



Solar Radiation Modification

Scientific evidence does not support SRM as a viable climate solution

As global emissions continue to rise, interest is growing in Solar Radiation Modification (SRM)—a set of speculative methods designed to reflect sunlight and temporarily cool the Earth. Often described as a “last resort” to address the negative impacts of temperature overshoot—when global temperatures exceed agreed targets—SRM deployment could pose significant and unintended environmental and social impacts with uncertain implications for both human health and natural ecosystems. The current state of scientific knowledge does not support SRM as a viable response to climate change as it does not address the root cause of the current anthropogenic climate change. With major knowledge gaps, no global governance and high uncertainty, the United Nations Environment Programme (UNEP) remains concerned about the viability, feasibility and potential risks of SRM, and urges caution, transparency and inclusive discussion of the topic—without diverting focus from urgent mitigation and adaptation. This Working Paper builds on and updates previous work, including UNEP’s *One Atmosphere report*, drawing on a May 2025 UNEP–World Meteorological Organization workshop, a September 2025 Multistakeholder consultative meeting and recent literature, including the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6).

UNEP is the leading global environmental authority that sets the global environmental agenda, promotes the coherent implementation of the environmental dimension of sustainable development within the United Nations system and serves as an authoritative advocate for the global environment with a mandate to keep the environment under review.

Emerging science, idealized approaches, knowledge gaps and the imperative for caution

SRM refers to a suite of proposed intentional planetary-scale methods designed to reflect a portion of incoming solar radiation back into space, with the aim of temporarily lowering global average temperatures. Proposals include Stratospheric Aerosol Injection (SAI)¹, Marine Cloud Brightening (MCB)² and more speculative, less explored concepts such as cirrus cloud thinning, space-based reflectors, surface albedo modification or sea ice management (National Oceanic and Atmospheric Administration [NOAA] 2024; Haywood *et al.* 2025; Siegert *et al.* 2025).

These approaches remain at an early stage of research, explored mainly through modelling. Nonetheless, they are drawing increased attention as concerns mount over climate inaction and projected warming beyond 1.5°C above preindustrial levels—when threats to ice sheets, coral reefs or early warning signals for other climate tipping points become more acute (Armstrong McKay *et al.* 2022; Lenton *et al.* 2025). Despite growing scientific interest, SRM remains poorly understood and carries significant uncertainties and environmental, social, geopolitical, ethical, legal and governance risks. With emissions still rising and 1.5°C at risk of being exceeded, some scientific communities view SRM as a potential ‘emergency’ measure. While the appeal lies in the prospect of rapidly lowering temperatures and offsetting certain climate change impacts—such as sea ice loss or coral reef decline—this framing raises fundamental issues of governance, legitimacy and justice, as well as the uncertainties in relation to environmental and social implications, particularly given States’ due-diligence obligations to prevent significant harm to the climate system (International Court of Justice [ICJ] 2025).

The current state of scientific understanding—including economic, socio-political, justice, equity and human rights research—does not support SRM as a viable climate response. Significant knowledge gaps persist regarding regional impacts, long-term ecological effects and risks associated with potential deployment. These uncertainties are compounded by a lack of agreed governance frameworks, by asymmetries in research capacity between developed and developing countries, and by clashing geopolitical interests and divergent stakeholder perspectives on whether SRM should be studied at all (Biermann and Gupta 2024; Futerman *et al.* 2025; McLaren 2025).

Crucially, SRM is neither a substitute for deep and sustained reductions in greenhouse gas (GHG) emissions, nor a form of climate adaptation. The most effective and essential responses to climate change remain ambitious mitigation and robust adaptation strategies. SRM proposed methods do not address the root cause of climate change³: They neither reduce emissions nor strengthen resilience to climate impacts. Achieving the goals of the Paris Agreement—including limiting warming to 1.5°C or ‘well below 2°C’—depends on immediate, deep and sustained reductions in GHG emissions, complemented by the rapid scale-up of carbon dioxide removal (CDR) (IPCC 2023; UNEP 2023).

1 SAI: Releasing reflective particles into the stratosphere to mimic the cooling effects of volcanic eruptions (Haywood *et al.* 2022; Lee *et al.* 2023; UNEP 2023).

2 MCB: Increasing the reflectivity of marine clouds by introducing aerosols, similar to the brightening seen in polluted ship tracks (Latham *et al.* 2014; Ahlm *et al.* 2017; UNEP 2023).

3 The IPCC does not classify SRM as a climate solution but has assessed it in response to Member State interest. Recent reports—including Working Group I (2021), Working Group III (2022) and the 2023 Synthesis Report—highlight critical knowledge gaps, significant and uncertain risks, and the absence of viable governance frameworks. SRM is excluded from mitigation scenarios and the Summaries for Policymakers. The Seventh Assessment Report (AR7) will include a dedicated assessment of SRM in Chapter 9 Working Group I contribution.

SRM research: Rising attention

Research on SRM is attracting attention and funding, but remains fragmented, with most peer-reviewed work led by researchers engaged primarily in modelling. As in any emerging field, resources are needed not only in scale but also with careful consideration of who provides them and with what underlying motivations, as early investments often shape the direction, scope and long-term priorities of the field.

Since 2020, SRM funding has expanded sharply, rising from roughly USD 35 million in 2010–2014 to more than USD 110 million in 2020–2024⁴, including about USD 31 million in 2024 alone. A growing share now comes from philanthropic sources, alongside new public and private commitments—such as USD 75 million from the United Kingdom’s Advanced Research and Invention Agency (ARIA)⁵—with over USD 100 million from private philanthropy. Annual funding could soon reach USD 40–55 million, with private actors providing nearly half of all identified support (Buck *et al.* 2025). Notably, this figure does not account for a subsequent October announcement by Stardust Solutions—a United States start-up with an Israeli R&D centre—which disclosed a USD 60 million raise, by far the largest known funding round to date for SRM-related companies⁶.

Yet despite this growth, SRM research remains limited, largely theoretical, highly uncertain, based on idealized scenarios that overlook major deployment uncertainties and concentrated in a handful of countries. The evidence base still offers only a limited understanding of SRM’s potential impacts on climate, ecosystems and societies.

Current SRM developments span multiple approaches, domains and disciplines—each with distinct risk profiles, institutional responsibilities and governance implications. Recognizing these distinctions is important to ensure appropriate oversight and public understanding.

