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CRITICAL REVIEW
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Showcasing work from Jorge Menna Baretto's studio and Sikina Jinnah's research group, University of California, Santa Cruz, United States.

Solar radiation management: a history of the governance and political milestones

Butter Architecture is a photographic series by Jorge Menna Barreto, presented here in dialogue with the critical review by Sikina Jinnah and Zachary Dove. Though created independently, the work became Barreto's response to the authors' invitation to bridge artistic and scientific perspectives. The melting butter tablets evoke the fragility of constructed worlds under heat, echoing SRM's tensions: between preservation and collapse, action and inertia. As environments dissolve, daily life continues—reflecting our difficulty in adjusting to a rapidly changing planet.

Jorge Menna Barreto, *Butter Architecture*, 2006–2021, photographic and film series; courtesy of the artist.

As featured in:

See Sikina Jinnah and Zachary Dove, *Environ. Sci.: Atmos.*, 2025, **5**, 656.

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Solar radiation management: a history of the governance and political milestones

Sikina Jinnah *[a] and Zachary Dove [b]

This paper provides a chronological review of the governance history of solar radiation management (SRM), also called solar geoengineering, from 2006 to 2024. Often characterized as an ungoverned space, we argue that the governance landscape for SRM is actually quite rich, though activity is primarily in the Global North, where research and governance capacity is concentrated. We illuminate the many governance initiatives and mechanisms in this area, explaining each mechanism's significance, relevant politics, and intersections with questions of environmental justice. We then identify gaps, limitations, possible future developments, and key contestations, including as related to justice. Crucially, as the chronological review shows, historical developments have largely occurred within a handful of countries in the Global North, laying bare the need to strengthen ongoing efforts to capacitate climate vulnerable countries in the Global South so they can more effectively shape the trajectory of SRM governance. We conclude by offering suggestions for future governance development.

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Environmental significance

Attention towards solar radiation management (SRM) is increasing and a number of efforts have been made since 2009 to govern its research. However, as we illuminate in this paper, the history of SRM governance has been largely driven by scientists and other actors in the Global North, whereas climate vulnerable communities particularly in the Global South have the most to gain or lose from decision-making on research and deployment. An international divide in the capacity to research and govern SRM risks undermining legitimate and informed decision-making and exacerbating climate injustice. Attempts to build research and governance capacity in the Global South must scale up alongside research on public engagement and global public perspectives in the context of a public, proactive, standardized, and centralized governance architecture.

Introduction

Solar radiation management (SRM) is a set of controversial technologies that might be considered to help ameliorate the worst impacts of climate change.† They would operate by reflecting a small amount of sunlight back into space, by for example, depositing reflective particles in the stratosphere, thereby cooling the planet. SRM does not address the underlying causes of climate change. Thus while controversial, there is consensus that if it is ever considered, it should never be used in place of mitigation or adaption. SRM is increasingly the subject of political discussions as climate change continues to worsen and policy lags far behind.

Although SRM is often characterized as an ungoverned space, we argue that the governance landscape for SRM is actually quite rich. We demonstrate this by providing a chronological review of SRM governance history from 2006 to 2024. We illuminate the many governance initiatives and mechanisms in this area, explaining each mechanism's significance, relevant politics, and intersections with questions of environmental justice. We then identify gaps, limitations, possible future developments, and key contestations, including as related to justice. Crucially, as the chronological review shows, historical developments have largely occurred within a handful of countries in the Global North, laying bare the need to strengthen ongoing efforts to capacitate climate vulnerable countries in the Global South so they can more effectively shape the trajectory of SRM governance. We conclude by offering suggestions for future governance development. Before delving into this history, we begin with a short discussion of what governance is and why it is important for guiding research, including on SRM.

What is governance and how can it guide research?

Governance is the set of structures and processes that are designed to organize and guide behavior on issues of public interest.[1] Governance is made up of norms, practices, policies,

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† Other synonymous terms used to describe these technologies include solar radiation modification and solar geoengineering.

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and other tools that steer or influence behavior in a particular issue area. It can be public or private, local, national or international, voluntary or mandatory, formal or informal (Table 1). Importantly, when well designed, governance can enhance benefits, decrease costs, and shape the distribution of costs and benefits across populations.

Governance has long been thought of as a constellation of overlapping and interacting parts. Building on the work of Nobel laureate Elinor Ostrom, scholars of the commons, particularly those interested in natural resource governance and public administration, have built a robust literature theorizing polycentric governance arrangements, wherein governance is characterized by multiple overlapping but decentralized centers of decision-making across scales, from the local to the global.[2,3] Those who focus largely on global governance have referred to these constellations as regime complexes, wherein several overlapping institutions steer behavior in a given issue area.[4] More recently scholars of global governance have identified hybrid institutional complexes, which include global but also private and sub-state institutions, among others.[5] Scholars have recently expanded the reach of governance even further, highlighting the role of expert assessments, such as those produced by national scientific academies as 'de facto' governance, which steers behavior by identifying and defining the very objects in need of governance.[6] All of these concepts have been extensively deployed to understand governance of climate change.[7–11]

On the ground, climate change governance includes a wide variety of tools including legally binding national requirements to report emissions or install best available technologies, voluntary corporate pledges for climate neutrality, international agreements that encourage the transfer of climate friendly technologies or the reduction of tariffs on climate friendly goods and services, comprehensive assessments of relevant scientific research, national-level emission reduction targets,

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Table 1 Types of governance

Governance can be	Example	Or	Example
Public	Law and policy	Private	University guidelines for public engagement
Local	City council permits	Global	United Nations resolutions; IPCC scientific assessments
Mandatory	Disclosure requirements; permitting; notifications	Voluntary	Best practices; codes of conduct
Enabling	Public funding; engagement as a means of building public trust	Constraining	Moratorium; ban

cross jurisdictional emissions trading schemes, public funding calls for climate-related research, expert assessments from scientific bodies, best practice guides for research, among many other tools and approaches.

Scientific research is also the subject of governance across fields. Research governance can be aimed at ensuring research remains in the public interest (*e.g.* Mission Driven Research), protecting human and environmental systems from negative impacts of research (*e.g.* Institutional Review Boards), identifying ethical standards (*e.g.* Helsinki Declaration) and best practices for scientific inquiry,[12,13] and setting standards for scientific excellence in prioritizing public investment (*e.g.* the UK's Research Excellence Framework).[14,15]

Importantly, governance is not synonymous with regulation. While governance tools can be used to regulate, constrain, or limit behavior in a mandatory way, this is just one governance approach. Governance can also be used to enable or push forward research. Governance can enhance opportunities for international collaboration by making research more transparent, creating public funding streams, and enhance legitimacy of novel science and technology development by aligning governance thereof more closely with societal values.[16–18] Some scholars have argued that expert assessments govern by institutionalizing and "normalizing" novel technologies.[6]

