carrington Event—the benchmark for extreme space weather events (Green and Boardsen, 2006). A current day Carrington Event would likely lead to widespread electrical failure and disruption for multiple months at minimum, potentially years (Eastwood et al., 2017; Loper, 2019; Ritter et al., 2020).

Extreme solar events are difficult to accurately and timely forecast. They are essentially random events⁷ which provide little forewarning. Solar radiation can travel at such high speeds that an extreme coronal mass ejection would likely reach Earth in less than a day. Other radiation and energized particles travel at or close to light speed—8 min to reach Earth. Even with the earliest detection possible there would be little response time (Royal Academy of Engineering, 2013). It would be a late flinch to an oncoming blow.

The impacts of extreme space weather events are vast. Aviation, satellite, and general electronic infrastructure are especially vulnerable. Energized particles can affect memory cells, for example changing a bit from a 1 to 0 and vice versa, that lead to erroneous commands or overall hardware failure (Jones et al., 2005). Global navigation and communication systems would experience disruption and downtime that could last several months (alternative navigation systems, like the US Alternate Position Navigation and Time programme, may still be affected by electrical damage) (Goodman, 2005; Royal Academy of Engineering, 2013). Aircraft crew would have greatly limited airtime due to limits of safe radiation exposure (Jones et al., 2005). Flights at higher altitudes and closer proximity to the Earth’s poles would be unlikely to continue (Dyer et al., 2003; Jones et al., 2005; Alvarez et al., 2016). The use of automated aircraft would be compromised by widespread electrical and avionic damage. Especially alarming is that SAI would likely depend on vulnerable aviation, satellite, and general electronic infrastructure for deployment, monitoring, impact attribution determination, calibration, and modulation.

Impacts of space weather events are not limited to human infrastructure. Substantially increased UV output can influence the Northern Hemisphere jet stream, ozone production (and ozone UV absorption and warming), and precipitation patterns (Jones et al., 2005). These systems, particularly precipitation, are the same systems that SAI is likely to greatly affect. Interaction between these impacts is currently unclear.

These disruptions appear enough to halt even a robust SAI system. Even with high uncertainties of potential infrastructural impacts (Royal Academy of Engineering, 2013; National Science Technology Council, 2019) and the nature of the event itself (Liu et al., 2014; Pulkkinen et al., 2015; Eastwood et al., 2017), the limited evidence so far indicates that SAI infrastructure would be vulnerable and exposed to damage, thus leading to termination shock if SAI was sufficiently thick (see section: *Latent Risk and SAI*). In the aftermath of an extreme space weather event, continued implementation or preservation of SAI infrastructure would have to compete for

⁷There is unresolved discussion as to whether extreme space weather events follow a power law or lognormal distribution (Riley and Love, 2017; Kataoka, 2020). The estimated probabilities of an extreme space weather event in the next decade or so range from 0.46–1.88% (Moriña et al., 2019), 4–6% (Kataoka, 2013), to roughly 20.3% (Riley and Love, 2017). This is all to say that while there are efforts to better understand the probability of extreme space weather events, there is little agreement in what the precise probability is. Nonetheless, even the lowest estimates are not negligible. In the face of such uncertainty, we take the lead of other policy analyses in the area (Royal Academy of Engineering, 2013; National Science Technology Council, 2019) and characterize these events as essentially random.

limited government attention. Damage would be widespread and international—ranging from railway failure (Ptitsyna et al., 2008; Wik et al., 2009; Eroshenko et al., 2010) to power failure (Royal Academy of Engineering, 2013; Juusola et al., 2015; Kai-rang et al., 2015; Matandirotya et al., 2015) to failure of satellite infrastructure (Odenwald et al., 2006). Governments and resources would be stretched thin and SAI reimplementation may be neglected. An extreme space weather event could lead to severe economic and infrastructural shocks (Loper, 2019) that make continued SAI deployment infeasible. At worst, widespread power failures could lead to ripple effects across food, health, and transport systems that extend recovery time potentially into decades, driving modern societies back to a more fractured pre-electronic state (Loper, 2019). It is unclear how SAI, with its high technical and information demands (MacMartin et al., 2019), could continue under these conditions. Troublingly, mitigation options are currently limited and highly depend on future (but relatively well-known) scientific and engineering solutions (National Science Technology Council, 2019). Considering the speed of space weather events, SAI infrastructure would have to be built to be resilient (with technology which does not currently exist) from the offset.

SAI is ultimately highly vulnerable to extreme space weather events. Widespread electrical damage would compromise SAI redeployment, making a termination shock highly likely and worsening the already catastrophic impacts of an extreme space weather event.