- **Basic scientific research** seeks to improve understanding of Earth system processes relevant to SRM, such as stratospheric chemistry, cloud-aerosol dynamics and ocean–atmosphere interactions. This research is foundational and often overlaps with broader climate science⁷.
- **Climate modelling and simulation** involve hypothetical SRM deployment scenarios and their potential outcomes. They are critical for risk exploration and comparative risk-risk analysis⁸, but their results are inherently conditional on modelling assumptions and scenario design, requiring systematic sensitivity analysis and careful interpretation to remain credible (Felgenhauer *et al.* 2025). Many studies are based on limited or single-model frameworks, constraining their ability to disentangle SRM signals from internal climate variability and to assess inter-model differences. As a result, SRM model outputs should be interpreted as conditional insights rather than predictive outcomes.
- **Laboratory experiments and observations** include controlled studies of stratospheric and sea-salt aerosols and their interactions with sunlight—including their potential to increase atmospheric reflectance—as well as measurements of stratospheric composition and chemistry used to improve climate models (NOAA 2024).

4 SRM 360. 2024. SRM Funding Overview, srm360.org/srm-funding-overview.

5 The Advanced Research + Invention Agency. 2025. <https://www.aria.org.uk/>

6 MIT technological review: How one controversial startup hopes to cool the planet, <https://www.technologyreview.com/2025/12/10/1129079/how-one-controversial-startup-hopes-to-cool-the-planet/>

7 The 2023 U.S. Congressionally Mandated Report emphasizes transparency, safety and periodic review for such activities: The White House. 2023. Congressionally Mandated Research Plan and an Initial Research Governance Framework Related to Solar Radiation Modification. <https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/06/Congressionally-Mandated-Report-on-Solar-Radiation-Modification.pdf>

8 Risk–risk analysis evaluates and compares the potential impacts of two or more risk sources—in this case, the risks posed by deploying SRM versus the risks posed by unmitigated climate change.

- **Outdoor field experiments** involve real-world testing of relevant processes, typically at small scale and limited duration. Proponents argue that such experiments are intended primarily to inform and improve computer simulations, for example by observing how SRM particles mix and disperse in the stratosphere (Jinnah *et al.* 2024). Others contend that outdoor experiments often blur the boundaries between basic research, investigations into technological feasibility and the development of operational capabilities (Scientific Advice Mechanism to the European Commission 2024). As a result, these activities raise distinct challenges around transparency, public trust and the potential normalization of SRM deployment, even if they do not themselves constitute deployment. To date, only a small number of such experiments have been attempted, with several cancelled amid public opposition⁹ (Scientific Advice Mechanism to the European Commission 2024).
- **Commercial exploration and prototyping**, often led by private-sector actors or start-ups, is an emerging frontier that introduces risks of profit-driven activity outpacing public oversight, in a field lacking shared norms or institutional guardrails (Scientific Advice Mechanism to the European Commission 2024).
- **Social, ethical and political research** examines how SRM is framed, perceived, deliberated, governed and communicated, and explores mechanisms for ensuring transparency, accountability and societal viability alongside physical risks.

Each of these domains may require different regulatory, ethical and participatory frameworks. Lumping them together as ‘SRM research’ risks obscuring differences and could hinder effective governance by making it harder to tailor rules, oversight and stakeholder engagement to the specific risks and contexts of each domain. Transparency, public communication and frameworks must therefore distinguish between these research types, rather than treat SRM research as a single catchall category.

Modelling SRM: Navigating climate model uncertainty and complex realities

Climate models are the primary tool for understanding how the climate system functions and for assessing changes resulting from different forcings. In this context, the Geoengineering Model Intercomparison Project (GeoMIP) was established to examine how the climate system responds to attempts to offset the radiative effects of GHGs without attempting to reduce their emissions (i.e. SRM approaches) (Kravitz *et al.* 2015; Haywood *et al.* 2025). Through coordinated modelling experiments, GeoMIP investigates the potential role of SRM in addressing climate change, the resulting climatic effects and impacts, as well as the underlying processes and associated uncertainties.

Model simulations show that SRM could reduce global temperatures, but also raise serious concerns about uneven regional impacts, ecological side effects and poorly understood feedback loops (Irvine, Ridgwell and Lunt 2010; Kravitz *et al.* 2021; Lockley *et al.* 2022). Yet models still face significant limitations in resolving fine-scale outcomes or long-term socio-economic impacts. Major uncertainties remain in capturing complex climate system processes such as aerosol characteristics, atmospheric chemistry and dynamics, aerosol-cloud interactions, ecosystem responses, human health and socio-political consequences (Eastham *et al.* 2025; Haywood *et al.* 2025).

SRM modelling research explores idealized modelling scenarios that assume globally coordinated governance, stable deployment over time and well-controlled interventions. These assumptions allow for structured comparison of theoretical outcomes, but they often neglect the complexities and risks associated with actual political, technical or ethical conditions (Irvine *et al.* 2010; Kravitz *et al.* 2021; Lockley *et al.* 2022; Beckage *et al.* 2025). SRM model outputs should therefore be treated as conditional insights for exploring ‘what-if’ responses of the climate system, not as precise forecasts nor as recommendations for deployment.

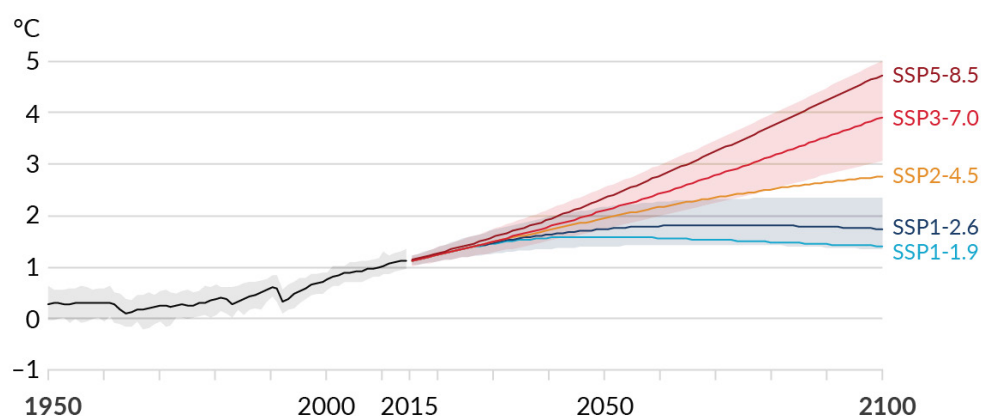
⁹ SRM 360. 2025. Outdoor SRM Experiments. <https://srm360.org/article/outdoor-srm-experiments/>

Like all climate change simulations performed using climate models, SRM simulations involve uncertainty. But the scale, complexity and unique risks of SRM amplify those uncertainties, particularly at regional scales where socio-ecological stakes are highest. As a result, numerous assessments urge extreme caution, calling for clear communication, greater transparency, inclusive deliberation and rigorous oversight. They also underscore the need for further theoretical and empirical research to better understand the potential impacts and risks of these approaches, given the significant scientific uncertainties, ethical and governance challenges they raise long before any potential real-world deployment could be contemplated (Jinnah and Dove 2025).

