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Solar geoengineering governance: Insights from a scenario exercise

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ABSTRACT

This paper concludes the collection on an extended scenario exercise that examined governance challenges and potential responses for solar geoengineering. It synthesizes the experiences of eight participant groups who worked with four scenarios of unauthorized use of solar geoengineering. It draws both substantive insights about solar geoengineering risks and governance and methodological insights for the use of scenario exercises to explore this issue, as well as identifying major uncertainties and questions raised by the exercise. Prominent themes include the need for strategic sequencing of actions by those initiating and responding to solar geoengineering challenges; the nature and foundations of potential opposition; the widespread interest in normalizing or domesticating a disruptive intervention after the fact; the importance of embedding solar geoengineering actions in the broader context of climate policy and the difficulty of doing so given their disruptive character; and the importance and likely structure of negotiations to move from initial disruptive action, whatever its initiators and form, to expand participation and embed solar geoengineering decisions in a broadly legitimate multilateral governance structure. In the closing section, we propose directions for further scenario-based explorations of solar geoengineering and its governance challenges.

1. Introduction

As a potential contribution to climate-change response, solar geoengineering presents high stakes, global scale, long time-horizons, and deep uncertainties. It thus poses diverse governance challenges that are well suited to investigation through scenario methods. The prospect that states facing extreme climate harms in coming decades might threaten, demand, or unilaterally initiate a solar geoengineering intervention appears plausible, and if realized would present serious geopolitical risks. Despite widespread speculation about such deployment challenges, there has been limited rigorous exploration of their origins or character, what specific risks they would present, or what responses might help mitigate these. The scenario exercise at the 2019 Geoengineering Summer School focused specifically on these uncertainties. The four preceding papers provide rich, contextualized discussions of the experience of the groups

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working on each scenario. Here, we extract broader insights from the exercise, about the risks and governance challenges of solar geoengineering and the uses, contributions, and limits of scenario methods in exploring these.

The next section summarizes the exercise's design, the four scenarios, and the participant groups' tasks, briefly recapitulating the detailed discussion in the collection's opening paper (Parson & Reynolds, 2021). Section 3 discusses six prominent themes of the groups' work and associated insights for solar geoengineering's risks and potential responses. After that, section 4 offers methodological lessons from the exercise regarding the contribution, design, and limitations of scenario-based methods. Section 5 synthesizes the exercise's main substantive and methodological conclusions and proposes promising directions for further investigation of solar geoengineering and its governance via scenario exercises.

2. The exercise and its scenarios

As discussed in the opening paper, the 2019 exercise used four scenarios, each presenting a distinct challenge to international governance from an announcement or demand related to solar geoengineering deployment. The scenarios were developed in advance of the exercise, to allow intentional control of which elements were common among scenarios and which varied, promoting participant experiences that were diverse but comparable across groups. All scenarios were set in 2040, with common background conditions that sought to make demands for solar geoengineering use at that time plausible. In that year, climate impacts are described as severe, worsening, and regionally unequal. There has been modest progress in scientific research on solar geoengineering but little on governance. The scenarios assumed only incremental changes in global politics and were silent on domestic politics, thus positioning climate change and geoengineering as first-rank tests of global governance and de-prioritizing other international issues. In the scenarios, the major climate responses have the same basic strategic structure as today. Deep emission cuts ("mitigation") and large-scale carbon dioxide removal (CDR) are still costly actions that bring global benefits, and thus present some degree of global collective-action structure. Solar geoengineering via stratospheric aerosol injection remains low in direct cost, uncertain in efficacy and risks, and subject to unilateral or small-group action due to its "free driver" structure (Weitzman, 2015).

Despite their dominant focus on climate change, the scenarios unavoidably conveyed some information on broader geopolitics and global power in 2040. For example, each presumed that the specified disruptive action is within the capability of those initiating it and is sufficiently threatening to the identified respondents that they cannot simply ignore it or costlessly shut it down. The scenarios did not specify geopolitical conditions more precisely, but as we note below, groups' discussions suggested that this attempt to simplify and focus the exercise raised significant problems. For example, the groups judged it unlikely that climate change and responses will trump all other international issues or be fully separable from them. Rather, the related conflicts and negotiations will be integrated into broader relationships and rivalries.

The major difference among the scenarios was who initiates the deployment challenge: two distinct coalitions of states in the Middle Powers (Dove, Horton, & Ricke, 2021) and Vulnerable States (Schenuit, Gilligan, & Viswamohanan, 2021) scenarios, and two transnational groups of non-state actors in the Grassroots Deployment (Pasek, Morrow, Lee, & Felgenhauer, 2021) and Private Sector (Belaia, Borth, & Weng, 2021) scenarios. Several other differences followed from this, including participant groups' roles and tasks, and the theme of their discussions. All participant groups represented advisory bodies for senior decision-makers. In the first two scenarios—those with states as initiators—these were senior intergovernmental groups of officials reporting to heads of government. In the scenarios with non-state initiators, participants represented more diversely constituted bodies advising ad hoc coalitions of globally influential religious, environmental, research, and philanthropic organizations, with limited state involvement. Consequently, discussions in the two state-led scenarios focused on inter-state negotiations and the role of new or existing intergovernmental bodies, while those in the non-state-led ones focused on the balance of state and private power and the role of informal, collaborative responses.

One additional factor distinguishes Middle Powers from the other scenarios. In the other three, the scenario describes provocative steps that initiators have already taken to which participants must respond. In Middle Powers, the initiator states have only offered broad outlines of their own deployment plan, and the groups—working as advisors for these initiator states—must design the intervention program, accompanying governance systems, and communications in line with their leaders' strategic direction. This is thus the only scenario in which groups specify a deployment program's detailed design, governance, and justification. They are asked to do this so as to advance their governments' aims to get solar geoengineering on the top-level international agenda, attract support, broaden participation, and avoid or deflect attempts to stop them.

