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Integrating Risk Perception with Climate Models to Understand the Potential Deployment of Solar Radiation Modification to Mitigate Climate Change

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About the Project

The Resources for the Future Solar Geoengineering research project applies tools from multiple social science research disciplines to better understand the risks, potential benefits, and societal implications of solar geoengineering as a possible approach to help reduce climate risk alongside aggressive and necessary mitigation and adaptation efforts. The project began in 2020 with a series of expert workshops convened under the SRM Trans-Atlantic Dialogue. These meetings resulted in a 2021 article in *Science* that lays out a set of key social science research questions associated with solar geoengineering research and potential deployment. The Project followed this with additional sponsored research, including a competitive solicitation designed to address research areas highlighted in the *Science* article. This paper is one of eight research papers resulting from that competition and supported by two author workshops. A key goal of the solicitation and the overall project is to engage with a broader set of researchers from around the globe, a growing number of interested stakeholders, and the public.

Sharing Our Work

Abstract

We develop a conceptual model that describes the transitions in the operationalization of solar radiation modification (SRM) as a climate intervention to reduce impacts from anthropogenic greenhouse gas forcing of the climate system. We distinguish predevelopment, postdevelopment, and postdeployment phases of SRM operationalization. We explore the interactions between the human system and climate system that drive transitions between these stages in the emergence of SRM as a climate intervention. We discuss the insights around SRM development and deployment that emerge from this conceptual model.

Contents

1. Introduction

Anthropogenic emissions of greenhouse gases (GHGs) continue to increase, driving concerns that emissions reductions may be too incremental and too far in the future to avoid dangerous climate change. Abatement requires a complex, expensive, and difficult energy transition to decarbonize the economy and reduce emissions to zero. Even if zero emissions are achieved, we may continue to experience climate impacts for decades because of the long residence time of carbon in the atmosphere and the large inertia in the climate system. Together, this means that some form of intervention may be considered to avoid dangerous climate change, likely as part of a multipronged solution that also includes abating anthropogenic emissions (Allen et al. 2018).

Solar radiation modification (SRM) is one form of climate intervention that cools the Earth by artificially reducing incoming solar radiation. Sulfate aerosol injection, for example, is a form of SRM that would insert sulfate aerosols into the stratosphere to reflect sunlight back into space, mimicking the natural effect of some volcanic eruptions. SRM has the potential to rapidly offset increasing global temperatures caused by anthropogenic GHG emissions at a modest cost relative to abatement (the direct reduction of anthropogenic emissions of GHGs) (Smith and Wagner 2018). But SRM is likely to induce other climatic impacts even while offsetting mean changes in global temperature. For example, spatial patterns of radiative forcing produced by SRM are unlikely to match that from increasing GHGs (Govindasamy and Caldeira 2000; Visioni et al. 2021). In addition, SRM will likely introduce other climate changes, such as affecting precipitation patterns (Irvine et al. 2019) and extreme events (Tye et al. 2022), modifying regional weather patterns (Haywood et al. 2013), and producing changes in stratospheric composition (Tilmes et al. 2022). SRM also cannot mitigate other effects of climate change, such as ocean acidification. Thus, SRM will mitigate aspects of climate change but may exacerbate others, with benefits and impacts that will be regionally variable and uncertain.

SRM is not currently an option for addressing climate change because of technical and governance challenges that remain unaddressed (Smith and Wagner 2018; Kravitz and MacMartin 2020). Implementing SRM requires that many different people, including policymakers, scientists, and the general public from disparate regions of the globe, come together to decide whether to develop, deploy, and continue deploying it (Raimi et al. 2020). Thus, models of SRM development and deployment must factor in these public perceptions to accurately simulate the decisions society might make about SRM going forward. These decisions may stem from weighing the perceived risks of SRM intervention against those of climate change (Visschers et al. 2017).

2. Perceptions of SRM

Research on public perception of climate interventions in general, and SRM in particular, finds that most laypeople have never heard of these technologies (Merk et al. 2015; Asayama et al. 2017; Cummings et al. 2017; Raimi 2021). For the roughly 20 percent of respondents who have heard of SRM or learn about it in the course of research studies, initial reactions are often wariness (Pidgeon et al. 2012; Wright et al. 2014; Braun et al. 2017; Klaus et al. 2020; Carlisle et al. 2020; Jobin and Siegrist 2020). Public acceptance of SRM is usually much lower than for other climate intervention strategies. For example, in a study of German respondents, only 26 percent supported SRM, compared to 87 and 51 percent who supported afforestation efforts or carbon capture and sequestration, respectively (Braun et al. 2017). Similarly, a study of US, Australian, UK, and New Zealand respondents found that only 24 percent supported small-scale sulfate aerosol injection trials, compared to 41–45 percent who supported similar trials of carbon removal technologies (Carlisle et al. 2020).

