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PERSPECTIVES

Emerging risk governance for stratospheric aerosol injection as a climate management technology

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Abstract
Stratospheric aerosol injection (SAI) as a solar radiation management (SRM) technology may provide a cost-effective means of avoiding some of the worst impacts of climate change, being perhaps orders of magnitude less expensive than greenhouse gas emissions mitigation. At the same time, SAI technologies have deeply uncertain economic and environmental impacts and complex ethical, legal, political, and international relations ramifications. Robust governance strategies are needed to manage the many potential benefits, risks, and uncertainties related to SAI. This perspective reviews the International Risk Governance Council (IRGC)'s guidelines for emerging risk governance (ERG) as an approach for responsible consideration of SAI, given the IRGC's experience in governing other more conventional risks. We examine how the five steps of the IRGC's ERG guidelines would address the complex, uncertain, and ambiguous risks presented by SAI. Diverse risks are identified in Step 1, scenarios to amplify or dissipate the risks are identified in Step 2, and applicable risk management options identified in Step 3. Steps 4 and 5 involve implementation and review by risk managers within an established organization. For full adoption and promulgation of the IRGC's ERG guidelines, an international consortium or governing body (or set of bodies) should be tasked with governance and oversight. This Perspective provides a first step at reviewing the risk governance tasks that such a body would undertake and contributes to the growing literature on best practices for SRM governance.

Keywords Climate engineering · Climate management · Geoengineering · Risk assessment · Risk governance · Solar radiation management · Stratospheric aerosol injection

1 Introduction

The use of stratospheric aerosol injection (SAI) as a solar radiation management (SRM) technology may provide a rapid and cost-effective approach to reducing climate change impacts, especially if used as part of a portfolio including greenhouse gas (GHG) emissions mitigation and adaptation.

SRM refers to a subset of climate management technologies intended to reflect sunlight and limit the solar energy that reaches the earth, and includes marine cloud brightening, space-based solar shading, increasing the reflectivity of land and sea surfaces, in addition to SAI that employs sulfur dioxide, alumina, or calcium carbonate as reflecting aerosols (Angel 2006; Rasch et al. 2008; Olson 2011; Cummings et al. 2017). Recent cost estimates for a SAI program on the order of $10-100 billion per year (Moriyama et al. 2017) are much cheaper (i.e., orders of magnitude) than an emissions mitigation effort that achieves the same amount of cooling (Barrett 2008; Bickel 2010; Bickel and Lane 2013). The need for cost-effective solutions that operate quickly is important because achieving the 1.5–2 °C warming limit fast enough to avoid the worst impacts may not be feasible through emissions mitigation alone (Climate Action Tracker 2017; Pasztor and Turner 2018). An analysis of the Paris Agreement on Climate found only an 8% chance of avoiding a 2 °C increase in global temperature by 2100 (Fawcett et al. 2015) if national mitigation commitments remain

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unchanged, with a median likely warming of 2.6–3.1 °C (Rogelj et al. 2016). This degree of warming is projected to result in a 15–25% reduction in per capita economic output by 2100 (Burke et al. 2018).

To meet the 1.5–2 °C warming target, several authors and organizations have suggested that climate management technologies need to be seriously considered as a part of a climate change response portfolio that includes other options, including emissions reduction, CO_2 removal, and adaptation (Olson 2011; Keith and MacMartin 2015; Keith and Irvine 2016; Pasztor 2017; Rahman 2018). Others have advocated for more research on climate management technologies in general and SAI in particular, to provide decision-makers and policy-makers with a basis for informed decisions if faced with an urgent need for SAI implementation (MacCracken 2006; The Royal Society 2009; Victor et al. 2009; Caldeira and Keith 2010; Morgan and Ricke 2010; Bickel 2013; Boettcher et al. 2017; Chhetri et al. 2018).

At the same time, SAI research has also been met with some opposition (Cicerone 2006; Hamilton 2013; Hulme 2014). Concerns include the possibility of unintended impacts on the earth's ecosystems, changes in precipitation patterns (e.g., regional droughts, impacts on monsoon cycles), depletion of the ozone layer, increases in acid deposition, and international tensions arising from regional disparities in climate change impacts. SAI also raises numerous ethical and legal issues, including unequal distribution of risks and benefits, potential for deployment by rogue actors, and the potential that such technocratic management of the climate will be undemocratic (Morgan and Ricke 2010; Olson 2011; Parkhill and Pidgeon 2011Pidgeon et al. 2013; Jones et al. 2017; Pasztor et al. 2017). SAI research itself has been called a "slippery slope" towards eventual deployment, with the potential to weaken emissions mitigation efforts (Morgan and Ricke 2010; ETC Group 2011; McKinnon 2018). SAI, and SRM technologies in general, face opposition from many environmental nongovernmental organizations (NGOs) (Scheer and Renn 2014), have been linked to conspiracy theories associating stratospheric aerosols with "chemtrails" (Temple 2018), and have led to conflict of interest allegations that resulted in the cancelation of field trials (Hale 2012; Pidgeon et al. 2013).