All participant groups, named after local animals, had a parallel sequence of three tasks. First, the two groups on each scenario worked separately to prepare initial governance proposals in response to the scenario's challenge. Next, each provided a stress-test for the other group's initial proposal, either as explicit criticism or as stipulated actions or events to probe the proposal's weaknesses. Finally, teams were asked to revise and strengthen their proposals based on the stress-tests, either continuing to work separately or joining forces to create a merged revised proposal. At this point, the Middle Powers and Grassroots Deployment groups chose to merge, while the Vulnerable States and Private Sector groups worked separately.

3. Implications for solar geoengineering governance

3.1. Strategic sequencing

Each scenario presented a snapshot of a challenge to which participant groups had to respond. This structure would be expected to encourage viewing the situation as a one-shot game, a single challenge followed by a single response. Groups' discussions showed the

inadequacy of such a static view, however, highlighting the need to consider strategic sequencing of actions, communications, and reactions. Every group considered strategic sequencing to some degree. For those responding to a challenge initiated by others—those in all scenarios except Middle Powers—this was limited to distinguishing their plans for near, medium, and long-term actions. These scenarios allowed only limited exploration of dynamics because the initiators were not represented by participants. The scenario specified initiators' opening actions, while their subsequent actions in response to groups' proposals were present only indirectly when groups provided stress-tests for each other. Groups' plans for later action were thus based on their speculation about others' responses to their earlier actions.

Middle Powers allowed more exploration of strategic sequencing, because these groups had to plan the initial intervention. They quickly realized that they could not achieve their goal in a single step, even if they had a clear view what their goal was. Instead, these participant groups reasoned explicitly through their initial moves, others' likely reactions, and their own subsequent responses and adjustments. This process yielded the insight that initial deployment actions would have multiple audiences and purposes. Even if the eventual goal is some desired climate conditions, the initial actions can only make small, uncertain contributions to this goal. The objectives of these early steps are thus dominated by other factors, particularly the initiators' attempts to manage others' perceptions and reactions.

3.2. Initiators: designing and explaining the challenge

Initiators are willing to take their bold step because severe climate impacts have put them in a situation that they judge to be intolerable. Consequently, one aim of their initial action is to shock world leaders out of complacency and bring solar geoengineering onto the agenda, but this is not their only aim. The initiators must also avoid triggering such extreme opposition that their efforts are crushed at the outset. They must broaden cooperation, promote reasoned discussion about all climate responses, and avoid escalating conflict. To pursue these aims, their first step must indeed be shocking—but not too shocking. The Middle Powers groups saw that this tension required their actions to be coherently coordinated in multiple dimensions: the deployment strategy, the accompanying governance measures, and the statements explaining what they were doing and why. They identified four ways to justify the disruption or make it appear less threatening: as a response to emergency conditions, as research rather than an operational intervention, as targeted regionally rather than globally, and as the first step toward broad multilateral cooperation.

Characterizing the initial disruption as an emergency response can help justify it and reduce the threat of a hostile reaction. Indeed, such suggestions were present, and taken seriously, in all scenarios. Rhetorically, even legally, a severe, imminent threat can excuse peremptory action and suspending normal decision procedures, perhaps even tolerating collateral damage. The power of emergency framing is clear in the current climate debate, especially in activists' calls for rapid mitigation, although this framing is also contested (Asayama, Bellamy, Geden, Pearce, & Hulme, 2019; Corbett, 2021). Justifying action by calling it an emergency response also has a few clear limits and risks. Others may suspect exaggeration of the threat or an attempt to ignore other relevant values. Moreover, people may agree on the presence of an emergency but disagree what action it warrants. Perhaps most importantly, an emergency can justify peremptory action for only a limited time, until other responses become available.

Portraying an initial solar geoengineering intervention as research can also mute hostile responses, again with limits. The need for expanded solar geoengineering research to inform climate-risk management is widely recognized, except by those who reject solar geoengineering under any conditions. In general, scientific research enjoys broad political support, as well as specific legal protections in some jurisdictions (Santosuosso, Sellaroli, & Fabio., 2007). Both Middle Powers groups described their initial interventions as research, although one of them—Bighorn Sheep—softened this in response to criticism for obscuring their subsequent operational aim. The most serious limit to justifying an intervention as research is that, as experiments expand in scale, research and implementation overlap: any intervention with expanded scale or intensity, or with new methods, will be uncertain in effect and thus serve a research function, even as impacts increase. If initiators plan to expand their activities, even conditionally on results of prior research, then justifying early steps as research can at most be temporarily true.

Presenting an intervention's aims and effects as regional rather than global can also frame it as less provocative and help deflect opposition. Interventions that aim to protect threatened national or regional resources, particularly uniquely valued ones, may attract widespread sympathy, or may be seen to fall within a state's sovereign discretion. For example, Australia's 2020 test of marine cloud brightening to protect the Great Barrier Reef attracted limited criticism, in contrast to the intense opposition to even small proposed experiments in stratospheric aerosol injection (Fountain & Flavelle, 2021). In Middle Powers, the Bear group took this approach by limiting their initial intervention to the Arctic region, which is highly sensitive to climate change and where their group had special interests—although they carefully avoided claiming any special legal authority to intervene there. The main limit to this framing is that no presently identified solar geoengineering method can achieve sustained, non-trivial regional climate effects without also having significant effects at larger and global scale. Issues of different methods' scale-dependence and implications for impacts and politics were not a major focus of this exercise but appear to be high priorities for further study.

