ANTICIPATING FUTURE DEBATES ON CLIMATE INTERVENTION

Workshop Summary

March 14-15, 2023

Center for Global Security Research
LAWRENCE LIVERMORE NATIONAL LABORATORY

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On March 14-15, the Center for Global Security Research (CGSR) at Lawrence Livermore National Laboratory (LLNL) hosted a workshop titled "Anticipating Future Debates on Climate Intervention." This session brought together over 130 participants drawn across academic, scientific, and policy communities. The workshop aimed to examine: the role of climate intervention strategies to combat climate change; the technical, geopolitical, legal, social, and environmental risks of various strategies; and the appropriate level and type of governance.

Discussion was guided by the following key questions:

- Should climate intervention strategies be a part of global efforts to combat climate change?
- How do types of interventions differ in their potential to reduce impacts, create new climatic and geopolitical risks, and redistribute risks among nations?
- What level of global governance is needed to oversee research and set ethical and legal standards and limits?

Key take-aways:

1. Climate intervention will likely become an increasingly debated topic in the future, comparable to current and past intense debates about global warming. There are many potential forms of intervention, each with its supporters and opponents. Supporters see opportunities to help supplement mitigation strategies and provide an option in the event of overshoot. Opponents see risks of multiple kinds (technical, social, environmental, and ethical). All agree there are no risk-free options; all actions have tradeoffs and consequences.

2. There are two different types of climate interventions—carbon dioxide removal (CDR) and

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solar radiation management (SRM), also known as solar geoengineering. The two have considerably different approaches—CDR takes excess carbon dioxide out of the atmosphere and SRM aims to artificially cool the planet. Their risk profiles are also different—CDR is viewed as less risky and better understood while SRM is not well understood and has a myriad of unknowns.

3. Panelists believe technology-based CDR will be an essential component to the world's climate response but cautioned it's a backstop technology that should not take priority over mitigation efforts, has multiple barriers, and warned against scaling it up too quickly before it is technically ready, emphasizing "slow is smooth, and smooth is fast." Panelists believe it's too premature to label CDR as a moral hazard as growing GHG emissions will likely present a moral imperative for its future use.

4. The two main SRM techniques—Marine Cloud Brightening (MCB) and Stratospheric Aerosol Injection (SAI)—both have unknowns, in terms of efficacy and secondary and tertiary effects. SAI is perceived as most risky because of its long-time scale, lasting decades possibly over a century, non-uniform global effects, and potential adverse effects on precipitation, ecosystems, and agriculture in some regions. Supporters believe developing SRM is important in case artificial cooling is needed in an overshoot scenario. The United States, China, European countries, India, Australia, and Canada dominate research on SRM.

5. Panelists expressed concern for unilateral deployments of SAI, noting that an ideal, coordinated deployment in an overshoot and peak-shaving scenario used in model runs is highly unlikely. Instead, there will likely be multiple and consecutive deployments that are uncoordinated and conducted by different state and/or non-state actors. Modeling is the main tool used by scientists to understand SAI, but the models have limited observations and assume coordinated, planned injections.

6. Due to risks and unknowns, SRM deployment by private sector actors was condemned as unethical. While start-up companies have been increasingly eager to help solve the climate problem, panelists warned there is a lack of understanding of SRM's impacts and effects, and there are dangers to moving too fast. While CDR is more fitting for private sector involvement, the business model should account for social concerns and not be purely profit-driven.

7. SRM and CDR both have geopolitical risks, but they are different in nature. Geopolitical risks associated with CDR primarily involve countries prioritizing CDR over emissions mitigation efforts, causing divide among governments at international climate forums on the means for addressing climate change. SRM has greater and broader geopolitical risks beyond moral hazard, including how state and non-state actors use these technologies, and potential conflicts stemming from a large-scale uncoordinated, unilateral deployment.

8. Climate motivations to deploy SRM may become superseded by hegemonic strategies to increase one's world standing and lead global decision making. A country may perceive a first-mover advantage in large-scale deployment to set the rules and norms that other

countries must follow. Moreover, this could increase proliferation risks as other countries deploy to obtain a seat at the table and influence norms and/or governance. Countries opposing these activities could have a hard time articulating red lines and may perceive that they are being marginalized on a topic with global ramifications, instigating a global divide.

9. Another concern was the absence of a global governance framework on SRM—spanning research to technology development to deployment—to set standards and limits. Speakers agreed governments need to take the lead on governance, decision making, and norm setting—not scientists. There was concern that scientists were already setting de facto standards. Nonetheless, governments will have to consult with scientists to understand the science, prompting a central question— "who to trust?" The scientific community is divided on whether SRM should even be considered for future deployment.

10. Arguments around governance spanned from calls to create a new comprehensive global governance mechanism, "small governance," and a non-use agreement. The development of a new comprehensive governance mechanism had the most support. But supporters acknowledged that would take time and suggested initial implementation of stopgaps to initiate international dialogue. Those supporting "small governance" feared comprehensive governance too early could restrict SRM development.

11. The most hotly contested proposal was for a non-use agreement. Proponents of a non-use agreement argued SRM will have uneven regional effects impacting the provision of basic needs like food and water, will reduce mitigation efforts, and nations will be incapable of establishing a way to govern SRM deployment as the world lacks experience with building global institutions lasting over a century—the potential time scale of a significant, sustained deployment. Opponents argue a non-use agreement would restrict scientific research or drive it underground.