Nuclear Weaponry

SAI would worsen any nuclear winter and our recovery from it. A nuclear war could occur due to either an accidental strike leading to escalation, or a full-blown exchange. Even a relatively smaller conflict between Pakistan and India would have global ramifications. The background risk of incidental or inadvertent nuclear deployment is present unless there is total nuclear disarmament (Barrett et al., 2013; Baum et al., 2018). In addition to nuclear winter, the physical blast, ionizing radiation, and electromagnetic pulse (EMP) would all contribute to widespread and severe damage of electronic infrastructure (Baum and Barrett, 2018), including SAI infrastructure. Indeed, EMPs are similar in effect to the “black-sky” events discussed in section: *Space Weather*. This leads to two key concerns. The first is the combination of SAI cooling with nuclear winter conditions, the second is the grim mixture of nuclear cooling combined with termination shock.

The combination of SAI’s existing cooling and additional nuclear winter would lead to short term overcooling, followed by medium- or long-term overheating due to termination shock (Baum et al., 2013). It would be global frost followed by global furnace. Alternatively, there may be the potential for SAI and nuclear winter layering to spark non-linear or unexpected cooling effects. This is an area that justifies further study. There is modeling on the impacts of a nuclear detonation, comparison of nuclear and climate threats via the “climate-nuclear nexus” (Scheffran et al., 2016), and modeling on the impacts of SAI deployment and termination shock. Yet so

far nothing integrates these two separate bodies of knowledge. The oversight is interesting given the entangled histories of climate science and nuclear weapons research (Edwards, 2012). In any case, such rapid swings in global temperature would be unprecedented for the Earth system and humanity.

A key question is whether a disrupted SAI system could be revived during nuclear winter to prevent a termination shock summer, and whether SAI was masking sufficient warming for termination shock to occur (see section: *Latent Risk and SAI*). But there also are reasons to believe that the re-establishment of an SAI system would not be able to occur during the buffer period in the wake of a nuclear cataclysm. First, technological damage may be so severe that timely deployment is impossible. Backup infrastructure like aircraft (and associated supporting infrastructure such as air traffic control) may be damaged beyond repair or be grounded for security purposes. Second, political and policy attention would likely be focused on other post nuclear issues, such as disaster recovery and the creation of alternative food systems. As with other disasters, governments would be stretched thin and may prioritize these more short-term issues. Lastly, a post-nuclear world would likely exhibit a lack of international cohesion that is seen as an enabling condition for effective SAI (Horton and Reynolds, 2016; Chhetri et al., 2018; Jinnah, 2019). Discussions over SAI have already been deadlocked (McLaren and Corry, 2021). It seems unlikely that a world of post-conflict lessened trust would be more conducive to speedy decision-making. Different countries may drop out of implementation, further complicating SAI deployment configurations, possible regional impacts, and concordant policy responses. Disagreement over resource allocation is likely to arise, as is the case for many disaster recoveries (Platt, 1999; Cohen and Werker, 2008; Doan and Shaw, 2019).

The presence of thick SAI greatly increases the potential consequences of nuclear warfare, and vice versa. The rapid temperature swings involved with a nuclear winter and termination shock summer would likely lead to ecological disaster, and a chaotic post-nuclear world would not likely reimplement SAI in a timely sensible manner.

Pandemics

A pandemic that reaches the level of a GCR could be enough of an economic or population shock to sever an SAI system (Baum et al., 2013). Whether the system could be reactivated during the buffer period would depend on both the severity as well as the length of the pandemic. COVID-19 provides a chilling reminder that states are not rational nor necessarily cooperative during a disease disaster. COVID-19, a far cry from being a GCR, has spawned fragmented responses and cases of both vaccine nationalism and vaccine diplomacy. Such multilateral behavior does not engender confidence that a pandemic with a significantly higher mortality rate would lead to survivors coolly and collectively reactivating an SAI system whilst dealing with the outbreak. Other issues, like keeping healthcare systems afloat, would likely be an overwhelming priority. With resources and capacity stretched thin, SAI may be neglected. A pandemic would be a severe shock to political and economic systems that may preclude continued SAI use. Not least rational, well-governed,

well-resourced SAI use. Whether this risks termination shock depends on the amount of warming masked.

There are also reasons (albeit speculative) to believe that SAI could contribute to a pandemic. SAI induced temperature changes and uncertain regional climatic effects can alter disease transmissions (Carlson and Trisos, 2018; Carlson et al., 2020). This could in turn affect pandemic dynamics. As with general ecosystem impacts (section: *Directly Catastrophic Impacts: Ecological Blowback?*), a larger and quicker SAI deployment can be expected to have more severe impacts. Critical nodes in urban and health systems may become exposed to diseases that are beyond typical immunity or resistance (see section: *Health* for more on SAI-health interactions). This could be the spark for a pandemic spread, particularly if decision-makers are unprepared to make early and rapid response measures. However, the most worrying (but thus far neglected) concern would be effects on animal populations. Similar concerns of low or lapsed immunity or resistance would apply to animal populations and new disease vectors. But animal populations would lack similar healthcare systems to keep disease spread at bay. Many contemporary pandemics have resulted from cross-species spill over (Christophersen and Haug, 2006; Cheng et al., 2007; Quammen, 2012; Plowright et al., 2017; Borremans et al., 2019; Johnson et al., 2020; Morens et al., 2020), including the 2009 Swine Flu Pandemic from pigs and birds, and the 2013–2016 Ebola Epidemic and COVID-19 Pandemic from bats. Altered animal disease dynamics, particularly those stemming from unpredictable regional SAI impacts, may increase the frequency and severity of future pandemics.