A final way that initiators sought to mute early opposition was to signal their intention to give up unilateral control by expanding participation over time. Initiators in both state-led scenarios did this, although only the Middle Powers groups explicitly considered how to do it. In addition to stating this intention, both of these groups backed up their stated intention up by announcing provisional governance systems that were clearly designed to enable broader participation and shared control. Concrete steps to broaden control would present difficulties for initiators, who took the risk of starting the intervention and might be unwilling to share control with others who categorically reject solar geoengineering. We discuss these issues below in Subsection 3.6.

3.3. Respondents: support, opposition, and their bases

For groups responding to initiators' challenges, the most basic choice is whether, and how strongly, to support or oppose the intervention. Relative to the wide potential range from uncritical support to fully mobilized opposition, groups' responses in the exercise varied over a limited extent. No group welcomed the intervention in their scenario, or even tacitly supported it while making *pro forma* objections. Perhaps more surprisingly, none expressed categorical opposition. Closest to these extremes were the two groups in the Vulnerable States scenario, Lynx and Cougar. Even more strikingly, no group expressed either opposition or support for solar geoengineering itself.

Instead, the participants stated particularized and concrete geopolitical concerns, based on potential regional climate effects and who was initiating the intervention. Most objections pertained more to the prospect of larger future interventions than to the small initial deployments in the scenarios. The character of objections thus suggested the possibility of negotiating cooperation over specifics of intervention programs and their governance. In this regard, groups stressed the importance of effective monitoring, mechanisms to adjust or stop interventions if monitoring shows alarming changes, and compensation for real or alleged harms. Unfortunately, the exercise did not provide the opportunity to explore the specifics of such negotiations, which would present a valuable opportunity for further scenario analyses.

Here too the Middle Powers groups were in a unique situation, because only they had to anticipate other states' responses while designing the initial intervention. Both of these expected that the strongest opposition would come from Russia based on its interests in Arctic development and transport.[1] They believed that this opposition would be stronger to later expanded deployment that might reverse global heating than to their small initial program, and that opposition could be addressed through negotiation over the form and intensity of any deployment. Given uncertainty in any intervention's effects, the two Middle Powers groups proposed structuring these negotiations around pre-agreed thresholds in regional climate conditions which, if triggered, would require an intervention to be slowed, modified, or stopped.

3.4. Geopolitics and power

Groups' responses were strongly rooted in widely varying assumptions about the structure of the international system in 2040 and the distribution of power within it. As noted, the six groups responding to other initiators took rather moderate views, if any, on the substance of the intervention. This might have reflected disagreement within groups on the merits of solar geoengineering, which could prevent them from expressing a common view on solar geoengineering per se and thus shift their reactions to other, arguably less central, aspects of the initiators' provocation. It appears plausible that such deflection of response based on internal disagreement might appear in real responses to a solar geoengineering provocation.

In the Middle Powers scenario, groups assumed that the initiating states' reputations as good global citizens and reliable multilateralists would persist in 2040 and would give them room to maneuver by muting hostile reactions. In line with this assumption, they expected the strongest opposition to come from Russia based on its material interests in Arctic development and navigation, not from principled objections to solar geoengineering. Questions about other great powers' responses also figured strongly in discussions, generating some skepticism about the scenario. Some participants judged it unlikely that these states would take such disruptive action without prior consultation and at least tacit approval from one or more great powers. Because other nations were not represented in the exercise, however, potential responses by the major powers to the initiators' provocation were not explored further.

In the Vulnerable States scenario, understandings of geopolitical power underlay the strongest divergence between any pair of groups. These groups were tasked to advise a coalition of great powers how to respond to a solar geoengineering deployment by a group of climate-vulnerable but otherwise heterogeneous states, the "Climate Emergency Coalition" (CEC). Lynx treated the initiative mainly as a CEC bid for global dominance and responded forcefully to defend their own principals' supremacy. They denounced the CEC (disingenuously) for breaching norms of open and collaborative global governance and demanded that action on solar geoengineering be led by the UN Security Council—over which, as permanent members, they would exercise substantial control. They also proposed to covertly split the CEC by recruiting India, its most powerful member, with the offer of a permanent Security Council seat. Cougar, by contrast, took a conciliatory approach. While publicly criticizing the CEC initiative, they also privately offered cooperation to establish a new joint decision-making body to take over the intervention, with the aim that the body would grow into a multilateral solar geoengineering governance authority. The stress-tests revealed that these responses reflected strongly divergent geopolitical assumptions. Lynx understood the states they advised were still powerful enough to assert control and could do so through the legacy institution of the Security Council. Cougar's members either believed this great-power group was less powerful or rejected the attempt to exercise such control on normative grounds. Notably, both reactions can be read as maintaining a historical North/South binary but sympathizing with opposite sides. They thus implicitly rejected one element of the scenario, which had sought to undermine this historical binary by including a mix of industrialized and developing states in both the initiator and responder coalitions.

Neither Vulnerable States group specified how they expected their response to influence CEC behavior. Lynx proposed a relatively muscular response working through the Security Council, but specified neither what inducements the great powers would apply through that channel nor what they would do if the CEC defied them or their attempt to split India from the coalition failed. As

[1] This anticipated opposition distinguishes Russia from other high-latitude nations that have occasionally been proposed as benefiting from global heating. No other nation has even hinted at such benefits, perhaps because they are mainly concerned with the welfare of their high-latitude communities while Russia evinces more interest in long-term geopolitical advantage by Arctic development, transport, and military presence.

Cougar's stress-test pointed out, perceived state interests on solar geoengineering are likely to be uncertain and labile, suggesting the intriguing possibility that both the CEC and the Great Power Bloc—and both initiator and reactor groups in general—might be unstable and vulnerable to coalition-splitting. Cougar did not explain how their collegial approach would persuade CEC to accept dilution of their control, how the new decision-making body would reach agreement, or what they would do if the CEC rejected their offer.