While most investigations of public perceptions of SRM have been conducted in wealthy, industrialized nations (Biermann and Möller 2019), there has been some work on perceptions of SRM among other communities that are particularly vulnerable to the effects of climate change, including Kenyans, Alaska Natives, and Solomon Islanders (Carr and Yung 2018). These initial studies suggest that people in these communities are also wary of SRM but even more concerned about the consequences that they face from climate change. Another study found that college students in the Global South supported SRM more than did those in the Global North, perhaps reflecting the finding that they were also more likely to anticipate large impacts of climate change for their countries (Sugiyama et al. 2020). Thus, fears of climate change may outweigh resistance to SRM, for both these communities and elsewhere. As the consequences of climate change become more dire, resistance to SRM might diminish if it is seen as the lesser of two evils.

In addition to regional differences, public perceptions of SRM are highly susceptible to how these technologies are framed (Raimi 2021). Given the lack of knowledge about climate interventions, people have very little to draw on when making judgments about SRM. Initial research indicates that resistance to SRM is frequently linked to concerns that it is not “natural” and tampers with the natural world (Corner et al. 2013; Mercer et al. 2011; Merk et al. 2015; Merk and Pönitzsch 2017; Visschers et al. 2017). While some people are more averse to tampering with nature (Raimi 2020), in general, the public tends to prefer climate intervention options, such as afforestation, that it believes interfere less with nature (Jobin and Siegrist 2020). Thus it is perhaps not surprising that people’s reactions to information about SRM change significantly depending on whether it is framed as a natural approach (Corner and Pidgeon 2015; Asayama et al. 2017; Bellamy and Lezaun 2017; Raimi et al. 2019; Bolsen et al. 2022).

An additional factor that is frequently linked to public resistance to SRM is a lack of trust. Trust in scientists (Merk et al. 2015), firms (Merk et al. 2015), governments (Merk and Pönitzsch 2017), or "decision-makers" more broadly (Klaus et al. 2020) each lead to greater support of SRM. People may have individual-level differences in the degree to which they tend to trust authorities and SRM technologies but also respond to new information about SRM. Thus, as news coverage of SRM development successes (or dangers) grows, so too would the public's trust (or distrust) in it as an approach to combating climate change.

Moral Hazard. Some other SRM resistance comes less from concerns about the technology itself but rather from moral hazard effects. "Moral hazard" refers to the concern that the availability of SRM and its ability to rapidly reduce some negative impacts of climate change will decrease global urgency to lower GHG emissions (Hale 2012; Raimi 2021). Scientists and other academics have presented this concern (e.g., National Research Council 2015; Hale 2012), as have members of the public when they participate in research about SRM (e.g., Corner and Pidgeon 2014; Weibeck et al. 2015; Visschers et al. 2017). However, most current research finds little evidence for this particular moral hazard. When examining public opinion, some research finds that learning more about SRM does not alter willingness to reduce emissions (Austin and Converse 2021; Fairbrother 2016) and in other cases increases willingness to purchase carbon offsets (Merk et al. 2016) or support a carbon tax (Cherry et al. 2021). Other research finds that moral hazard effects can emerge but primarily when technologies are oversold as a silver bullet solution to climate change (Raimi et al. 2019). Research focused on climate experts find that those with more expertise in SRM do not differ in their climate mitigation policy preferences from those with less expertise (Merk et al. 2019). Research using a climate disaster economic role-playing game found that "citizens" did not alter how much they contributed to mitigation efforts when the "policymaker" implemented a climate intervention (Andrews et al. 2022). However, the "policymaker" believed that citizens would respond by reducing mitigation and therefore frequently did not implement a climate intervention even though it would have benefited all. This indicates that concern about moral hazards may play a greater role in decisionmaking than the actual moral hazard itself.

Evolving Perceptions. A large caveat is that all research on public perceptions of SRM has been conducted prior to its development and implementation. Any insights into public perceptions of SRM in the current context are limited to the predevelopment stage of SRM since no respondents have yet experienced the effects of SRM nor is SRM currently deployable. At this stage, people's perceptions are driven by broad psychological concepts of naturalness, trust, and moral hazard.