THE SYSTEMIC RISKS OF CLIMATE ENGINEERING

Both previous societal collapses and disasters in the modern world are marked more by the accumulation of many stresses leading to failure, rather than single abrupt shocks destroying systems (Homer-Dixon, 2008; Haldane and May, 2011; Helbing, 2013). Seemingly modest stressors can cascade to catastrophe. This section analyses the potential of SAI to create and be impacted by biophysical and political stresses which contribute to global systemic risk.

The world currently exists in a deeply interconnected, and increasingly homogenous state which is prone to systemic risk (Helbing, 2013). One ship blocking the Suez Canal in March 2021 led to losses of roughly \$6–10 billion (Russon, 2021). More serious stressors could lead to far more severe consequences. The economic and political state of the world would be central in determining whether risk cascades. It is unclear how SAI could or would adjust the structure of the globalized economy. Hence, instead we focus on a few critical systems that SAI might be expected to impact and where there have been initial attempts to gather evidence: agriculture, health, and international politics⁸.

⁸We exclude other areas such as telecommunications and finance due to a lack of published literature.

SAI would likely not alter any of these system structures, but would rather aggravate existing systemic vulnerabilities.

Agriculture

SAI's effects on temperature and precipitation distributions would likely affect agricultural systems. The precise nature of these impacts are unclear (Kortetmäki and Oksanen, 2016; Irvine et al., 2017; Svoboda et al., 2018; Pamplany et al., 2020). For example, some studies have shown that the low temperature high carbon dioxide environment of a SRM deployment might increase yields: maize yields may increase in China (Xia et al., 2014), as could overall global yields of maize, wheat, and rice (Pongratz et al., 2012). On the other hand, solar dimming might reduce yields of groundnut in India (Yang et al., 2016) or offset benefits of reduced temperature (Proctor et al., 2018). These effects would all further differ across crop and area. The differing approaches to analysis [Xia et al. (2014) focus on SRM to offset a 1% increase in carbon dioxide from preindustrial levels for 50 years, whereas Pongratz et al. (2012) focus on SAI masking carbon dioxide concentrations of 800 ppm] as well as use of outdated equatorial injection in these studies (see section: *The Means of Deployment*) make clear conclusions difficult to discern. The main point is that SAI would affect agriculture, but the precise impacts are unknown.

Regardless, the sensitivity of these key staple crops is alone cause for concern. Small variations in yields of staple crops could induce disproportionate price fluctuations and cascades into socio-political violence, particularly in areas with political instability and weaker governance (Natalini et al., 2015, 2017; Richards et al., 2021). Additional uncertainties with attribution between SAI and agricultural yields could compound potential political difficulties.

Even in the case that SAI provides agricultural benefits, these are likely to be marginal if other issues affecting agricultural productivity, such as habitat loss and soil degradation, continue unabated (Kortetmäki and Oksanen, 2016). An SAI high carbon dioxide low sunlight world would also require additional adaptation on the part of agricultural actors. This does not look likely given agricultural adaptation to climate change has so far only been modest (Proctor et al., 2018). Large-scale changes in yield and precipitation are likely to create at least short-term food insecurity. There is evidence that existing population density and economic growth are closely tied to the existing climate niche. The narrow climatic envelope of $\sim 13^{\circ}\text{C}$ has provided beneficial environmental conditions within which most humans and societies have tended to historically cluster (Burke et al., 2015; Xu et al., 2020). Our agricultural systems almost certainly are similarly tied to this niche, and any sudden change at a global level is likely to affect short-term yields and prices.

Politics

SAI could feasibly spark conflict and instability. There are already some emerging empirical links between food price shocks and socio-political violence. Moreover, the very act of undertaking SAI could be grounds for dispute. States may look to develop their own SAI capabilities before others do, creating more extensive backup infrastructure to avoid dependencies on others,

or even construct counter SAI capabilities (see Horton and Reynolds, 2016 for a review in this area; McKinnon, 2020). Existing political order may become undone by SAI (Keith, 2013; Corry, 2017). A novel and interesting example could be high historical emitters like the US using the Common but Differentiated Responsibilities and Respective Capabilities principle as an instrument to assert SAI control or leadership (“we are mostly responsible for climate change, therefore it is ‘just’ that we lead the response”). Manipulation of the climate could become a new frontier for political conflict or even warfare. Different cross-boundary impacts on different regions would create large sets of winners and losers, alongside questions of attribution (MacMartin et al., 2019) and compensation. Whether such disputes could snowball into conflict is beyond prediction. Nonetheless, it is reasonable to say that unless enacted as altruistic, cooperative endeavor over multiple decades, the project of SAI would load further pressure onto existing international tensions. But even in the most altruistic cooperative scenarios, there may still be sub-national tensions in and/or between “donor” and “recipient” populations.