In these two state-centric scenarios, coalitions are central. To the extent that solar geoengineering flattens and spreads the distribution of global power—a process for which there are several plausible mechanisms—this would raise the importance of broad coalitions. But a flatter distribution of global power would also undermine the "club" model of climate cooperation, which requires a few countries with outsized influence leading global cooperation (Nordhaus, 2015). Moreover, to the extent that solar geoengineering's uncertainties shift or destabilize perceived national interests, this may make any related coalitions unstable. The implications for solar geoengineering governance, and for climate response overall, may be large. For example, coalitional instability may call into question the widely expressed view that solar geoengineering must be governed in a global forum with universal participation. If relevant coalitions are unstable, they may be hard to form in the first place. And to the extent coalitions surmount this difficulty through strong internal commitment mechanisms, these may make intermediate-sized coalitions "sticky" by obstructing the flexible adjustment of commitments needed to attract new members as they expand toward global participation.

Whereas the two scenarios with state initiators highlighted assumptions about power distribution and potential conflict among states, the two with non-state initiators emphasized power relations between state and non-state actors. In Grassroots Deployment, participant groups—Elk and Mountain Goat—reasoned that any decentralized grassroots program like that described would present two serious physical risks that their response would have to address. First, uncoordinated grassroots action would likely be spatially heterogeneous, yielding uneven and potentially harmful effects. For example, a large imbalance between North and South hemispheres might shift the inter-tropical convergence zone and disrupt climate at low latitudes. Second, a program reliant on broad public participation might fluctuate widely as enthusiasm rises and falls. If such a program reached a scale with significant global climate impact, it would then present a risk of sudden termination.

Both groups in this scenario identified two specific governance capacities needed to address these risks: the ability to monitor interventions and effects with sufficiently fine resolution, and the ability to take over the intervention and smooth any resultant disruption in the event the program collapses. The groups agreed that states should start building these capabilities immediately but not attempt to control or stop the program before these are developed, as this might trigger a contrarian or more volatile response. They disagreed, however, whether governments should take immediate steps to prepare for such a future intervention or takeover. Mountain Goat proposed starting negotiations immediately for a treaty on solar geoengineering, as this might take years to complete. Elk, more concerned that even this step might trigger an unstable response, proposed delaying these negotiations while building up monitoring and contingency response capability.

For both Grassroots Deployment groups, the central question of this scenario was whether its main premises—an uncoordinated movement scaling to achieve a significant global effect, and governments having limited ability to control or stop it—were plausible enough to consider in planning. Probing this raised two potentially important issues about decentralized solar geoengineering movements that have not previously been considered. First, such movements might not be as "grassroots" as they appear. The scenario's sketch of a technology executive supporting the movement as a pet project raised questions of how much a decentralized program might be quietly driven by networks of concentrated private technology, capital, and power. Second, this prospect in turn implied the possibility of clandestine state support. The same climate urgency that motivated states to act directly in the first two scenarios could also lead them to fund and otherwise aid an ostensibly non-state initiative. Even limited, low-key backing might let states shape the movement, or subtly influence or test the reactions of other states, all while maintaining public deniability. Such tacit state support could strengthen the movement's ability to make a significant climate impact. If several states with diverse aims did this, the situation might resemble other forms of proxy inter-state conflict—uncoordinated, largely unaccountable, and unrestrained by international negotiations—and so risk making the initiative stronger, more volatile, and perhaps more destabilizing. On the other hand, if the scenario's premise of global scalability is wrong, then the program would serve only a symbolic or signaling function. In this case, tacit state involvement would still be possible, but would pose fewer risks and might even help. Quiet backing might help normalize solar geoengineering, provide a means for states to learn and communicate, or lay the groundwork for subsequent explicit state and international action.

The Private Sector scenario also raised doubts about plausibility, but these mainly concerned initiators' motivation rather than their capability—in particular, their interest in operating the program for public rather than private benefit. Both groups examined a few possible motives for participating firms. If governments are paying generously for CDR, firms might join simply to make money. They might seek to expand or signal their power and stature by filling a need at which governments failed. If some firms have grown to possess state-like scope of authority, their interests might also have broadened to overlap more with the public interest. Finally, fossil fuel producers might participate to defend their present businesses, as in the previous failed CDR effort described in the scenario.

Whatever firms' motivations, the Private Sector scenario also raised clear concerns about the scale of private power and the feasible extent of state scrutiny and control. Both groups with this scenario judged that states could probably prevail in a direct confrontation over control of the program, using a mix of legal, regulatory, and communication tools to attack the firms and weaken support for the initiative. Both also realized that such direct confrontation would be a blunt tool, not sufficient and perhaps not helpful in establishing effective public control. Moreover, even if states could fully take over the program, they might prefer to influence it indirectly and maintain deniability in case of mishap or harm.

The groups in the Private Sector scenario differed over states' likely ability to exercise and coordinate effective near-term public control. Otter suggested that firms might thwart state control efforts by simply concealing their activities or moving them to other jurisdictions. They thus proposed limiting near-term state response to "meta-governance" (see e.g. Coglianese & Mendelson, 2010):

imposing monitoring and transparency requirements while letting firms continue to design and implement the program. Wolf, more confident of state power, proposed that a group of states assert control by folding the initiative into a new public procurement program, which would contract for both solar geoengineering and CDR from firms and other organizations. This would provide revenues to support the project—an important element not clearly specified in the scenario—while shifting higher-order control over the scale, type, and trajectory of interventions from private to public actors. The proposed procurement program would also impose procedural requirements including, crucially, allowing additional firms or other organizations to bid to participate in implementation. Two key design questions not resolved in group discussions are: first, whether the new procurement program immediately displaces the private one or operates alongside it; and second, whether there is a single procurement program jointly operated by multiple governments, or separate ones overseen by states, presumably under some coordination or agreed high-level principles. The initiator firms' acquiescence to state control and participation by others would depend in part on financial flows large enough to make this change attractive. At the same time, the inclusion of both solar geoengineering and CDR in the same procurement program might alleviate concerns about excessive reliance on solar geoengineering, assuming that policy-makers can develop prudent and acceptable ways to manage the balance between these two activities while maintaining strong incentives for mitigation.