12. While there was broad consensus that governments should lead the charge on decision making, there was disagreement over who should be in the driver's seat. Some favored U.S. leadership in rule-setting. Some favored a one-country, one-vote system for better representation of Global South countries. Some argued a power structure will naturally form based on SRM capabilities. For example, if there are 10 nations capable of significant, sustained unilateral deployment of SRM, then they will likely dominant decision making and global governance.

Panel 1: Climate Intervention Controversy: The Good, the Bad, & the Unknown

- What types of climate intervention research is being pursued?
- What are the main debates and controversies around climate interventions?
- Should intervention strategies be a part of global efforts to mitigate or counter the effects of climate change?
    - What are public attitudes towards interventions?

Panelists provided an overview of climate intervention being pursued worldwide. Most current climate intervention activities are carbon dioxide removal (CDR) projects because CDR is more accepted and better understood among scientific and policy communities relative to solar geoengineering methods. Some examples of technology-based CDR projects include direct air capture (DAC) and storage projects in Iceland and Canada, bioenergy with carbon capture and storage (BEECS) in the United Kingdom, and enhanced weathering in Australia.

In terms of solar geoengineering, research is primarily done using models, such as the Geoengineering Model Intercomparison Project (GeoMIP) based out of Rutgers University. Some exceptions include a Marine Cloud Brightening (MCB) project in the Great Barrier Reef in Australia and Stratospheric Aerosol Injection (SAI) research and tests through Harvard University. While both MCB and SAI are both controversial—because of their potential global impact, uneven regional effects, and unknown primary, secondary, and tertiary effects—MCB is generally perceived as a more localized approach that can be used to intervene in the conservation of targeted environments, though effects will be felt beyond the research area. Space-based geoengineering—deploying an interplanetary sun shield for artificial dimming—is another solar geoengineering method, though underexplored and not widely accepted, and likely costing trillions of dollars.

Panelists stressed there are no risk-free options when addressing climate change; all decisions and actions have tradeoffs and consequences. Panelists emphasized climate intervention should always take the backseat to mitigation strategies. Panelists agreed solar geoengineering, also known as solar radiation management (SRM), is riskier than CDR, though the latter is not without risks, particularly ocean-based CDR. A 2022 study consisting of 125 expert interviews found 90% of experts believed CDR would be necessary to keep temperature rise from exceeding 1.5 or 2 degrees Celsius, while two-thirds believed SRM would not be needed. When looking at co-impacts of deploying 20 climate intervention options (10 CDR and 10 SRM), experts cited 52 reasons to pursue it and 55 reasons to not, spanning political, technical, environmental, and social reasons.

There were differing opinions among panelists and participants on whether CDR and SRM should be jointly discussed or kept separate. Those in favor of joint conversations noted discussions comparing the two could help policymakers decide what to choose from, pursuing SRM without CDR overtime would be dangerous because of excess greenhouse gas (GHG) in the atmosphere, and SRM could interfere with CDR—dimming the sunlight could affect bioenergy, solar energy, winds, and ocean currents. Those opposed to joint discussions noted CDR and SRM methods and risk profiles are too different, and lumping the two could lead to public opposition against both without fully understanding their differences.

Panelists expressed concern for unilateral deployment of SAI, noting that model runs of an ideal, coordinated deployment in an overshoot and peak-shaving scenario is highly unlikely in reality. Instead, there will likely be multiple and consecutive deployments that are uncoordinated and conducted by either different states and/or non-state actors. Another concern was the absence of an overarching governance framework on SRM—spanning research, development, and deployment—to set standards and limits. Potential weaponization and militarization by rogue actors or the redistribution of military assets to protect CDR storage sites, for example, was also in question. A future large-scale SAI deployment could lead to miscalculation and misattribution if one country blames another for a prolonged drought. Furthermore, countries may seek to develop counter-geoengineering techniques to monitor, detect, and then counteract cooling.

There are some governments engaging in conversations about climate intervention options, but for the most part governments in the Global North and South understand very little about these options, especially SRM. While governments recognize in private that overshooting the 1.5-degree target is likely, they are hesitant to speak publicly in fear it will reduce the public resolve to act. Nonetheless, there are signs the resolution proposed by the Swiss at the 2019 United Nations Environment Assembly—which recommended a preliminary governance framework for CDR and SRM response options but was not adopted—might be revived in an updated form and put forth for potential adoption.

Local opposition towards SRM has led to the suspension of some projects. Most notably, Harvard's SCoPEx project test, which was planned to take place in Sweden in June 2021, was canceled by the Swedish Space Corporation following protests from local indigenous and environmental groups. Some SRM projects have re-branded away from solar geoengineering by correlating with specific benefits such as "reef protection."

A central question that governments and their respective populations will face is "who to trust?" On SRM, the scientific community is divided on whether it should even be considered for future deployment. Several climate advocacy groups caution against climate intervention altogether over concerns of moral hazard—that climate intervention will detract from emissions abatement. Moreover, this issue is rife for conspiracy theories and disinformation, which can influence public opinion. Surveys are underway to understand how various groups, including faith-based groups and various groups in the Global South, view SRM. Surveys and interviews conducted thus far with participants in the Global South have generated mixed results, with some workshop participants expressing concerns with ways in which questions are framed to survey participants.

Panel 2: Carbon Dioxide Removal: The Acceptable Approach?

- What are barriers (political, economic, and technical) to large-scale deployment of technology-based CDR (land- and ocean-based)?
- What level of deployment is acceptable? What are potential risks?
- To what extent should large-scale deployment efforts be coordinated and measured across countries?