There is also the possibility that politics would worsen SAI. SAI and politics is a two-way street. Political conflict can cascade to affect SAI deployment and its impacts. Previous studies have made a compelling case that the direct weaponisation of SAI is unlikely (Fleming, 2007; Olson, 2011; Horton and Reynolds, 2016; Lin, 2016; Halstead, 2018). High impact uncertainties, management difficulty, low precision, and preferable alternative weaponry make SAI an unappealing instrument in state arsenals. However, this does not mean that SAI has limited military use. SAI may not have usefulness as a direct weapon, but can function as a support system or a threat. Indeed, early attempts at cloud seeding were used by the US military during the Vietnam War as a tactical weapon to extend the Monsoon Season and disrupt North Vietnamese supply lines (Operation Popeye).

Another avenue for political dynamics to worsen a SAI deployment, and that has received relatively little attention, is via cyberwarfare. In May 2021, a ransomware cyber-attack forced a US fuel pipeline out of service. A \$5 million ransom was paid to restore service (BBC, 2021). As a globally critical (and potentially highly politicized) piece of infrastructure, SAI would likely be a target for private or state actors. SAI deployment dependent on any software or advanced algorithmic system (Rolnick et al., 2019; Schroeder de Witt and Hornigold, 2019), which is likely given the high technological and informational demands of deployment (MacMartin et al., 2019), would be vulnerable to cyberattack.

Cyberattacks do not need to come from external forces. For instance, the notorious 2000 Maroochy Cyberattack was from a disgruntled ex-employee (Slay and Miller, 2008). SAI would likely depend on a large workforce and have numerous reasons for controversy.

These political dynamics would have decades to play out. A cooperative and benevolent deployment of SAI could crumble into chaos with a change in actor preferences (or vice versa). Politics and its broader conditions are likely to change substantially over coming decades. Interactions between future geopolitics, warming and emissions, and technology are all high

impossible to predict or even foresee (Wells, 2001), but would be of critical importance to SAI and its governance. Relying on one set of optimal political assumptions would be greatly unwise.

Health

SAI could negatively impact human health by both changing disease vectors and range (and therefore pandemics, see section: *Pandemics*), and by undermining existing health system infrastructure. The regional variations of SAI’s impacts on temperature and other ecological factors would likely affect disease transmissions. SAI-induced reductions in monsoon rainfall may increase cholera risk (Carlson and Trisos, 2018), and temperature changes can affect transmission of vector borne diseases like malaria (Carlson and Trisos, 2018; Carlson et al., 2020). Yet such health impacts are chronically understudied: currently only 4 papers focus on the health impacts of SAI (Effiong and Neitzel, 2016; Carlson and Trisos, 2018; Eastham et al., 2018; Carlson et al., 2020). The lack of coverage is significant since these studies have critical limitations, namely an assumption of equatorial injection (see section: *The Means of Deployment*). The impacts of other forms of deployment are largely unknown. Similarly, there is little research on the health impacts of exposure to SAI aerosols (Effiong and Neitzel, 2016), and the few quantitative assessments of mortality related to air quality and changes in UV exposure carry significant uncertainty (Eastham et al., 2018).

Despite these limitations, the research to date does point toward potential dangers. Alterations of disease transmission are especially important because diseases may reach populations which have lapsed or little immunity or resistance (Carlson and Trisos, 2018), or may have relatively weak or vulnerable public health systems. These critical nodes in health and urban systems, which otherwise would be less exposed, may amplify health risks and impacts: an epidemic may be amplified to become a pandemic (section: *Pandemics*). The uncertainty of SAI’s potential deployment configurations, associated impacts, and state of existing health systems means that early identification of different critical nodes would likely be difficult and insufficient. Overall, systemic effects between health and SAI currently seem modest and carry high uncertainty. However, they are not negligible.

LATENT RISK AND SAI

Latent risk refers to risks that are dormant, but could become manifest during times of heightened societal vulnerability. The most obvious example would be the additional risks that arise in the aftermath of a collapse (widespread, significant, and enduring loss of life, political organization and economic capital) or another global catastrophe, for example violent conflict over food and water. Latent risks are particularly important as they can provide one tangible way in which recovery from global shocks could be undermined and spiral toward extinction risk (Cotton-Barratt et al., 2020). We have already dealt with these partly in sections: *Directly Catastrophic Impacts: Ecological Blowback?–The Systemic Risks of Climate Engineering*. In short, latent risk is perhaps the largest risk factor for SAI. SAI changes the nature

of climate risk by making the “likely” outcomes less severe, but making “less likely” (or “fat-tail”) outcomes substantially more severe. The risk of termination shock thickens the tail. Large amounts of SAI loading could create a precarious condition in which any sufficiently large global shock is likely to be compounded by a tumultuous termination shock.

While there is subjectivity as what a “threshold” for termination shock would be, Parker and Irvine (2018) put it at termination that causes at least 0.3 degrees warming per decade. This would imply an SAI cooling threshold of around 0.6 degrees. Kosugi (2013) puts the threshold at 0.2 degrees, implying a cooling threshold of around 0.4 degrees.