How are SRM scenarios built?

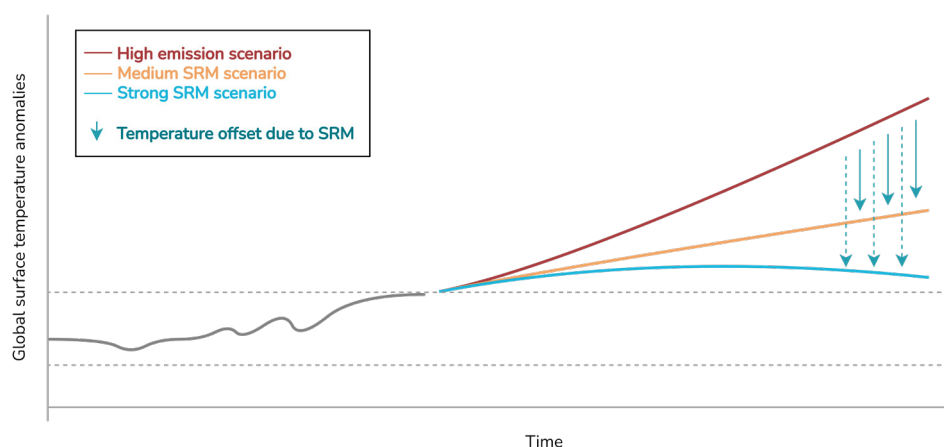
SRM scenarios often follow the structure of Shared Socioeconomic Pathways (SSPs) used in current climate research (Figure 1). This is largely because the majority of SRM modelling studies are conducted within GeoMIP, which is embedded in the broader CMIP/ScenarioMIP framework that standardizes the use of SSP-based scenarios (Haywood *et al.* 2025).

Figure 1. Shared Socioeconomic Pathways and their associated global surface temperature changes relative to 1850–1900 (Source: AR6 IPCC 2021)



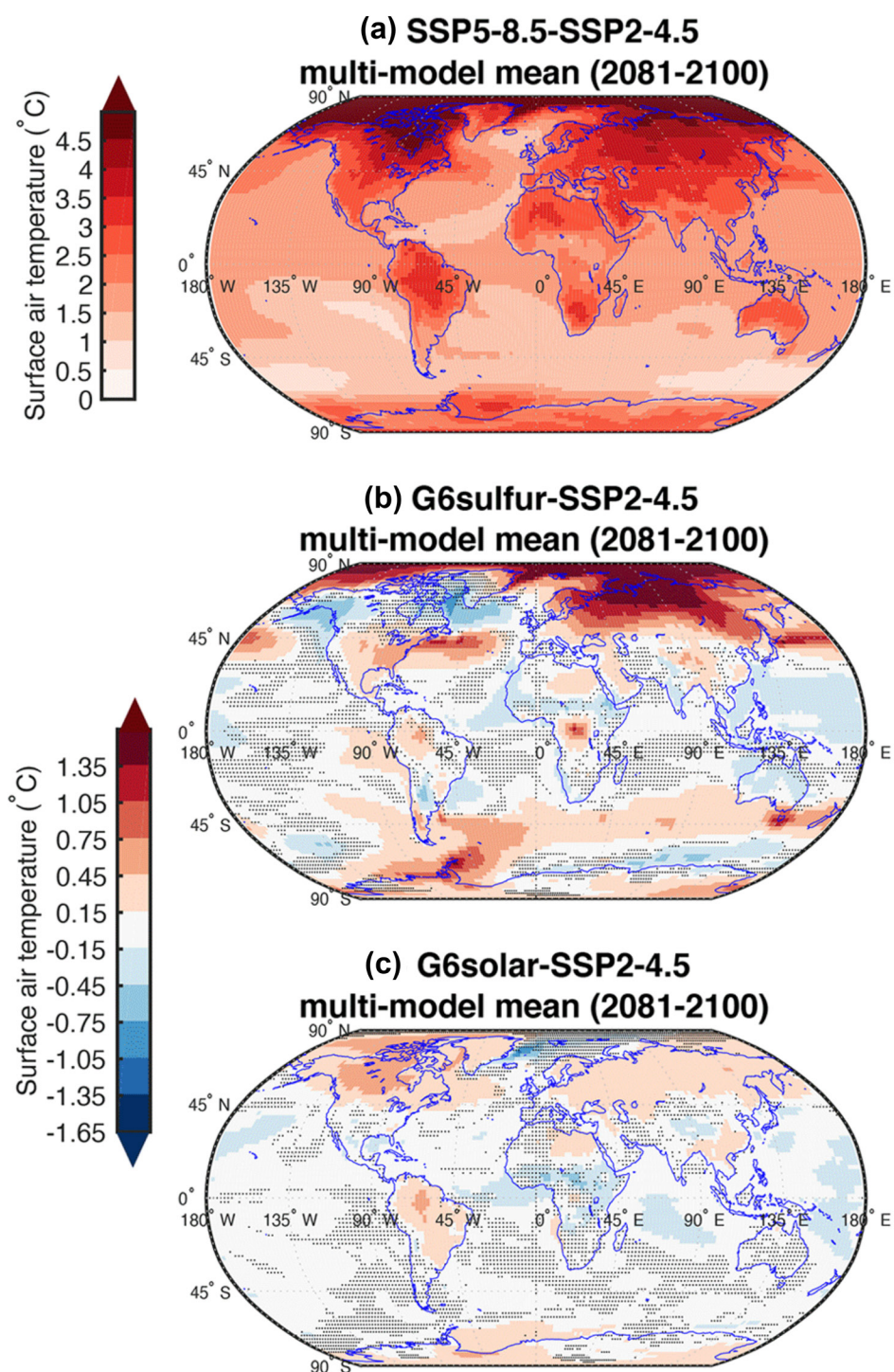
An emission SSP (e.g. high emission - SSP5-8.5, dark red line) may be combined with an SRM intervention (e.g. stratospheric aerosol injection) to simulate alternative temperature pathways (World Meteorological Organization [WMO] 2022), such as medium SRM (orange line) and strong SRM (turquoise line) scenarios (Figure 2).

