ENVIRONMENTAL RESEARCH
LETTERS

PURPOSE-LED PUBLISHING™ Part of the ENVIRONMENTAL RESEARCH SERIES

LETTER • OPEN ACCESS

The strategic and governance implications of solar radiation modification: perspectives from delegates of international climate negotiations

To cite this article: Todd L Cherry *et al* 2025 *Environ. Res. Lett.* **20** 014053

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

The strategic and governance implications of solar radiation modification: perspectives from delegates of international climate negotiations

Todd L Cherry[1,*], **Steffen Kallbekken**[2], **David M McEvoy**[3] **and Wai Yan Siu**[4]

[1] Department of Economics, University of Wyoming, Laramie, WY, United States of America
[2] CICERO Center for International Climate Research, Oslo, Norway
[3] Department of Economics, Appalachian State University, Boone, NC, United States of America
[4] Institute for Coastal Adaptation and Resilience, Old Dominion University, Norfolk, VA, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: tcherry@uwyo.edu

Keywords: solar geoengineering, climate governance, solar radiation management, COP delegates

Supplementary material for this article is available online

OPEN ACCESS

RECEIVED
23 August 2024

REVISED
6 December 2024

ACCEPTED FOR PUBLICATION
11 December 2024

PUBLISHED
27 December 2024

Abstract

The lack of progress in addressing climate change has led to increased interest in solar radiation modification (SRM)—a collection of large-scale interventions that cool the planet by managing the amount of solar radiation that reaches the earth. SRM complicates climate change governance because, in addition to advancing collective action to reduce greenhouse gas emissions, governance needs to restrain unilateral SRM action while balancing diverging actor interests, ethical risks and scientific uncertainty. We survey international climate policy experts for their assessments of the potential for effective global governance of SRM and the likelihood of possible international responses to unilateral SRM scenarios. Experts are pessimistic about the global community achieving effective SRM governance, and they believe unilateral SRM action will trigger international responses and conflicts. Experts believe softer responses are most likely (e.g. diplomatic sanctions) but the potential for stronger responses, including military action, are non-trivial. Relative to the Global North, experts from the Global South are relatively more supportive of SRM, including the development of SRM, the inclusion of SRM in international negotiations, and the deployment of SRM in a climate emergency.

1. Introduction

Recent reports by the Intergovernmental Panel on Climate Change (IPCC 2023) and the World Meteorological Association (WMO 2024) provide strong evidence that the global community is falling short of the greenhouse gas (GHG) emissions reductions needed to avoid dangerous climate change. Faced with rising temperatures, increasing climate extremes (AghaKouchak *et al* 2020), and the failure to reduce global emissions (Friedlingstein *et al* 2023), climate interventions are increasingly seen as a viable response to a warming climate. Solar radiation modification (SRM) is a collection of large-scale interventions to cool the planet by managing the amount of solar radiation that reaches the earth (NASEM 2021).

The appeal of SRM stems from the potential to reduce global temperatures quickly with existing technology and at a relatively low cost (Smith 2020). However, SRM presents governance concerns because it 'turns the politics of climate protection upside down' (Victor 2008). While mitigation calls for collective action, the low cost of SRM allows a single actor to unilaterally deploy and determine the global average temperature (Barrett 2008). Thus, a single country or a small group of countries could potentially determine the global average temperature, which likely differs from what other countries per (Weitzman 2015). Similarly, unilateral action imposes outcomes on countries with divergent positions on ethical considerations (Pasztor 2017, Jinnah *et al* 2020), intellectual property and liability

(Reynolds 2019), and scientific uncertainty regarding SRM impacts (Grieger *et al* 2019).

A growing literature sheds light on the strategic and governance implications of SRM[5]. The potential that the existence of SRM could crowd out conventional mitigation, often referred to as moral hazard, has been a key criticism of SRM (Shepherd 2009, Lockley and Coffman 2016)[6]. Research however provides mixed evidence and tends to indicate that concerns of crowding out may be overstated (e.g. Merk *et al* 2016, Cherry *et al* 2023, Schoenegger and Mintz-Woo 2024). Another leading concern is the free-driver problem, which is when an actor with the highest preferred level of SRM unilaterally deploys and determines the global temperature for everyone (Wagner and Weitzman 2012, Weitzman 2015). Heyen *et al* (2019) argue that the free-driver incentive could lead to an escalating conflict if other countries engage in counter-geoengineering—i.e. 'counteracting the cooling effect of solar geoengineering through technical means' that may include releasing warming agents or removing the original aerosols (Parker *et al* 2018). Experimental research suggests that the free-driver problem may lead to excessive SRM but not to the extent predicted by theory, and consistent with Heyen *et al* (2019), counter-geoengineering leads to costly conflict with little impact on ultimate SRM levels (Abatayo *et al* 2020, Cherry *et al* 2024). Another concern raised in the literature is the potential that conflict may escalate to military action. The literature typically focuses on potential military action that disrupts deployment, such as shooting down aircraft (Parker *et al* 2018), disrupting SRM supply chains (Lockley 2019), and eliminating rivals' SRM capacity (Lockyer and Symons 2019). However, military action may be unlikely due to the strong incentives to resolve conflict with negotiation rather than intervention (Lockley 2016).