Given the risks of SAI weighed against an urgent need for climate change solutions, many authors and organizations have expressed a need for robust risk governance approaches applicable to the full research-to-deployment continuum (Barrett 2008; Morgan and Ricke 2010; Pasztor 2017; Gupta and Möller 2018; Jinnah 2018; Nicholson et al. 2018; Talberg et al. 2018). Risk governance refers to "the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analyzed and communicated and management decisions are taken"(Society for Risk Analysis 2015). The need for SAI risk governance is especially germane, as there are not yet any national or international governance initiatives or laws specifically covering SAI or SRM, and any potentially applicable agreements were designed for other purposes (Talberg et al. 2018).

The International Risk Governance Council (IRGC) is an independent, international, non-profit organization that aims to improve understanding and governance of systemic risks of global importance. The IRGC is a science-based think tank that promotes independent, multidisciplinary evaluations of diverse risk governance topics and often provides policy advice for key decision-makers. Previous topics addressed by the IRGC include carbon capture and storage technologies, synthetic biology, nanotechnology, and the comparison of risk regulations across countries. The IRGC's approach to risk governance combines technical evaluation of potential impacts, decision-making, management strategies, and multi-stakeholder engagement with robust communication strategies (IRGC 2017). While members of the IRGC have published commentary on SAI and SRM risk governance (Morgan and Ricke 2010), application of the IRGC's emerging risk governance (ERG) framework to SAI as a climate management technology has not yet been performed.

This Perspective reviews the applicability of the IRGC's ERG framework (IRGC 2015) to the development and deployment of SAI as a climate management technology. Our goal is to use the lens of the IRGC's ERG to highlight key research and governance concerns that should be addressed. We also provide recommendations for decision-makers involved in considering robust risk governance strategies for SAI.

2 Emerging risk governance and the IRGC's approach

Emerging risks are those that are new or arising in new conditions and, as a result, are not nearly as well understood as existing risks (Flage and Aven 2015; IRGC 2015; Mazri 2017). Examples come from across both social and natural systems and include artificial intelligence, nanotechnology, genetic engineering, the subprime mortgage crisis, climate change, and cyber security. Emerging risks are generally characterized by high uncertainty over potential impacts, greater complexity, and systemic dependencies that may lead to non-linear impacts and/or potential surprises (Renn et al. 2017). For these reasons, emerging risks can warrant different governance strategies than familiar risks (Linkov et al. 2018), including specific mechanisms for learning and data acquisition along with flexible and adaptive management procedures. Organizations, risk managers, and decision-makers dealing with emerging risks need to be prepared for risks that can evolve as well as for conditions of extensive and fundamental uncertainty. Therefore, measures that deal specifically with management of emerging risks may be needed rather than measures designed to handle more familiar risks (IRGC 2015).

The IRGC Guidelines for Emerging Risk Governance (IRGC 2015) are distinct from its overall risk governance framework (originally published 2005, revised 2017). The ERG guidelines provide strategies to anticipate and respond to emerging risks, categorize emerging risk types, identify and assess contextual factors that could influence the evolving nature of the emerging risk, and guide a transition from emerging risk into familiar risk categories. The approach aims to provide a more proactive, adaptive response to identify and manage an emerging risk that is characterized by multiple uncertainties. While decision-support is inherent in parts of the ERG guidelines, the guidelines are not intended to serve primarily as a decision-making framework. Rather, robust decision-making processes are recommended to be used in conjunction with the ERG to formulate decisions regarding the emerging risk in question, including the selection of risk management option(s) to implement. The guidelines include five steps. See Renn 2014; IRGC 2015; Renn et al. 2017 for details.