The remainder of this paper provides a chronological review of the governance history of solar radiation management (SRM) from 2006 to 2024. SRM refers to a set of highly controversial speculative technologies that appear capable of reducing climate impacts by reflecting sunlight away from the planet, thereby intentionally altering the Earth's radiative balance.[1] SRM is not a substitute for mitigation, adaptation, and CO_2 removal as it does not alter concentrations of atmospheric greenhouse gasses, however it appears capable of reducing climate risks in ways these other responses alone cannot.[1] Attention towards SRM has ramped up in the past couple of years as indicated by an explosion of new philanthropic research funding and the release of a plethora of high-level assessments commissioned by states and international organizations. This attention is likely to continue to increase in the context of a potential breakdown of international cooperation on climate action as well as alarming observations of global warming and its impacts, notably with global average temperatures peaking in 2024 at +1.6 °C relative to the temperature at the beginning of last century (the 1880–1920 average).[19] Though SRM may eventually end up being a useful tool within a broader climate response portfolio for achieving international temperature targets, SRM also raises an array of environmental and social risks and challenges that necessitate effective and inclusive governance of research and deployment, including in the near-term.[1]

Often characterized as an ungoverned space, we argue that the governance landscape for SRM is actually quite rich. We illuminate the many governance initiatives and developments in this area, explaining each development's significance and relevant politics. We then identify gaps, limitations, and key contestations within the broader historical trajectory of SRM governance, including as related to justice. Justice provides an important tool to evaluate historical developments in the governance trajectory of SRM. Justice is concerned with the fair treatment of people and other living things. It is also a broad and often contested concept that addresses many different types of concerns, including how decisions are made and how they impact different groups of people.[20] A key procedural principle of justice is that affected populations are able to influence and participate in decision-making on matters that affect them, particularly when they are impacted disproportionately.[20] The Global South, which is broadly vulnerable to climate change, is therefore expected to have the most at stake in decisions about whether and how SRM is researched and deployed.[21,22] Crucially, as the chronological review below shows, historical developments have largely occurred within a handful of countries in the Global North, laying bare the need to strengthen ongoing efforts to capacitate climate vulnerable countries in the Global South so they can also shape the trajectory of SRM governance. We conclude by offering suggestions for future governance development.

Decades of SRM governance (2006–2024)

Here we provide a chronological overview of the history of SRM governance by focusing on key developments and milestones from 2006 to 2024 (Table 2). Our aim here is not to be exhaustive of all developments but rather to highlight those developments, activities, and events that have – or are likely to – significantly shape or contribute to how SRM is researched, discussed, and governed. The overview is intended to be useful primarily to an audience of natural scientists that may be less familiar with SRM governance. In line with our broad understanding of governance discussed previously, we include here academic and NGO proposals and recommendations for SRM governance. Importantly, these governance proposals are considered sources of research governance in their own right, because they "seek to *identify and articulate* norms to influence how SRM R&D is

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Table 2 Timeline of key developments in SRM governance

Date	Key development	Type
2006	Paul Crutzen's *Climatic Change* editorial	Academic paper
2009	UK Royal Society's landmark report	Expert assessment
2009	Oxford Principles	Governance principles
2010	Asilomar International Conference and report	Governance principles
2010	Convention on Biological Diversity decision	International decision
2010	SPICE project funded	Research experiment
2010	SRMGI is established	NGO activity
2010	GeoMIP is established, standardizes simulations	Research community
2015	First NASEM report on geoengineering	Expert assessment
2017	Code of conduct for responsible research	Code of conduct
2018	FCEA ad hoc report on governance	Expert governance proposal
2018	Tollgate Principles on ethics and justice	Ethical principles
2018	SRMGI launches modelling research fund	Research program
2019	First resolution at UN Environment Assembly	International organization negotiation
2021	Second NASEM report on geoengineering	Expert assessment
2022	SRM non-use agreement proposed	Academic paper, open letter
2023	Make Sunsets and response from Mexico	Commercial deployment stunt, state response
2023	African Ministerial Conference call for non-use	Regional government resolution
2023	European Parliament resolution on SRM	Supranational government resolution
2023	United Nations Environment Programme report	Expert assessment
2023	White House Office of Science and Technology report	Government assessment
2023	DSG is founded	NGO activity
2024	Second resolution at UN Environment Assembly	International organization negotiation
2024	SCoPEx cancelled, Advisory Committee report	Research experiment
2024	Alameda marine cloud brightening experiment	Research experiment
2024	Emergence of US bills banning SRM on state-level	Subnational legislation
2024	AGU Ethical Framework for research	Ethical framework
2024	Pazstor governance report for Stardust Solutions	Commercial governance recommendations
2024	European Commission scientific and ethics reports	Expert assessment

conducted" (emphasis original).[23] Measuring the influence of these proposals is beyond the scope of this paper, however they are included because they are frequently cited and discussed in the SRM governance literature. We suggest that this indicates their influence on expert discussion which may translate into substantive contributions as more formal governance arrangements develop. As previously discussed, expert assessments can also order and shape SRM inquiry and discussion and therefore we include high-level authoritative assessments and reports as well.[6] We also discuss key developments in SRM research activity, including how they contribute to or are subject to governance. Interested readers can refer to more detailed reviews and analyses of these developments for further information.[24–27]

Although SRM has been discussed since at least the 1990s,[28] many credit Paul Crutzen's 2006 editorial in *Climatic Change* for initially catalyzing SRM in climate response discussions by challenging the taboo on SRM research.[29] In that paper Crutzen argued that while it is not the preferred solution, research on the potential benefits and risks of SRM should ramp up due to the "grossly unsuccessful attempts" to lower greenhouse gas emissions (212).[29]

On the heels of Crutzen's proposal, in 2009 the United Kingdom's Royal Society issued the first in a series of expert assessments of SRM.[30] Centrally, the report laid out foundational ideas that provided a framework for future governance discussions. Namely that: (1) SRM should never be considered a substitute for reducing emissions through mitigation; (2) deployment should never proceed governance; (3) more research is needed before any decisions can be made; (4) social and political issues will be equally important as technical ones; and (5) governance is missing but crucial.[30] The first idea – that SRM should not replace mitigation – has been mirrored in virtually every governance or scientific assessment or report that has followed. The norm reflects a consensus on the need to avoid moral hazard (also called mitigation deterrence), in which attention towards SRM reduces efforts to mitigate climate change through reducing emissions on individual or societal levels.[31,32] Though some dispute whether and how this would actually occur, moral hazard was a primary reason for the longstanding taboo on SRM research and continues to be a source of controversy.[31] The report was also influential for highlighting the importance of the social and specifically, governance dimensions of SRM, by emphasizing that the acceptability of SRM "will be determined as much by social, legal and political issues as by scientific and technical factors."[30]

2010 was a momentous year in SRM history. The Royal Society report directly set in motion several research and governance activities that would influence the trajectory of the field for the next decade and beyond. First, following publication of the Royal Society report, the UK House of Commons Select Committee on Science and Technology appointed a group of academics to recommend how geoengineering should be governed. That process yielded a list of five high-level principles for SRM research governance, which have come to be known as the Oxford Principles.[33] The Oxford Principles have been incredibly

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impactful, being reiterated time and again in nearly all subsequent expert assessments on this topic. See Box 1 below.