Figure 2. Diagram representing a high-emission scenario paired with an assumed temperature offset to represent the potential cooling influence of SRM (Source: Modified from WMO 2022)



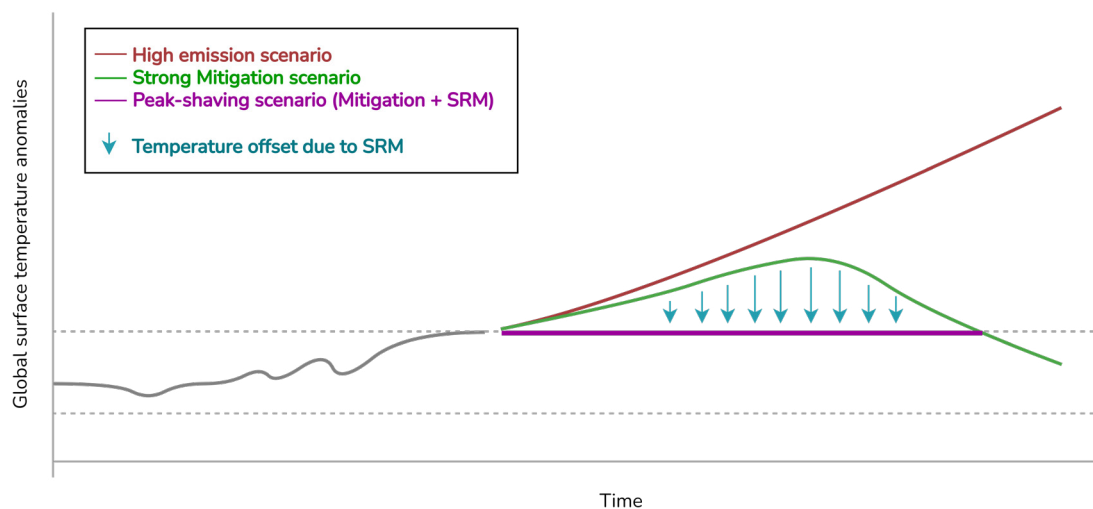
Outputs (e.g. a medium SRM scenario such as G6sulfur or G6solar) are then often compared with baseline(s), in this case, a scenario with a lower emissions pathway (e.g. SSP2-4.5) that produces a similar global mean surface temperature to assess differences in climate system responses despite comparable global temperatures (Figure 3). However, depending on the experimental design—for example the choice of baseline or magnitude of the temperature offset—such assessments can be substantially affected.

Figure 3. Scenarios comparison for SSPs (a, with two different global mean temperatures, one warmer), SSP and SAI simulations (G6sulfur) (b, here, equatorial SAI, same global mean temperature between scenarios) and SSP and solar dimming (G6solar) (c, same as b) (Source: Adapted from Vioni *et al.* 2021)



Concurrently, ‘peak-shaving’ scenarios (Figure 4) have emerged, exploring time-limited SRM deployment, paired with aggressive emissions reductions and CDR (NOAA 2024). The goal is to reduce near-term warming and avoid triggering critical climate thresholds (Scientific Advice Mechanism to the European Commission 2024). These scenario experiments are typically tested in coordinated multi-model ensembles (e.g. CMIP/GeoMIP; Vioni *et al.* 2024) that allow structured comparison across multiple climate outcomes.

Figure 4. Diagram representing a ‘peak-shaving’ scenario: Aggressive mitigation and CDR paired with time-limited SRM deployment to avoid temperature overshoot (Source: Modified from WMO 2022)



While intended to reduce peak temperature-related risks, these scenarios remain hypothetical and hinge on assumptions about timing, spatial distribution, aerosol types, socio-economic trajectories and the availability of scalable CDR. Moreover, these scenarios depend on continual management and assume reversibility of deployment—assumptions that may understate procedural, political and ecological uncertainties. Existing frameworks also under-represent sub-optimal or geopolitically constrained deployments (e.g. unilateral, poorly coordinated or regionally targeted interventions), which can diverge significantly from scientifically optimized designs and should be explored explicitly.

Real-world decision-making would face immense political uncertainty, divergent national or regional interests and profound challenges in defining what constitutes a ‘safe’, temporary or legitimate deployment—especially without multilateral governance frameworks. Therefore, while modelling studies provide valuable insights, their results should be interpreted with caution, especially when considering feasibility, acceptability or reversibility in practice. Put simply: confidence in simulated physical responses does not imply confidence in social license, institutional capacity or legitimacy.

Improving SRM modelling requires more realistic scenarios—enhanced representation of physical, chemical and biological processes—and integration of ecological, political and ethical dimensions. To address the limitations, SRM modelling must expand in both scope and real-world relevance. This includes developing a broader range of scenarios that go beyond idealized assumptions and reflect more complex and plausible climate futures. It also requires improved representation of key processes such as aerosol chemistry, cloud–aerosol interactions, regional climate variability and climate feedback mechanisms where significant uncertainties remain (Eastham *et al.* 2025).

Equally important, SRM research frameworks must acknowledge that public trust and social responses could profoundly shape how SRM research or deployment is understood, accepted or resisted. Risk is not confined to physical or climatic dimensions—it is also political, psychological and normative.

Institutional coordination is also essential: perspectives from the World Climate Research Programme highlight the importance of transparent, globally inclusive approaches to climate intervention research (Haywood *et al.* 2025). While the term ‘intervention’ can imply temporally bounded action, emerging evidence suggests that some deployment scenarios could extend across multiple decades, raising risks related to committed use, multi-generational governance and technological dependency (Baur *et al.* 2023). Such coordination, including stronger Global South participation, would help align technical advances with legitimacy and equity considerations, enabling appropriate engagement and dialogue.

In this context, enhanced modelling capacity should not be interpreted as a step toward deployment; rather, it is a prerequisite for informed risk assessment, including the risks of both action and inaction (Haywood *et al.* 2025).

Field research in SRM: potential insights, ethical concerns and communication risks—how much is too much?

In parallel with improved modelling, targeted observations and small-scale field studies—typically brief, localized and designed to address specific research questions—could help refine model accuracy and reduce uncertainty for fundamental processes, including aerosol chemistry and microphysics, cloud interactions or model parameterization, without simulating deployment or inducing climate effects (Kravitz *et al.* 2015; National Academies of Sciences, Engineering, and Medicine 2021; Määttänen *et al.* 2024; Haywood *et al.* 2025). Such studies must be carefully designed, transparently governed and guided by inclusive and precautionary principles (Jinnah *et al.* 2024; Haywood *et al.* 2025; McLaren 2025).

Yet, despite their ability to improve understanding of microphysical processes, small-scale studies are inherently limited in scope. Their brief duration and localized nature mean they cannot resolve uncertainties in global-scale climate responses (Kravitz *et al.* 2015; National Academies of Sciences, Engineering, and Medicine 2021; Määttänen *et al.* 2024).

Scale also fundamentally shapes perception. Experiments lasting minutes or confined to the size of a football field are not climate interventions—yet public or media views and perceptions of such studies can blur the line between exploratory research and real-world deployment. This can erode public trust, distort policy debates and risk prematurely normalizing a technology that remains deeply uncertain.