The challenge of governing the behavior surrounding SRM has received considerable attention with studies exploring the potential for international use and non-use agreements (e.g. Heutel *et al* 2016, Finus and Furini 2023, McEvoy *et al* 2024). Many studies offer insights on public perceptions of SRM as they, in part, determine the efforts to govern SRM. Results reveal considerable public support, albeit with concerns, for research into SRM and even its deployment. However, findings also report that the public is largely unaware of SRM (Mercer *et al* 2011, Scheer and Renn 2014, Mahajan *et al* 2019, Raimi 2021). Consequently, stated support has been shown to be sensitive to the framing of the technology (e.g. Bolsen *et al* 2024), trust in decision makers (e.g. Cummings *et al* 2017), and cultural worldviews (e.g. Cherry *et al* 2021), among other factors[7]. Previous studies on SRM perceptions have focused on the general public, but Dannenberg and Zitzelsberger (2019) provides an exception by considering climate policy experts[8]. Half of their respondents think more investments should be directed to research and development of SRM, and 52% support SRM deployment in the event of an approaching climate emergency. Also, they report that 42% of respondents consider it important to include SRM in the United Nations Framework Convention on Climate Change (UNFCCC) climate negotiations.

Dove *et al* (2024) points out the research on individual perceptions of SRM typically underrepresents the Global South. However, recent research has begun to consider regional perspectives. Baum *et al* (2024) surveyed the general population in 30 countries and reports that respondents from the Global South, as compared to the Global North, are 'significantly more favorable about potential benefits and express greater support for climate-intervention technologies.' Contzen *et al* (2024) finds a similar result from a 20-country survey that compares SRM attitudes among the public across the Global South and Global North. Sugiyama *et al* (2024) conducted a more limited survey but finds that people in developing countries were 'more concerned about climate change and more supportive of SRM' but were still concerned about the environmental and governance risks associated with SRM[9].

Herein we contribute novel empirical evidence by collecting and synthesizing climate policy expert assessments of potential international governance of, and responses to, the emergence of SRM. To that end, we conducted a survey of recent delegates to the UNFCCC Conference of the Parties (COP). COP delegates are particularly relevant because many of them have substantial expertise on climate policy and would likely be involved if SRM were to be included in the UNFCCC negotiations. Whereas most COP delegates have little direct experience with SRM, they do have experience navigating other unfamiliar, controversial and potentially high-risk climate strategies

[5] See Moreno-Cruz *et al* (forthcoming) for a comprehensive review of the strategic and governance issues of SRM and the related studies that offer theoretical and empirical evidence.

[6] Scholars have discussed the appropriate terminology that characterizes crowding out in the SRM context. For discussions, see Lockley and Coffman (2016), Tsipiras and Grant (2022) and Moreno-Cruz *et al* (forthcoming).

[7] See Raimi (2021) for a comprehensive review of the determinants of public perceptions.

[8] Climate policy experts in Dannenberg and Zitzelsberger (2019) included party members of the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties and Intergovernmental Panel on Climate Change (IPCC) authors and reviewers.

[9] Hussain *et al* (2023) conduct a survey of stakeholders in Pakistan, Nigeria, and Kenya, and results indicate a majority of respondents are supportive of climate engineering technologies to counter global warming.

(such as bioenergy with carbon capture and storage, direct air capture, etc). Our sample of climate experts includes over 800 delegates from COP 26 and COP 27, and our analysis is focused on Party and Observer responses (controlling for media and other attendees). See supplementary information (S1) table S1.

Our survey focuses on stratospheric aerosol injection (SAI), which has received the most attention among the SRM technologies (Moreno-Cruz *et al* forthcoming). SAI is the process of spraying inorganic particles into the upper atmosphere to act as a reflective barrier and create a cooling effect. The survey consists of two main parts. First, it replicates previous work (Dannenberg and Zitzelsberger 2019) by asking climate policy experts about their support for public funding for SAI research, deployment of SAI in response to a climate emergency, and inclusion of SAI in UNFCCC negotiations. We add insights to the underlying reasons for support or opposition and elicit beliefs about the likelihood the global community will achieve effective governance of SAI. Second, the survey asks the climate experts to assess the likelihood of possible responses to a country taking unilateral action to create SAI capacity or to begin SAI deployment, including developing counter measures, diplomatic sanctions, and military responses. This part also asks experts to assess how including SAI in international climate negotiations would impact negotiation outcomes, such as reaching global emission reduction targets, developing effective global governance of SAI technologies, and conflicts during negotiations. Throughout, we collect information on the delegate and represented country to facilitate stratified results by delegate role and geographic region, which yields new findings on region-specific perceptions (e.g. Global South and Global North).

2. Methods

The survey was designed to replicate and extend previous studies on the perceptions of SRM among climate policy experts. To that end, the online survey consisted of four sections—knowledge and support, negotiation, strategic responses, and respondent background (see SI for survey instrument). The *knowledge and support section* first provided a brief summary of SRM and SAI, and then presented questions about the respondent's knowledge of SAI, support for SAI research funding, confidence of effective governance of SAI, support for SAI deployment in climate emergency, and reasons for support/opposition. The *negotiation section* asked respondents' level of support for including SAI in the UNFCCC negotiations and then their views on how including SAI would affect outcomes of negotiations. The *strategic responses section* first presented a scenario of a country developing the capacity to deploy SAI and then asked the respondents' assessment of the likelihood that a country would respond in each of five possible ways. The section then presented a second scenario of a country announcing that it will start to deploy SAI and then asked the likelihood of the same five possible responses. The *respondent background section* asked respondents about their COP participation, including delegate role, type of organization represented, country's regional group, number of years attending COPs, and academic/professional field.

Unless explicitly mentioned, reported summary statistics include all responses, even if the survey was not fully completed. The conditional results and *p*-values reported are from linear probability models estimated using ordinary least squares ($n = 622$)[10]. The regressions were used to estimate how delegate characteristics impact the likelihood of anticipated responses to SAI initiatives. For the *negotiation section*, a separate model was estimated for each of the possible six outcomes of including SAI in UNFCCC negotiations (e.g. reaching global emissions targets under the Paris Agreement). The dependent variable in each regression equals one if the respondent answered 'more likely' and zero otherwise. The controls are dummy variables that include the delegate's role (Observer, Party or Other (omitted)), organization type (government, research, private, environmental NGO or Other (omitted)) and region (Global North or Global South (omitted))[11]. Likewise, models were estimated for each of the two scenarios in the *strategic responses section*. Each scenario had five anticipated outcomes, and for each outcome the dependent variable equals one if the respondent answered 'very likely' or 'likely' and zero otherwise. The same control variables were used in all regressions. See SI for the complete regression results and further discussion.