There was consensus among panelists that carbon dioxide removal (CDR) strategies will be an essential component to the world's climate response but cautioned that it's a backstop technology that should not take priority over mitigation efforts, has multiple barriers, and warned against scaling up technology-based CDR too quickly before it is technically ready. Panelists believed it was too premature to label CDR as a moral hazard as growing GHG emissions will likely present a moral imperative for its future use. Models show by the mid-century, the world may need up to 10 gigatons of CDR per year—equivalent to twice the size of the global oil industry today—to support global climate efforts. One panelist noted CDR may also be needed to avoid riskier intervention like SRM.

There are various types of CDR technologies—direct air capture (DAC), BEECS, and carbon capture, utilization, and storage (CCUS) at power plant and industrial sites—all worthy of some research, but none are clear winners. Barriers to technology-based CDR include geological storage, land use, energy use, costs, and food tradeoffs. Geological storage is needed to store the extracted carbon underground. In the United States, there is potential for large geological storage along the Gulf Coast, but pipelines would have to be built to enable transportation to storage sites.

Land use is a major barrier, likely to constrain the expansion of CDR rather than cost. Land is needed for infrastructure to support CDR operations like DAC facilities and pipelines, for associated infrastructure like solar and wind farms to provide clean energy to facilities, and to grow bioenergy. CDR technologies require substantive amounts of energy to fuel operations, and the additional amounts of clean energy needed to operate facilities would add to costs. There's also the concern of leakage—taking renewable energy away from other uses. Natural gas supplies will likely be needed to power DAC facilities in the interim absent enough renewable energy. Cost is also a concern, as technology-based CDR is very expensive, but the cost of CDR is expected to fall as the amount of carbon extracted and stored increases. Cost estimates for DAC range from $100 to $300 per tonne of carbon dioxide.

Panelists emphasized discussions around barriers should also include social dimensions, examining how CDR operations will affect society and vulnerable communities. The location of CDR facilities and storage sites are also of concern, particularly if they are located alongside vulnerable or rural communities living in areas that land is less costly. CDR methods incorporating biomass prompt concerns about competition with food.

While CDR is widely accepted as a supplement to mitigation by policymakers in several developed, emerging, and developing countries alike, there are non-governmental environmental organizations that believe it's a false, profit-driven solution that detracts from mitigation. Panelists noted the business model the CDR industry follows will in part influence the public's trust or distrust. Panelists stressed the business model should account for social concerns and not be profit-driven—though the latter will prove difficult as financial incentives are needed to prompt investments if public funds are insufficient. The United States—given its energy, land, and sequestration resources—may be well positioned as a test bed for figuring out how to develop a business model with reasonable costs, not overly profitable, but offers enough financial security to incentivize private sector participation.

A central question with CDR is how much should be done within rational guard rails and provide benefits? A national study found 500 million tons per year of removal was achievable in the United States. Another recent study "Getting to Neutral: Options for Negative Carbon Emissions in California" provides an example of how other states or countries can determine the level of removal. The study included nature-based CDR, biomass solutions, and DAC. However, panelists noted shortcomings and uncertainties with nature-based CDR, like reforestation and wetlands restoration, and believed nature-based options cannot alone fix the GHG problem. Panelists also noted getting high quality removal is difficult, and the additional benefits of nature-based solutions are at times speculative.

While panelists hailed the positive prospects of technology-based CDR, they warned against hastily scaling up the industry and promoted the maxim "slow is smooth, and smooth is fast." Recent announcements indicate billions of dollars will be poured into CDR projects, by various governments, including the United States, and private actors. However, panelists warned the market maturity for CDR is low and the technology is still immature and not ready for large-scale, widespread deployment. If deployed too prematurely, then technical issues might arise that affect the livelihoods of surrounding communities, like chemical spills or uncontrolled release of pressurized gases, triggering public opposition. Hence, CDR done poorly can damage public trust.

Panelists also believed it was too premature to start coordinating CDR deployments and measurements across countries before knowing how the industry will evolve. More specifically, because national-level CDR markets are still nascent and immature, it is likely too premature to build global consensus for agreements on how to account for all carbon removals. Different countries will need different market standards, incentives, and government policies to grow technology-based CDR. International standards for carbon accounting are ill-suited to incorporate carbon removal, and carbon accounting is already done in an inconsistent manner. Thus, international discussions on how CDR will be counted and verified under Paris agreement commitments is a good place to start.

Panel 3: Solar Geoengineering: The Technical Context

- Does it work? What are the economic costs?
- Do risks outweigh the perceived climate benefits?
- What do we not yet understand about possible unintended effects and do capabilities exist to evaluate this? What level of detection (of deployment and impact) is possible?

Panelists spoke about the two main SRM techniques—MCB and SAI. MCB increases the reflectivity of low clouds over parts of the ocean by shooting particles into clouds to make them brighter. It was inspired by emissions from ships, which hit marine clouds and increased their reflectivity. However, MCB's efficacy is still in question, and there is insufficient research to attribute cooling to MCB. Even if MCB could provide some level of cooling, there is still variability as some clouds are more susceptible to brightening than others, potentially limiting the prospects of MCB.

MCB is perceived as a less risky form of SRM compared with SAI as its effects are expected to be more local; however, there is not enough information to know how the technology would work on a regional or even global scale. MCB may still pose risks that have technical, social, and ethical impacts. Additionally, it takes years, on the scale of a decade, for ocean temperatures to adjust, so knowing the benefits and risks would require a longer form study.