The speed of termination shock depends on the form of SRM. SAI has a half-life of ~8 months (approximately half the levels of coolants would still be present after 8 months) and warming would still take several years to reach its unmitigated levels (Parker and Irvine, 2018). Depending on the amount of warming masked, SAI has a distinctly high latent risk due to termination shock. A temperature rise of 6 degrees in the space of centuries would be an order of magnitude faster than the warming experienced during the Great Permian Dying (Lynas, 2020). If experienced in a period of decades, it would be an order of magnitude faster still. Current warming rates are geologically unprecedented; this speed would be chillingly rapid.

Critics have framed termination shock as an overblown problem for numerous reasons. These include that countries are unlikely to willingly reverse SAI, that there would be a sufficient buffer period to resume SAI, and it is unlikely to be hiding a large amount of warming (Reynolds et al., 2016; Parker and Irvine, 2018). These all seem to align with the inclination for both modeling and analysis of geoengineering to focus on the “best-case.” That there would be sufficient cooperative governance and deployment of SAI, that there would be rational responses to any system lapse or shock, and that SAI would be used to only shave-off a small amount of warming (Ott, 2018). Yet, SAI is widely portrayed as an emergency response: it is most likely to be used in a worst-case high warming scenario, not a best-case limited warming one. Moreover, the likelihood of high-end warming, governance fragmentation, or another GCR occurring are all disarmingly large.

The likelihood of a catastrophe curtailing SAI efforts and causing termination shock is usually dismissed as very low. This is likely mistaken. We have covered some of these catastrophes in section: *Interactions With Other Global Catastrophic Hazards*. While there is considerable uncertainty, the likelihood of a GCR in the coming centuries does not appear to be vanishing. Estimates for a large-scale space weather event over the next decade or so range from 0.46% (Moriña et al., 2019) to 20.3% (Riley and Love, 2017). Estimates of the probability of nuclear war are few and vary, but one model of inadvertent conflict between the US and Russia using historical data put it at 0.9% per year (Barrett et al., 2013). SAI could also be slowly scaled-back as mitigation and CDR efforts increase (Reynolds et al., 2016). But this would likely require multiple additional decades which would (assuming no mitigation of other global threats) incur a higher likelihood of another catastrophe striking.

A more compelling retort is that SAI could be reintroduced within years at a reasonable cost. Some have suggested that given that SAI could be run at >1% of the GDP of the G20 and hence even losses of 75% of GDP (an unprecedented economic disaster) would be insufficient to keep an SAI system deactivated (Parker and Irvine, 2018). Such analysis overstates the coherence and rationality of states responding to crisis. The value of an extra 3 billion doses of COVID-19 vaccines would provide benefits of \$17.4 trillion, at a cost of around \$18–120 billion (Castillo et al., 2021). Yet vaccine production remains chronically low. Even in far less dire circumstances we can clearly not trust decision makers to take the optimal course of action.

SAI can be seen as one vast project to make the climate system more tightly coupled and synchronized with the global economic system. From a resilience perspective, such efforts are a liability. It makes it far more likely that the failure of one system will spill-over into another, sparking non-linear feedback loops that result in “synchronous failures” (Homer-Dixon et al., 2015). There are of course ways to make such complex engineering systems more resilient and robust, namely via backups and redundancies. However, current economic incentives for efficiency (particularly via cost reduction), mean that strong redundancies are rarely in place. SAI redundancies specifically are likely to be expensive and thus inconsistently implemented (Halstead, 2018; Parker and Irvine, 2018; McKinnon, 2020). In any case, it is unclear what redundancies would be effective at making an SAI system catastrophe-proof. Making SAI resilient to natural disasters or terrorist attacks seem relatively straight-forward (Parker and Irvine, 2018; Rabitz, 2019), but the same cannot be said of a true global catastrophe.

The inherent unknowns of highly complex technological systems also contribute to the possibility of termination shock. Highly complex systems, like SAI would be, are prone to “Normal Accidents” (Perrow, 1999; Maas, 2019). Large-scale accidents and disruptions are to be expected in sufficiently complex and tightly coupled systems. Unforeseen technological failures are simply a fact of life.

While latent risk is a genuine concern, it is a danger for only the greatest threats on the horizon and the “thickest” SAI deployments. A true, dramatic, global calamity would be needed to both disable an SAI system masking a large amount of warming and keep countries either preoccupied or incapable of reinstating it for several years.

In **Table 2** we summarize our analysis of direct impacts, GCH interactions, systemic risks, and latent risk.

DISCUSSION: BUILDING THE POLICY BOUNDARIES FOR CLIMATE ENGINEERING

The Means of Deployment

Our analysis thus far has assumed a “default” deployment of optimal conditions of a global material approach to mitigate climate change. This is not necessarily the most likely scenario and the means of deployment and context will dramatically

TABLE 2 | Summary of SAI's direct impacts, GCH interactions, systemic risks, and latent risk.