The sampling, protocols and instrument were reviewed and approved as exempt by the University of Wyoming's Institutional Review Board (#20230525TC03580). The initial sample of COP delegates was created by pulling names and affiliations from the provisional list of registered participants of COP 26 (Glasgow) and COP 27 (Sharm el–Sheikh). Email addresses were searched and scraped on the internet using public sources. Of these emails, we delivered an initial invitation to participate in the survey. Each invitation was followed by three reminder emails. The first two reminders were delivered two and four days after the initial invitation, and the third

[10] Regression results from the linear probability models are qualitatively similar to probit specifications.

[11] Given that our study is focused on UNFCCC delegates, respondents are organized into the UN regional groups of African States, Asia-Pacific States, Eastern European States, Latin American & Caribbean States and Western European & Other States. In our study, the 'Global North' states are the Eastern European States and the Western European & Other States.

reminder was delivered about a month after the initial invitation. To boost response rates, the survey was purposefully streamlined to take only 5–10 min. To minimize impacts of varying time zones, the timing of the first two reminders were spaced about 8 h across the 24 h interval.

Importantly, the survey was completely anonymous without any collection of individual respondent information. Anonymity was preserved for two main reasons. First, we wanted to mitigate any concerns about participating in the survey and providing honest responses to the questions. Second, we were required to satisfy the EU's General Data Protection Regulation. The consequence of anonymity is that the final data for the analysis only includes responses to the survey questions.

We sent invitations to 22 760 people in our sample of COP delegates. Of these, 2925 were immediately bounced back and 8147 were not opened. Thus, 11685 people received and opened an invitation to take the survey. A total of 871 people participated in the survey, which translates to response a rate of 4.4% (871/19835)[12]. Of the 871 people who responded to the survey, 622 or 71.4% completed all questions. The response rate is comparable to previous studies with similar samples (e.g. Karlsson *et al* 2011, Kesternich 2016, Dannenberg *et al* 2017). A summary of participants can be found in table S1 in the SI. Though we cannot rule out selection bias in the data, the concern is mitigated because, when there is overlap, our findings correspond to those reported in previous studies (e.g. Dannenberg and Zitzelsberger 2019, Baum *et al* 2024). Moreover, our study provides insights from the relative findings across strategic responses, delegate roles, and country economic classification.

3. Results

3.1. Support for SRM

We begin by reporting the level of support for government funding for SAI research and development, the deployment of SAI in the event of a climate emergency, and the inclusion of SAI in international climate negotiations (UNFCCC). Figure 1 summarizes the results. We segment responses by the delegate's role in the negotiations (Party, i.e. official country representative, or Observer, i.e. non-governmental, governmental) and whether they represent a country in the Global North or Global South[13]. Overall, 82.2% of respondents that completed the survey were at least slightly informed about SAI technologies.

While the distribution of party delegates is roughly even between Global North and Global South regions (52% and 48%, respectively) most of the Observer delegates are from the Global North (84% and 16%, respectively). The UNFCCC has recently recognized the biased distribution of Observer delegates from the Global North and has adjusted its quota system in an attempt to reduce this bias[14]. Note that the regression results reported in this section control for delegate role, organization and region in order to isolate the individual effects (see SI for more details).

One common theme is that Party delegates and respondents from the Global South are generally more favorable toward SAI compared to Observers and those from the Global North. Party delegates show relatively high levels of support for more SAI research (54.1%), deployment in an emergency (44.6%), and for including SAI in UNFCCC negotiations (49.7%). These results are similar to those reported by Dannenberg and Zitzelsberger (2019). It is noteworthy that respondents from countries in the Global South are the most supportive of greater funding for SAI research (58.4%) and including SAI in negotiations (52.2%), and they also show relatively strong support for deploying SAI in an emergency (44.1%). These results align with the major findings from other studies exploring regional perceptions and opinions of SRM[15].

Overall, Observer delegates (NGOs, IGOs, and UN representatives) tend to be least favorable toward SAI with only 35.6% supporting more research, 28.0% supporting emergency deployment and 31.3% favoring SAI being included in negotiations.

To better understand the positions of delegates, we asked for the underlying reasons for support or opposition for deploying SAI in response to a climate emergency. The summary of responses is displayed in figure 2. To highlight a few key results, for climate experts who oppose using SAI in a climate emergency, 81% believe it to be too risky and 68% think it will lead to crowding-out of mitigation (also known as moral hazard). For those in favor, 61% think SAI will buy time to adequately reduce GHG emissions, while only 28% indicate the relatively low cost of SAI as a reason for support.

We asked delegates for their views on the likelihood that the 'global community will create an

[12] Given unopened emails may not have been received (e.g. diverted to spam folder), the response rate of 10.7% (871/11685) for only opened emails provides an additional measure of responsiveness.

[13] Figure 1 reports results for *Party and Observer* categories but not the *Other* category. See supplementary table S1 for summary of sample.

[14] See the Forward from the UNFCCC Executive Secretary to the COP 29 Observer Handbook: https://unfccc.int/sites/default/files/resource/Observer%20Handbook%20for%20COP29%203008%20pub%20%281%29.pdf

[15] The survey collected each respondent's field of expertise, and results indicate the strongest supporters of SAI initiatives earned their highest degree or training in engineering. In contrast, natural scientists and social scientists are far less supportive. This may have important implications for participation shaping outcomes. See SI figure S1.