1. *Make sense of the present and explore the future* This horizon scanning step provides an early warning system to identify potential threats or risks as well as contributing factors that could lead to risk amplification or dissipation. A critical aspect in this step is to understand and search for unappreciated connections between potential triggers and negative consequences.
2. *Develop scenarios based on narratives and models* Scenarios are identified that describe the emerging risk, potential impacts, contributing factors, and key intervention points. These scenarios should not be guided only by probability assessments of expected outcomes. Unlikely sequences of events should be included as well to understand the vulnerabilities of each activity, technology, or intervention that could give rise to the emerging risk.
3. *Generate risk management options and formulate strategy* Risk management options are identified for each scenario, preferably using decision science. Possible strategies include: (i) acting on factors that contribute to risk emergence; (ii) developing precautionary approaches; (iii) reducing vulnerability; (iv) modifying the risk appetite in line with the new risk; (v) using risk governance instruments to manage familiar risk; and (vi) doing nothing.
4. *Implement strategy* The selected risk management option(s) are implemented in conjunction with communication and outreach. Often measures to reduce emerging risks imply costs incurred now to achieve future benefits (or avoided losses), which may not be popular among affected organizations or the public.
5. *Review risk development and decisions* The implemented risk management option(s) are reviewed and revised if necessary. A comprehensive monitoring system is required, particularly for complex risks that may extend into domains and areas distinct from their origin.

The IRGC emphasizes the importance of adequate resources and dedicated leadership throughout the ERG process, including identification of a "conductor" to oversee the governance process and facilitate communication.

3 Applying the IRGC emerging risk governance guidelines to SAI as climate management technology

In this section, we review the applicability and suitability of the IRGC's guidelines for ERG for SAI as a climate management technology. The state of the science and state of governance are highlighted in relation to each of the ERG steps. Figure 1 provides an overview.

3.1 Step 1. Make sense of the present and explore the future

Most research on SAI is in its early stages, with an emphasis on identification of appropriate materials and strategies. Candidates for aerosols include sulfur particles (sulfate, sulfuric acid, or sulfur dioxide), titanium dioxide (rutile and anatase), silicon carbide, diamond, calcium carbonate, aluminum oxide, silica dioxide, zinc oxide, and dust (SPICE Project 2018). Research is also underway to improve the solar reflectivity of particles, minimize the impacts on stratospheric chemistry, control their lifetime in the stratosphere, and minimize the costs and potential health and environmental impacts (MacMartin et al. 2013; Dai et al. 2018; SPICE Project 2018).

To date, only two outdoor experiments related to SRM have been conducted with aerosol particles (Doughty 2015). The Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE 2011) involved ship- and aircraft-based observation of emitted smoke and salt particles off the central California coast (Russell et al. 2012). In 2008, a Russian experiment conducted 500 miles southeast of Moscow observed the effect of aerosols dispersed from a helicopter and car (Izrael et al. 2009). E-PEACE was not intended to study SRM, though the data collected could be applicable to marine cloud brightening research. The results of the Russian experiment have received little attention, perhaps because the particles were injected into the lower

Fig. 1 The IRGC's ERG guidelines applied to the use of SAI as a climate management technology

troposphere rather than stratosphere. One field experiment—the Stratospheric Particle Injection for Climate Engineering (SPICE) experiment in the UK (Hale 2012; Pidgeon et al. 2013; SPICE Project 2018)—was canceled before being conducted due to public outcry and accusations of conflict of interest. Another set of field experiments—the stratospheric controlled perturbation experiment (SCoPEx) (Dykema et al. 2014; ScoPEx 2018)—is still being planned after earlier versions were postponed after pushback from the media (Tollefson 2018).

No international law has specifically addressed SRM or SAI technologies, no internationally adopted climate engineering governance initiatives yet exist, and no international monitoring programs are yet in place for climate engineering projects (Reynolds 2016; Pasztor et al. 2017; Talberg et al. 2018). Several treaties could apply, including the United Nations Framework Convention on Climate Change (FCCC) which in article 4(1)(f) calls on parties to "employ appropriate methods, for example impact assessments … with a view to minimizing adverse effects on the economy, on public health and on the quality of the environment, of projects or measures undertaken by them to mitigate or adapt to climate change"; and the United Nations Convention on Biodiversity, which in 2010 passed a non-binding moratorium on climate engineering activities that could have significant adverse effects on biodiversity (although the United States is not a party to the Convention) (Reynolds et al. 2016). The UN Environmental Modification Convention (ENMOD) prohibits the hostile use of weather modification technology on an international scale (Talberg et al. 2018). Other international legal instruments may also be applicable, such as the Convention on Long Range Transboundary Air Pollution, the UN Convention on the Law of the Sea, and the Outer Space Treaty, although the direct relevance to SAI is not always clear (Talberg et al. 2018).

Several authors and researchers have made recommendations on governing the research and development (R&D) of climate management technologies, which in turn can be applied to SAI. These include the Oxford Principles for climate geoengineering, that emphasize the importance of independent oversight and assessment, public participation in decision-making, governance specifically for deployment (Rayner et al. 2013; Oxford Geoengineering Programme 2018), and the Code of Conduct for responsible geoengineering research, that includes plans for research cooperation, public participation, assessment of outdoor research experiments, and post-project monitoring (Hubert 2017). Other recommendations for SAI development include the collection of more data and information on potential impacts and consequences, transparency in research activities, stakeholder involvement, and developing robust international collaboration and governance structures specifically for climate engineering (Caldeira and Keith 2010; Morgan and Ricke 2010; Parson 2014; Renn et al. 2014; Pasztor 2017; Pasztor et al. 2017; Conca 2018; Horton et al. 2018; Carnegie

Climate Engineering Governance Initiative 2018; Jinnah 2018; Nicholson et al. 2018).