Box 1 – Oxford Principles[33]

Solar geoengineering should be regulated as a public good
Participation is required in decision making
Research should be disclosed and open access
Research should be independently assessed
Robust governance structures should be in place before any deployment takes place

Second, following on the heels of the Royal Society report's recommendation to fund an SRM research program, several of the UK Research Councils hosted a 'sandpit' in 2010 to develop novel research ideas related to geoengineering.[34] One of two research projects funded out of the sandpit was the Stratospheric Particle Injection for Climate Engineering SPICE project, which broadly aimed to investigate potential stratospheric aerosol particles that could be used to reflect sunlight, possible delivery mechanisms for those aerosols, and their potential impacts.[35] Significantly, part of the project included an outdoor engineering field test of a scaled down balloon and hose delivery system, which would have released a small amount of water to test the dynamics and behavior of the tethered balloon.[35] A stage gate process was established to govern the project, through which the research team would need to progress through several 'gates' in order for the Research Councils to release the funds for the outdoor portion.[34] The ultimate decision to release the funds would be made by the UK Research Councils, but on the advice of an independent stage gate panel consisting of several academics (natural and social sciences) and an NGO representative.[34] The criteria for the stage gates were inspired by the framework for responsible innovation that was at the time being developed by several social scientists, and which remains in use within the UK Research Councils to this day.[34,36] Briefly, the responsible innovation framework calls for research and innovation to be *anticipatory*, *reflexive*, *inclusively deliberative*, and *responsive* to the prior activities, ultimately aiming to ensure that research and innovation are responsive to society.[36] As informed by this framework, the SPICE research team was required to fulfill five criteria in order to proceed, related to: safety, risk management, and regulatory compliance (criteria 1 and 2), clear public communication of the project (criteria 3), anticipation of potential future applications and impacts (criteria 4), and engagement with publics and other interested groups (criteria 5).[34] The SPICE project PI eventually cancelled the field test. The reasons for the cancellation are complex and still debated, but include in part concerns surrounding a patent that included a member of the research team, as well as broader issues of governance and public engagement.[37] The SPICE project was significant within the wider trajectory of SRM governance for several reasons. First, it was the first proposed outdoor SRM related experiment that was subject to a deliberate governance effort, and which was informed by ideas surrounding responsible innovation that continue to be influential in SRM governance discussions to this day. Second, the project introduced SRM to wider public scrutiny and was the focus of intense controversy, fueled in part by a campaign led by a network of NGOs opposed to research and consideration of SRM, organized as a loose coalition under the Hands Off Mother Earth (HOME) Alliance, and which continues to be active.

The third significant development that occurred in the wake of the Royal Society report was the establishment of the Solar Radiation Management Governance Initiative (SRMGI), which has spearheaded capacity building and engagement surrounding SRM in the Global South. SRMGI was established in 2010 as a partnership between the Royal Society, the Environmental Defense Fund (EDF, a US-based NGO), and The World Academy of Sciences (TWAS, an Italy-based international organization acting as the academy of sciences for the developing world). The self-described governance initiative aimed early on to "foster an interdisciplinary and international discussion to develop ideas on how SRM research could appropriately be governed…" which was done "by assembling a working group and a range of international partner NGOs, and by producing background papers on SRM research governance, hosting an international conference, and by publishing [a] report of the process" which was hoped to inform SRM policy-making.[38] The international conference, hosted in 2011 in the United Kingdom, informed SRMGI's governance report, published in 2011. The report proposed a set of categories for different types of SRM research and discussed governance considerations for each category of research, emphasizing that 'differentiated governance arrangements' for different types of research would be more effective than a 'one-size-fits-all' approach to governance.[38] After releasing the report, SRMGI shifted focus to the Global South and began to host outreach workshops with local partner organizations "to start well-informed conversations about SRM in the local climate community and to get participant ideas on any next steps in their countries or regions."[39] SRMGI is responsible for co-organizing the first major events on SRM in the Global South, and has run close to 30 such workshops which have included over a thousand climate experts to date.[40,41] These efforts have made important contributions to expanding the conversation on SRM in the Global South.

Building on the model of the famous 1975 bioethics/biotech discussions at the same California location, the *Asilomar International Conference on Climate Intervention Technologies* was held in March 2010. That conference yielded a report entitled "Recommendations on Principles for Research into Climate Engineering Techniques."[42] Mirroring and extending beyond some of the ideas laid out in the Royal Society report and the

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Oxford Principles, the Asilomar report called for (1) promoting the collective benefit of humankind; (2) developing new mechanisms for the governance and oversight of large-scale climate engineering research activities; (3) research to be conducted openly and cooperatively, with broad international support; (4) iterative, independent technical assessments of research progress to inform the public and policymakers; and (5) public participation and consultation in research planning and oversight, assessments, and development of decision-making mechanisms and processes.[42] The report signals scientists' early awareness of the potentially controversial implications of SRM research and the need for researchers to carry out research responsibly.

Later that same year, the international policy community took up geoengineering, with a decision from the Conference of the Parties to the Convention on Biological Diversity (CBD). Often inaccurately referred to as a "ban" or a "moratorium", the decision "Invites parties…in the absence of science based, global, transparent and effective control and regulatory mechanisms for geoengineering… that no climate-related geo-engineering activities that may affect biodiversity take place…"[43] while important in articulating caution, the decision is not actually a ban because it is voluntary or non-binding, in that parties are "invited" not required to do this. Had this been intended as mandatory, the language would have said parties "shall" do this. This is a huge difference in terms of legal obligation and enforceability, which is often mischaracterized in SRM debates. The CBD decision was also limited in that it doesn't cover small scale outdoor experiments that would not affect biodiversity. It is also important to note that the US was not (and still is not) a party to the CBD, despite being a locus of geoengineering science. The decision was therefore highly circumscribed in terms of both scope and applicability.

Also significant for understanding the history of SRM governance is the initiation of the Geoengineering Model Intercomparison Project (GeoMIP) in 2010, which currently coordinates SRM modelling experiments among almost two dozen modelling groups in North America, Europe, Asia, and Australia. The community project is relevant to governance as the community hopes "to gather model consensus as to the likely climate effects of geoengineering in order to better inform the scientific community, policy makers, and the public."[44] GeoMIP does not aim to govern SRM research nor to prescribe specific policies.[44] However by coordinating SRM modelling experiments for the ultimate purpose of better informing SRM policy, governance experts have deemed that its activities are "likely to prove essential to future climate policy making and global governance."[45] GeoMIP is further noteworthy in demonstrating the self-prescribed role of many SRM experts in informing policy and catalyzing discussion on SRM, which suggests that scientists are not passive subjects of SRM governance, but are rather agents that purposefully inform or shape governance.

SRM governance was then relatively quiet until 2015, when the United States National Academies of Science, Engineering and Medicine (NASEM) released its first report on SRM, entitled "Climate Intervention: Reflecting Sunlight to Cool the Earth."[46] That report again underscored the Royal Society's recommendation from 2009, that mitigation must come first and importantly underscored that any research program on this topic must also include examination of human dimensions. It also recommended a deliberative process to examine governance of SRM research.