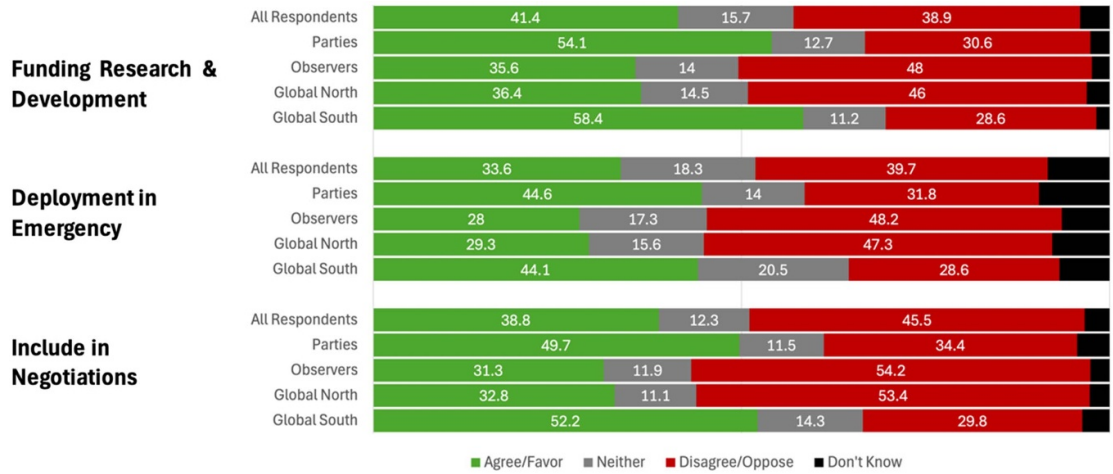

Figure 1. Support for SAI R&D, deployment in emergency, and inclusion in negotiations.

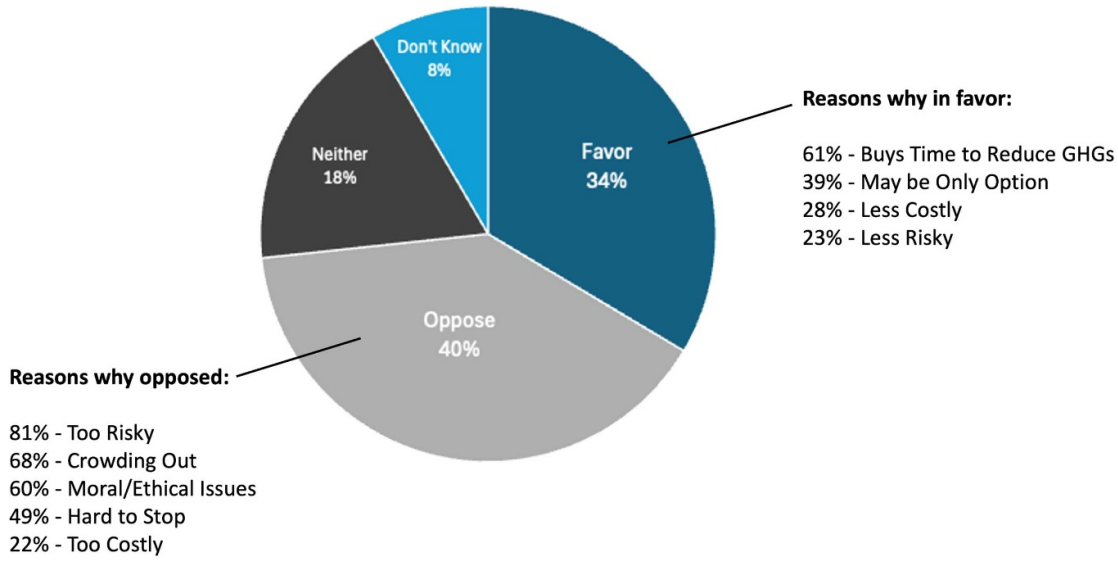

Figure 2. Support for deploying SAI in a climate emergency and the underlying reasons.

effective governance system for managing SAI'[16]. In general, respondents are pessimistic about the governance of SAI. Less than 20% of all respondents think effective governance is likely, with Observers and delegates from the Global North being the most pessimistic (12.5% and 11.1%, respectively). Global South representatives are the least pessimistic with 34% thinking effective governance of SAI is likely.

3.2. Anticipated responses to SRM

Understanding the level of support for different SAI activities is informative for understanding likely future developments, but we now turn to exploring the potential strategic responses to the arrival of SAI. Specifically, if SAI is developed, deployed or included in the negotiations, what are the likely consequences? Although this remains speculative due to the lack of empirical evidence, COP delegates are arguably the best-informed group to provide a considered view. Due to the role of the COP as an arena for intergovernmental negotiations, we have limited the scope to actions taken by countries but acknowledge that at least some SRM technologies are of a cost and complexity level that might allow also private actors to act unilaterally.

3.2.1. Responses to research and development

We asked climate experts their opinions about potential global responses to SAI capacity building, deployment and inclusion in negotiations. Respondents were first asked to consider a scenario in which a country started to develop the capacity to deploy SAI and to provide their opinions on the likelihood that

[16] We left the interpretation of 'effective' to respondents, acknowledging that effectiveness has a wide range of uses and definitions in the international relations literature (Young 2011).