SAI is perceived as a risky technology simply due to the vast number of unknowns. SAI entails sending liquid or solid particles into the stratosphere, where they can reflect some sunlight back into space. The concept is based on large volcanic eruptions that send particles and sulfur gases into the stratosphere, causing a cooling effect. However, volcanic cooling events are much smaller and temporary in scale compared with the SAI necessary to lower global temperatures overtime. SAI's efficacy—if it can produce significant cooling over the entire globe and over long periods of time—is unknown. Modeling is the main tool used by scientists to understand SAI, but the models have limited observations and assume a coordinated, planned injection, rather than multiple uncoordinated injections by multiple actors, which panelists and participants agreed would be the most likely scenario.

Scientists do not know the best injection strategy for SAI—where to inject, how often, how much, how long, and for what level of effect? The level of aerosol injections needed for an exact amount of cooling is not fully known. Panelists emphasized SAI would likely have non-uniform effects globally, and thus different nations will have different objectives for SAI, making a cohesive strategy difficult. The efficacy of SAI will also depend on the GHG emissions scenario the world is in, as the chemistry of the atmosphere will change the effects of SAI, thus making it even more complex to predict the impact. There could also be unknown impacts on biodiversity, and a possibility SAI could alter atmospheric chemistry in ways unknown.

Panelists agreed there is potential to evaluate, to an extent, some of these unknowns simply by fact that the field is understudied. Many of the unanswered research questions are due to limited funding and only a few groups of researchers studying the climate models. Additionally, increased collection of data from volcanic eruptions can help provide information on SAI. However, it would still be difficult to impossible to know all the unknowns, as there are significant limitations with extrapolating from field experiments to global effects.

Panelists noted the best method of deploying SAI was with aircraft, rather than balloons, which deploy at insufficient altitudes and amounts. To deploy SAI at an altitude to increase the efficacy of the aerosols, aircraft would have to be developed that can fly at altitudes above 20 kilometers. Though, it was noted that injections could happen at lower altitudes in certain parts of the world. A participant cited a 2020 study estimating the direct cost of a SAI program through the end of the century at $18 billion per year per degree Celsius of warming avoided; however, the amount of injections needed for an exact amount of cooling is not fully known.

The panelists emphasized the technologies, even if they produced cooling effects, could have negative, and uneven regional effects. Thus, deciding if the technology “works” depends on one’s perspective, as it may provide benefits to some and costs to others. While models have shown uneven regional effects and changing precipitation patterns, or even reductions in precipitation, there are still many unknowns. How will the introduction of aerosols effect the ozone layer? How would biodiversity, marine species, and ecosystems react to injections? How would it effect the food supply in certain regions? These are all unknowns.

Panelists agreed detection of deployment was possible as satellite imagery can detect volcanic eruptions. However, smaller scale deployments may be difficult to detect, but that level of deployment may be benign. Panelists agreed attributing cooling to SAI and MCB is not likely possible with current technologies, and it would take years of studying deployment to attribute the impact.

Panel 4: Solar Geoengineering, Part 2: The Global Context

- Which countries are researching and/or coordinating field tests?
- What are differences in international perspectives?
- What do modeled studies show about the regional and global effects of geoengineering experiments and potential “termination shock”?

The United States, China, European countries, India, Australia, and Canada dominate research on SRM, based on publications data from the Web of Science from 2009 to 2022. Ten countries make up 90% of publications. Researchers from the United States account for about 25% of publications, researchers in China for 20%, and the remaining countries are less than 10% each—the United Kingdom (U.K.), Germany, India, Italy, Australia, Spain, France, and Canada—which are listed in order of ranking. Panelists and several participants pointed out the Global South was underrepresented in academic publications on SRM and was often underrepresented or absent from international discussions about the direction of SRM and other geoengineering strategies. Nonetheless, there have been efforts to develop modeling teams from developing countries to analyze the impacts of SRM—one such project is the Degrees Modeling Fund started in 2018.

There have been surveys to gauge if developing countries support or do not support SRM. However, it was acknowledged the way polling questions are framed can introduce biases, and survey participants likely possess insufficient knowledge on SRM and its potential uneven impacts. A survey conducted with participants in Australia, Japan, South Korea, China, India, and the Philippines found varying feelings about SRM but strong agreement on the need for governance. An online survey of participants in Australia, Japan, India, and Philippines showed participants from the latter two countries supported climate geoengineering, but it was unclear whether that support was more for CDR or SRM.

Panelists overviewed various forms of SRM and related research occurring globally. In the United States, the University of Washington is conducting outdoor MCB field tests. A group at Harvard University is undertaking SAI research and experiments. In Japan, there is a project looking at typhoon modification called “TyphoonShot.” In China, there is ongoing research and publications, and the Sky River artificial rainmaking project, among other weather modification activities. Australia is undertaking a MCB project with its reef restoration and adaption program. India’s Council on Energy, Environment, and Water (CEEW) is conducting joint work with the Carnegie Climate Governance Initiative (C2G).

Panelists emphasized the social justice dimensions of SRM, and the importance of accounting for social justice when thinking about SRM. There are two feuding justice perspectives. The first perspective asserts SRM will promote the current systems of inequities and injustices and exacerbate tensions between the Global North and South. Powers in the Global North are likely to make decisions on deployment levels and location, among other factors, which may adversely affect developing countries because of the uneven regional effects. The alternative social justice perspective questions the underlying assumption of the traditional perspective that Global South countries will not want SRM. It asserts one should not assume developing countries would oppose SRM in the future because they are some of the most vulnerable to the effects of climate change. Nonetheless, there is some overlap between the two perspectives. Both perspectives urge for more direct engagement with the Global South to better understand their viewpoints. Both perspectives also promote increasing civil society engagement. Panelists, however, did not address potential divisions within the Global South (e.g., India prefers SRM but some countries in Africa are against it) or divisions within a given country as many countries in the Global South are not represented by democratic governments (e.g., the government wants to do it but the population fears outcomes of the risks).