The NASEM report catalyzed a series of interventions that took up the recommendations to look at both social dimensions of SRM and research governance. In 2017 (updated in 2021), Ann Maria Hubert released a Code of Conduct for Responsible Geoengineering Research.[47,48] The code promoted near-term governance and aimed to guide decision making on topics, including: mitigation deterrence/moral hazard, cooperation, assessment, public participation, monitoring, and access to information, among others.[48] Being developed in tandem over three years and released in 2018, was the Forum for Climate Engineering Assessment's (FCEA) ad hoc expert group report on SRM, entitled "Governing Solar Radiation Management" (SRM).[49] FCEA's report again amplified key elements of prior governance reports and extended them in some important ways as well. FCEA recommended four objectives (Box 2) for SRM research governance, and 12 recommendations. Three recommendations are particularly important. First, FCEA underscored that the time of self-appointed expert reports (including their own) was over and that the field demanded the creation of public deliberative bodies to consider these highly controversial technologies. Second, drawing on learnings from the academic literature in global environmental politics, they emphasized that a new international institution was not necessarily needed nor possible. Rather they called on states to leverage capacities in international institutions to govern SRM. Third, while not the first to do so, it is worth noting that FCEA further underscored the importance of making research transparent and accountable. Importantly, although the experts disagreed on the desirability of SRM, the report represents a consensus statement on the need to govern research.

Box 2 – Forum for Climate Engineering Assessment's objectives for SRM Research[49]

Objectives
1. Keeping Mitigation and Adaptation First
2. Thoroughly and Transparently evaluating risks, burdens, and benefits
3. Enable responsible knowledge creation
4. Ensure robust governance before and consideration of deployment

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Also in 2018 ethicists Gardiner and Fragnière released the Tollgate Principles, which extended beyond prior frameworks in explicitly and more robustly centering ethics and justice.[50] Importantly, the authors noted that "…the original Oxford Principles… do not sufficiently lay the groundwork for the more substantive ethical debate that is needed, especially around values such as justice, respect and legitimacy" (143).[50] The Tollgate Principles called for organizing geoengineering policies such that they facilitate trust and accountability across nations, that decisions only be made after notification and consultation with those impacted, that for SRM to be policy-relevant, ethically defensible forms of it must be technically feasible on the relevant timeframe, that governance is ethically necessary, that geoengineering policies focus on protecting basic ethical interests and concerns (*e.g.* human rights), and that geoengineering policy should respect general ethical norms that are well-founded and salient to global environmental policy (*e.g.* justice, autonomy, beneficence).[50]

2018 is also noteworthy for the launching of SRMGI's DECIMALS Fund (Developing Country Impacts Modelling Analysis for SRM), now called the Degrees Modelling Fund (DMF) following SRMGI's transformation to the Degrees (DEveloping country Governance REsearch and Evaluation for SRM) Initiative in 2022. The Degrees Initiative also launched a Socio-Political Fund (SPF) for social science research in 2024. Both the DMF and SPF are the first research funds focused on funding SRM research in the Global South and they are "now the largest SRM research programme in the world and have supported over 170 researchers working across 37 projects in 22 developing countries."[51] Importantly, although the Degrees Initiative does fund research, it retains a governance focus, as indicated by its mission to change "the global environment in which SRM is evaluated, ensuring informed and confident representation from developing countries."[52] Its efforts to build SRM expertise in the Global South could in the future significantly influence international negotiations surrounding SRM, including as it extends its activities "to connect researchers with policymakers by supporting them to give briefings, contribute to reports and attend international discussions."[53] Scientific capacity and other SRM expertise is also a vital capacity needed to govern SRM.[54] As such, and as we discuss below, the Degrees Initiative's interventions have made important contributions to enabling greater agency and influence in the Global South to shape SRM discussion, research, and ultimately governance.

In 2019, the international policy community again took up the issue, this time within the United Nations Environment Assembly (UNEA). At that meeting parties considered a resolution on geoengineering that was put forward by Switzerland with support from Burkina Faso, Micronesia, Georgie, Liechtenstein, Mali, Mexico, Montenegro, Niger, Republic of Korea, and Senegal. The resolution was quite modest in scope, requesting that parties prepare an assessment of the status of geoengineering technologies to: define technologies, assess the current state of science, identify relevant actors and activities, assess knowledge of risks, benefits, and uncertainties, assess the state of governance and potential governance frameworks.[55] The proposed resolution did not pass. Rather, it was ultimately withdrawn from the floor before being voted on due to differing understandings of the governance landscape, the precautionary principle, and the lack of technical understanding across parties.[55]

The next important milestone in SRM governance was the release of the second NASEM report on the topic in 2021. This second report entitled, *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*, outlined a robust research agenda, across the social and physical sciences, including a recommendation for US$100–200 million in research funding with 20% of that going to the social dimensions.[56] Particularly important for governance of SRM, the report recommends additional work on public perceptions and engagement, exploring the implications of SRM for international relations, developing effective and adaptive governance processes and institutions for SRM governance, international cooperation on capacity building efforts, and incorporating ethics and justice consideration for current and future generations of SRM research and research governance.

SRM governance took an important turn in 2022 when a group of largely European scholars published an open letter and associated article promising a "non-use agreement".[57] The non-use agreement called for 5 things: no public funding;‡ no outdoor experiments; no patents; no deployment; and no institutionalization of SRM as a policy option, including in assessment by the Intergovernmental Panel on Climate Change (IPCC) (5).[57] The open letter has been signed by more than 500 people around the world and has catalyzed several responses in the form of competing open letters supporting research,[58,59] and academic responses.[60,61] The latter have pushed back especially on the demand to restrict international assessment, which would significantly limit capacity for informed governance on this set of highly controversial and potentially dangerous technologies. There have also been several statements of support for the non-use agreement in important political arenas. For example, the African Ministerial Conference on the Environment called for a non-use agreement in August 2023 (Decision 19/5), and it was also mentioned in a European Parliament Resolution in November 2023.[62,63]

In January of 2023, in response to a Silicon Valley-based startup called Make Sunsets deploying small scale SRM activities in their borders, Mexico issued a public statement prohibiting "any large-scale practice with solar geoengineering," citing

‡ There is some ambiguity in the call for no public funding. The graphical abstract of the non-use agreement article published in WIREs Climate Change says only "no public funding". In the text of the article, it appears the authors specify no public funding for development of the technology, calling on potential signatory countries to "prohibit their national funding agencies from supporting the development of technologies…". However, the lead author stated on his personal blog that the call is for no public funding for research (and presumably development too): "One argument is clear: the Open Letter calls upon governments to reserve all public research funding for decarbonization. Not for pipedreams of planetary geoengineering. Public research funding is taxpayers' money, and such budgetary decisions have nothing to do with "academic freedom". Societies must decide which type of research they want to pay for. We argue: public funds for mitigation research." See https://www.frankbiermann.org/post/solar-geoengineering-no-publicly-funded-research-without-a-plan-for-global-governance accessed March 27, 2025.