3.5. An integrated climate-change response

Although all four scenarios presented a solar geoengineering challenge after a long period of insufficient mitigation and CDR, a response to climate change dominated by solar geoengineering would be inadequate and dangerous. Yet the occurrence of the challenge could provide an opportunity to strengthen other responses and build an institutional structure for an effective integrated climate response. With weak mitigation and CDR, and no prior building of capacity to effectively govern solar geoengineering, moving from the specified challenge toward an effective climate response would require intensive international negotiations. These would have a broad agenda: to sharply strengthen mitigation and CDR, to legitimately govern solar geoengineering, and to integrate all elements of climate response. As discussed in the special collection's opening paper (Parson & Reynolds, 2021), the leading model for an optimal climate response that integrates geoengineering with other elements involves mitigation and CDR expanding over a century or so to stabilize then reduce atmospheric greenhouse gas concentrations, while a temporary program of solar geoengineering ramps up and down to reduce climate-change impacts until the other responses have reached full scale (Long & Shepherd, 2014). But while this model illustrates the contribution solar geoengineering can make, it is silent on how the various response types might interact, and on the political and policy conditions needed to sustain and coordinate them over a century or more. Commentators have especially noted the difficulties of ensuring that mitigation, CDR, and solar geoengineering complement and support each other, rather than competing for investment and political support (Parson, 2014; Reynolds, 2020).

Participants addressed these interactions among response types only to a limited degree. The Middle Powers groups viewed strong expansion of mitigation and CDR as essential for building effective climate governance and included strong commitments to these in announcing their solar geoengineering program. They could not explore these interactions further because other states were not represented in their scenario. Groups in the Private Sector scenario identified achieving an optimal mix of mitigation, CDR, and solar geoengineering as an objective, but struggled with how states could effectively steer powerful nonstate actors toward this end. Other groups' governance proposals did not specify how they expected negotiations over mitigation or CDR to interact with their proposed approaches to solar geoengineering governance.

This lack of explicit consideration of linkage to other responses may have reflected a limitation built into the scenarios. The saliency and shock of the proposed deployment challenges tended to focus groups' attention on immediate responses, particularly given the time constraints of the exercise. This may in turn have militated against the consultations needed to develop a more integrated climate-change response. This suggests that targeted explorations of these interactions would be a high-value area to investigate in future scenario exercises and related analyses.

3.6. Expanding participation in governance

Any effective and legitimate climate-change response will eventually require broad international cooperation. Consequently, even under the unfavorable background conditions in the scenarios, an initial challenge related to solar geoengineering deployment should be followed by negotiations to expand participation, institutionalize governance, and link solar geoengineering with other responses. Discussions in the exercise provide some insights into these subsequent steps, although its structure gave limited opportunity to consider them in depth.

All six reacting groups criticized the initiators' action as illegitimate, mainly based on narrow participation and lack of advance notice. This commonality is unsurprising. The critique that an action is illegitimate is often available but not necessarily informative as to what would be required to make it legitimate, other than the infeasible rhetorical endpoint of gaining the consent of all those affected by solar geoengineering (Szerszynski, Kearnes, Macnaghten, Owen, & Stilgoe., 2013). A more surprising uniformity was that no group tried to induce the initiators to reverse course, to put the solar geoengineering genie back in the bottle. Instead, groups protested to varying degrees but mainly worked to reduce disruption by bringing the initiators' action inside the fold of legitimacy by normalization or domestication.

While legitimacy requirements are ambiguous and contested, discussions suggested that moving solar geoengineering toward legitimacy would require two elements: expanding participation and control beyond the initiators, and institutionalizing governance, including decision-making, risk assessment, transparency, and compensation for harms. Building these elements will require international negotiations among initiators, initial opponents, and others. The large-scale shape of these negotiations would probably

involve initiators making concessions in the design and control of deployment programs, in return for others initially less favorable to solar geoengineering joining the program. Several groups' discussions implied that they expected this pattern. For example, the Middle Powers groups considered how to deal with anticipated Russian opposition and offered vague conditions on which others would be welcome to join, such as "if they support the basic aims of the program."

Other negotiation pathways are possible, however. This suggested negotiation structure assumes that states act from fixed and known material interests pertaining to solar geoengineering. In fact, the intensity, foundation, and stability of parties' views on solar geoengineering are not knowable at present, and may vary strongly under continuing climate change and response efforts. Some (non-initiator) states may categorically reject solar geoengineering use, despite the intriguing regularity that no group took that stance in this exercise. Others who were initially passive or opposed for reasons of conformity or blame avoidance might re-assess their stance once the initial challenge occurs. Once done for the first time, solar geoengineering might appear more normal and less frightening—a prospect that could mitigate some risks (e.g., global conflict) while exacerbating others (e.g., excessive reliance and mitigation displacement). Facing this range of possible responses, initiators might reject significant concessions except under concerted international pressure. This seems particularly likely if they view others as categorical opponents who are seeking control just to shut the program down or as rent seekers who threaten to veto and stymie negotiations in order to get a greater chare of the social surplus. Alternatively, having taken the first risky step, initiators may prefer to avoid responsibility and scrutiny by diluting or giving away control.

These issues were engaged most explicitly in the Middle Powers scenario, where groups advanced relatively specific governance proposals. These clearly aimed to approximate longer-term governance needs, based quite straightforwardly on proposals in the current literature. The exercise allowed detailed examination of neither these nor the shape of subsequent negotiations, due partly to the exercise's structure and time limits and partly to groups' reticence to express views on the substance of solar geoengineering. Exploring these negotiations should be high priorities for further scenario work on solar geoengineering.