In general, differences in perspectives of SRM are fueled by a lot of unknowns about the impacts of SAI and a lack of high-fidelity models with global observations that could reduce uncertainties. There is not yet a model that all scientists all over the world can trust because of information gaps, which are larger for some parts of the world that models lack observations for. Some studies showed how—depending on the crop, temperature rise, carbon dioxide concertation, and location—calorie yields from agriculture would fall in some regions and increase in others; this dynamic could complicate future negotiations about winners and losers and who should control the “global thermostat.” Similarly, studies have shown SRM could produce perturbations to seasonal rainfall, like reductions in summer monsoons, adversely impacting whole regions. One study showed injections in the tropical stratosphere and Arctic would cause cooling but might disrupt the Asian and African summer monsoons, reducing precipitation to the food supply for billions of people. Another showed an increased risk of malaria in certain regions due to changing movements of mosquitos in response to new climate conditions. There has not been an adequate study done to understand SAI’s impacts on ecosystems, as ecosystems that have adapted to higher temperatures might experience unintended, adverse effects in an event of artificial cooling.

Questions about destabilization of the climate when SAI is halted were discussed, commonly known as “termination shock.” How quickly the climate would shift after SAI stopped and how different regions would feel those repercussions varied, but almost all participants and panelists expressed uncertainty about their assessments and models. Another major complication is the burden placed on future generations, as scientists believe injections would have to continue for decades, possibly over a century to stabilize the system. There are unknowns on how and when injections could stop without inflicting termination shock. There were also questions about the GHG strategy pursued during this long period of injections; if GHG emissions continued growing during the artificial cooling period then that could complicate termination.

One panelist emphasized volcanic eruptions cannot be used to demonstrate the safety of SAI, contrary to a panelist on the previous panel. The panelist noted that the mission of the United Nations Framework Convention on Climate Change (UNFCCC) is to prevent dangerous anthropogenic interference with the climate system. While UNFCCC is focused on GHG emissions, the panelist questioned if SRM should also be included in UNFCCC's mission.

Panel 5: Localized Interventions: A Gateway to Solar Geoengineering?

- Does the growth in weather modification programs worldwide (like in China, the United States, and Middle East) present a gateway to solar geoengineering?
- Do localized interventions, such as cryosphere interventions in the Arctic, ease social license for solar geoengineering?
- How is the precautionary principle applied in the context of interventions? Does the principle support or oppose them?
    - Does the answer differ for localized interventions verses global interventions like solar geoengineering?

Panelists discussed forms of localized intervention like cloud seeding and cryosphere interventions in the Arctic. Panelists noted some similarities between local interventions and global interventions, in terms of unknowns with efficacy and impacts. However, panelists believed localized interventions did not present risks at the scale of SAI, though uncertainties would increase the larger the targeted area. Panelists noted opportunities for lessons learned for SRM researchers, such as engaging with local communities, agreements made between states in America on cloud seeding, and the role of the Northern American Weather Modification Council, which provides a venue for sharing experiences across states. Panelists did not address if localized interventions eased social license for solar geoengineering as it may be too premature to conclude.

Cloud seeding, which was used interchangeably with the term weather modification, is happening all around the world—the United States, China, Australia, United Arab Emirates, Saudi Arabia, South America, Europe, and Africa. Cloud seeding entails dispersing silver iodine into a cloud by aircraft, ground-based generators, or some countries use rockets. Ground-based seeding is cheaper but has challenges with dispersing it evenly, whereas aircraft are better at dispersing. The origins of cloud seeding date back to scientists in the United States in 1946 when the proof of concept was discovered. Although nearly 80 years ago, there are still unknowns with the science, especially with attribution—once a cloud is seeded there is currently no way of knowing what the cloud would have done without seeding. Because of variability of weather, cloud seeding experiments do not provide a large enough sample to achieve statistically significant results. However, a recent American experiment, SNOWIE, generated unambiguous test results that helped categorize and capture the potential for cloud-seeding to produce enhanced precipitation. Local agriculture communities in parts of the United States have expressed support for cloud seeding programs.

The unknowns of cloud-seeding technology mirror some of the unknowns and concerns with SRM. There are scientific concerns and unknowns with the efficacy of seeding and measuring impact, and societal and environmental effects are also potential worries. The possible liability of downstream effects from precipitation enhancement, like flooding, are difficult to quantify and calculate the risk. Similarly, understanding the environmental and health impacts of silver iodide as a seeding material, particularly as it accumulates in runoff or seeps into soil, is an important area of future research. However, unlike SAI, cloud seeding effects are over shorter time scales; therefore, adverse effects from seeding can be somewhat mitigated by halting the program, using existing suspension criteria.

The uncertainties around efficacy and impacts increase as a program scales up, and therefore, one panelist warned the ongoing expansion of China's cloud seeding program warrants more attention, especially as it could have cross-border effects. In Beijing, weather modification is done to improve weather conditions for large public ceremonies, and locals generally believe it works. Panelists disputed the efficacy of cloud seeding in China—as one noted the difficulties with attributing impacts but the other noted the consistency of good weather during major events.