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among others a lack of consultation.[64] Interestingly, early academic work in Mexico finds that the Mexican public is generally more open to the possibility of SRM than publics in the United States and United Kingdom.[65,66] 2023 continued to be a active year for SRM governance with the release of a new expert report from the United Nations Environment Program (UNEP), entitled "One Atmosphere: An Independent Expert Review on Solar Radiation Modification and Research,"[67] as well as a report from the US White House[68] and a call for proposals from the US National Science Foundation.[69] On the former, UNEP called for a globally inclusive scientific assessment process, a multilateral governance framework, and enabling of more equitable participation, especially in developing countries.[67] The June 2023 US White House Office of Science and Technology's (OSTP) report was issued in response to a mandate from the US Congress and called for examination of societal and well as scientific dimensions and underscored the importance of international partners in research.[68] This was followed a few months later in September by a "Dear Colleague Letter" from the US National Science Foundation, soliciting SRM proposals that integrate physical and social sciences, to engage with ethical frameworks, governance structures, and/or environmental justice.[69]

2023 also saw the founding of another NGO likely to be influential in shaping the next chapter of SRM governance. The United States-based The Alliance for Just Deliberation on Solar Geoengineering (DSG) is "working towards the globally participatory and inclusive governance systems necessary for any [SRM] research and potential deployment."[70]§ Through a range of activities conducted collaboratively with partners in the Global South, the NGO aims to build governance capacity[61] for civil society and policymakers primarily in the Global South, foster regional collaboration, and enable informed and meaningful engagement in international discussion and decision-making. Some of the activities DSG co-hosted in their first full year of operation include a UNEA simulation exercise at Air University in Pakistan, capacity building workshops with youth organizations in Kenya, and an SRM scenario development workshop in India with an Indian research institute and a US-based scientist.[71] With a focus on policy and governance, the NGO aims "to provide science-based, impartial input into how to shape governance processes in the public sector and externally", by providing "a pathway for civil society organizations to provide input governance processes."[72] In 2024 DSG staff also engaged in international governance discussions on SRM, including through attendance at UNEA-6 and at Conferences of the Parties to the Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC).[71]

SRM came up again at UNEA in 2024, where another nearly identical resolution was proposed this time by Guinea, Senegal, Monaco, Switzerland, Georgia and Israel. There is no publicly available summary of the negotiations and reports from observer participants diverge in some ways. However the text of the proposal faced very strong disagreement,[73,74] especially from African countries, with Djibouti, on behalf of the African Group stating:

"SRM… poses severe and maybe even existential risks to Africa and to the world… The African Group also believes that SRM deflects responsibility for the fight against climate change from the humans who are responsible … SRM is likely to be considered as a silver bullet and will weaken our collective resolve to fight climate change. Additionally, there are so many uncertainties about SRM, including the impacts and risks of the use of the technology. Therefore, in accordance with the precautionary principle and in the absence of evidence of its safety and a full global consensus on its acceptability, the African Group continues to hold serious concerns about SRM. [We propose that] UNEP compile the views of the member states on this matter".[75]

Interestingly, despite this resistance to SRM, the Africa Group also proposed "a scientific consultative group on SRM with balanced regional representation" and supported UNEP leading international governance efforts on SRM.[75] The original Swiss proposal was eventually pared down to a new proposal, submitted by the Africa Group, for the Executive Director of UNEP to prepare a report outlining options for the creation of a publicly accessible repository of existing information, research, and activity on SRM, plus relevant submissions from states and interested groups.[73,74] Nevertheless, even this modest request was not accepted and the proposal was again withdrawn from the floor before a vote, with extensive debate on which institutions should be involved, if benefits should be researched alongside risks and uncertainties, if social science research should be included alongside scientific research, and if activities should go beyond compilation and access to information.

It should be noted that the non-use agreement was also referenced at this meeting, enjoying support from African countries, Brazil, Pakistan, and Fiji, and with opposition from the US.[73,75] Mexico, supported by Colombia, further "Deplor[ed] in the strongest possible terms, geoengineering experiments that have taken place without the authorization and consent of states, Indigenous People, or local communities."[75] This shift in language is interesting in that it suggests that Mexico's opposition is conditional on consent not absolute.

Another important governance effort has surrounded what would have been the first outdoor stratospheric aerosol injection experiment led by a team of scientists at Harvard University. The proposed experiment, called the Stratospheric Controlled Outdoor Perturbation Experiment (SCoPEx) was designed to measure the stratospheric behavior of aerosols in plumes to advance scientific knowledge relevant to SRM. In 2019, Harvard established an independent advisory committee to advise the university on if and under what conditions the experiment could proceed. SCoPEx was cancelled in March 2024 citing issues related to public engagement and several technical issues. However, the Advisory Committee did produce a comprehensive framework for governing individual experiments, outlining how to address issues related to five key areas: engineering and safety, scientific merit, financial transparency, legal compliance, and societal engagement,[76] while also noting

§ Note both authors have affiliations with DSG. Jinnah is a research partner and Dove is a research fellow.

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that experiment-level governance is "extremely challenging and should only be used in the absence of a more standardized and centralized approach".[77] Importantly, the Advisory Committee underscored that governance should be put in place, not only before deployment as called for widely in the literature, but also "long before any research plans are finalized."[76]

The importance of public engagement around outdoor experimentation was further underscored by the halting of another outdoor experiment in the US, this time a marine cloud brightening experiment in April 2024 in Alameda, CA. A team of researchers primarily from the University of Washington initially received permission from city staff to conduct an experiment involving a sea-salt aerosol spraying device on the back of a decommissioned aircraft carrier in the San Francisco Bay, but importantly, did not publicize the experiment prior to its commencement to minimize public controversy.[78] A New York Times article published after the experiment began featured quotes from the research team and at least one funder, and stated "the idea of interfering with nature is so contentious, organizers of Tuesday's test kept the details tightly held, concerned that critics would try to stop them."[78] This strategy appeared to backfire when community members and NGOs voiced an array of concerns to the city council, who eventually voted to end the experiment.[79] Representatives of NGOs opposed to SRM claimed "[s]trong interventions from numerous organisations including the Indigenous Environment Network, Friends of the Earth USA, Biofuelwatch, the Centre for International Environmental Law and Ocean Care also made sure that civil society voices counterbalanced those of the project's backers."[80] It appears that public engagement was planned to occur but only after the experiment began, as suggested by a press release from SilverLining, an NGO that partially funded the research. The press release, which was released a day following the New York Times article, suggested that the facility established at the aircraft carrier would be for both scientific research and public engagement.[81] Following the SPICE project and SCoPEx, this was the latest in a string of cancelled outdoor experiments and suggests future outdoor experimentation of any kind is likely to attract similar public scrutiny and controversy.

Also in the US, 2024 saw the emergence of over a dozen state-level bills banning geoengineering. The bills explicitly reference SRM, stratospheric aerosol injection, cloud seeding, and other forms of environmental modification, but appear to have been inspired by the 'chemtrail' conspiracy theory, which alleges that the US government or another entity is currently releasing harmful materials into the atmosphere *via* jet contrails for various nefarious purposes.[82] A Tennessee bill, which was successfully passed into law, for example, "prohibit[s] the intentional injection, release, or dispersion, by any means, of chemicals, chemical compounds, substances, or apparatus within the borders of this state into the atmosphere with the express purpose of affecting temperature, weather, or the intensity of the sunlight".[83] Similar bills were introduced in other states including Illinois, Kentucky, Minnesota, New Hampshire, Pennsylvania, Rhode Island, and South Dakota, but of these states, the bills are either dead or stalled. However, similar bills have been introduced in 19 states since the start of 2025.[84] Most ban and criminalize deployment, however the impact on any SRM research occurring in these states is unclear. Crucially, although the bills are inspired by the erroneous belief that someone is already deploying SRM, if passed into law there is concern they could create legal consequences for researchers hoping to conduct legitimate research on SRM.[84] As a lot of SRM research is dual-use, in that SRM research also contributes to our understanding of climate change and its impacts, this could potentially harm climate science more broadly.