4. Insights for scenario exercises

In addition to these substantive lessons on solar geoengineering governance, the exercise also provides insights into scenarios' uses and potential contributions. Developing the exercise presented a wide range of design choices, including the content of scenarios; the number and characteristics of participants; the tasks assigned to them, including required outputs, sequence, and interactions with other participants and organizers; the supporting materials and resources provided, including time; and the distribution of control between participants and organizers. While there is a large body of practical experience on these design elements, there is no single correct way to specify them. Instead, these choices are parameters to be adjusted and combined in ways that creates coherent, engaging, and productive experiences, suited to the issue being addressed and the objectives of the exercise. In this section, we discuss the lessons of the exercise from a methodological perspective, assessing strengths, weaknesses, and potential new directions.

This exercise targeted an issue marked by high stakes, long time-horizons, sharp disagreement, and deep socio-political and physical uncertainties for which prior research and practical experience provide little guidance. It sought modest progress against this dearth of information, aiming to generate better questions, sharpen and bound uncertainties, and suggest preliminary insights. While many aspects of solar geoengineering governance present serious and contested uncertainties, the exercise focused on one area: the initial form and instigator of challenges related to unauthorized deployment of solar geoengineering. The methods and process used should be assessed relative to these aims.

4.1. Participation

Two methodological criticisms made in the debriefing are quite general, applying to many scenario exercises, but still merit considering how applicable they are here: narrowness of participation and insufficient time. Concerns about participation's lack of breadth typically pertain to either expertise or identity dimensions such as gender, race, age, indigeneity, socio-economic status, religion, and nationality. Broader expertise expands the knowledge and conceptual base for discussions and is especially important when the tasks require specific competencies. Broader representation also serves the aim of strengthening processes and products by bringing in diverse styles of thought, but is particularly crucial in exercises whose aims relate closely to government or other authoritative decisions, where appropriate representation is necessary for the process or outputs to be viewed as legitimate. Too-narrow participation of either type relative to the exercise's focus, character, and purpose can lead to its outputs their being ignored or summarily rejected based on a flawed process.

Given this exercise's exploratory aims and long distance from any authoritative decision, the participation breadth requirements to meet the threshold of meriting consideration were neither particularly specific nor demanding. While further improvement is possible, in our view the exercise did acceptably well. Participation was limited, as so often, by practical constraints such as having a fixed set of participants at the Summer School and keeping each group small enough to encourage intensive collaborative work. Regarding expertise, the Summer School's participants and instructors included a substantial fraction of what presently exists regarding solar geoengineering and its governance. On the other hand, on issues marked by deep uncertainty, the precise areas of expertise that turn out to be relevant may not be known, or even knowable, in advance, but rather become evident as the work proceeds. In this exercise, more expertise in strategic international relations outside the climate and environmental context would have been helpful.

Regarding participant identity, the exercise did credibly, with sixty participants—leading researchers, post-graduate students, early-career researchers, and professionals—from sixteen countries. Given that a common symptom of insufficient diversity is too-easy convergence on a narrow technocratic perspective, the range of views expressed and vigor of arguments in the exercise suggest it

avoided that failure mode.

4.2. Time

Concerns about insufficient time are also advanced for many scenario exercises, as they were here. In those that assign roles, participants are often given demanding tasks that would in reality be assigned to large teams of highly competent, well-resourced professionals. In this respect, scenario exercises are like models: representations that greatly simplify reality to focus on the most important elements for the given problem. If participants take their assigned tasks seriously, they will be keenly aware—as ours were—of the disparity between what they can do and what those actually holding the specified responsibilities could do. Yet despite their simplification, scenario exercises can contribute significant insights. The outputs from this exercise, in our view, pass the bar of meriting serious consideration and are not discredited by the limitation of time.

Still, there are specific respects in which this exercise clearly did suffer due to time limitations. Participants were under acute deadline pressure at every step. This made for a few instances of task confusion and misunderstanding between groups, which could have been avoided with more time for calm consultation and more robust communication. Time pressure may also have diverted participants' attention toward meeting immediate demands and encouraging point-counterpoint argument using familiar formulas, rather than viewing the challenges with fresh eyes. Time pressure may also help explain the prominence of arguments and concerns from the present solar geoengineering debate in a greatly different context twenty years in the future: e.g., the prospect of solar geoengineering undermining emissions cuts, unequal regional impacts, and potential termination shock from abrupt cessation of a strong intervention—when the scenarios specified unauthorized but small deployments taking place after an additional twenty years of weak mitigation. Of course, the persistence of these concerns across diverse scenarios could have other possible interpretations. It may suggest the enduring importance of these concerns and their robustness to markedly changed circumstances, or reflect participants' deep engagement in the present debate, leading them to keep these issues front and center.

4.3. Plausibility

A widespread, although unintended, aspect of this exercise was participant skepticism about some scenarios' plausibility: most modestly, in Middle Powers, regarding the identified states' willingness to act alone; more so in Private Sector, regarding the leading firms' incentives; and most strenuously in Grassroots Deployment, regarding the network's ability to make a significant climate impact and states' inability to stop them. Participants nevertheless suspended their disbelief, with varying degrees of comfort. This led to two types of result, which are in some mutual tension other but appear to validate the scenarios' positioning on the boundary of plausibility—which is what the organizers sought.