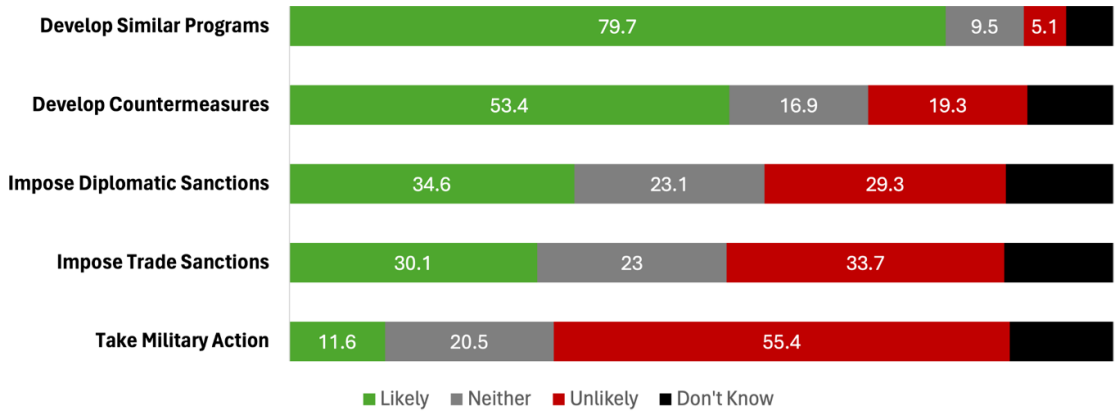

Figure 3. Anticipated global responses if one country starts to develop the capacity to deploy SAI.

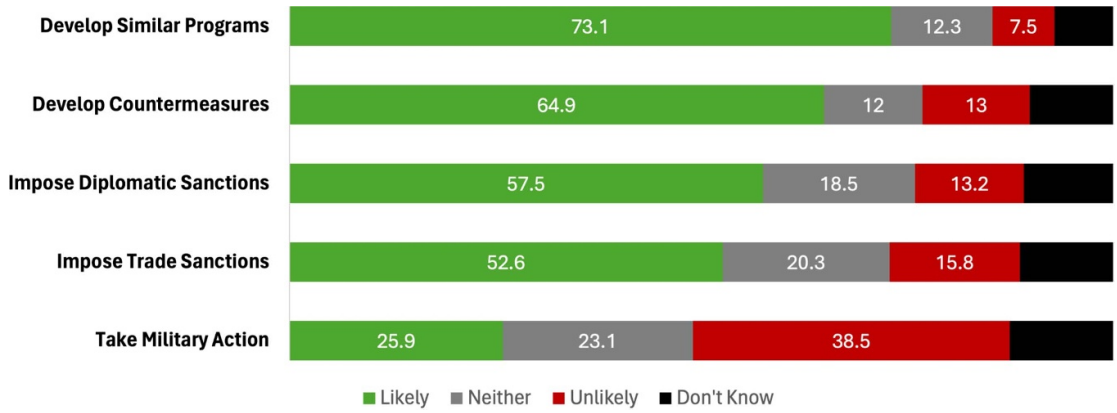

Figure 4. Anticipated global responses if one country announces it will immediately start deploying SAI.

one or more countries would respond in the following ways: develop similar programs, develop countermeasures, impose diplomatic sanctions, impose trade sanctions, and take military action.

We summarize the results for each of the five response options for all participants. Figure 3 shows that the likelihood measure of anticipated responses cascades down as the potential responses become more extreme. Most climate experts anticipate that if a country develops capacity to deploy SAI, at least one other country will respond in kind (79.7%). A slim majority anticipate countermeasures or 'counter geoengineering' being used (53.4%). Only a minority of experts think responses will elevate to diplomatic or trade sanctions (34.6% and 30.1%, respectively) and 11.6% think that military responses are likely.

Estimates from probability model regressions confirm there is little statistical difference in responses by delegate's role (Observer, Party or other), organization type (government, research, private, environmental NGO, other) and represented country's region (Global North/South). Full results are reported in SI table S3. However, we do find that Party delegates are statistically more likely to anticipate counter measures compared to Observers ($p = 0.070$) and delegates with other roles ($p = 0.230$), and less likely to anticipate diplomatic sanctions compared to Observers ($p = 0.065$). Delegates from government organizations are less likely to anticipate a military response compared to delegates from research institutions ($p = 0.047$), environmental NGOs ($p = 0.060$) and other organizations ($p = 0.052$). Delegates from government organizations are also less likely to predict trade sanctions as a response compared to those from other organizations ($p = 0.007$)[17].

Responses to immediate deployment. We next asked delegates for their opinions about the likelihood of potential responses to a country announcing immediate deployment of SAI. The potential responses were the same as in the previous question on building capacity to deploy SAI. The summary results are in figure 4 (additional results reported in SI table S4).

[17] We also estimated the models when conditioning for how informed respondents are about SAI. In general, uninformed respondents are slightly more pessimistic concerning anticipated responses to SAI initiatives, but most impacts are statistically insignificant.

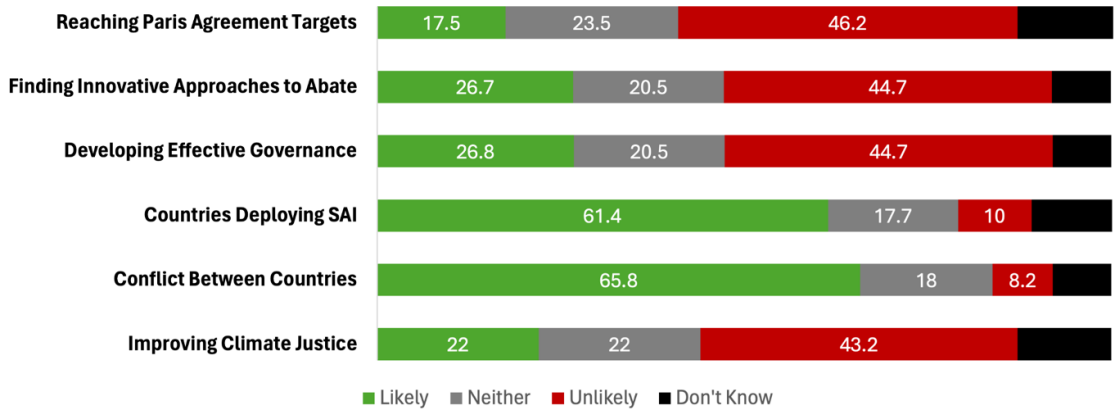

Figure 5. Anticipated change in the likelihood of outcomes if SAI is formally included in climate negotiations.