Outdoor experimentation is one of the most contentious dimensions of SRM research. Some scientific and civil society groups have called for moratoria or bans, citing environmental, ethical and geopolitical risks (Jinnah and Dove 2025). Others argue that carefully governed, micro-scale experiments are essential to avoid making future decisions ‘in the dark’, particularly for vulnerable regions that may face outsized risks from either SRM deployment or unchecked warming.

It is also important to distinguish between indoor or laboratory-based research (which carries lower direct environmental risk and is often part of broader climate science) and outdoor experiments, which involve real-world environmental interventions and therefore raise distinct governance, ethical and public trust concerns¹⁰. The limitation of empirical evidence increases uncertainty. While ‘natural experiments’ such

¹⁰ For example, see: SRM 360. 2025. News Reaction: UK’s ARIA Announces £45m Funding for 21 “Climate Cooling” Research Projects. <https://srm360.org/news-reaction/aria-45m-funding-21-climate-cooling-research-projects/>

as volcanoes and wildfire emissions can provide some insights, they cannot fully constrain the physical processes involved in SAI nor the ethical and social aspects, particularly for larger-scale interventions (Kravitz *et al.* 2015). This reinforces the imperative for precaution: decisions about SRM cannot be based solely on theoretical models or cost estimates; they require assessment of systemic risks, ethical trade-offs and governance readiness (Scientific Advice Mechanism to the European Commission 2024; Felgenhauer *et al.* 2025; Haywood *et al.* 2025). Where SRM research is undertaken, it should be approached with transparency, humility and inclusive public engagement.

Regional disparities in climate effects raise concerns about justice, equity and geopolitical risk

Translating global SRM modelling results into meaningful regional or local assessments is extremely challenging because outcomes depend strongly on the modelling framework, the magnitude and duration of deployment, the underlying climate scenario, among other factors. Most model outputs suggest that SRM could lower average global temperatures, but can also influence tropospheric and stratospheric ozone, terrestrial ecosystem, terrestrial carbon and hydrological cycle by changing the physical climate system and atmospheric chemistry producing uneven and potentially unintended side effects, particularly for precipitation patterns, monsoons and drought risk (Irvine *et al.* 2010; Pinto *et al.* 2020; Zhao and Cao 2022; Haywood *et al.* 2025).

SRM interventions could produce heterogeneous regional impacts. For instance, simulations indicate changes in precipitation extremes related to flooding over the bulk of China that are induced under climate change may be abated by SRM, but changes in dry days relating to drought are likely to be enhanced (Wang *et al.* 2024). Targeting one objective—such as reducing regional heat extremes—could unintentionally induce major side effects on monsoons, snowpack, glacier melt and water availability in vulnerable regions of South and East Asia. These effects could significantly affect agricultural productivity, food security and livelihoods, particularly in Least Developed Countries (LDCs) and Small Island Developing States (SIDS), where climate-sensitive resources are limited (Low *et al.* 2024; Scientific Advice Mechanism to the European Commission 2024; Wang *et al.* 2024; Fu *et al.* 2025).

Without rigorous, region-specific analysis, SRM may amplify existing global inequities and undermine the principles of climate justice, especially in Southeast Asia, Latin America and Africa (Irvine *et al.* 2010; Moreno-Cruz, Ricke and Keith 2012; Heyen, Wiertz and Irvine 2015; Zhao and Cao 2022) and particularly among vulnerable populations, including women, who often face disproportionate impacts due to gender-differentiated responsibilities for water, food and household care. In the absence of inclusive, transparent and accountable governance, such disparities could fuel geopolitical tensions, distrust or even conflict over perceived harm or benefit distribution.

These dynamics reinforce the need for SRM modelling to move beyond global averages and advance the understanding of regional distribution of environmental, social and political risks—especially among vulnerable populations.

SRM could have serious ecological impacts—especially in fragile systems

Emerging studies exploring SRM effects on ecological and hydrological systems emphasize that while global temperature reductions may be achieved, the consequences for ecosystems, biodiversity and ecosystem services are uneven and potentially destabilizing. SRM does not reduce atmospheric carbon dioxide (CO₂) concentrations, meaning that CO₂-driven processes such as ocean acidification and plant physiological responses remain largely unmitigated, adding further complexity to ecosystem responses.

SRM interventions can interact with the water–vegetation–carbon nexus under heat stress and varying atmospheric CO₂ concentrations, affecting net primary productivity, species distributions, soil moisture, carbon cycling (Dagon and Schrag 2019; Zarnetske *et al.* 2021) and soil biogeochemistry (Visioni *et al.* 2020). Importantly, SRM may also induce hydroclimatological changes, including shifts in precipitation extremes and temperature, leading to alterations in snowpack, glacier mass balance, with implications for seasonal freshwater availability (Simpson *et al.* 2019; Ricke *et al.* 2023; Wang *et al.* 2024) although the magnitude and direction of these effects remain uncertain.

Beyond terrestrial systems, SRM may trigger atmospheric and ocean chemistry perturbations. For example, some studies highlight potential changes in stratospheric ozone chemistry, as well as changes in atmospheric circulation due to stratospheric heating, wintertime warming in mid- and high-latitudes, atmospheric drying over polar regions and overcooling in the tropics (Zarnetske *et al.* 2021; WMO 2022; Wells *et al.* 2024; Futerman *et al.* 2025; Siebert *et al.* 2025). In addition, while SRM aerosols are injected into the stratosphere, downward transport and deposition could influence surface air quality and may further exacerbate changes in ocean biogeochemistry (Zarnetske *et al.* 2021; Siebert *et al.* 2025). Abrupt termination of SRM would pose an additional risk, potentially exposing ecosystems to rapid warming and hydrological shifts beyond adaptive capacity (Trisos *et al.* 2018; IPCC 2021; Futerman *et al.* 2025; Gay *et al.* 2025).

Such risks could be particularly pronounced for sensitive systems like coral reefs, Arctic tundra, Antarctica's ice dependent marine ecosystems and dryland biomes (Zarnetske *et al.* 2021; Siebert *et al.* 2025). Crucially, these ecological impacts do not align neatly with political borders or governance capacity. Communities already facing high climate exposure—particularly in low- and middle-income countries (LMICs)—may also face disproportionate harm from SRM effects.

Proposed deployment scenarios are idealized and evidence serious environmental and geopolitical risks

Recent estimates suggest that SAI could reduce global temperatures at relatively low financial cost—estimated between USD 2.5 billion to USD 20 billion per year (Moreno-Cruz *et al.* 2025). Yet the outcome of SRM proposed methods depends heavily on where and how they are deployed, as deployment choices are likely to alter climate patterns on which many tropical and vulnerable countries depend (Quagrain, Abiodun and Essien-Baidoo 2025). The projected cost figures are purely theoretical and do not capture the broader economic, ecological or political consequences of deployment. Recent analysis estimates that the all-things-considered 'price' of SRM could be vastly higher, with SAI potentially generating up to USD 809 billion annually in side-effect harms, and MCB likely exceeding this range (Bronsther and Xu 2025).