On the one hand, groups' probing their doubts about plausibility raised informative new questions and led to instructive, sometimes creative, consideration of overlooked issues. In some cases, useful insights arose from reasoning backwards: instead of asking how likely are the scenario's stipulated actions, asking *if* these actions *did* occur, what would it mean about the state of world, the actors taking them, and the wider decision context? For example, doubts about Middle Powers raised the question, what could have led these countries to take such a disruptive step without prior consultation with great powers? This suggested several possibilities: that they are, in fact, acting with tacit backing from one or more great powers, which could be using the middle powers as proxies to test others' reactions; or that the great powers are still not paying attention to climate change, perhaps because they are preoccupied with defending their hegemony. Similarly, skepticism that a grassroots movement could achieve the specified intervention led to fruitful speculation that the initiative could only reach such scale with tacit support from powerful actors, government or private; or alternatively, that such a movement can only be a symbol or protest, aiming to demonstrate and normalize the method to induce states to take it over, scale it to effective levels, and integrate it with other climate responses.

On the other hand, these explorations affirmed groups' intuitions rejecting the scenarios' plausibility, absent such additional considerations. That these doubts were strongest and most persistent for the two nonstate-led scenarios suggests a surprisingly strong outcome of the exercise: that, contrary to one theme in the present literature, unauthorized deployments by non-state actors are unlikely absent tacit involvement of more powerful state actors (Parson, 2014). Consequently, consideration of future deployment may reasonably be limited to state actors.

An unanticipated methodological issue, with some commonalities to these implausibility objections, arose in the case of one participant group whose members objected to their assigned role in the Vulnerable States scenario. Cougar essentially declined to fully assume their assigned role advising a coalition of great powers, rejected the presumption of these great powers' continued hegemony and the Security Council's role in sustaining it, and spent considerable effort trying to help the vulnerable-state initiators to whom they were responding. This could be viewed as a failure of the exercise, insofar as the group's output could not predict or inform the actions of the great powers, but that was not the exercise's sole or even primary purpose. This group's stance revealed the possibility for scenario exercises to generate more motivated, penetrating, and potentially informative critique. Indeed, this experience provides a counterpoint to the frequently advocated use for scenarios, that of jointly building shared visions of desired futures. The group's reticence suggests the potentially generative value of putting participants in situations of moral discomfort. As with subjecting them to scenarios on the border of plausibility, such extremity—if it can be predicted and managed, which is difficult—may stimulate more intense, sustained, and penetrating inquiry.

4.4. Degree of control

In contrast to prominent strands in current scenario work, which give participants broad discretion to construct or revise scenarios within a larger-scale structure, this exercise imposed relatively strong constraints on groups. This was done for three purposes: to focus all groups on a specific identified risk, unauthorized solar geoengineering in the context of no international governance; to span a wide range of potential realizations of that risk; and to keep groups' outputs mutually comparable to facilitate inquiry into the robustness of their experiences and responses as well as the significance of their differences. One consequence of this design is to push the exercise toward breadth—considering multiple potential realizations of one important area of uncertainty—with resultant limitation to the depth of inquiry possible within each realization.

The exercise affirmed the benefits of this approach, but also revealed some of its limitations. The push to breadth made for imbalance among scenarios, both in plausibility and in depth of interest. In addition, some issues identified in discussions clearly merited more extensive exploration, including—as noted below—introducing more interactivity among distinct roles. The exercise lacked the flexibility to re-assess in mid-course, re-focus attention on these issues, and investigate them more deeply. It does, however, give guidance for further work, helping prioritize aspects of future deployment challenges for further exploration. We discuss these in the next section.

5. Synthesis and further work

In this section, we summarize the most salient insights from the exercise, both substantive and methodological, and identify areas for further use of scenario methods to explore solar geoengineering governance in the context of broad climate response.

Regarding solar geoengineering and its governance, the exercise first affirmed a few familiar points from the existing literature. For example, it reinforced the high value of early research on methods, efficacy, and risks, so future decisions related to deployment can be made based on a more robust knowledge base. It also confirmed the importance of an early start to consultations on governance, even if these begin not through official interstate channels but through alternative vehicles such as international cooperation on research programs, or "Track Two Diplomacy" exercises involving expert participants not presently in government office (Diamond, McDonald, & McDonald., 1996). The scenarios sharpened these familiar observations by showing how disruptive climate intervention-related challenges could occur even without such prior research and governance work, and how this lack of prior work would impair responses. As noted above, the exercise also re-affirmed, more ambiguously, several specific concerns that are prominent in the present debate, including mitigation displacement, regionally disparate impacts, and termination shock—although the prominence of these may be artifacts of methodology and participation.

Second, the scenario exercise demonstrated the unexpected difficulty of considering geoengineering, or climate-change response in general, separately from large-scale geopolitical issues. This reinforces the benefits noted above of starting research and governance development early, so responses to future challenges can draw on this prior work rather than being fully subsumed into the international politics of the time. It also suggests that further scenario work on solar geoengineering should be based on a range of explicit assumptions about the structure of international affairs and the distribution of power within it. For general climate-change assessments, the Shared Socio-Economic Pathways have developed such alternative global visions (O'Neill et al., 2017), which could with modest modifications support solar geoengineering scenarios.

Third, groups tended to react to even unprecedented and disruptive challenges by taming and normalizing them, bringing them within the fold of normal international politics to limit destabilizing risk, rather than confronting them or trying to shut them down. This follows the common tendency to integrate novel experiences into familiar categories of understanding and action. But the uniformity of this result across scenarios and groups is surprising, especially in view of widespread claims that any use of solar geoengineering not authorized by legitimate global bodies would be dangerously destabilizing. This regularity is reassuring insofar as it suggests the first reaction to a deployment challenge might not be confrontation and escalation, even without a robust governance capacity in place. The world is different after a disruption, so alarming advance statements about what a disruption will do often turn out wrong—particularly if the intent of those statements was in part to deter the disruption. This result may help calm the most extreme concerns about global conflict following a solar geoengineering deployment—although, like all scenario-based results, its validity as a real-world prediction must be viewed with caution.