We again observe a decreasing likelihood of responses as the possibilities become more extreme but note that a higher percentage of climate experts anticipate more extreme responses compared to the scenario about building capacity to deploy. Notably, roughly 26% of experts believe a military response to deployment is likely. Though the type of military response is not defined, the literature typically indicates it would be limited to targeting the deployment itself (Parker *et al* 2018, Lockyer and Symons 2019)[18].

Conditional estimates confirm very little statistical difference in responses across delegate characteristics with the exception of those from countries in the Global North anticipating a higher likelihood of diplomatic sanctions compared to those from Global South countries ($p = 0.030$). Party delegates are less likely than Observer delegates to expect a response of another country developing a similar program ($p = 0.057$).

Responses to inclusion of SRM in negotiations. Our sample of climate experts were also asked to consider a scenario in which SAI is formally included in the global climate negotiations. They were then asked how this would affect the likelihood of the following outcomes: reaching global emissions targets under the Paris Agreement; finding innovative approaches to reduce emissions; developing effective global governance of the technologies; one or more countries deploying SAI; conflict between countries within negotiations; and improving climate justice concerns. The summary results for all respondents are in figure 5 (see SI table S5 for the full set of results).

Overall, climate experts are generally pessimistic about the outcomes of including SAI in UNFCCC negotiations. Consistent with the moral-hazard conjecture, the largest fraction of delegates believe that including SAI in the formal negotiations will further frustrate global climate actions on mitigation. The modal response expects inclusion of SAI will reduce the chances of achieving the Paris Agreement targets (46.2%) and realizing innovative approaches to reduce GHG emissions (44.7%). Similarly, the largest fraction of climate experts (43.2%) think including SAI in negotiations is unlikely to improve climate justice concerns. A majority of experts believe it will lead to a higher likelihood of countries actually deploying SAI (61.4%) and will increase conflict between nations (65.8%).

Regression estimation reveals some interesting heterogeneity in responses that are consistent with the overarching theme that delegates from countries in the Global South are more optimistic about SAI compared to those from the Global North (see SI table S5). Delegates from the Global North are less likely to think including SAI in negotiations will help meet Paris Agreement targets ($p = 0.000$) or lead to innovative GHG abatement ($p = 0.000$). Delegates from the Global North are more likely to think that including SAI in negotiations will lead to deployment ($p = 0.009$) and increased conflict ($p = 0.025$) compared to those in the Global South. The regression results control for delegate roles and home organizations and we find all control coefficients to be insignificant.

We also find that delegates from governmental organizations are more likely to believe that including the topic in negotiations will help reach Paris Agreement targets compared to those from environmental NGOs ($p = 0.097$) and less likely to believe it will lead to deployment of SAI compared to those from the private sector ($p = 0.028$).

4. Discussion and conclusion

The emergence of SRM complicates climate change governance as it needs to restrain unilateral deployment of SRM in addition to the conventional task of advancing collective action to reduce GHG emissions

[18] We note that Irvine *et al* (2019) points out that conflict may not be inevitable because SGE deployment may offer widespread benefits, especially if deployed in moderation.

and adapt to climate change. We survey delegates from recent UNFCCC COP meetings to gain insights on the perceptions of the use, development and governance of SRM technologies, particularly SAI, that are held by this important group of climate policy experts and decision makers. We find that half of the Party delegates in our sample support including SRM in the UNFCCC climate negotiation process. We also find that a majority of Party delegates support SRM research and development and just short of a majority support the deployment of SRM in the event of a climate disaster.

Despite a relatively high willingness to research and deploy SRM, our sample of climate policy experts are relatively pessimistic about the international community creating effective SRM governance. Less than 20% of respondents believe that effective governance is likely. And despite the support for including SRM in climate negotiations, respondents are pessimistic about the benefits of doing so. They generally believe it would sour the negotiations by making it less likely to make progress on mitigation and increase the likelihood of conflict in the negotiations. Experts anticipate conflict if a country were to unilaterally develop or deploy SRM. While softer responses, such as developing counter measures, are considered most likely, the perceived likelihood of stronger sanctions, including military action, is noteworthy.

The overall picture that emerges is one where many of the negotiators and observers attending the COP appear willing to address SRM more seriously as a strategy, despite the potential for a range of negative consequences. Respondents express little hope for effective international governance of SRM, which may be the reason some delegates support including SRM in the UNFCCC negotiation process because it ensures some level of international coordination and the alternatives (e.g. SRM left ungoverned) would lead to worse outcomes.

A key and consistent finding is that experts from countries in the Global South are relatively more supportive of SRM than those from the Global North. This is generally consistent with previous studies based on the opinions of the general population (Baum *et al* 2024, Sugiyama *et al* 2024). We extend this literature with results that indicate the Global South is not only more supportive of SRM but are more optimistic about SRM. The delegates from countries in the Global South, relative to those from the Global North, anticipate better outcomes from including SRM in the UNFCCC climate negotiations. And relatedly, the Global South is more optimistic that the global community will achieve effective governance of SRM technologies. The relatively supportive and optimistic perceptions of SRM in the Global South may reflect that countries in the Global South expect to suffer disproportionately from global climate change damages. It is unsurprising that vulnerable regions are more willing to seriously consider SRM as an option to potentially reduce climate impacts. In terms of 'distributive justice' (i.e. perceptions of fairness regarding the outcomes from SRM) the Global South may have the most to gain from climate interventions. However, there are also important concerns in the Global South regarding 'procedural justice' (i.e. fairness and inclusion in the decision-making process) (Fritz *et al* 2024). The non-use agreement proposed by Biermann *et al* (2022) has led to concerns about the agreement violating both types of justice related to SRM. The non-use agreement does not protect the Global South from impending climate damages, while most of the signatories to the non-use agreement are from the Global North, which challenges notions of procedural justice in SRM decision making (Parson *et al* 2024).