2024 also saw the release of the American Geophysical Union's (AGU) Ethical Framework Principles for Climate Intervention Research, the first attempt by a scientific membership body to develop an ethics-based code of conduct for SRM research.[85] AGU's ethical framework provides guidance on best practices for ensuring responsible research, holistic climate justice, inclusive public participation, transparency, and informed governance. The AGU underscores that its framework should "grow and evolve, remaining open for updates as society's collective understanding of climate intervention technologies, governance frameworks, climate impact risks, and global societal needs evolves" (4).[85]

Across the globe in Israel (although with offices in the US) a private venture capital company, called Stardust Solutions, "aims to de-risk some of the critical technical challenges associated with SAI and to develop the necessary technological building blocks required for a safe, robust, and practical future deployment of SAI".[86] Stardust appointed an independent consultant, former United Nations Assistant Secretary-General for Climate Change and former Executive Director of the Carnegie Climate Governance Initiative (C2G), Janos Pazstor, to prepare a governance report for the company.[87] In his final report Pazstor noted that Stardust plans to develop and follow a voluntary Code Conduct. Pazstor further recommended that the company undertake its work with maximum transparency, proactively do outreach and engagement with key stakeholders, make the draft Code of Conduct publicly available as soon as possible, and obtain external validation of the scientific, technical, and socio-economic and cultural aspects of their work.[86] Crucially, Pazstor also recommended that, in light of widespread recognition that private ownership of SRM technology is not appropriate, Stardust and its investors should consider ensuring any intellectual property is freely available worldwide. Pazstor's report notes that Stardust has welcomed his recommendations and had no fundamental disagreement with them,[86] though Stardust has not yet indicated it plans to make its intellectual property freely available.

Finally, in 2024, the European Commission released reports from the Group of Chief Scientific Advisors[88] and the European Group on Ethics in Science and New Technologies[89] focused on the science and ethics of SRM, respectively. Importantly, both reports recommend a Europe-wide moratorium on SRM deployment, but with an exemption for responsible outdoor research and a regular review of the moratorium that may lead to its suspension if stringent criteria related to international governance, scientific evidence, and public inclusion are met. The

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reports also urge the negotiation of an international treaty and inclusive global governance system to operationalize the moratorium and ban SRM deployment in the near term, and also to proactively create a legitimate multilateral decision-making process for any future deployment of SRM.[88,89] Though more pronounced in the report focused on ethics, both reports emphasize the importance of responsible research and discussion on governance and justice issues and call for broad and inclusive public deliberation in assessing SRM's potential risks and benefits and shaping SRM research agendas. These are not the first reports to include competing expert viewpoints on the wisdom of SRM, they are remarkable for reflecting arguments from across the spectrum of opinion on SRM, demonstrating that SRM continues to remain deeply controversial and expert opinion is still split even within disciplinary boundaries.

Governance gaps and trajectory: more walk, less talk?

The historical trajectory of SRM governance laid out previously shows a rich backdrop of ideas and activities arising from 30 important developments and milestones that occurred since 2006. Though the SRM governance landscape is not an empty void, SRM is not sufficiently governed in at least two ways.

First, although some existing international organizations and processes have relevant mandates, policy and governance experts emphasize that none currently appear fully capable of effectively managing all of the risks and challenges associated with growing attention towards SRM.[49,55,90,91] Governance is fragmented, weak, reactive, and as our historical narrative shows, it has been largely driven by academics and NGOs, with public authorities so far mostly reluctant to enter the foray. With some exceptions highlighted previously, states and international organizations have so far largely failed to identify – let alone build – the governance capacities they will need to make legitimate and informed decisions about research or deployment.[49,55] Looking forward, states and the international organizations they create can take a stronger role in the next stages of SRM governance by translating the norms, principles, and other ideas in existing governance proposals thus far into specific and concrete mechanisms, initiatives, and processes.[23] This is not to say that governance initiatives from non-state or sub-state actors and efforts to elicit and integrate wider views and perspectives on governance should not continue; only that prospects for effective governance for SRM hinge on more state involvement, and on ideas being put into action. In other words, if 'talk' most accurately characterizes the history of SRM governance so far, to ensure sufficient governance capacity exists before decisions are made, the next stage of SRM history would benefit from a shift towards 'walk', especially among states.

Crucially, 'walk' does not mean deployment – it refers to various activities and initiatives that can expand state capacity to manage and balance risks and benefits associated with SRM research and deployment. The development of national SRM research programs may be near-term examples of 'walk', but other actions are possible and important to consider as well, such as the initiation of a national public awareness and engagement processes or the negotiation of international agreements to advance assessment activity and/or decision-making processes for research or deployment. 'Walk' may also take the form of national commitments to refrain from developing SRM technologies or negotiation of an international non-use agreement.[57,73]

Some SRM governance experts have previously argued based on previous work that, for example, the creation of a national research program is more likely to be placed on national agendas for serious consideration when the strategic efforts of policy advocates take advantage of a policy window under favorable conditions.[92,93] Policy windows may arise from changes in politics (such as an electoral change or shift in national mood) or from how climate change is understood (such as a threat to national interests or security following an extreme weather event). Policy advocates are also more likely to succeed in placing SRM on a national agenda when other favorable conditions are met, including when climate change is understood as a problem of national importance (*e.g.*, indicated by extreme weather events and public concern for climate change); when national political actors are advocating for an SRM research program (*e.g.*, indicated by public awareness of SRM and the dynamics of environmental NGOs); and when advocates advance proposals for research programs that, for example, reflect widely held values and are consistent with prevailing policy paradigms.[92,93] Additionally, for countries that understand their role within global politics as promoting multilateralism or stability, these countries are unlikely to 'walk' without others, such as the US, taking the first steps.[92]

These factors are likely to influence whether states create national SRM research programs or take other steps too. More broadly, these conditions are likely to be influential in shaping the trajectory of SRM governance moving forward. The perceived intensity of climate impacts, shifts in domestic and international politics and culture, progress (or lack thereof) in climate action, public awareness and perception, developments in scientific knowledge and technology, and actor's strategic activities are all likely to be some of the most important factors driving the next stage of SRM governance history.

The second way in which SRM is not sufficiently governed relates to unevenness in governance sources, capacity, and activity. SRM as we have shown is not ungoverned but it is governed unequally; the capacity to research, assess, and govern SRM is concentrated in a handful of countries in the Global North,[94,95] who as shown in our historical overview have played an outsized role in driving the history of SRM governance so far. This means that not all states are currently capable of 'walking' as fast or as far as others. Concrete disparities in scientific capacity and expertise, as indicated by SRM research output, have already been documented.[94,96,97] The capacity divide has been highlighted many times by others,[96] but it remains an important defining feature of the field's historical trajectory, though as discussed below there are some positive indications that this may be changing.