Developing and deploying SAI as a climate management technology has many ecological, economic, social, ethical, legal, and international ramifications. Olson (2011) identified a top ten list of concerns, many of which have been echoed by other researchers and organizations (Robock 2008; Hamilton 2013; Hulme 2014; Parson 2014; Horton and Reynolds 2016):

1. Unintended negative consequences to the Earth's complex geophysical and ecological systems (e.g., ozone layer depletion, regional droughts, changes in precipitation patterns, extreme weather responses).
2. Potential ineffectiveness arising from a lack of information on field scale efficacy.
3. Risk of undermining mitigation efforts by redirecting research and political effort.
4. Risk of sudden catastrophic warming if SAI were discontinued as GHG concentrations continue to rise in the meantime.
5. Inequality in receiving the benefits of SAI, potentially resulting in conflicts.
6. Even greater difficulty in reaching international agreement than for mitigation.
7. Potential for weaponization given past experiences with weather modification being used for military purposes.
8. Reduced efficiency of solar energy from decreased incoming solar radiation.
9. Danger of corporate interests overriding the public interest.
10. Danger of research driving inappropriate deployment, as experienced with other technologies.

These risks could grow or shrink through changes in SAI's technology maturity, costs, and efficacy; environmental or climate conditions; and international or national social pressures. For example, potential risks could emerge if climatic tipping points (Bickel 2013) are reached or there are increased impacts of climate change on society that create greater pressures to find solutions to the climate crisis. One possibility is that a climate emergency could spur the deployment of SAI technologies prior to their full development or before their potential consequences are well understood. Similar concerns could arise if there were unilateral deployment without a consensus, by a state or by a rogue actor, leading to potential national or international tensions and conflicts (Parson 2014; Horton and Reynolds 2016). These potential risks could dissipate if research on SAI technologies found them to be more or less effective, costly, or risky than expected, or if global emissions mitigation were achieved, obviating the need for SAI. Of course, the aforementioned risks of deploying SAI have to be compared to the consequences of unmitigated climate change (Burke et al. 2018; Felgenhauer et al. 2018) coupled with the potential risks and benefits of other strategies to deal with climate change, such as other climate management technologies, mitigation, and adaptation. This presents policymakers, risk managers, and other decision-makers with a need to compare one set of risks with another, often referred to as a risk versus risk trade-off (Graham and Wiener 1995a, b; Wiener 1995).

3.2 Step 2. Develop scenarios based on narratives and models

Stratospheric aerosols present risks at multiple points in the research, development, and deployment chain, and therefore require multi-faceted scenario development. For instance, R&D may occur in either the public or private sector. Public support would require a dramatic shift in federal funding, which seems unlikely given current funding priorities and political environments for climate change-related research (Keith and Irvine 2016; Jotzo et al. 2018). Private investments are an option but could raise some ethical and governance questions over who can control technologies with potentially global impacts and whether private funders or markets could create adverse incentives (Gunderson et al. 2018). If major private investments are involved, there is greater potential for deployment of immature technologies associated with incomplete knowledge or understanding of interactions between stratospheric aerosols and environmental systems or impacts on socio-economic, legal, and international parameters.

Several researchers have hypothesized scenarios that could unfold concerning the deployment decision. Among these, Morgan and Ricke (2010) highlight cases in which: (i) the world faces a climate emergency, field and laboratory experiments indicate that SAI is a cost-effective solution, and there are manageable and known externalities to deployment, (ii) after several decades of laboratory and field studies, SAI proves to be ineffective or presents too many adverse impacts and externalities to be considered further, and (iii) no SAI research is pursued, and therefore if the situation arises, decision-makers will not have enough knowledge to make informed decisions. Olson (2011) identifies six scenarios related to the development and deployment of SAI that depend on funding priorities for energy and climate management technologies and the urgency to respond to climate change impacts. Three of the six scenarios exclude SAI, as the technology is deemed to be unnecessary or too problematic for implementation. The other three scenarios implement SAI as an insurance policy, a mechanism to avoid reaching a climate tipping point, or as a part of a broader portfolio of mitigation and climate engineering. Political environments and political are also likely to be key factors in scenarios regarding the development of SAI research and decision-making (e.g., Horton and Reynolds 2016).