Localized intervention research efforts are growing to conserve ice sheets in the Arctic, Greenland, and Antarctica. Scientists are looking into preserving ice sheets and sea ice by positioning underwater curtains in the deep channels to keep out warmer water, known as seabed anchored curtains, with a project being considered in Greenland. Researchers hope this can later be applied in Antarctica, though the legality of interventions in Antarctica is in question. Scientists have also looked into "targeted SAI" over the Arctic and believe it can cool the Arctic; however, the use of the word "targeted" may be a misnomer as the deployment would still affect areas beyond the Arctic. Moreover, Antarctica would probably need to be cooled by similar amounts, and balancing seasonal injections in the North and South would be tricky. In addition, the effects on the ocean and ozone are unknown.

Panelists stressed the importance of engaging with local communities to gain buy-in and learn from them. While local interventions can be used to alleviate climatic impacts on local communities, it may also present tradeoffs. For example, preserving ice sheets will affect the local fishing industry as melting ice expands fishing opportunities. Scientists must work with local communities to understand these tradeoffs.

A panelist emphasized localized interventions dealing with conservation of ice sheets are justified by the precautionary principle because doing nothing will cause environmental harm as ice thaws that cannot be refrozen. It was acknowledged, however, that it would be hard to apply the precautionary principle to solar geoengineering because of the global effects and non-uniform regional effects.

Panel 6: Private Sector Endeavors: Jumping the Gun or Innovating for the Future?

- How does one ensure public oversight of private sector activities (commercial and non-commercial)?
    - Is private funding a concern or an opportunity?
- What are the risks of companies commercializing solar geoengineering?
- Should there be restrictions on patenting solar geoengineering and/or CDR technologies?

There was broad consensus among panelists and participants that SRM should not be commercialized, and if proven to be an appropriate response to climate issues, should be considered a public good. There was disagreement among panelists and participants on whether there were risks with the commercialization of CDR. Some believed there were no unique risks with CDR commercialization, beyond the typical problems that could arise from the commercialization of emerging technologies in general. While others believed CDR commercialization could increase the risk of moral hazard and environmental problems associated with CDR operations. Nonetheless, all agreed that SRM commercialization and private sector involvement apart from government was most problematic, shifting the panel's focus to SRM.

Panelists provided an overview of the types of private actors that might unilaterally attempt to deploy SAI. "A lone Greenfinger, self-appointed protector of the planet," as described by political scientist David Victor in his 2008 article, is a depiction of a wealthy individual with the financial means to deploy SAI. Climate advocacy groups, as an act of civil disobedience, might also attempt some form of SAI deployment to catalyze actions on climate and make them feel like they are doing something to address the problem. Profit-driven, private companies may see a business case to starting SRM operations, though panelists pointed out a business case and model does not exist. A smaller scale SAI deployment isn't cost prohibitive for a wealthy person or group, but a large-scale, sustained SAI deployment might prove financially challenging for non-state actors.

Panelists emphasized private actors motivated by fear, fame, fortune, and/or fanaticism will be untrustworthy, and profit generation from SRM activities would be unethical. The role of the private sector in SRM should be reduced to providing procurement services for government decision makers. However, it was acknowledged that managing the private sector's role would be challenging absent governance at the national and/or international level.

The recent balloon launches by the U.S.-based start-up venture Make Sunsets and separately by U.K.-based researchers—in an attempt to inject aerosols into the stratosphere—showcase the challenges of keeping private actors at bay. While start-up companies have been increasingly eager to help solve the climate problem, panelists warned there is a lack of understanding of SRM's impacts and effects, and there are dangers to moving too fast. Panelists agreed the balloon launches by Make Sunsets were negligible without any likely effects. However, panelists stressed that its business model was misleading and could lead to other similar deceptive schemes, especially as it received $750,000 in venture capital funds to start. Make Sunsets sells $10 in cooling credits for releasing one gram of particles in the stratosphere and offsetting the warming effect of one ton of carbon for one year. Panelists and participants agreed those scientific claims of cooling and offsetting the warming effects of emissions by exact amounts were false, and launches were ineffective based on their scale.

The discussion on SRM deployment by the U.S. and U.K. entities led to a number of questions that proved difficult to answer. How do we set boundaries and limits for private actors? Who should draw those boundary lines—government regulators or a professional trade organization? Will private launches help to legitimize SRM or create a backlash? How do we avoid a start-up culture? There was also concern that developing countries would seek out SRM solutions from private actors ahead of governance dialogues.

Panelists had somewhat varying views on patenting SRM techniques and technologies. While panelists and many participants alike, were generally not in favor of SRM patenting, speakers also recognized the difficulties of limiting or prohibiting patents. Some of these challenges included the need for coordination across different governments to limit patents, uncertainty around what constitutes as a SRM invention, and the belief that patenting is a social norm. Some potential policy options to limit SRM-related patents discussed were implementation of compulsory licensing or march-in rights, (compulsory) patent pool, defensive patenting and defensive publication, or outright exclusion from patentability. While some believe SRM patents are inherently wrong, others contend they are not too concerned about patents but more so profit-driven companies deploying ineffective SRM that then become capable of influencing decision making.

Panel 7: Assessing Geopolitical Risks

- What are the geopolitical risks of large-scale climate interventions?
- Can some intervention strategies be weaponized?
- How would we ensure non-state actors do not get a hold of these capabilities?

SRM and CDR have geopolitical risks, but they are different in nature. Geopolitical risks associated with CDR primarily involve countries prioritizing CDR over emissions mitigation efforts, causing divide among governments at international climate forums on the means for addressing climate change. SRM also carries this similar risk of moral hazard, if some countries wish to use it to short-cut mitigation, causing a rift with other countries that believe it's an irresponsible option.