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Other disparities in capacity specific to SRM that are likely to be relevant for global governance have yet to be identified or documented in detail. These are likely to relate to other forms of capacity required for governance, including capacities related to societal deliberation, consensus building, representation in international negotiations, and policy formulation and implementation.[94] While academic analyses can be helpful for identifying capacities that are needed for governance and pointing towards the most important existing gaps, we suggest that detailed investigations of concrete governance capacity gaps are best conducted by integrating the knowledge and experience of policymakers or other local actors that are familiar with what local capacities already exist and where it makes sense to prioritize capacity building efforts as informed by local needs.[94] Co-production of capacity assessments may be one promising way forward, including as informed by relevant literature on capacity building, international development, and policy capacity.[98,99]

The possibility of a growing divide in terms of research and governance capacity between North and South is likely to be a key barrier to establishing multilateral and inclusive governance that can enable responsible research activity to proceed, further undermining the potential for informed and legitimate multilateral decision-making on SRM.[94] There are several reasons why we should expect the substantive and normative quality of governance to suffer if SRM research and governance capacity remains so unevenly distributed between North and South. First, although disagreement remains on details of implementation, broad participation is widely seen as desirable on normative grounds, as a cornerstone of good governance and as a key principle for just decision-making.[1,21,22,49,100–102] In other words, enabling more equal global engagement in governance is the right thing to do and aligns with widely shared values. Second, governance scholars observe that those who participate in decision-making are more likely to accept the ultimate decision as legitimate and thereby either comply with the decision or refrain from contesting it further.[103] The effectiveness of decision-making requires that its participation, transparency, and processes are widely seen as legitimate, and countries are unlikely to accept being excluded from key decisions.[90] Third, the Global North does not have a monopoly on information and knowledge that can be helpful in making wise and prudent decisions about SRM.[22,103] By involving the Global South in assessment and governance, and thereby integrating their knowledge, perspectives, and worldviews into a deliberative decision-making process, decisions are likely to be more robust.[22,103]

Several ongoing and previously discussed NGO-led efforts to close the SRM research and governance capacity divide aim to enable climate vulnerable countries in the Global South to more effectively shape the next chapter of SRM history. The Degrees Initiative, previously the Solar Radiation Management Governance Initiative (SRMGI), remains the longest running effort to broaden the SRM conversation and build SRM expertise in the Global South. Additionally, the US-based The Alliance for Just Deliberation on Solar Geoengineering (DSG) is far newer but has hit the ground running. Both of these NGO's efforts appear promising so far. For example, in 2024 alone, and in its first full year of operations, DSG hosted or co-hosted 13 workshops or other events across 7 countries and engaged with over 100 civil society organizations and policymakers, including one workshop series co-hosted with the African Climate Foundation that convened 180 participants from 14 African nations to engage in SRM governance discussions.[71] Additionally, as already discussed, the Degrees Initiative's research funds have to date supported over 170 researchers in 22 countries, and the supported researchers have published 35 articles (as of February 2025), including the first studies of SRM impacts in South America and the Caribbean, Africa, the Middle East, and Southeast Asia.[51] Additionally, some of the scientists that entered SRM research through the Degrees Initiative are playing influential roles in the field – including by serving on UN expert panels, contributing to efforts to plan modelling experiments through GeoMIP, and engaging with policy-makers, publics, and other interested groups on local, national, and regional levels, thereby further expanding the conversation on SRM in the Global South. The capacity divide is large, and closing it will require scaling up efforts and impacts over time. These efforts also are occurring in the context of a recent expansion of research funding from and for the Global North, meaning the relative capacity divide may widen even further despite gains in Global South capacity.

These efforts may be undermined by NGOs that are categorically opposed to SRM, often rejecting SRM as a 'false solution' on behalf of climate vulnerable communities and countries. Organized as a loose coalition under the Hands Off Mother Earth (HOME) Alliance, NGOs such as the Canada-based ETC Group, Germany-based Heinrich Böll Foundation, and the US-based Indigenous Environmental Network are vocally opposed to further research, assessment and international discussion on SRM, and support restrictive bans on outdoor experiments and deployment.[104] They have opposed with varying degrees of activity all SRM research experiments discussed previously and have also criticized many of the expert assessments and reports, which generally recognize the risks associated with SRM but also call for further research and discussion.[105]

Whether these NGOs gain greater influence on this topic is likely to depend on both their own efforts and activities and on many of the conditions discussed previously. For example, we might expect the influence of anti-SRM NGOs to grow if public concern towards SRM grows, if research identifies intolerable risks, and if opponents put forward sensible policy proposals (and *vice versa*).[92] We suggest this might also occur following unilateral or irresponsible SRM research, or the entry of actors such as commercial actors or militaries. Generally, if key concerns about SRM are widely perceived to manifest, including as related to moral hazard, ungovernability, misuse, and intolerable risk, we would expect these NGOs to become more influential and demand for a non-use agreement to grow. Alternatively, we might expect the influence of these NGOs to wane if climate impacts intensify, climate action continues to fall short, if support among publics particularly from countries in the Global South grows, and if research engenders greater

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confidence in the benefits of SRM. Similarly, their influence may also wane if countries demonstrate genuine effort to establish governance processes that are widely seen as legitimate, or if a well-run national research program provides clear public benefit.[106]

Recent activity discussed previously in the historical overview suggests non-use agreements and other forms of bans or moratoriums are likely to be a key battlefield in SRM politics into the near future. There are several ways a non-use agreement could be designed. On one end of the spectrum, and close to the vision outlined in the recent EC reports,[88,89] a temporary moratorium on deployment could enable responsible public research and assessment to proceed alongside further governance consultation and capacity building.[73] As with any attention towards SRM, the primary challenge will be to ensure mitigation through emissions reduction remains the priority. On the other end, a highly restrictive ban could prevent public funding for research and discourage international cooperation on research, assessment, and capacity building. This would likely widen the capacity divide and leave limited capacity at the international level to initiate broad, inclusive, and informed decision-making on SRM down the road.[61]

Several recent developments are also concerning for what they suggest might come next. On opposite ends of the spectrum, the rise in unconstrained profit-motivated commercial activity in the SRM field (Make Sunsets and Stardust Solutions) and the move to ban or criminalize SRM on the state level in the US is stoking fears that SRM either moves forward for private and not public benefit or is discarded prematurely, both of which would threaten prospects for the transparent and informed discussion and decision-making commentators agree is needed.[84]

Additionally, the political and economic turmoil occurring in the early months of the second Trump presidency in the US is creating tremendous uncertainty for the future of SRM and global governance writ large. The administration's recent actions to rollback, eliminate, or defund climate policy, action, and science, of which there are too many to name here,[107] undermine our ability to understand and reduce the risks of both climate change and SRM. Other actions that are reshaping US foreign policy and relationships with friends and adversaries alike also pose uncertain consequences for global politics, the distribution of power, and the international order.[108] International deadlock on SRM appeared likely even before Trump took office for the second time.[73] Because the US has been a key player in SRM research and negotiations at UNEA, and as the international politics of SRM are likely to play out in the context of wider tensions, dynamics, and relationships between states, these actions leave the fate of SRM – and the next chapter in the history of SRM governance – on very uncertain ground.