Large-scale SRM remains entirely untested and highly controversial. Risks include disruptions to hydrological and ecological systems, uneven regional effects and the potential for reduced political will to cut emissions—the so-called ‘moral hazard’ effect (Robock *et al.* 2009; McLaren 2016; Baur *et al.* 2023; IPCC 2023; Huynh and McNeill 2024). One of the most severe concerns is the risk of termination shock: if large-scale SRM were deployed and then abruptly halted, its cooling effect would quickly disappear, leading to a rapid and potentially catastrophic rebound in global temperatures (Trisos *et al.* 2018; UNEP 2023).

In 2023, the Montreal Protocol’s Scientific Assessment Panel issued its first formal review of SRM, warning that SAI could alter stratospheric temperatures, circulation patterns and ozone dynamics. These findings reinforce existing concerns about atmospheric feedbacks that remain poorly understood—and potentially irreversible.

SRM is also viewed by some experts as a potential trigger for geopolitical conflict, particularly if unilateral deployment were to benefit high-income countries at the expense of lower-income or vulnerable regions—echoing historical patterns of external decisions imposed on regions such as Africa (Quagrain *et al.* 2025).

Together, these risks underscore that SRM is not a neutral or merely technical intervention—it is a geopolitical, ecological and intergenerational gamble that demands robust scrutiny before any consideration of deployment.

SRM is attracting growing attention—and growing governance controversy

The increased visibility of SRM has been accompanied by intensifying debate. Within the scientific community, among Member States and across civil society, views diverge over whether SRM should be studied further—and if so, under what conditions. Recent discussions at the United Nations Environment Assembly (UNEA-6) underscored deep divisions. In the twentieth session of the African Ministerial Conference on the Environment (AMCEN-20)¹¹, African ministers of environment unequivocally rejected stratospheric aerosol injection and other forms of solar geoengineering as unacceptable climate responses, citing their profound environmental, ethical and geopolitical risks. Through Decision AMCEN/20/Dec.9¹², they called for the establishment of a solar geoengineering non-use agreement and urged its promotion in international negotiations.

These institutional divisions are unfolding alongside a shifting political discourse, where the growing use of the terms such as ‘abrupt climate change’, ‘tipping points’ and ‘climate emergency’ adds further complexity. While not formally defined in international law, it is often used to signal urgency and the inadequacy of current responses (Ripple *et al.* 2019; Cottey 2022). In the SRM debate, this framing risks positioning SRM as a ‘last-resort’ option, heightening the perception of urgency but narrowing space for inclusive deliberation and precaution. It also raises questions about who has the authority to declare an emergency and what such declarations mean for governance legitimacy. Some see this framing as justification for accelerating research or even deployment under extreme scenarios; others warn it could fuel premature action, increase public distrust or sideline vulnerable voices (Stephens and Surprise 2020; Fritz *et al.* 2025).

11 Twentieth Ordinary Session of the African Ministerial Conference on the Environment: <https://www.unep.org/events/unep-event/twentieth-ordinary-session-african-ministerial-conference-environment-amcen-20>

12 Decision AMCEN/20/Dec.9: Africa’s engagement at UNEA-7: <https://wedocs.unep.org/handle/20.500.11822/48283>

These debates highlight widespread concerns about potential unintended consequences, uncertain effectiveness and the risk of undermining efforts to address the root causes of climate change (GHG emissions), while creating additional uncertainty for mid-term adaptation planning by making it unclear what climate impacts to anticipate. There is concern that heightened focus on SRM could dilute the urgency of mitigation and adaptation by creating false expectations or redirecting resources, particularly when it is framed as a fallback strategy rather than a matter for precautionary inquiry.

The growing discourse surrounding SRM illustrates a core dilemma: while some argue that research could clarify risks and preserve decision-making options, others warn that even early-stage exploration may create pressure for future deployment, especially in a context of climate emergency¹³. These divergent perspectives reinforce the need for clarity on how ‘climate emergency’, ‘tipping points’ and ‘abrupt climate change’ language is used in relation to SRM, and for transparent, inclusive dialogue to guide governance pathways. For now, there is a broad scientific consensus, including among SRM researchers, that mitigation and adaptation are far more reliable, necessary and urgent (IPCC 2023; The Royal Society 2023; UNEP 2023).

Shifting public and expert perceptions

While public awareness of SRM remains limited and opinions are often ambivalent, research on public perceptions is also scarce, particularly in Africa, where studies are rare (Quagraine *et al.* 2025). Support for SRM tends to be context-dependent—stronger in regions perceiving acute climate risk (e.g. India, the Philippines and other Global South countries) yet tempered by concerns over environmental side-effects, governance and moral hazard (Sovacool *et al.* 2024; Sugiyama *et al.* 2025). A cross-cultural survey by Contzen *et al.* (2024) further underscores this variability, finding higher acceptance in parts of the Global South, lower support in the non-WEIRD¹⁴ Global North and intermediate levels in the WEIRD Global North. Demographic factors such as age and gender had only minor effects, while education proved more influential, with less-educated respondents expressing greater scepticism. More importantly, across regions, support is conditional and largely framed as a last-resort option, acceptable only if negative impacts are minimal and mitigation efforts continue.

Social media insights reveal that SRM still attracts minimal specific attention, and when it does, it is biased toward negativity and conspiracy (notably chemtrails), whereas carbon dioxide removal gains more favourable, nature-aligned sentiment (Müller-Hansen *et al.* 2023). At the same time, high-profile controversies—such as cancelled experiments, stalled processes and rising unease over philanthropic and private-sector actors (including tech start-ups) pursuing SRM—are intensifying scrutiny and fuelling growing public concern over who controls such high-stakes climate interventions and could ultimately serve to undermine public trust (Jinnah and Dove 2025).

Expert perspectives add a further layer of complexity: survey evidence from Finland suggests that while experts remain pessimistic about the pace of emissions reductions, they see SRM as undesirable under current conditions due to uncertainty, governance gaps and the risk of not addressing root causes (Haaslahti 2024). At the same time, many expect indoor SRM research to expand and view it as useful for informing decision-making, while large-scale deployment is seen as highly unlikely and undesirable. Given that any SRM deployment would have cross-boundary climate effects, African experts stress that the continent cannot remain a passive recipient—it must play an active role in governance, research and public engagement (Quagraine *et al.* 2025), particularly as premature or uncoordinated deployment by powerful actors could exacerbate inequities, undemocratic values and power relations (Haaslahti 2024; Siegert *et al.* 2025).