Contribution to catastrophic risk	Type of contribution	Nature of evidence base and uncertainty	Dependency on mode of deployment
Destabilizing ecological systems	Ecological blowback	Limited evidence base and high uncertainty. Lack of study on worst-case ecological impacts. High regional variations and uncertainty.	High dependency. Direct SAI impacts vary with thickness and other injection variations.
Volcanic eruption leading to political SAI difficulties	GCH interaction	Limited evidence base. Study of SAI interactions with a volcanic eruption is limited.	Medium dependency. Dependent on potential SAI supply routes, but also external political dynamics.
Extreme space weather event damaging SAI and global electronic and power infrastructure.	GCH interaction	Limited evidence base. No specific study of the impact of an extreme space weather event on SAI. Varying estimations of space weather probability.	Medium dependency. External SAI support systems are vulnerable. Thick SAI leads to more severe termination shock.
SAI-nuclear winter overcooling or nuclear frost-termination furnace.	GCH interaction	Limited evidence base. Existing study on nuclear winter effects and SAI effects, but nothing that studies interactions between both.	Medium dependency. Dependent on external political dynamics. Thick SAI leads to more severe termination shock.
Political instability of a post-nuclear world on SAI redeployment	GCH interaction	Limited evidence base. Existing study on post-nuclear politics and SAI politics, but nothing that studies interactions between both.	Low dependency. Dependent on external political dynamics.
Pandemic leading to population or economic losses that make continued SAI infeasible.	GCH interaction	Limited evidence base. Limited study of SAI-health intersections and no study of SAI-pandemic interactions.	Medium dependency. External pandemic, economic, and political factors are critical drivers. But thick SAI leads to more severe termination shock.
SAI weakening agricultural systems.	Systemic risk	Limited evidence base and high uncertainty. Little study of SAI's agricultural impacts and high regional variance is likely.	High dependency. SAI's agricultural impacts are highly dependent on deployment configuration.
SAI sparking political conflict	Systemic risk	Initial study of the political dimensions of SAI, but high uncertainty of how these political effects would play out.	Low dependency. Dependent on external political dynamics.
Political dynamics that compromise SAI safety	Systemic risk	Low uncertainty that international geopolitics over a multi-decadal timescale is not ideal for optimum SAI governance. High uncertainty and limited evidence base as to how specifically this would play out.	Medium dependency. Political instability and conflict is core to the multilateral system, but nature of uneven SAI impacts and differing objectives contribute to political instability.
SAI affecting disease transmissions	Systemic risk	Limited evidence base and high uncertainty. Limited study of SAI-health intersections and highly dependent on external urban and health policy dynamics.	Medium dependency. Thicker SAI more likely to affect disease dynamics. But external pandemic, economic, and political factors are primary drivers.
Termination shock	Latent risk	Limited evidence base and high regional uncertainty of precise termination shock impacts. But low uncertainty that termination shock would be catastrophic.	High dependency. Thick SAI leads to more severe termination shock.

impact SAI's catastrophic risk profile. One of the critical variables to consider is the overall objective of a SAI deployment.

There are multiple potential objectives of SAI deployment, ranging from temperature reduction (of different extents), precipitation impact management, to biodiversity conservation (Lee et al., 2020; Zarnetske et al., 2021). These objectives will also depend on existing emissions reduction policies. There are also multiple potential "design" options for deployment configuration (Kravitz et al., 2016), ranging from deployment timing, extent, placement, to aerosol selection (Pope et al., 2012; Keith et al., 2016; MacMartin et al., 2017, 2019; Kravitz et al., 2019; Visioni et al., 2020a). The extent of cooling for example not only depends on how much aerosol is released, but the height of injection in atmosphere (lower stratosphere injection produces more cooling) (Bala, 2009; Krishnamohan

et al., 2020). Much of the existing study on SAI assumes injection along the equator (MacMartin et al., 2017). Equatorial injection is the most efficient if the only deployment objective is to maximize Earth's *overall* cooling. However, this would lead to high variance in temperature distributions, namely overcooling of the tropics and undercooling of poles (MacMartin et al., 2017). Impacts discussed in section: *Directly Catastrophic Impacts: Ecological Blowback?* also can change with a non-equatorial injection – Arctic SAI for instance would have less of an effect on Monsoon precipitation (Sun et al., 2020). Across all these there are key caveats. Neatly framed and optimized objectives found in modeling will not necessarily be reflected in messy and contested real life preferences, nor will SAI necessarily perfectly result in desired "design" outcomes (Wiertz, 2016; McLaren, 2018).

It is also important to consider that SAI may not be used solely to respond to climate change. The multiplicity of potential SAI goals opens the door to hidden agendas (McConnell, 2018), self-interest, and misuse. In addition, even if SAI is deployed under an idealistic scenario of climate altruism, there is no guarantee that this would persist. Considering that political preferences are unlikely to remain static over decadal timescales (see section: *Politics*), SAI functions may slowly “creep” (Koops, 2021) into currently unknown possibilities of misuse. Such “Function Creep” and potential misuse are highly understudied in current SAI literature⁹.