Of course, the social world is complex and outcomes are driven by many competing and interacting factors and dynamics that shape and are shaped by the purposive actions of creative social beings.[109] We cannot say what will happen, let alone what configuration of factors will with certainty deliver particular outcomes. Carefully planned scenario research can help us better explore key elements of uncertainty within possible futures of SRM governance including how different assumptions about changes in underlying conditions in the natural and social world could drive varying outcomes.[110] Scenarios can also help us explore the risks and opportunities associated with different potential actions – or forms of 'walk' – and help us dispel the not always helpful assumption that current trends will continue.[110] Ideally, scenario research can inform near-term decision-making by identifying research, capacity-building, and other forms of 'walk' that enable more capable navigation of future challenges.[110]

With any path forward, the prospect of path dependency, whereby past and current decisions shape the options available for future action, demands careful attention. There is a real risk that current actions create harms for future generations,[111] including by making the slope to deployment too slippery, or possibly even too sticky, in the case that future decision-making is overly constrained by bans and procedural hurdles created in the present.[112] To address these possibilities, anticipatory governance can be helpful, which entails building a set of capacities needed to manage emerging technologies while it is still possible to do so.[113,114] Efforts to build capacities related to foresight, societal engagement, and integration of diverse knowledge types can help governance steer SRM on a desirable trajectory, as defined through careful and inclusive deliberation between scientists, publics, policymakers, and other interested groups.[114]

In the near term, and in conjunction with the enhanced capacity building efforts already discussed, we identify three priority areas for strengthening anticipatory governance based off of our previous work. First, despite widespread agreement that decision-making should be shaped by the perspectives of climate vulnerable communities particularly in the Global South, we still know little about how climate vulnerable communities think about SRM and its research and governance.[115,116] Research that explores what and how different groups of people think about SRM is growing,[115] and there are several recent groundbreaking efforts to explore SRM perspectives research on the Global South.[117–121] However, given the quantity and diversity of people and perspectives in the Global South, these efforts represent the tip of the iceberg in terms of what we would need to be confident that we know what people think about SRM. Moreover, as our previous work shows, most perspectives research focuses on investigating whether people support SRM.[115] This is important information for decision-making, however, other aspects of what people think about SRM can help inform pressing challenges. These include, for example, public preferences for SRM governance such as whether they support different versions of a non-use agreement; public understandings of what justice means or requires in the SRM context; and when and how different publics expect to be engaged in decision-making.[115]

Second, as demonstrated throughout the historical narrative in the prior section, engagement with publics and impacted communities is frequently if not almost universally called for across authoritative assessments, reports, and governance proposals, signaling widespread agreement that engagement is desirable, at least in some ways, for some people, at some point in time, and for some purposes.[26,122,123] However, engagement does take many different forms, and people have varying

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opinions on who should be engaged, how, when, by whom, and for what purposes.[124,125] Though some general guiding principles are helpful, we do not believe that these are questions that can be answered *a priori* and divorced from particular contexts, as the answers are likely to depend on specific needs, available resources, and sociopolitical context.[124] Generally, we think that engagement is most useful when it occurs early, in advance of SRM field trials or other outdoor experiments so that research plans can be responsive to public values and knowledge.[126] We think that early engagement is also in general a necessary but not sufficient ingredient for enabling responsible research to proceed without steadfast public opposition, but others disagree. Some are instead worried that engagement will actually create or encourage public opposition in the first place, at least under certain conditions. For example, David Keith, who was previously involved in the cancelled SCoPEx experiment, told the media that while "not being open at all" is not the right approach, he also wonders whether the level of openness and engagement they aspired to achieve "maybe really doesn't work in a conflictual environment", and "[s]o maybe we should have been significantly less open and had a few limited sets of checks."[127] A New York Times article also quotes Keith as saying, "[a] lesson I've learned from this is that if we do this again, we won't be open in the same way."[128]

For those who believe that meaningful engagement requires providing an opportunity for local communities or a national public to say 'no' to controversial research, a retreat from engagement and openness raises concern. Others may counter that, in the case of outdoor experiments, local communities should not be able to veto research that could benefit climate vulnerable groups across the globe. This is likely to be an ongoing dilemma and source of debate. As debates surrounding public engagement and research have both ethical and empirical implications, ethical and empirical research on engagement can inform this debate and help us better understand how engagement should proceed. Engagement in general is also difficult to do well, and the abstract, uncertain, and speculative and technical nature of SRM raises additional methodological challenges engagement practitioners must face such as related to how the technology is framed.[123] Successful engagement requires leveraging capacities to, for example, identify its goals and assess who needs to be engaged and what is the most effective way to engage; adequately inform engagement participants to enable their meaningful participation without overly framing the issue; and integrate diverse perspectives into appropriate decision-making related to SRM research and governance. Capacity assessments should include these as well.

Third, empirical experience with governing small scale experiments has led experts to argue that the above suggestions should be implemented within the framework of a public, standardized, and sometimes centralized governance architecture that can draw on sufficient resources, capacity, and authority.[129] Ideally, this would look like a public government body at the national level (or subnational if necessary) that has the legal authority and capacity to spend public funds and enforce decisions related to whether and how SRM experiments can proceed. Such a body is needed for the purpose of setting clear standards and creating consistent and predictable processes for research experiments of different types. The exact processes used to govern experiments would need to be tailored to existing regulatory authority, culture, and practice, but would likely relate to criteria used to govern previous experiments on an ad-hoc basis, such as SCoPEx and SPICE. These include criteria as related to legal compliance, health and safety, scientific merit, public communication and engagement, financial transparency, and anticipation of the downstream uses of the research. Previous experience with ad-hoc governance at the level of individual research experiments highlights severe deficiencies with this approach, including as related to rushed timelines, internal disagreements, unclear lines of accountability, unpredictability, less chance of learning across experiments, and delayed communication and engagement.[129] Additionally, with SRM research currently being mostly funded through a patchwork of private organizations, the resulting lack of public oversight and transparency undermines public trust, constrains what is researched and discussed, and possibly even enables suppression of negative results.[130] A public body could helpfully standardize governance for privately funded experiments, but we think public funding is ideal, in part so that funds are released only after governance approval. Within the context of a publicly funded and governed mission-driven research program, public resources and regulatory experience can be used to ensure research activity is governed on the basis of clear standards and researchers, universities, funders, and other involved actors have the time, resources, and knowledge needed to fulfill them.[106,129] Weather modification permitting programs may be one place to look for inspiration to realize a standardized governance process for SRM experiments.[131]

National public research programs should be further enmeshed within an international framework for cooperation on research, assessment, and decision-making. The newly initiated Lighthouse Activity on Climate Intervention Research at the World Climate Research Programme (WCRP) may provide useful steps towards an assessment process that draws on broader forms of expertise and has a broader scope for assessment.[132] The Intergovernmental Panel on Climate Change (IPCC) has also decided to include SRM in its 7th assessment report.[133] Time will tell if international negotiations will yield constructive decisions to enable cooperation on a broader and more inclusive assessment process. These recommendations should be taken up with increased urgency as SRM research funding increases sharply through new philanthropic sources[134] and as the United Kingdom's Advanced Research and Invention Agency (ARIA) is set to announce funding awards for SRM research, including possibly outdoor experiments.[135]

In conclusion, the future trajectory of SRM governance has yet to be determined, and should be carefully shaped through broad, inclusive, and informed deliberation between publics, interdisciplinary researchers, decision-makers, and other interested groups from across the world.

Data availability

All data used for this article were gathered from freely available online sources, including government and NGO websites as well as news media.

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Conflicts of interest

There are no conflicts to declare.

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