Integrating risk perception with climate models to understand the potential deployment of solar radiation modification to mitigate climate change.

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Abstract

Introduction

Avoiding dangerous climate change is increasingly likely to involve some form of geoengineering or climate intervention in addition to the reduction of anthropogenic emissions of greenhouse gases (GHGs) (Allen et al. 2018). Solar radiation modification (SRM) is one form of climate intervention, involving the artificial reduction of incoming solar radiation, for example, through sulfate aerosol injection (SAI) into the stratosphere. SRM has the potential to rapidly offset increasing global temperature caused by rising GHGs at a relatively modest financial cost. Mitigation, in contrast, requires a complex and expensive economic transition with reduction in climate impacts likely not seen for decades or longer. However, SRM will imperfectly mitigate regional temperature changes even when offsetting global temperature increases because the radiative forcing produced by SRM is unlikely to perfectly match that from the increasing CO_2 (Govindasamy and Caldeira 2000, Visioni et al. 2021). In addition, SRM will not mitigate other effects of climate change such as ocean acidification and will introduce other changes to climate, for example, reducing precipitation (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). In summary, SRM will mitigate aspects of climate change but is likely to exacerbate others, with variable and uncertain benefits and impacts.

There are technical challenges that must be addressed before the implementation of SRM is an option to address climate change (Smith and Wagner 2018, Kravitz and MacMartin 2020). Beyond these technical challenges, there are also social and political uncertainties in the willingness to develop and deploy SRM. Implementing SRM requires that many different people, including policymakers, scientists and the public (i.e., the selectorate), come together to decide whether to develop, deploy, and then to continue deploying SRM over time (Raimi 2021). This decision may stem from weighing the perceived risks of using SRM intervention against the perceived risks from climate change (Visschers et al. 2017). Policy makers may even defer from developing the capacity to deploy SRM capacity over concerns that the existence of SRM as an option will reduce the impetus to directly address the cause of anthropogenic climate change through greenhouse gas (GHG) abatement--this concern is sometimes referred to as “moral hazard” (Hale 2012, Raimi 2021). Additionally, SRM risk perceptions also vary based on a range of individual factors, including preference for naturalness and concerns that SRM seems unnatural (Visschers et al. 2017, Raimi et al. 2020) and trust in the scientists, firms, or governments (i.e., the elite) that will be deploying SRM (Merk et al. 2015, Merk and Pönitzsch 2017, Jobin and Siegrist 2020). When examining different nations, it is also likely that differences emerge since those that are at greatest risk from climate change are also often at high risk from SRM (Carr and Yung 2018, Biermann and Möller 2019). If SRM is deployed, then the considerations around the continuation and magnitude of SRM will involve similar calculations of risk except that climate impacts might now be attributed to either SRM or to climate change, correctly or incorrectly. Attribution of these events will also depend on social factors such as preference for naturalness and trust in the elite.

We first review risk perception with respect to SRM, present a conceptual framework for understanding how the development and deployment of SRM may be driven by perceived risk, and then translate our conceptual framework into a computational model. We analyze our computational model to better understand the potential pathways for how the development and deployment of SRM may emerge from perceptions of risk from SRM and anthropogenic climate change.

Perceived risk of SRM

Research on public perception of geoengineering 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% of respondents who have heard of SRM or who learn about it in the course of research studies, initial reactions are often wary (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 that of other climate engineering approaches. For example, in a study of German respondents, only 26% agreed that we should use SRM to counteract climate change, compared to 87% who supported afforestation efforts and 51% who supported carbon capture and sequestration (Braun et al. 2017). Similarly, a study of US, Australian, UK, and New Zealand respondents found that only 24% supported small-scale SAI trials, compared to 41-45% who supported similar trials of carbon removal technologies (Carlisle et al. 2020).

While most investigation of public perceptions of SRM has been conducted in wealthy, industrialized nations, there has been some work on perceptions of SRM among other communities that are 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, both for these communities and elsewhere. As the consequences of climate change become more dire around the globe, it is plausible that resistance to SRM might diminish if it is similarly seen as the lesser of two evils.

In addition to regional differences, public perceptions of SRM are currently highly susceptible to how these technologies are framed (Raimi 2021). Given the lack of existing knowledge about geoengineering, people have very little to draw on when making judgements about it. Thus it is perhaps not surprising that people's reactions to information about SRM change significantly depending on how that information is presented (Corner and Pidgeon 2015, Asayama et al. 2017, Bellamy and Lezaun 2017, Raimi et al. 2019, Bolsen et al. 2022).