Initial exploration of SAI has revealed potential risks, including reduced precipitation, increased ocean acidification, depleted stratospheric ozone, and the potential need to continue SAI indefinitely once begun by, e.g., Robock (2008), Hamilton (2013), and Hulme (2014). Subsequent author groups argued that these risks are not characteristics of SAI itself but instead of implementation scenarios that were somewhat extreme and unrealistic (Keith and MacMartin 2015; Reynolds et al. 2016). Indeed, many of the risks and regional variance of SAI's potential negative impacts could be reduced under different implementation scenarios: SAI utilized at lower amounts, on a temporary basis, or incorporating learning over time (Keith and MacMartin 2015), SAI that varies by latitude and season to optimize solar reduction with fewer aerosol particles (MacMartin et al. 2013), SAI that employs calcite rather than sulfate aerosols to reduce or even reverse stratospheric ozone depletion (Keith et al. 2016), and SAI that uses two types of aerosols that vary by latitude, altitude, and season of injection (Dai et al. 2018).

One major point of consideration is the choice of the comparative reference scenario employed when conducting an SAI risk assessment (Chhetri et al. 2018). In Step 2, the IRGC's ERG guidelines use "reference" scenarios to explore the full range of possibilities in scenario development analysis. If the reference scenario is unchecked climate change, any type of climate management technology might fare comparatively well in comparison, as supported by (Bickel 2013). If, however, the reference scenario includes strong mitigation, then the comparative advantages of SAI are reduced. Several authors conclude that different scenarios should be included in parallel as a screening exercise. Such a comparative review could also highlight the potential and political feasibility of functionally equivalent strategies to combat global climate change (Bickel and Agrawal 2013; Boettcher et al. 2016; Irvine et al. 2017).

3.3 Step 3. Generate risk management options and formulate strategy

This step proposes six options to manage the identified emerging risks. We describe these here and show how they might apply to SAI (Fig. 2).

(i) *Act on the factors that contribute to risk emergence* Additional R&D on SAI could be effective in better controlling the technology, improving its cost-effectiveness, and understanding its behavior (Morgan and Ricke 2010; Carnegie Climate Geoengineering Governance Initiative 2018). Additional research could help guide innovation towards more sustainable or "green" design principles to exhibit, e.g., decreased impacts on human or ecological systems or decreased potential exposures, especially for vulnerable populations or sensitive ecological areas. These strategies to promote the sustainable design and innovation of stratospheric particles also contribute to the development of precautionary approaches to prevent potential harms. Such strategies have been used in other

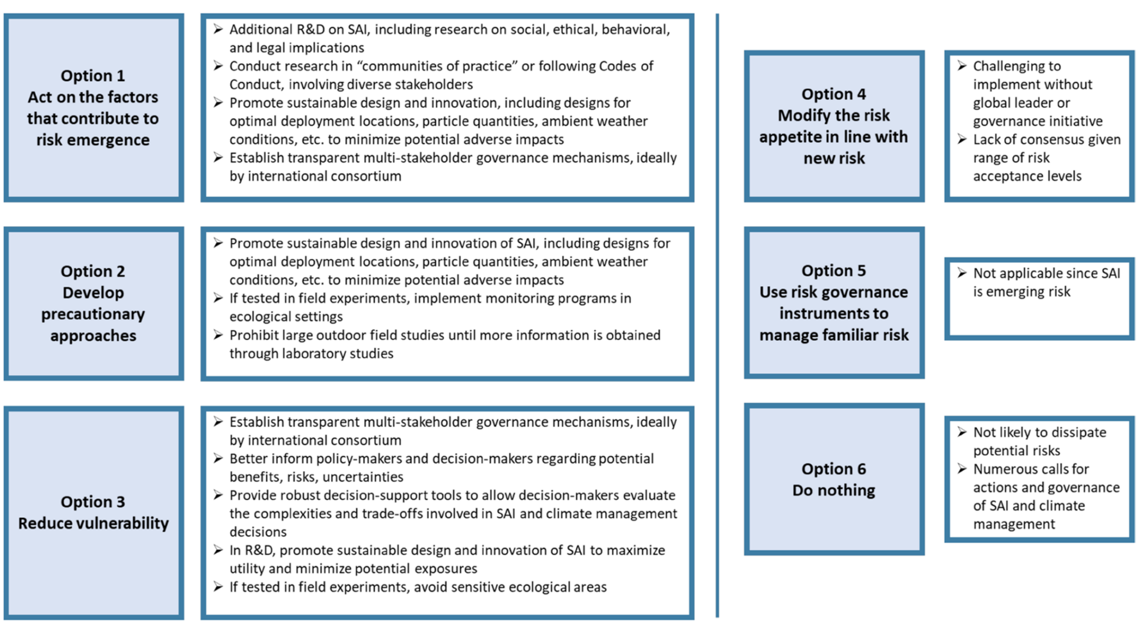

Fig. 2 Risk management options that could be applied to SAI as a climate management technology