Yet overall acceptance and individual drivers of perceived benefits and risks are likely to change after development of SRM. Once investments and political negotiations begin, SRM will be a more realistic policy option. At this stage, people can observe if their moral hazard concerns came to fruition. If the rate of GHG emissions begins accelerating, then support for SRM may be reduced because it appears to be reducing the urgency to decrease GHG emissions. But if the rate of GHG emissions decline, then support for SRM may increase. Alternatively, increasing GHG emissions or increasing negative impacts of climate change could make SRM more urgent, and a downward trajectory in emissions or climate impacts might make SRM seem less necessary.

Perceptions of risk from and support of SRM will evolve once it is actually deployed. If SRM is deployed, people will experience its effects, both positive and negative. For example, concrete, community-level issues, such as the changes in temperature or weather patterns and their positive or negative effects on local crops, may become much more prominent in public discourse. Trust in the technology may shift due to these perceived effects or media coverage of its potential effects. Additionally, extreme weather events that previously would have been attributed to climate change now may be attributed to either climate change or SRM itself, and the accuracy of any specific attribution may be unclear. Similarly, the malleability of how SRM is perceived is likely to decrease as this topic becomes more discussed, supporting and opposing factions are created, and people begin to interpret the observed effects of SRM for themselves.

3. Conceptual Model

We synthesize these results into a conceptual model that describes the stages and transitions that lead to the operationalization of SRM. In our conceptual framework, transitions through stages in development and deployment center on perceived risk from both SRM and anthropogenic GHG forcing of climate. We distinguish three phases: predevelopment, postdevelopment, and postdeployment. We next define each of these phases, describe how we expect the drivers of perceived risk to vary, and explore the social and behavioral processes that govern transitions between phases.

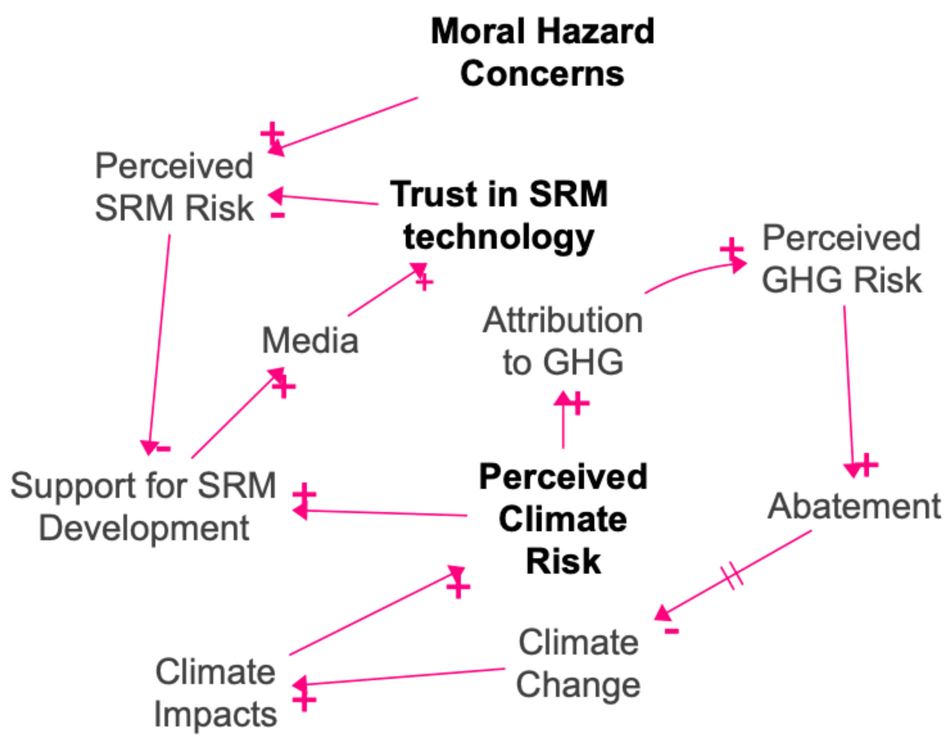
Predevelopment: SRM exists as an idea and is theorized about in the abstract but not available. While the technology is not yet developed, potential support for SRM may grow due to the increasingly severe impacts of climate change that increase urgency to address it, leading to policymaker agreement and societal support for SRM development. If sufficient societal support emerges, resources will be invested in developing SRM capabilities, and we move into the next phase.