Predicting or even foreseeing potential future SAI functions will forever be mired in uncertainty. This is part of why Function Creep is such a difficult policy problem. Initial study in this area for SAI highlights the potential to use SAI to “optimize” or create “designer climates” (Preston, 2013; Talberg et al., 2018). Actors may for example advocate for deployment configurations that lead to more favorable conditions for critical staple crops, especially in response to warming impacts. These decisions may be the product of misjudgement or misinformation on SAI’s causal nature. SAI may also be used to justify the continued existence of fossil fuel industries. This is a potential adverse incentive core to the “moral hazard” problem (Reynolds, 2015; Lockley and Coffman, 2016). This could even create a new atmospheric political economy. The fossil fuel industry and other vested interests benefiting from the SAI system would have incentives to both use it as a way to slow decarbonisation and perhaps even thicken SAI deployment over time. This would heighten latent risk. Assuming SAI as a benign climate change response is unwisely narrow. Other more sinister SAI uses, whether purposeful or inadvertent, are critical determinants of SAI’s desirability.

There are many more SAI deployment options that are not currently well-captured in extant governance literature. SAI risks for example take a drastically different form if artificial intelligence (AI) is one of the central aspects of deployment design. With the vast amounts of information feedback and constant operational adjustments required (MacMartin et al., 2019), an advanced deep reinforcement learning system may be used to manage SAI deployment (Rolnick et al., 2019; Schroeder de Witt and Hornigold, 2019). This would introduce a raft of new issues, for instance “black box” opacity of decision processes (Rudin and Radin, 2019) or inappropriate generalizations of incomplete data (Martin et al., 2012; Christie et al., 2020).

Given the high variance of potential SAI objectives and potential deployment configurations, a highly political, uncoordinated, and decentralized (Reynolds and Wagner, 2020) “Wild West” deployment scenario, with unclear direct impacts, is possible. States and private sector actors are not likely to find agreement on a single defined “set” of objectives, how they should be prioritized, and how these objectives should manifest in deployment configuration. These intensely political and

self-interest driven considerations are likely key determinants of SAI deployment impacts, and should be priority areas for future governance research.

The means of deployment for other GCHs also affect SAI risks. An intentional weaponised pandemic may *intentionally* leverage SAI dynamics, like changes in disease transmission via changes in temperature distribution, to target critical nodes in health and urban systems. Such potential for now is speculative, but ultimately plausible.

Interconnections

Our analysis has focused on individual pathways for SAI to contribute to GCR. However, none of these are mutually exclusive. Each of the four steams overlap and feed into the same waterway. For instance, uni- or minilateral deployment of SRM systems could be driven by geopolitical distrust and conflict. This would likely be a world in which other GCHs are more likely, SAI deployment is less coordinated and damaging, critical systems are less resilient, and the world is less likely to quickly and effectively deal with a termination shock.

There is also an important intersection between systemic and latent risk. Most mechanisms that increase systemic risk will tend to raise latent risk as well. For instance, just in time delivery systems and tightly coupled systems with few backups, while efficient, are both more susceptible to shocks and can impede recovery. In **Figure 1** we provide one brief attempt to map some of the linkages between different risks and factors in SAI deployment. More interconnected systems mean a higher chance of synchronous failures, and SAI is likely to be a highly interconnected system.

Building the Policy Boundaries

Analysis of catastrophic downside risks can help illuminate the contours of what “effective” SAI governance would do. This is a useful complement to the policy literature that has focused mostly on structure and architecture (Reynolds, 2019). We add to the knowledge on policy *instruments* by providing further detail on policy *approach*.

To effectively mitigate against the (limited) number of threats and systemic risks outlined in this paper, SAI governance would have to be wide ranging, robust, and persist over decades. SAI and its backup infrastructure would need to be built to be resilient to extreme space weather or nuclear EMP events. Effective SAI governance is also not limited to SAI itself, but encompasses other policy areas like health, agriculture, AI, and energy. Ensuring ambitious emissions reductions and greenhouse gas removals would be needed to ensure SAI did not continue indefinitely. Effective SAI governance would also prevent future misuse and balance shifting preferences and multiple deployment goals in a just and inclusive manner. Governance arrangements to ensure SAI deployment or reimplementation in the wake of a major shock like a recession, pandemic, or nuclear attack would also be necessary. These would all be in addition to the herculean technical informational demands necessary for SAI deployment, which alone may be a larger undertaking than an IPCC report (MacMartin et al., 2019). This optimistically assumes that SAI’s climatic outputs can be clearly and cleanly measured, that

⁹There is the ethical question of how research in SAI misuse should be undertaken. Will researching SAI misuse possibilities inadvertently encourage SAI misuse? This is a question beyond the scope of this paper but is regardless a critical issue that deserves future attention.

there would be widespread international capacity for effective monitoring (McLaren, 2018), and that this monitoring would also be resilient to critical shocks. Substantial advancements in climate science and observation, as well as additional international capacity building for monitoring and transparency, would be needed. All of these would then have to be maintained over the course of decades.