Panelists agreed SRM has greater and broader geopolitical risks beyond moral hazard, but somewhat disagreed on the degree of risk. The main risks identified are how state and non-state actors use SRM technologies, and potential conflicts stemming from large-scale uncoordinated, unilateral deployment. SRM could exacerbate existing tensions if a country blames its adversary for weather disasters and other perceived anomalies. Furthermore, tensions may flare if SRM techniques are applied in areas with divided ownership, like the Arctic. For instance, how would Russia react to intervention in the Arctic? SRM may not always be a key driver of conflict but could add to an array of existing issues underpinning tensions.

Climate motivations to deploy SRM may become superseded by hegemonic strategies to increase one's world standing and lead global decision making. A country may perceive a first-mover advantage in large-scale deployment to set the rules and norms that other countries must follow. Moreover, this could increase proliferation risks as other countries deploy to obtain a seat at the table and influence norms and/or governance. Countries opposing these activities could have a hard time articulating red lines and may perceive that they are being marginalized on a topic with global ramifications, instigating a global divide.

There was broad consensus that it was too early to conclude if SRM could be weaponized in the traditional sense of a direct weapon—due to our current understanding of its imprecise nature in terms of targeting, timing, and accuracy—but SRM could be weaponized in the broader sense as a tool of coercion or blackmail or become militarized. However, three issues make it difficult to use SRM effectively in that manner. First, SRM has global effects, meaning an attempt by a country to induce bad outcomes for another would have consequences for other countries, to include possible allies. Secondly, conducting SRM covertly is challenging because detection techniques and technologies exist, though attribution could prove difficult. Thirdly, the impact and effects of SRM, particularly SAI, typically have a long-time scale, so using SAI in a conflict situation may not produce the desired effects within a shorter timeframe. Nonetheless, the future emergence of new SRM techniques that act within smaller time scales, are difficult to detect, and have higher levels of precision and targeting cannot be ruled out, and governments should be aware and cautious of possible misuse of the technology.

While the existence of detection techniques makes it challenging for non-state actors to covertly deploy SRM, detection is unlikely to be enough to deter non-state actors. Therefore, thinking on SRM needs to shift away from evaluations of an ideal deployment in an overshoot and peak-shaving scenario because this assumes only a few state actors have deployment capabilities and/or are willing to deploy. Recent separate deployments by the two U.S. and U.K. private entities back that. Deployments can occur at various altitudes, and although they may not achieve cooling, it could spark the interests of other actors, state or non-state, to develop SRM capabilities.

Panelists identified opportunities for the United States, in partnership with other countries, to reduce risk. This includes closer cross government coordination; early multilateral standard setting to establish limits on the global level; better collaboration among scientists, defense and intelligence officials, and policymakers; and running unideal SAI scenarios to understand risks and anticipate responses. Due to the lack of formal multilateral discussions among governments on this topic, countries are not well-equipped with knowing what to do if there is a large-scale deployment and how to respond in a coordinated fashion. Issues of trust will likely plague a quick and coordinated global response. Governments and their respective populations will likely have trouble trusting scientists and models outside of their country. Moreover, countries will likely vie for leadership to fill the governance vacuum.

Panel 8: Anticipating Debates on Governance

- Should a governance mechanism be established?
  - If so, how does the world decide who controls the global thermostat?
- Can existing international legal mechanisms be used to set standards or limits?
- What interventions should be most and least supported, in terms of benefits versus costs or opportunities versus risks?

The panel focused on the governance of SRM, as the governance of CDR was viewed with less urgency, given lower overall risks, and the two interventions were too different to adequately address both. There was consensus that some form of governance or oversight for SRM was needed, but there was disagreement over the extent of governance. Most speakers believed a comprehensive, new governance mechanism was needed, but in the interim, stopgap measures would likely be more practical. Some expressed preference for incremental or "small governance" as to not restrict SRM development.

Those in favor of a comprehensive global governance mechanism emphasized that SRM is an unprecedented global issue with planetary and intergenerational ramifications. An SRM deployment could last decades, possibly over a century, thus charging future generations with the responsibility of maintaining the system and the present generation with the responsibility of creating a governance mechanism that can stand the test of time. The world lacks experience with building global institutions that can last over a century—the potential timescale of a SAI program.

Panelists and participants struggled to identify an analog for SRM deployment and its governance. The nonproliferation treaty, agreements between space powers, and genetic engineering (i.e., CRISPR) were briefly discussed as partial analogs, but differences were noted. One panelist likened a large-scale SRM deployment to an unprecedented, huge experiment with 8 billion people, triggering varying regional effects on ecosystems, weather conditions, and agriculture that would be unknown until years after deployment.

There was skepticism that the United Nations (UN) would be capable and equipped to govern SRM. The UN General Assembly lacks enforcement powers and decisions are not binding. The UN Environment Program is constrained in its capacity and mandate on environmental issues. The UN Framework Convention on Climate Change lacks the ability to manage the full spectrum of issues associated with SRM that go beyond climate like geopolitical risks and militarization. The UN Security Council has a strong mandate and veto power, but countries outside the council, which would be effected by a large-scale SRM deployment, would not like that five major countries have veto power on decision making on SRM. The UN Security Council, however, might be capable of playing a role in helping to resolve SRM-related conflict.

Panelists explained existing international legal mechanisms would likely be insufficient to set standards or limits. There are some existing international laws that discretely address aspects of climate interventions but fall far short from comprehensively addressing the issue. Existing international legal mechanisms include:

- Environmental Modification Treaty, which prohibits weather modification as a weapon.