Given the lack of support for SRM, scholars have tried to investigate the drivers of this resistance. Initial research indicates that resistance to SRM is frequently linked to concerns that the intervention is not "natural" and tampers with the natural world (Corner et al., 2013; Mercer et al., 2011; Merk et al., 2015; Merk & Pönitzsch, 2017; Visschers et al., 2017). While some people are more averse to tampering with nature than others (Raimi, 2020), in general, the public tends to prefer geoengineering options such as afforestation that they believe interfere less with nature than SRM (Jobin & Siegrist, 2020). An additional factor that is frequently linked to public resistance to SRM is lack of trust. Trust in scientists (Merk et al., 2015), firms (Merk et al., 2015), governments (Merk & Pönitzsch, 2017), or "decision-makers" more broadly (Klaus et al., 2020) each lead to greater support of SRM.

Some other SRM resistance comes less from concerns about the technology itself, but that availability of SRM and its ability to rapidly reduce some negative impacts of climate change will in turn reduce global urgency to mitigate GHG emissions (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 & 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 & Converse, 2021; Fairbrother, 2016), and in other cases increases their willingness to purchase carbon offsets (Merk et al., 2016) or their support for a carbon tax (Cherry et al., 2021). Other research focused on climate experts find that those with more expertise in SRM do not differ in their climate mitigation policy preferences than those with less expertise (Merk et al., 2019). Interestingly, research utilizing a climate disaster economic role-playing game found that "citizens" did not alter how much they contributed to mitigation efforts when the "policy-maker" implemented geoengineering (Andrews et al., 2022). However, the assigned "policy-maker" believed that citizens would respond by reducing mitigation and therefore frequently did not implement geoengineering although it would have benefited all. This indicates that concern about moral hazards may play a greater role in decision-making than the actual moral hazard itself. A large caveat here is that all this research has been conducted prior to the implementation of SRM, and therefore it is unknown if the moral hazard may play out differently in that new future.

Of course, any insights into public perceptions of SRM in the current context are limited by the fact that no respondents have actually experienced it yet. In the abstract, people's perceptions of SRM are driven by broad psychological concepts of naturalness, trust, and moral hazard concerns. Yet overall acceptance as well as individual drivers of perceived benefits and risks are likely to change if and when SRM is deployed and people experience its effects, both locally and globally. For example, concrete, community-level issues like the effects of SRM on local crops may become much more prominent in public discourse in the future. Trust in those making the deploying decisions may also shift due to these perceived effects. Similarly, the strong effects seen in early studies of how SRM is framed in public communications is likely to fade as this topic becomes more discussed, factions are created in support and opposition to it, and people begin to see the effects of SRM for themselves.

SRM Deployment

There are challenges modeling the deployment of SRM in models. SRM can be deployed on an extrinsically determined date as is usually done in climate modeling simulations, e.g., MacMartin et al., 2022 where the starting date has been decided at 2035 as the first date of an eventual deployment if an early decision to deploy was taken in the next few years. Alternatively, one can find some thresholds after which SRM would be intrinsic to the model, for example, deciding on a temperature target that, when reached, would lead to SRM deployment. This would be in line with a focus on global climate policy and activism around temperature targets such as 1.5 or 2 degrees above pre industrial levels. The passing of such a symbolic threshold could be used to argue for SRM deployment. Alternatively support for the development or deployment of SRM may emerge organically from increasing perception of risk of climate change as informed by extreme weather events, crop failure, etc., beyond which the selectorate would feel sufficient urgency to develop or deplogy SRM. The perception of SRM would also be different before and after its initial implementation. Before, there may be concerns around moral hazard, and the current levels of trust in science and the trust in international institutions would affect an eventual decision to deploy. After deployment, moral hazard concerns would be less relevant but the reduction in perceived risk from anthropogenic climatic change and the emergence of secondary climatic impacts from SRM (e.g., ozone changes, deposition, changes in precipitation, novel climatic features) would influence risk perception of SRM.

Conceptual framework

Our conceptual framework for the development and deployment of SRM is centered on the perception of risk from both SRM and anthropogenic GHG forcing of climate change (Figure 1). We expect the drivers of perceived risk to vary across the pre-development, post-development and post-deployment phases of SRM.