Predeployment: Significant financial investments have been made into research and design of SRM technologies, preliminary testing, and negotiations among policymakers across nations regarding how it will be deployed. The operational deployment of SRM is an option, but SRM has not yet been operationally deployed.

Postdeployment: SRM is being used to engineer climate, but questions still remain about how much to deploy. New governance questions arise as the effects of SRM are felt, in both the regional reduction in temperatures and other potential side effects. However, it will often be unclear if given extreme weather events are due to SRM itself or to climate change from prior GHG emission, and so these effects may be correctly or incorrectly attributed to SRM.

Distinguishing these phases is important because the social and behavioral processes governing public risk perceptions of SRM technology will likely change during each phase. In the **predevelopment** phase, support for development is driven by the perceived risk of climate change and of SRM (Figure 1). Perceived climate risk increases with climate impacts that include economic damage, as these impacts are frequently attributed to anthropogenic GHG emissions. This leads to support for abatement of GHG emissions, but emissions reductions affects climate with a significant lag, reflecting long residence times of atmospheric CO_2 and the large inertia in the climate system. Increasing perceived climate risk also implies urgency to address climate change, leading to support for SRM development and deployment. However, the operationalization of the technology also depends on the perceived risk: perceptions of high risk can limit the rate of or completely block development.

Figure 1. Predevelopment Stage



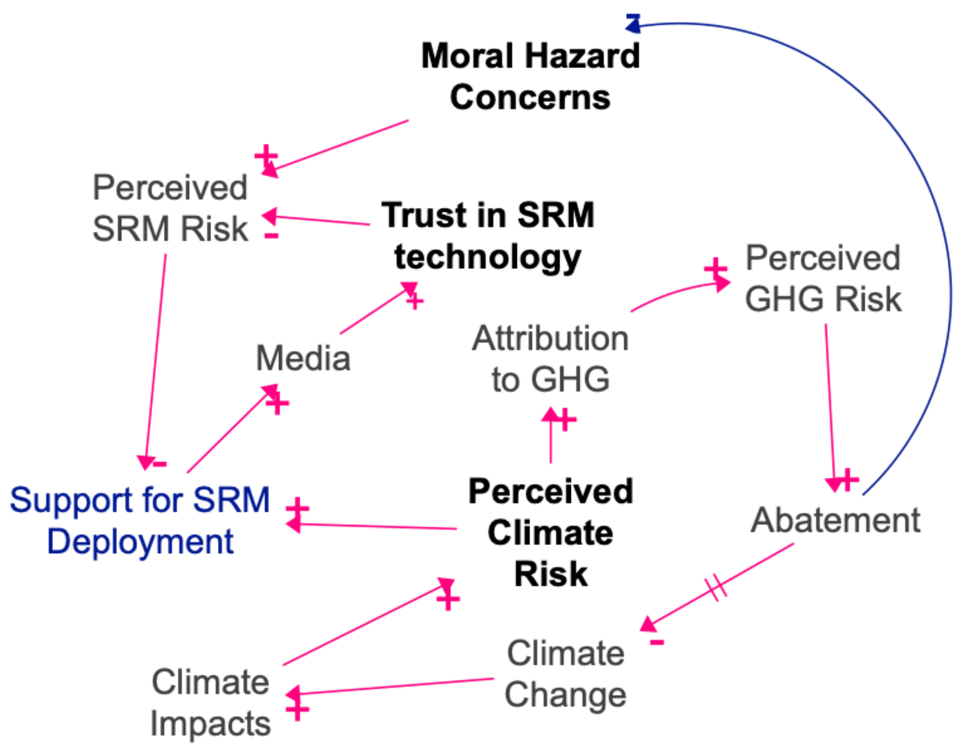
Notes: This figure represents the social and behavioral processes governing the development of the technological and governance structures for SRM. The double lines in the connection from Abatement to Climate Change represent a time delay.

In the predevelopment phase, the perceived risk of SRM is dependent on both the concerns around moral hazard and trust in technologies. Moral hazard concern will be manifested by policymakers' reluctance about potential reduction of the incentive to abate GHG emissions, thereby addressing the root cause of anthropogenic climate change. In the predevelopment model, this concern will be purely hypothetical and not reflect actual changes in GHG abatement.

Members of the public differ in their individual levels of trust with technologies in general and climate interventions in particular, so in the predevelopment phase, the trust in technology will reflect a distribution across regions and demographic groups (Raimi et al. 2020). Trust will also be affected by media reporting on discussions of SRM, although in our model, the media acts as a feedback amplifying support (or opposition). As support increases, media coverage will increase, heightening the salience of SRM in public consciousness. As this salience increases, this will magnify the effects of people's underlying trust or distrust (Wolske et al. 2019).