emerging technologies (e.g., engineered nanoparticles) to minimize potential exposures and/or promote more sustainable design using e.g., different particle coatings to reduce toxicological impacts (Yu et al. 2012; Osborne et al. 2013). Sustainable innovation could also focus on designing optimal deployment locations, particle quantities, surrounding weather conditions, and other methodological details to minimize potential adverse impacts. For instance, some have suggested the use of "allowed zones" for outdoor field studies to better understand the behavior of stratospheric aerosols in more realistic environmental settings compared to laboratory studies while also confining exposures to a designated, limited area (Morgan and Ricke 2010).

In terms of social, ethical, legal, political, and international implications and risks, robust multi-stakeholder governance mechanisms are needed to address societal concerns and reduce the likelihood of international conflict over SAI (Conca 2018). Governance mechanisms—potentially led by an international consortium dedicated to SAI—should ensure transparency, accountability, trust, and communication (IRGC 2017). Social and ethical concerns should also be addressed through transparent research, potentially in "communities of practice" or following codes of conduct to guide research programs and involve diverse stakeholders in the process (Carnegie Climate Geoengineering Governance Initiative 2018). This approach could also decrease societal and ethical concerns by limiting the potential for private control over SAI research (Morgan and Ricke 2010). Dedicated research on the social, ethical, behavioral, and legal impacts of SAI would also help to better understand concerns and formulate best practices to respond to them.

(ii) *Precautionary approaches* If stratospheric aerosols are tested using field experiments, monitoring could be performed to better understand the behavior of stratospheric aerosols. Key ecological endpoints could also be monitored as part of an early warning system to identify any potential impacts. A second precautionary approach could include the prohibition of large outdoor field studies until more information is obtained through laboratory studies on efficacy and potential impacts. This approach is similar to calls for a moratorium on SAI deployment until more information is obtained or robust international governance mechanisms are in place (e.g., the UN Convention on Biological Diversity) (Parson and Keith 2013; Carnegie Climate Geoengineering Governance Initiative 2018; Oxford Geoengineering Programme 2018). At the same time, too stringent a prohibition or moratorium could also hold back the research needed to inform good governance, and thereby could risk hasty deployment of SAI in a crisis, without full understanding of the risks. This dilemma highlights the need for research and governance to inform good decisions without leading to premature deployment and adverse impacts (McKinnon 2018).

(iii) *Reduce vulnerability* To reduce social, ethical, legal, political, and international vulnerabilities of SAI, a robust governance mechanism would need to be established, led by an international consortium to manage, control, and communicate with diverse stakeholder groups issues of innovation and potential deployment of SAI. Such governance would need to be transparent, involve numerous opportunities for feedback from multiple stakeholder groups, and include a plan for decision-making. It should include not only representatives of governments but also economic and social stakeholders, environmental NGOs, potentially affected populations, and other concerned groups. Other authors have provided recommendations on conducting multi-stakeholder dialogs in the case of climate engineering to strengthen social learning, promote governance norms, and arrange political space for governance by states (Conca 2018). Recommendations for exploring the underlying governance structures and geopolitical implications have also been made (Gupta and Möller 2018). Clearly, to implement a form of inclusive governance on the global level is not an easy task, but recent attempts to address global policy issues and their constraints support the idea of global participatory processes that are operational and functional (e.g., United Nations Framework Convention on Climate Change Conference of the Parties (UNFCCC COP) meetings) (Gunderson 2018).

Another option to reduce vulnerabilities is to better inform policy-makers and other decision-makers regarding the potential benefits, risks, and uncertainties related to SAI (along with climate change impacts) coupled with a set of decision-making tools. While making decisions on the development and deployment of stratospheric aerosols, policymakers and decision makers could benefit from having tools that allow them to evaluate the complexities and trade-offs involved in SAI decisions. Such tools should include large amounts of data and a wide literature scope. The use of multi-criteria decision analysis (MCDA) could be one approach to help visualize and compare trade-offs between options that involve multiple criteria (Bellamy et al. 2013; Linkov et al. 2018).