¹³ Climate emergency is a call by governments, scientists, and civil society to highlight the urgency of the climate crisis and the insufficiency of current responses, urging faster action to prevent severe or irreversible impacts.

¹⁴ WEIRD: Western, Educated, Industrialized, Rich and Democratic Countries.

Political perspectives further shape the debate. Some countries, including the United States of America, Australia, the United Kingdom and China, have supported continued research and assessment of SRM, stressing the importance of maintaining future policy options (Biermann and Gupta 2024; Sipra and Talati 2024). By contrast, African states and Pacific Small Island States have led calls for an international non-use agreement (NUA), emphasising disproportionate risks to vulnerable populations (Biermann and Gupta 2024). Intermediate positions are also evident, particularly within parts of the European Union, where precautionary approaches—including potential NUAs—are being explored alongside support for further research. These contrasts highlight that positions on SRM are shaped not only by scientific risk assessments but also by equity, responsibility and geopolitical standing.

These dynamics highlight the importance of broadening participation in SRM governance debates, including careful consideration of the role of scientists, attention to ecosystem and biodiversity issues and participatory approaches grounded in stakeholder rights. Youth perspectives, in particular, stress that geoengineering proposals should not be treated in isolation but assessed alongside adaptation and mitigation strategies to ensure effective long-term solutions can be identified through research, with greater attention to intergenerational justice in decision-making (Dunlop *et al.* 2022; Reynolds *et al.* 2022). Rather than shifting responsibility to individual choices, young people call for empowerment through inclusive policy processes¹⁵. Emerging youth-led initiatives—such as SRM Youth Watch¹⁶, the Youth Voices in Emerging Climate Governance project¹⁷, the Green Africa Youth Organisation (GAYO) program¹⁸ and Mind our Future! Critical Youth on Solar Geoengineering¹⁹—reflect this momentum strengthening the representation of youth perspectives in global discussions on SRM governance.

Concerns over governance, equity and commercialization are evident

SRM research developments have raised concerns that the pace of activity is outstripping the development of governance frameworks. In particular, the involvement of private companies introduces potential conflicts of interest, including the risk that commercial incentives may shape research agendas in ways that do not reflect broad societal priorities or the interests of climate-vulnerable communities.

Over the past years, SRM patents have remained limited but show some growth, scattered across jurisdictions such as the United States of America, Europe, China and Japan, and often originating from individuals or small entities rather than large corporations. Recent literature also highlights the emergence of market-driven approaches to SRM, including the proposal of cooling credits that claim to monetize the climate benefits of aerosol-based solar interventions (Diamond, Wanser and Boucher 2023; Surprise *et al.* 2025). Many patent filings are abandoned or difficult to trace due to the absence of a dedicated classification, and alongside these market initiatives raise concerns about transparency, governance and the potential private appropriation of technologies with global implications (Cressey 2012; Ramos and Duarte Santos 2025).

Without clear international norms, transparency mechanisms and mechanisms for inclusive oversight, SRM research risks proceeding in ways that could erode public trust and exacerbate global inequities.

15 Children and Youth Major Group: <https://www.cymgenv.net/post/unea-6-postmortem-solar-radiation-modification>

16 Solar Radiation Modification Youth Watch (SRM YW) initiative: <https://c2g2.net/highlights-from-the-global-launch-of-srm-yw-initiative-at-new-york-climate-week/>

17 C2G's Youth Voices in Emerging Climate Governance project: <https://c2g2.net/youth/meet-c2gs-youth-climate-voices/>

18 Empowering Africa's Youth: GAYO's Groundbreaking Initiative in Climate Intervention Education: <https://greenafricayouth.com/2024/10/07/empowering-africas-youth-gayos-groundbreaking-initiative-in-climate-intervention-education/>

19 Mind our Future! Critical Youth on Solar Geoengineering: <https://mindourfuture.org/about-mof/>

These risks underscore the need to ensure that any SRM-related activity is governed by principles of transparency, equity, precaution and accountability.

Global governance debates on SRM underscore its disruptive potential, as deployment could cause large-scale, unintended and possibly irreversible impacts on societies, ecosystems and international stability (Cherry *et al.* 2025; Gupta *et al.* 2024). Concerns over transboundary effects, profound uncertainty, governance gaps, moral hazard and equity risks have fuelled calls for an NUA to address systemic and politically destabilizing threats (Biermann *et al.* 2022; Biermann and Gupta 2024). Proponents argue that legitimizing SRM as a policy option risks path-dependence and the ‘normalization’ of a speculative technology (Oomen 2024), potentially undermining emission reductions and diverting political attention from mitigation and adaptation (Biermann *et al.* 2022; Gupta *et al.* 2024).

A planetary-scale NUA would commit states not to deploy any SRM approaches currently under consideration and, in some versions, to restrict certain field experiments (Biermann *et al.* 2022; Gupta *et al.* 2024). Such an agreement would draw a clear normative boundary against unilateral or premature action, while allowing exceptions that reflect differences among technologies in scale, purpose and geopolitical risk (Oomen 2025). Because SRM side effects would cross borders, potentially threatening water and food security in vulnerable regions, justice demands preventing powerful actors from unilaterally introducing pollutants in the stratosphere and shaping the global and regional climate (Biermann *et al.* 2022; Oomen 2025). In this view, a NUA serves both as a governance safeguard and as a signal against technological shortcuts.

However, critics caution that a strict NUA could constrain legitimate science, reduce preparedness for emergencies and diminish transparency that internationally coordinated research could provide (Climate Intervention Research Letter Initiative 2023; Parson *et al.* 2024; Brent, Simon and McDonald 2025; McLaren 2025). Prohibiting research might also drive activity underground, eroding oversight (Brent *et al.* 2025; Jinnah and Dove 2025). Transparent, internationally supervised inquiry is widely considered a public good, essential to preventing unilateral or opaque experiments (Parson *et al.* 2024; Brent *et al.* 2025). From this perspective, halting knowledge production risks leaving gaps to be filled by less accountable actors. As climate risks escalate, some argue it would be imprudent to forgo information about a possible—though risky—emergency tool, and that carefully governed SRM could serve as a risk–risk management option under extreme warming (Parson *et al.* 2024; Brent *et al.* 2025).

The core governance challenge lies in balancing precautionary prohibition with delimited exploration. A pragmatic pathway may be strict prohibition on deployment, while permitting transparent, internationally supervised research that centres equity and reinforces the primacy of rapid emissions reduction (Climate Intervention Research Letter Initiative 2023; Parson *et al.* 2024; Brent *et al.* 2025).