Perceived risk of SRM will in turn serve to reduce support for SRM development but will be balanced by the perceived risk of climate change and urgency to mitigate climate impacts in light of the long time horizons for GHG abatement to lead to noticeable mitigation of climate impacts. The urgency for rapid measures to mitigate climate change may drive the development of SRM as a deployable option.

Figure 2. The Predeployment Phase



Notes: SRM has been developed but not deployed. There is feedback from Abatement to Moral Hazard Concerns and support is now for SRM deployment rather than development. Changes from Figure 1 are shown in blue.

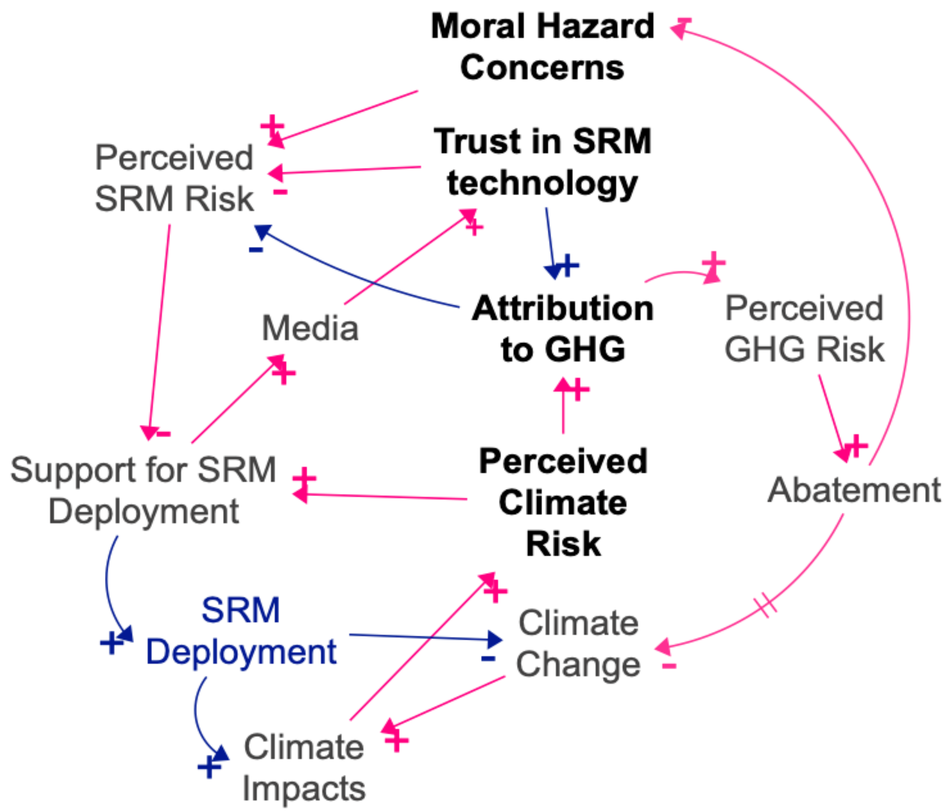
In the **predeployment** phase, the key drivers remain the same as in the predevelopment stage. However, at this stage, actual GHG abatement behavior will affect moral hazard concern (Figure 2), as the development of SRM technologies could draw from financial resources or political will that would otherwise drive abatement.

To the extent that abatement does not diminish (or grows), concerns about moral hazard may decrease, but if abatement diminishes or fails to increase, then moral hazard concerns may grow. Of course, individuals may perceive differently what the level of abatement and thus of moral hazard would have been without deployable SRM. In our representation, increased abatement reduces the perceived risk of SRM by reducing moral hazard.

As in the predeployment stage, perceived risk of SRM will mediate support for deployment (Figure 2). Increasing impacts and intensity of climate change that threaten the functioning of society will lead to growing perceived risk of climate change. For example, drought and heatwaves can lead to agricultural impacts that threaten food security, leading to perceived urgency for rapid actions to address climate change, potentially increasing support for SRM deployment.