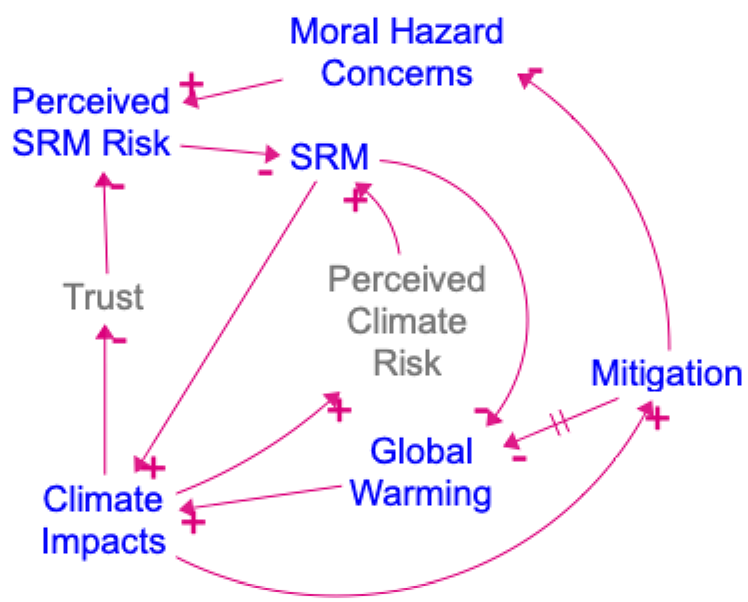

Figure 1. Conceptual diagram of the relationship between SRM and the human and climate systems. The implementation of SRM results from the balance of perceived climate risk and perceived SRM risk. Mitigation addresses climate change with long delays (decades to centuries) because of long residence times of GHGs (connector with double bar indicates a delay) while SRM can reduce global warming at much faster (sub-decadal) time scales.

In the ***pre-development*** phase of SRM, perceived risk of SRM will be determined by concerns over moral hazard and trust--trust in the efficacy and safety, and ultimately trust in the governing elites. Moral hazard will be manifested by policy makers and their reluctance to develop SRM because of concern over potential diminution of the incentive to abate GHG emissions. Concerns over development of SRM 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. The urgency for rapid measures to mitigate climate change may drive the development of SRM as a deployable option.

In the ***pre-deployment*** (but post-development) phase, perception of SRM will be driven by the perceived risk of climate change. Accelerating impacts from climate change that increase in intensity and that threaten business as usual function of society will lead to growing perceptions of risk. For example, drought and heat waves 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. Concerns over moral hazard may decrease because SRM is now a deployable option but will continue to be driven by the potential for SRM to reduce commitment to GHG abatement.

In the ***post-deployment*** phase, perceptions of risk will depend on the magnitude of climate impacts and whether the impacts are attributed to SRM or GHG forcing of the climate system. *Climate impacts.* SRM will reduce mean global temperature but unevenly across the world, and will also lead to myriad anticipated and likely some unanticipated climate impacts, e.g., temperature change, precipitation, and extreme events. The net effect of SRM deployment will depend on how SRM is deployed--the magnitude and details of deployment--and its effect on climate and climate impacts is thus uncertain. SRM will reduce mean global temperature, but will also affect other aspects of climate (e.g., precipitation, diurnal temperature cycles, cloud physics, etc.), and the regional distribution of climate benefits are likely to be heterogeneous. The net change in climate impacts from SRM will be a reduction in impacts from reducing global temperature and a likely increase in impacts from achieving this through SRM as opposed to reductions in atmospheric concentrations of GHGs. *Attribution*. While the magnitude of climate impacts drives perception of risk in our model, the attribution of these climate impacts to SRM or GHG-driven climate change is critically important. Attribution of impacts to SRM will reduce support for continued SRM while attribution to GHG-forcing will increase support for continued SRM. Thus, it is the combination of total climate impacts and their attribution that is key for determining support for SRM post-deployment.

Computational model

We will examine the net effect of SRM on climate by integrating the human and climate components of the Earth system using a system dynamics (SD) framework (Meadows 2008). Our model will include modules (i.e., sub models) for different components of the coupled human and climate system including climate, extreme events, risk processing, SRM, and the economy. We briefly describe how each of these modules function.

<u>Climate</u>. The climate module receives an input of CO2 equivalent (gigatons per year) and returns mean global temperature as the temperature anomaly relative to pre-industrial (degrees Celsius). The climate module is taken from the C-Roads carbon model of Climate Interactive and has been tuned to represent temperature projections from GCM ensembles (Sterman et al. 2012, Fiddaman et al. 2020).

<u>Extreme Events</u>. Our extreme events module translates mean global temperature into climate impacts from extreme events. We model the distribution of extreme events based on normal distribution of daily maximum temperature with the variance (16.7) from Donat and Alexander (2012), while the location parameter is given by mean global temperature anomaly.

We then calculate a specified right hand side tail area (i.e., 0.9 percentile) of the normal distribution for baseline climate and the same normal distribution except with its location shifted by climate change. The ratio of those two tail areas is used to adjust the number of extreme events from the baseline climate to the current climate: The number of extreme events in the baseline climate is modeled as a Poisson distribution defined by a lambda parameter. The lambda parameter is multiplied by tail area ratio to give the number of extreme events in the current climate. Our baseline period is the climate normal for period X and this approach leads to a nonlinear increase in extreme events with warming global temperatures. We note that while the parameterization of variance is based on maximum daily temperatures, the representation of extreme events is meant to be broadly representative of climate impacts.