(iv) *Modify the risk appetite in line with the new risk* Different organizations and institutes may have varying "risk appetites" or tolerances of risk. Risk appetite is defined as the "amount and type of risk an organization is willing to take on risky activities in pursuit of values or interests" (Society for Risk Analysis 2018). It has been argued that an organization can deal with emerging risks by modifying their risk appetites, such as increasing tolerance for the risk and/or revising strategies to deal with a potential risk if it arises (IRGC 2015). While such an approach could work well for other emerging risks, it is expected that this may be particularly challenging to implement in the case of SAI given the complexities, uncertainties, and lack of a global leader or governance initiative to control research, innovation, and deployment. It is also known that there are vastly different risk attitudes regarding climate change, environmental issues, and climate management technologies (Cummings et al. 2017). These perceptions and worldviews, along with issues of trust in government and industry, are likely to play strong roles in the risk appetite for SAI (Siegrist et al. 2005; Belanche et al. 2012; Renn et al. 2014; Cummings et al. 2017).

To alter risk appetites concerning SAI, multiple engagements would need to occur that focus on the degrees of risk that a diverse set of stakeholders would be willing to accept to confront climate change impacts. Obtaining such a consensus would be challenging, given the range of risk appetites across different individuals and groups. Concerns over equity could also be raised given a likely unequal distribution of SAI costs and benefits between powerful and less powerful international actors. It is much easier for an individual or group to engage in risk-prone behavior if others will most likely experience the negative consequences (Preston 2013).

It is interesting to reflect on the apparently similar risk appetites of both proponents and opponents of SAI. Proponents advocate for a cost-effective approach to combat some of the worst effects of climate change, while some opponents are concerned over potential impacts (and unforeseen consequences) of SAI itself as well as issues of trust in control and management (ETC Group 2011; Hamilton 2013). Essentially, both groups are advocating for a more precautionary future, and the question is whether the use of SAI can contribute to that vision. Similar tensions have been seen in the use of other emerging environmental technologies, such as the use of engineered nanoparticles to clean up contaminated soils and groundwater (e.g., (Grieger et al. 2010) or the use of biological organisms to combat invasive species (Access Science Editors 2017). In these areas a technological solution could pose risks of its own in an attempt to improve environmental quality.

(v) *Use "conventional" risk governance instruments to manage familiar risks* Given the early stage of SAI research and the long list of uncertainties and data gaps, using more familiar risk management options would be applicable in the future and not in the near-term. In contrast to emerging risks, familiar risks generally have lower levels of associated uncertainty and risk managers/decision-makers often have prior experience managing these risks (e.g., risk of developing foodborne illness after consuming contaminated or spoiled food; physical risks arising from high-impact sports). In these cases, there is in fact a wide range of risk management, prevention, and governance approaches for identifying, mitigating, managing, and communicating risks to different target audiences. For SAI to transition to a familiar risk category, substantial research and investments would be needed to understand the technology and its impacts.

(vi) *Doing nothing* Not implementing any risk management strategy(ies) is a final option. There could be various reasons for a do-nothing approach, such as cost limitations, an inability to form consensus and/or make decisions, and hoping for better and less risk-prone solutions in the future. In economic terms, deferring policy would be warranted if the costs of acting early would be greater than the costs of waiting to respond later. However, even if more knowledge over time might reduce the costs and risks of SAI measures, this might still imply acting now to gain more knowledge by intensifying research and engaging in experimental trials within controllable conditions. Another argument for doing nothing would be to let natural processes occur rather than to further intervene. A do-nothing approach is often considered within environmental remediation practices when natural degradation processes could be the "best" option that a risk manager takes after factoring in other technologies, their effectiveness, costs, and potential side-impacts (Grieger et al. 2010). Even if a do-nothing approach is implemented, environmental monitoring can still take place to capture potential impacts or measure the state of the environment over time.

After all the risk management options are identified in Step 3, the risk manager should select the best option(s) to implement, preferably using a decision support process or framework that is robust and transparent. The selection of the risk management options should align with the organization's priorities and prior strategies for dealing with risk. Among other decision support approaches, the use of MCDA could be used by risk managers to identify the best risk management strategies using a combination of decision criteria (e.g., cost, feasibility, effectiveness, risk–risk tradeoffs, fairness, public acceptance, ability to govern, etc.) and judgement and values, using a flexible and easily adaptive framework (Bellamy et al. 2013; Bates et al. 2016; Linkov et al. 2018). After the risk management options are selected, these should be communicated back to stakeholders with the rationale for the decisions and to highlight areas of uncertainty.

3.4 Steps 4–5. Implement strategy and review risk development and decisions

Step 4 of the IRGC's ERG guidelines is to implement the selected risk management strategy. For this to occur, risk managers and affiliated organization(s) need to create the conditions for effective implementation and ideally help support an appropriate culture to handle the emerging risk(s). Risk managers need to identify and secure appropriate resources for implementation, define roles and responsibilities, and communicate with internal and external stakeholders regarding the objectives and rationales for the selected options. Furthermore, a risk communication, and even more importantly a risk involvement, strategy must be designed to assure public support and institutional backing. Communication and stakeholder involvement throughout the implementation process are important to respond to new or different information or monitor the impacts of the risk management options.