Closely related to the absence of confrontational responses was the fact that no group expressed a substantive view about solar geoengineering in general, either favorable or opposed. (Russian opposition in the Middle Powers scenario is not an exception, because this was participants' speculation about another actor's response to their actions, not their own views.) All objections about deployment concerned specific conditions of anticipated risks, governance arrangements, or who was initiating the intervention. One possible explanation may be internal disagreement within groups, such that they could agree on reactions to peripheral or contingent matters that mapped more clearly onto familiar concerns, but not on the central novel challenge. This may offer a real insight into the difficulties of coalition-building and collective action on novel, uncertain, and polarizing technologies: Coalitions may be unstable, and internal agreement may be stronger and more stable on peripheral or procedural issues than on core substantive ones of the technology's acceptability or governance requirements.

Another possible implication of the normalization and the limited opposition is that opposition to solar geoengineering may be stronger and more categorical while it remains a hypothetical prospect. If and when the prospect is realized, more specific, practical, and contingent concerns may come to dominate. This suggests that disagreements over deployment may be manageable through negotiations over specific aspects of solar geoengineering's development, use, governance, and integration into climate policy. The importance of such discussions, and the possibility that they may suddenly be needed in a crisis, again indicate the high value of

advance exploration of broadly acceptable governance arrangements. Even if formal international negotiations are not feasible in advance, states should still do this contingency planning, separately or in small groups. Moreover, they should do this independent of their initial views of solar geoengineering, because it appears unlikely that a great or even medium power that perceives climate change as an existential threat could be deterred from pursuing solar geoengineering.

If a solar geoengineering challenge is then followed by formal negotiations, these observations suggest that negotiations may be less like militaristic brinksmanship and more like those on trade and finance, where mutually beneficial compromises are attainable, assuming the discussions have not been poisoned. Both challenge and response could thus be multi-step, iterative processes, by which initiators adjust their actions, widen participation, and dilute their control in search of stable and legitimate climate policy. Anticipating this process, initiators' objectives may be more concerned with signaling and setting the terms of subsequent negotiations, than with pursuing a specific climatic objective – although this process of course provides no guarantee against serious geopolitical conflict over the use of solar geoengineering.

Regarding scenario methods, the exercise affirmed the suitability and value of scenario-based methods for exploring solar geoengineering governance challenges. This was evident in the richness of discussion and the breadth, novelty, and plausibility of the insights generated. The exercise also provided guidance on how to direct future scenario-based explorations of solar geoengineering to deepen inquiry into more focused issues. For example, it suggests that future scenario-based inquiries should prioritize solar geoengineering challenges led by states rather than non-state actors. These should initially consider the implications of diverse states or coalitions as initiators, possibly with additional examination of state influence in deployment challenges ostensibly led by others.

These inquiries should be based on explicit, widely diverse assumptions about geopolitics and state power, including how widely or narrowly power is distributed and which states are dominant. Alternative assumptions on these matters may influence what kind of states or coalitions are more likely to initiate some form of solar geoengineering challenge, alter the likelihood of such a challenge, and modify the character of the actual or threatened climate intervention.

Based on this exercise, further scenario work on solar geoengineering should incrementally shift design and implementation, in several directions. It should shift from breadth toward depth, allowing more sustained exploration of specific areas that are important, complex, and difficult. It should increase interactivity by explicitly representing distinct actors negotiating with and reacting to each other, rather than just parallel groups doing the same tasks and critiquing each other. Without the push for breadth across diverse deployment scenarios that guided design of this exercise, further exercises should relax central direction and give participants more control. Finally, a diverse range of scenarios—up to the boundary of plausibility—and of exercise participants should be engaged.

Promising specific areas for further scenario-based explorations include, first, more extended examination of interactions around a deployment challenge. Both those initiating and reacting to the deployment challenge should be explicitly represented by participants—in effect, combining the initiator perspective of Middle Powers and the responder perspective of the other scenarios. This approach would allow deeper examination of relevant uncertainties, not just at the point of an initial provocative action but also in subsequent reactions and adjustments. It would entail giving participant teams more flexibility, both to develop their own responses and to probe and criticize others' actions and the design of the exercise, perhaps through periodic "process review" sessions. Optimal design would probably be sufficiently constrained to control the overall focus of the exercise and maintain comparability among groups, but somewhat more open and flexible than this exercise. Examination of potential deployment challenges and responses could also consider a broader set of intervention methods with different spatial scales, including marine cloud brightening and regionally targeted interventions, particularly in polar regions.

These exercises could represent the first part of a multi-step exploration, with subsequent parts representing further actions after an initial deployment. After the dust has settled on an initial challenge and the immediate, ad hoc reaction, there will remain the large task of negotiation to broaden participation toward an effective and legitimate global regime. Scenario exercises can explore various strategic tensions in these negotiations, initially that between expanding participation and diluting initiators' control, including explicit examination of the prospect that states' views may change after an initial unauthorized deployment. Related explorations of post-deployment issues might include responding to disagreements over goals, particularly in the context of parallel efforts to sharply scale up mitigation and CDR; managing complex interactions among solar geoengineering and other climate responses to sustain an effective overall climate-change strategy; dealing with unexpected climate changes that might be caused by an intervention program; and addressing claims of harm. A variant with a more optimistic premise, exploring such negotiations that aim to build effective governance capacity in advance of a disruptive deployment challenge, could complement these explorations of after-the-fact negotiations.

Solar geoengineering is a high-stakes but thus far neglected element of potential climate-change response which presents substantial potential gains as well as risks. It is growing more salient and controversial, and will very likely continue to do so as long as climate change remains a serious and inadequately managed concern. While much associated uncertainty is physical and technological, the most prominent uncertainties are deeply intertwined with social and political processes. These characteristics make it well fit for exploration and insight-generation through scenario exercises. This exercise demonstrates the potential value of such exercises, and urge further explorations using a wide range of methods and background assumptions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.futures.2021.102805.

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