Deployment of SRM generates collateral impacts. We model these by generating additional extreme events using the magnitude of SRM deployed, where the magnitude is represented by the reduction in mean global temperature by SRM. The number of extreme events associated with the magnitude of SRM is further mediated by a tunable parameter (Collateral impacts). The number of extreme events from SRM is then given by a Poisson distribution with a mean given by collateral impacts parameter multiplied by the magnitude of SRM applied. SRM extreme events are then combined with the climate extreme events for a total number of extreme events.

<u>SRM</u>. Our model of SRM is simple. We model SRM by reducing the mean global temperature calculated by the climate module. The magnitude of SRM corresponds to the amount of reduction in mean global temperature i.e., degrees C of mean global cooling achieved. The reduction in global temperature from SRM reduces the extreme events associated with GHG-forcing of climate but adds additional extreme events from deployment of SRM (described below). The SRM generated extreme events are meant to represent collateral impacts of SRM.

The magnitude of SRM deployed is determined by perceived risk from anthropogenic GHG forcing of climate (GHG climate change) and perceived risk from SRM deployment as described in the Risk module. High perceived risk from GHG climate change translates into urgency to act to reduce climate impacts. The ratio of perceived risk from SRM to perceived risk from GHG climate change drives the development and deployment of SRM. We assume a 10 year lag between the decision to develop SRM capacity and the ability to deploy SRM.

<u>Perceived Risk.</u> Perceived risk from climate change emerges from two components: annual extreme events and damage to economic production. We include habituation as a component of cognition in the processing of annual extreme events: Humans acclimate to increasing numbers of extreme events, reducing the perception of risk. We model habituation using a weighted moving average for the number of extreme events that defines the expected number of extreme events and the difference between this expectation and the actual number of extreme events (on an annual basis) drives the perceived risk from anthropogenic climate change. Damage to the economy is based on the DICE formulation of temperature driven loss of economic production (Nordhaus 2018). We scale both of these components of risk (annual extreme events and climate damage) to a 0-1 basis and combine them into an average, where both components are weighted equally.

Perceived risk from climate change is then partitioned into two components: perceived risk from anthropogenic GHG forcing and, if SRM has been deployed, then into perceived risk from SRM. The partitioning into these two components is based on attribution of climate impacts to anthropogenic GHG forcing or SRM. The attribution to SRM is based on the magnitude of SRM deployed and trust (or distrust) of the elite.

People are heterogeneous in their perceptions of risk from climate change and SRM, reflecting their individual demographic and cultural characteristics. We attempt to account for this heterogeneity by modeling perceptions of risk using probability distribution. We will assume that perceived risk is normally distributed across a population with the mean and variance describing the heterogeneity across populations. Larger variance would lead to greater heterogeneity in perceived risk. We could additionally use more than a single normal distribution to capture multiple modes across populations. We will use cumulative distribution functions (CDF's) and means to translate these distributions into mitigation responses.

Mitigation Response. We distinguish two mitigation responses. One mitigation response is abatement of GHG emissions. This incurs a cost in economic production as resources are diverted to invest in reducing emissions as in a DICE formulation. The climatic response to abatement is also slower as the climate system responds to reduced emissions contributing to the pool of atmospheric GHGs. The second mitigation response is deployment of SRM. This has a negligible (0 in our model) economic cost and produces rapid diminution of mean global temperature while leading to other climate impacts, e.g., see extreme events section above. The magnitude of the mitigation response is determined by the total perceived risk from climate change, whereas the mixture of abatement and SRM is determined by the relative perceived risk of each. As the perceived risk increases to high levels, there will be additional perceived benefit from the rapidity of the SRM response relative to abatement.

Expected model behavior. Here are some limiting cases that illustrate the functioning of this model:

1. Climate change occurs relatively slowly, so that habituation maintains a low to nonexistent perception of risk. Since perceived climate risk is low, there is little to no mitigation response.
2. Climate change is rapid enough to contribute to moderate perception of climate risk. This elicits modest pressure to mitigate, favoring abatement given perception of risk from the potential for deployment of SRM.
3. Climate change is rapid, generating high levels of perceived risk of climate change, leading to intense pressure to mitigate, with SRM deployment being driven by urgency of reduction in climate impacts. Subsequent continuation of SRM will depend on the additional climate impacts generated by SRM as well as the attribution of climate impacts.

Results

Discussion

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