These altogether represent an incredibly challenging governance task. The lack of success of the climate regime, with its similarly intense political and wide-ranging nature, does not inspire confidence in the feasibility of wide-ranging and long-term governance for an issue as political as SAI. Basic discussion over climate engineering as a whole has been stymied under the UN Environment Assembly (McLaren and Corry, 2021). Future and more consequential SAI debate will be subject to more severe political hurdles. Even less complex and smaller scale governance arrangements, like COVID-19 mask mandates, have been mired in politicization and competitive dynamics. A “mask” over the Earth, and its associated governance considerations, would face even tougher political challenges to effective implementation.

What would happen if a SAI deployment went ahead without these governance safeguards? It could very well be the case that agricultural or health impacts of SAI are limited or even positive. A disaster like an extreme space weather event may not happen in the decades where SAI is implemented. The stars of international politics could align and allow for a smooth SAI implementation and cessation.

There is indeed no guarantee that the catastrophic pathways outlined in this paper will materialize. But *if* they do, they would likely result in severe and cascading consequences. SAI has many extreme downside risks. “Imperfect” SAI governance can be compared to living without health insurance. The extra safeguards and protection aren’t strictly necessary... until something goes wrong. Given what we know about the instability of international geopolitics, SAI with imperfect SAI governance puts the world in a precarious position and introduces a climatic Sword of Damocles. The ultimate question becomes: are we willing to bet *the climate* that no catastrophe or systemic cascade will trigger SAI’s downside potential over the coming decades?

In a world of imperfect safeguards, two interconnected options are available to alleviate catastrophic risks. The first option is thinner SAI deployment. Thin SAI has a lower risk of catastrophic termination shock, thus posing less of a threat even if triggered by another calamity or systemic cascade. The second option is to ensure diversity in the overall climate engineering portfolio. Reducing reliance on SAI would better allow for a thinner SAI deployment. Other climate engineering approaches, particularly those which are less technology based, would also not necessarily share the same vulnerabilities as SAI. Trees for instance are not vulnerable to extreme space weather. These would reduce the potential of an SAI termination, but ultimately would not completely remedy the political complications SAI would create.

There seem to be three major¹⁰ pathways moving forward. The first is living in a highly vulnerable scenario of imperfect

SAI governance—the “Damocles Pathway.” This is clearly undesirable. The second is living with well-governed SAI that will not exceed policy boundaries of catastrophe—the “Miracle Pathway.” This seems infeasible. The final middle ground is to accept the inevitably imperfect contours of SAI governance, but greatly limit the extent of SAI deployment—the “Limited Pathway.” But this again would rely on robust and resilient governance and is still vulnerable to geopolitical shocks. SAI may be thickened or thinned along changing political tides.

A core conclusion here is that there is little use in asking whether SAI is a GCR or not. It depends on the level of loading and wider geopolitical landscape. All risks, especially latent risk, will increase with greater loadings and political conflict. This is a critical insight for the wider study of GCRs. A risk cannot be judged in a vacuum. Its severity will inevitably be determined by the scenario and system in which it unfolds.

CONCLUSION: THE FRYING PAN AND THE FLAME

We map the different contributions of SAI to Global Catastrophic Risk (GCR). The direct risks through irreversible extreme ecosystem impacts are currently unknown. No mechanisms for this have been identified. But extreme ecosystem impacts cannot be confidently ruled out given the nature of the Earth systems. SAI could have numerous diffuse impacts on critical systems such as agriculture, politics and health. These currently appear modest, but we cannot rule out the possibilities of systemic cascades or synchronous failures. It appears unlikely that SAI would trigger any other calamitous hazards unless it ignites geopolitical conflict between great powers. Instead, SAI’s greatest contribution is through latent risk: the ability for termination shock to significantly worsen any other GCR. For each of these areas the evidence base is significantly underdeveloped.

Is SAI worse than the initial problem of climate change? The question for now is largely unanswerable and lies outside the scope of our analysis. This paper represents a first step in understanding the multitude of risks of SAI. But critical gaps in understanding of both high-end warming and SAI remain. The climate comparison also depends on specific details, such as level of warming, state of politics, and availability of alternatives to SAI (such as rapid large-scale carbon dioxide removal). SAI is also deeply dependent on governance and the level of use. A constrained use of SAI with coherent, coordinated governance would most likely be benign and beneficial. Yet it is in a scenario of extreme warming, political fragmentation, and a search for an escape clause that SAI use appears most likely. Such thick and uncoordinated use of SAI is unwise and an unwise risk management strategy. We would face a planetary Sword of Damocles.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

¹⁰There are likely going to be many “in-betweens,” but these seem like the major contours of SAI’s future.

AUTHOR CONTRIBUTIONS

AT and LK contributed to all tasks involved with manuscript creation and revision, including conception, and design and drafting. AT led on each of these tasks. All authors contributed to the article and approved the submitted version.

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