The governance challenges of SRM can be exacerbated by strategic incentives for exclusive coalitions, where smaller groups of actors (clubs) may pursue SRM for their regional benefit at the expense of broader global interests, an issue made more relevant by the large differences we find in regional attitudes towards SRM. These dynamics could risk undermining equity and inclusiveness in decision-making, adding emphasis to the importance of institutional frameworks that deter exclusionary practices and foster broad participation to ensure fair and globally representative governance (Ricke *et al* 2013).

The findings should be considered within the study's limitations. First, previous work has established that the pre-existing knowledge about SRM is very low and quite susceptible to the framing and information presented (e.g. Raimi 2021). Our chosen target population is better informed about climate change and climate policy than the general public but are not experts on SRM. To focus on respondent perceptions based on their existing understanding, we limited the amount of framing of SRM in the survey. Therefore, findings represent a baseline that would evolve over time with continued discussions. Another limitation of our study is that because SRM has not yet been widely deployed, the responses about anticipated responses are necessarily speculative. While the delegates are highly knowledgeable about international climate policy, their assessments may still lack empirical grounding for this new and unfamiliar policy option. Furthermore, the results cannot speak to the intensity of anticipated responses to SRM capacity building and deployment. For example, a military response could range from a relatively benign action, such as a single country's involvement in domestic SRM development, to a more extreme scenario, like a global climate conflict.

As the prospects for SRM become more likely, it is important to understand the potential strategic and governance implications from the emergence of

SRM. Our findings offer new insights, including a non-trivial risk for conflict and a daunting task of effective governance. The risk of international conflict highlights the need for the global community to be prepared for likely security implications of SRM (e.g. Versen *et al* 2021). Also, results reveal important differences between the Global North and South, where respondents from the South are generally more supportive of SRM, and more optimistic regarding the consequences of including SRM in the climate negotiations.

Data availability statement

The data and code that support the findings of this study are openly available at https://osf.io/m7rgz/.

Acknowledgment

This research is based on work supported by the United States National Science Foundation under Grant No. 2033855.

Conflict of interest

The authors declare no competing interests.

ORCID iD

Todd L Cherry https://orcid.org/0000-0002-9561-8350

References

Abatayo A L, Bosetti V, Casari M, Ghidoni R and Tavoni M 2020 Solargeoengineering may lead to excessive cooling and high strategic uncertainty *Proc. Natl Acad. Sci.* **117** 13393–8

AghaKouchak A, Chiang F, Huning L S, Love C A, Mallakpour I, Mazdiyasni O, Hoftakhari H, Papalexiou S M, Ragno E and Sadegh M 2020 Climate extremes and compound hazards in a warming world *Annu. Rev. Earth Planet. Sci.* **48** 5190548

Barrett S 2008 The incredible economics of geoengineering *Environ. Resour. Econ.* **39** 45–54

Baum C M, Fritz L, Low S and Sovacool B K 2024 Public perceptions and support of climate intervention technologies across the Global North and Global South *Nat. Commun.* **15** 2060

Biermann F *et al* 2022 Solar geoengineering: the case for an international non-use agreement *WIREs Clim. Change* **13**

Bolsen T, Palm R and Kingsland J T 2024 How scientific and partisan media shape support for research on stratospheric aerosol injection *Environ. Politics* 1–22

Cherry T L, Kallbekken S, Kroll S and McEvoy D M 2021 Does solar geoengineering crowd out climate change mitigation efforts? Evidence from a stated preference referendum on a carbon tax *Clim. Change* **165** 6

Cherry T L, Kroll S, McEvoy D M and Campoverde D 2024 Solar geoengineering, free-driving and conflict: an experimental investigation *Environ. Resour. Econ.* **87** 1045–60

Cherry T L, Kroll S, McEvoy D M, Campoverde D and Moreno-Cruz J 2023 Climate cooperation in the shadow of solar geoengineering: an experimental investigation of the moral hazard conjecture *Environ. Politics* **32** 362–70

Contzen N, Perlaviciute G, Steg L, Reckels S C, Alves S, Bidwell D, and Sütterlin B 2024 Public opinion about solar radiation management: a cross-cultural study in 20 countries around the world *Clim. Change* **177** 65

Cummings C, Lin S and Trump B 2017 Public perceptions of climate geoengineering: a systematic review of the literature *Clim. Res.* **73** 247–64

Dannenberg A and Zitzelsberger S 2019 Climate experts' views on geoengineering depend on their beliefs about climate change impacts *Nat. Clim. Change* **9** 769–75

Dannenberg A, Zitzelsberger S and Tavoni A 2017 Climate negotiators' and scientists' assessments of the climate negotiations *Nat. Clim. Change* **7** 437–42

Dove Z, Jinnah S and Talati S 2024 Building capacity to govern emerging climate intervention technologies *Elem. Sci. Anth.* **12** 00124

Finus M and Furini F 2023 Gobal climate governance in the light of geoengineering: a shot in the Dark? *J. Environ. Econ. Manage.* **122** 102854

Friedlingstein P *et al* 2023 Global carbon budget 2023 *Earth Syst. Sci. Data* **15** 5301–69

Fritz L, Baum C M, Low S and Sovacool B K 2024 Public engagement for inclusive and sustainable governance of climate interventions *Nat. Commun.* **15** 4168

Grieger K D, Felgenhauer T, Renn O, Wiener J and Borsuk M 2019 Emerging risk governance for stratospheric aerosol injection as a climate management technology *Environ. Syst. Decis.* **39** 371–82

Heutel G, Moreno-Cruz J and Shayegh S 2016 Climate tipping points and solar geoengineering *J. Econ. Behav. Organ.* **132** 19–45