- Montreal Protocol on Substances that Deplete the Ozone Layer, which regulates specified ozone-depleting substances.
- Convention on Biological Diversity, which imposed a moratorium on the deployment of geoengineering. It permits it once there is “adequate scientific basis on which to justify such activities” but does not provide a criterion to determine sufficient “scientific bases.”
- London Convention and London Protocol, which contains non-binding amendments prohibiting marine geoengineering.

Panelists stressed the importance of establishing governance before a crisis occurred to avoid heat-of-the-moment decision making. A central question is—what would a new governance mechanism look like? Would it be a one-country, one-vote system, or a weighted-voting system? Would a governance mechanism comprise a coalition of likeminded countries, or a coalition of countries with the technological and financial capabilities to run a sustained program? Absent a planetary manager that is rational and benevolent, governments will have to start making these tough decisions. Panelists put forth some considerations for a new global governance mechanism. Considerations included:

- Governance should encompass the different stages of SRM—from research, technology development, and deployment—and address how governance differs across those stages. The boundary lines between the stages are contested and blurred, and governments should come together in a multilateral forum to set norms to distinguish those boundaries.
- A governance framework could use the approach of explicitly listing prohibited and controlled activities.
- A governance framework should indicate if deployment is permitted or not, and if so, under what conditions, who can deploy SRM, for what duration, in what manner, at what level of intensity, and what location of deployment. It should address the question—who controls the global thermostat? Procedures should be put into place to guide how those decisions are made, such as a voting system, along with procedures for notification, transparency, and verification.
- Governance should address how to deal with uneven effects of SRM. Some countries might experience additional flooding or crop failure. Governance should address secondary and tertiary affects, if affected countries will be compensated, and if so, then how.
- Governance should account for geopolitical risks and establish some type of dispute mechanism.

Speakers agreed governments need to take the lead on governance, decision making, and norm setting—not non-state actors like scientists. There was concern that scientists were already setting de facto standards in some countries, which presented risks. But scientists will have to play a role in helping decision makers understand the science and what they are dealing with. Hence, the question of “who to trust” resurfaced. Given scientific unknowns, disagreements among scientists, and the field’s heavy reliance on modeling, which suffers from limited observations and is not always accurate, policymakers will likely have trouble determining who to trust about the science. In addition, policymakers will likely favor scientists from their home country as their assumptions and approaches might better account for their country’s interests.

While there was broad consensus that governments should lead the charge on decision making, there was disagreement over who should be in the driver’s seat. Some favored U.S. leadership in rule-setting, such as a U.S. catalyzed international approach that could be formal or informal. Some favored leadership from democratic nations in general, as their government decisions are more reflective of their populations. Some favored a one-country, one-vote system for better representation of Global South countries. Some argued a power structure will naturally form based on SRM capabilities. For example, if there are 10 nations capable of significant sustained unilateral deployment of SRM, then they will likely dominant decision making and global governance.

Panelists also recommended piecemeal and stop gap measures that might be more feasible to implement in the near term—emphasizing that some governance is better than no governance. It was noted that governance is often reactive, and thus, establishing a comprehensive global governance mechanism while SRM is at a premature stage would be difficult, especially as very little work is being done on this currently. Moreover, global consensus-building and figuring out enforceability will take some time. These stopgaps could at least serve as first steps to initiating dialogue among governments. Stopgap measures put forth for consideration included:

- Governance can focus on research alone, as a stepping-stone to broader international cooperation.
- States can establish and adhere to procedural norms—such as notification, transparency, and verification.
- States could enact domestic geoengineering legislation to set standards or limits. In early 2023, Mexico announced it would implement a strategy prohibiting SRM deployment within its national boundaries.
- An international organization or non-governmental organization can bring together scientists from the Global North and Global South to exchange information and build collaboration networks.
- States can come together to discuss potential large-scale SRM deployment scenarios, how states would engage in the event of conflict, and ways to reduce conflict.
- Early governance can draw a line between small and big interventions to distinguish between interventions that are innocuous versus those deserving of international attention.

An intensely debated proposal was the International Non-Use Agreement on Solar Geoengineering. The associated open letter has over 430 academic signatories, including some authors associated with the Intergovernmental Panel on Climate Change (IPCC) and about 90 scholars from the Global South. The open letter notes "proliferating calls for solar geoengineering research and development are cause for alarm." The letter expresses three fundamental concerns: 1) SRM risks are poorly understood and it will have varying regional effects on weather patterns, agriculture, and the provision of basic needs of food and water, 2) speculative hopes about SRM reduce the resolve for decarbonization and mitigation—the moral hazard, and 3) states will be unable to establish a way to govern SRM deployment globally "in a fair, inclusive, and effective manner." The non-use agreement contains commitments to no public funding, no outdoor experiments, not patents for SRM technologies, no SRM deployments, and no institutionalization of SRM as a policy option in global institutions.

Arguments against the non-use agreement emphasized SRM activities should be publicly funded to avoid profit-driven SRM activities and/or rogue actors making false scientific claims. There were also concerns a non-use agreement could restrict science research, decrease the diversity of research, and/or push research underground toward irresponsible actors. However, non-use agreement proponents contended the open letter commits to restrictions on deployment, not research, and scientists doing research into SRM have signed the letter. An element making this argument challenging is the overlapping and contested boundaries of research, technology development, and deployment. For example, one may categorize outside experiments as research, while another may say it’s a form of development or deployment. It was emphasized that governments should decide those boundaries, not scientists.

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