Step 5 monitors the emerging risk(s) after the management options are implemented, reviews associated decisions, and updates the governance strategy as necessary. Similar to the previous step, information exchange and communication are essential to understand the state of the emerging risk in terms of its growth or dissipation. If, for example, the implemented risk management options are not effective, the risk manager(s) may choose to re-evaluate the emerging risk context and initiate the ERG guidelines from Step 1 or re-evaluate the options selected in Step 3 and implement new or alternative options for further evaluation.

To apply Steps 4 and 5 as envisioned by the IRGC, some organization or regulatory body (or bodies) tasked with the oversight of SAI would be needed to implement the selected risk management options and review their implementation. To follow the IRGC's ERG guidelines throughout the process, successful execution of the five steps will be strongly dependent on a "risk conductor" to coordinate and communicate essential information to diverse stakeholders. A coordinator is clearly a necessary component of any robust risk governance process, although we recognize that this role may be particularly challenging in cases of international consortia that rely on input from diverse stakeholders. In these cases, adequate resources will be needed for the risk conductor to carry out the IRGC ERG guidelines and clear stakeholder incentives will be needed to ensure cooperation and communication throughout the steps.

4 Discussion and conclusion

This Perspective examines the applicability of the IRGC's ERG guidelines for SAI as a climate management technology, in light of the IRGC's experience in governance of other complex and emerging technologies. We reviewed the state of the science and governance initiatives related to SAI, corresponding to each of the five steps in the ERG guidelines, although we recognize that the use of SAI would likely fit within a broader portfolio of other climate change management options that includes emissions reduction, CO_2 removal, and adaptation. Through this analysis we find that the IRGC's ERG guidelines would add value to management of the complex, uncertain, and ambiguous emerging risks presented by the development and use of SAI. The five steps outline a clear process for the identification of emerging risks and their subsequent handling and monitoring. To apply the IRGC's ERG guidelines as envisioned by the IRGC, an organization or regulatory body (or bodies) tasked with the oversight of SAI would be needed.

Step 1 reveals that most research is in its early stages, with an emphasis on technology development and efficacy, with very few outdoor experiments conducted or planned for the near future. Similarly, the current state of governance is such that there is no directly-applicable international or national regulation on SAI, although several treaties may potentially apply. It might be beneficial to conduct framing workshops on a global scale that specify under which legal and political conditions SAI measures could be launched and administrated. The risks used in such framing workshops could emerge or evolve through different scenarios—highlighted in Step 2—that are influenced by research and funding priorities, environmental and/or climate conditions, political factors, a growing sense of urgency to respond to climate change impacts, and unilateral deployment.

In Step 3, we highlight the options for emerging risk management that may be particularly applicable to the R&D phase of SAI, given the early state of science and governance. These include: investing in additional R&D; conducting research in "communities of practice" or following codes of conduct; promoting sustainable design and innovation; establishing transparent multi-stakeholder governance mechanisms; implementing monitoring programs; prohibiting large outdoor field studies until more information is known (via other studies); limiting or controlling exposures; better informing policy-makers and decision-makers; and providing robust decision-support tools to evaluate complexities and trade-offs in SAI decisions. Other strategies for robust decision-making include MCDA-based risk governance approaches for emerging technologies in which diverse alternatives are evaluated against defined decision-criteria to identify the best alternative(s) (Linkov et al. 2018).

Steps 4 and 5 implement the selected risk management options and monitor their performance. Based on findings, the risk governance process would be reviewed and revised as necessary. Managing and governing SAI technology should involve a dedicated, organization or regulatory body and a strategic governance initiative with international cooperation (Stavis et al. 2014; Jinnah 2018). The IRGC's ERG guidelines could provide one approach to carrying out such a governance initiative in a way that provides support for stakeholder engagement and communication. For the implementation phase, the consortium or body would be tasked with oversight of the governance process to develop the most acceptable strategies for dealing with climate change challenges, including stratospheric aerosols and climate change management more broadly. In this work, we found it somewhat surprising that, despite decades of research and international discussions on climate change and geoengineering technology, there is not yet a clearly defined organization or consortia that would be tasked with SAI governance and oversight. Nonetheless, this Perspective describes the steps, based on the IRGC's ERG guidelines, which such a body would need to undertake.

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Compliance with ethical standards

Conflict of interest Two of the authors of this Perspective are active members of the IRGC (Ortwin Renn and Jonathan Wiener associated with the IRGC Council Foundation), although their views should not be construed as representing the organization.

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