Heyen D, Horton J and Moreno-Cruz J 2019 Strategic implications of counter-geoengineering: clash or cooperation *J. Environ. Econ. Manage.* **95** 153–77

Hussain A, Sipra H F K, Waheed A and Ukhurebor K E 2023 Exploring the stakeholders perceptions of solar geoengineering in developing countries *Resources for the Future Working Paper* (*23–25 September 2023*)

IPCC 2023 Climate change 2023: synthesis report *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H Lee and J Romero (Core Writing Team) (IPCC) pp 35–115

Irvine P, Emanuel K, He J, Horowitz L W, Vecchi G and Keith D 2019 Halving warming with idealized solar geoengineering moderates key climate hazards *Nat. Clim. Change* **9** 295–9

Jinnah S, Nicholson S and Flegal J 2020 Toward legitimate governance of solar geoengineering research: a role for sub-state actors *The Ethics of "Geoengineering" the Global Climate* (Routledge) pp 133–52

Karlsson C, Parker C, Hjerpe M and Linnér B 2011 Looking for leaders: perceptions of climate change leadership among climate change negotiation participants *Glob. Environ. Politics* **11** 89–107

Kesternich M 2016 Minimum participation rules in international environmental agreements: empirical evidence from a survey among delegates in international climate negotiations *Appl. Econ.* **48** 1047–65

Lockley A 2016 Geoengineering: a war on climate change? *J. Ethics Emerg. Technol.* **26** 26–49

Lockley A 2019 Security of solar radiation management geoengineering *Front. Eng. Manage.* **6** 102–16

Lockley A and Coffman D M 2016 Distinguishing morale hazard from moral hazard in geoengineering *Environ. Law Rev.* **18** 194–204

Lockyer A and Symons J 2019 The national security implications of solar geoengineering: an Australian perspective *Aust. J. Int. Affairs* **73** 485–503

Mahajan A, Tingley D and Wagner G 2019 Fast, cheap, and imperfect? US public opinion about solar geoengineering *Environ. Politics* **28** 523–43

McEvoy D, McGinty M, Cherry T L and Kroll S 2024 International climate agreements under the threat of solar geoengineering *J. Assoc. Environ. Resour. Econ.* **11** 853–86

Mercer A M, Keith D W and Sharp J D 2011 Public understanding of solar radiation management *Environ. Res. Lett.* **6** 044006
Merk C, Ponitzsch G and Rehdanz K 2016 Knowledge about aerosol injection does not reduce individual mitigation efforts *Environ. Res. Lett.* **11** 1–6
Moreno-Cruz J, McEvoy D M, McGinty M and Cherry T L forthcoming The economics and governance of solar geoengineering *Rev. Environ. Econ. Policy*
NASEM 2021 *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance* (National Academies of Sciences, Engineering, and Medicine (NASEM))
Parker A, Horton J B and Keith D W 2018 Stopping solar geoengineering through technical means: a preliminary assessment of counter-geoengineering *Earth's Future* **6** 1058–65
Parson E A, Buck H J, Jinnah S, Moreno-Cruz J and Nicholson S 2024 Toward an evidence-informed, responsible, and inclusive debate on solar geoengineering: a response to the proposed non-use agreement *Wiley Interdiscip. Rev.: Clim. Change* **15** e903
Pasztor J 2017 The need for governance of climate geoengineering *Ethics Int. Aff.* **31** 419–30
Raimi K T 2021 Public perceptions of geoengineering *Curr. Opin. Psychol.* **42** 66–70
Reynolds J L 2019 Solar geoengineering to reduce climate change: a review of governance proposals *Proc. Royal Soc.* A **475** 20190255
Ricke K L, Moreno-Cruz J B and Caldeira K 2013 Strategic incentives for climate geoengineering coalitions to exclude broad participation *Environ. Res. Lett.* **8** 014021
Scheer D and Renn O 2014 Public perception of geoengineering and its consequences for public debate *Clim. Change* **125** 305–18
Schoenegger P and Mintz-Woo K 2024 Moral hazards and solar radiation management: evidence from a large-scale online experiment *J. Environ. Psychol.* **95** 102288
Shepherd J G 2009 *Geoengineering the Climate: Science, Governance and Uncertainty* (Royal Society) (available at: https://royalsociety.org/-/media/policy/publications/2009/8693.pdf)
Smith W 2020 The cost of stratospheric aerosol injection through 2100 *Environ. Res. Lett.* **15** 114004
Sugiyama M, Asayama S, Kosugi T, Ishii A and Watanabe S 2024 Public attitude toward solar radiation modification: results of a two-scenario online survey on perception in four Asia–Pacific countries *Sustain. Sci.* 1–16
Tsipiras K and Grant W J 2022 What do we mean when we talk about the moral hazard of geoengineering? *Environ. Law Rev.* **24** 27–44
Versen J, Mnatsakanyan Z and Urpelainen J 2021 *Preparing the United States for Security and Governance in a Geoengineering Future* (Brookings Institution) (available at: https://coilink.org/20.500.12592/zxrc5gon27Nov2024.COI:20.500.12592/zxrc5g)
Victor D G 2008 On the regulation of geoengineering *Oxford Rev. Econ. Policy* **24** 322–36
Wagner G and Weitzman M 2012 Playing god *Foreign Policy*
Weitzman M L 2015 A voting architecture for the governance of free-driver externalities, with application to geoengineering *Scandinavian J. Econ.* **117** 1049–68
WMO 2024 *State of the Global Climate 2023* (World Meteorological Organization) WMO-No. 1347, Geneva. permalink: (available at: https://library.wmo.int/idurl/4/68835)
Young O R 2011 Effectiveness of international environmental regimes: existing knowledge, cutting-edge themes, and research strategies *Proc. Natl Acad. Sci.* **108** 19853–60