In the **postdeployment** phase (Figure 3), SRM is deployed to reduce global temperature but is likely to affect other aspects of climate, such as precipitation, diurnal temperature cycles, and cloud physics, leading to both desired and undesired effects on climate. SRM will thus lead to a reduction in climate impacts through decreased global temperature but also concomitant increase in impacts through unintended “add-on” climate impacts. The overall magnitude of climate impacts and change in perceived climate risk from SRM deployment will thus depend on the relative changes in temperature driven reductions and the add-on increases in climate impacts. Furthermore, the relative strength of these two contrasting effects is likely to change with both the magnitude of SRM deployed and the strength of GHG forcing.

Figure 3. Postdeployment Phase



Notes: SRM has been deployed and influences the climate system. This figure represents how social and behavioral processes integrate the existence of SRM and its consequences into technological and governance structures. Changes from Figure 2 are shown in blue.

Additionally, in this stage, climate impacts may now be attributed to either anthropogenic GHG or SRM. Therefore, the frequency and magnitude of climate impacts affect perceived SRM and GHG risks. Attribution of impacts to SRM is determined by trust in the technology and reduces support for continued SRM, and attribution of climate impacts to GHG forcing will increase support for continued SRM.

The net effect of deployment will depend on its magnitude and details. Its effect on climate and a range of climate impacts is thus uncertain. The net change in climate impacts from SRM will include some combination of a reduction in impacts from reducing the global temperature and a likely increase in other impacts concomitant with achieving this temperature reduction through SRM versus reductions in atmospheric concentration of GHGs. The global distribution of the positive and negative impacts and regional attribution thereof will vary. Trust in SRM technology varies regionally, for example, with evidence emerging suggesting that regions of the Global South may be more supportive of SRM than the Global North (Carr and Yung 2018; Sugiyama et al. 2020). But, in general, the combination of total climate impacts and their attribution is key for determining support for SRM postdeployment.

4. Model Insights

Our conceptual model leads to some insights into the mechanisms likely to be important in determining transitions in SRM development and deployment:

- Growing frequency and severity of impacts from climate change may increase the perception of risk and the urgency to address climate change. For example, the perception of risk will increase rapidly as concerns around climate change move from abstractions around 1.5°C or 2°C of warming by the end of the century to threats against current food security. This perception of risk and urgency will push up against the inertia and time lags inherent in transforming societal infrastructure to reduce GHG emissions and the slow response of the climate system to reductions in anthropogenic GHG emissions. High levels of perceived climate risk may then be rechanneled to support SRM development and deployment. Thus, the rate of climate change and the severity and salience of impacts will mediate the pressure for both abatement of GHG emissions and the development and deployment of climate intervention technologies.
- Rising levels of abatement could facilitate SRM development and deployment through reductions in concerns that SRM will act as a moral hazard. Concern that existence or deployment could reduce incentives to pursue abatement would likely erode if abatement continues even as SRM technologies emerge or are deployed.
- Development and deployment are centered around trust in SRM technology. This trust encapsulates implicit beliefs around the naturalness of SRM techniques and beliefs about the relative strength of direct reductions in climate impacts from SRM-driven reductions in global temperature versus SRM-driven increases in (and sign of) add-on climate impacts. A better understanding of beliefs around these contrasting impacts may be key to understanding movement or stasis on developing and deploying SRM.
- Postdeployment, the attribution of climate impacts to either GHG forcing or the add-on impacts of SRM will emerge as a critical feature of the level of and continuation of deployment. The attribution of climate impacts will mediate the perception of risk from SRM and GHG-driven climate change and determine support for the continuation and magnitude of SRM. In our conceptual model, attribution is determined by trust in SRM technology, which is in turn driven by the media. But, in reality, this trust integrates trust in government, policymakers, businesses, and others, which are a function of demographics, existing belief systems, culture, etc.
- The failure to develop SRM at present reflects the belief that the a) impacts of anthropogenic climate are occurring at a rate that is sufficiently slow to allow for both societal transformation toward GHG abatement and delays in the response of the climate system and/or b) add-on impacts of SRM outweigh the direct benefits of temperature reductions. This lack of trust in

SRM technology can emerge from beliefs around interference in the natural world, a lack of trust in governing policymakers, or a host of other factors.

- The knowledge around climate intervention may also be low, indicative of low awareness of these technologies among the general public. This means that initial narratives around SRM, either positive or negative, could quickly gain traction and determine the prevailing social norm around this technology.

Our conceptual model provides a framework to better understand how the potential pathways for the development and deployment of SRM may emerge from perceptions of risk from SRM and anthropogenic climate change. We are working on a computational model that captures these relationships to better understand and quantify the implications of these relationships between climate and human behavior in the context of SRM.

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