Although SRM research has grown, it remains overwhelmingly concentrated in high-income countries (HICs), led by institutions in the United States of America, the United Kingdom and Australia. Analysis by SRM360 shows that at the end of 2024, HICs institutions received approximately USD 188 million in SRM funding since 2007—over 50 times more than the USD 3.5 million received by LMICs institutions collectively. Less than two percent of total funding went to researchers in LMICs, including LDCs and SIDS. Recent growth—with annual global funding surpassing USD 30 million in 2023 and 2024 and projected to climb further with the United Kingdom’s USD 75 million ARIA programme and over USD 100 million in new philanthropic pledges—risks reinforcing this skew as most new resources continue to flow through high-income institutions. A 2025 governance review further confirms that SRM research and policy dialogues have been shaped primarily by actors of HICs, with limited LMICs leadership or institutional participation.

This imbalance risks excluding the voices and perspectives of communities most vulnerable to climate change, who may also be disproportionately affected by any future SRM decisions or impacts. It also limits the legitimacy of any global discussions on SRM governance, experimentation or possible future use.

Addressing this inequity requires more than traditional forms of capacity building. A shift is needed toward reciprocal capacity sharing, grounded in mutual learning, co-development of knowledge and respect for diverse epistemologies, including Indigenous knowledge systems. This approach must also be gender-responsive, recognizing that power, vulnerability and access to knowledge and decision-making are shaped by gender and other intersecting inequalities (UNEP *et al.* 2020). Long-term support for local research institutions, regionally relevant scenario development and inclusive governance processes are essential to ensure that SRM conversations do not repeat or reinforce global power asymmetries.

Equity, transparency and trust must be central to any international dialogue on SRM. Research and governance frameworks should be guided by interdisciplinary approaches that prioritize environmental integrity, social justice and critical scrutiny—rather than viewing SRM as a technocratic fix.

As SRM enters scientific and policy discourse, there is growing recognition that questions of ethics, justice and legitimacy are not peripheral but central. These include concerns over equity between countries and communities—especially regarding risk distribution—intergenerational fairness and procedural justice. The potential for SRM to create or exacerbate global inequalities has prompted early-stage frameworks that emphasize inclusive participation, clarity of intent and accountability in decision-making. Expert elicitation in Finland underscores these risks, with many anticipating that premature or uncoordinated SRM by powerful actors could emerge as an undesirable ‘emergency’ response and exacerbate inequities, reinforcing the need to prioritize justice and legitimacy from the outset (Haaslahti 2024).

Several initiatives have laid out guiding principles. For instance, the American Geophysical Union’s ethical framework²⁰ outlines expectations for transparency, accountability and precaution in geoengineering research (Flegal *et al.* 2019). However, such principles are not yet consistently applied across institutions, disciplines or national contexts. Consistent with these concerns, experts expressed strong support for international monitoring of SRM research and standard-setting, an IPCC-style special report, and robust public information and engagement, while showing lower support for national-only approaches and scepticism toward market-based mechanisms—indicating a preference for science-led, internationally coordinated governance (Haaslahti 2024).

In 2023, the UN Human Rights Council Advisory Committee released a report²¹ on climate-altering technologies, including SRM. It emphasized the importance of embedding human rights protections, procedural safeguards and consideration of vulnerable populations as core components of any future governance. These findings reinforce broader calls for ethical reflection to be a central, not secondary, pillar of SRM assessment and governance.

20 American Geophysical Union. 2024. Ethical framework principles for climate intervention research. Retrieved from <https://www.agu.org/ethicalframeworkprinciples>

21 UN Human Rights Council Advisory Committee. 2023. Impact of new technologies intended for climate protection on the enjoyment of human rights. <https://www.ohchr.org/en/hr-bodies/hrc/advisory-committee/impact-of-new-technologies>

Many are calling for strengthened governance—grounded in precaution, rights and shared responsibility. Some wish to silence discourse.

Effective governance of SRM must rest on legal, scientific and ethical principles, including the precautionary approach, human rights obligations and commitments to equity, transparency and environmental stewardship. These principles are essential to guide early-stage research and support informed public engagement. Transparency is particularly critical, not only in terms of open access to data and disclosure of funding sources, but also through mechanisms such as registries of SRM research, independent review and pre-registration of studies, which together can help build legitimacy and public trust (Talati, Buck and Kravitz 2025). However, some advocates of restrictive governance frameworks argue that even discussing—or researching—solar geoengineering risks legitimizing it and diverting attention from the urgent need to decarbonize global socio-economic systems, and thus open debate on SRM is often framed as counterproductive to effective climate action (Gupta *et al.* 2020; EnviroNews 2024; Oomen 2025).

While interpretations of precaution vary, there is a growing consensus that precaution does not mean inaction, but rather demands careful, inclusive and globally coordinated oversight. This is particularly urgent given that no shared institutional mechanisms currently exist to govern SRM-related activities, even as research interest and policy debate accelerate. The lack of international norms or institutions for transparency, consent or accountability raises serious questions about legitimacy and the potential for fragmented or unilateral responses.

At the same time, recent analysis highlights that SRM is not entirely ungoverned: existing treaties and institutions—such as the Convention on Biological Diversity, the Vienna Convention and Montreal Protocol, and human rights agreements—already cover aspects of SRM’s potential impacts. Other existing treaties, including the Antarctic Treaty, are beginning to assess the potential impacts of geoengineering²². However, this governance landscape is fragmented, creating overlapping mandates, enforcement deficits and gaps in coordination, which collectively constrain the prospect of coherent and equitable governance (Reynolds *et al.* 2022; Ruddigkeit, Bruggink and Gupta 2025).

Strengthening governance will require the development of common standards for transparency, independent scientific review and mechanisms for inclusive public accountability—especially for any outdoor experimentation or cross-border impacts. Such measures are vital to ensure that negative or inconclusive findings are not hidden, that research agendas are not steered by narrow interests and that legitimacy and trust extend beyond the scientific community to the broader public. Yet transparency alone cannot substitute for regulation: it must be embedded within participatory and internationally coordinated oversight, since fragmented or opaque approaches risk inviting unilateral action, exacerbating inequities and eroding public trust (Talati *et al.* 2025). Without such mechanisms in place, SRM discussions may outpace the capacity of current institutions to manage them responsibly.

22 Antarctic Treaty Consultative Meetings: Geoengineering in Antarctica is not a solution to rapid ice loss and irreversible sea-level rise. https://www.asoc.org/wp-content/uploads/2025/11/atcm47_ip126_Geoengineering-in-Antarctica.pdf

Responsibility extends both to action and inaction—and demands urgent governance clarity

As the global conversation around SRM advances, questions of responsibility are becoming more central—not only for the potential harms that research or deployment might cause, but also for the risks of inaction if SRM is dismissed without adequate exploration, and for the potential moral hazard on mitigation and adaptation associated with considering SRM. Some experts argue that further research may be needed to preserve future decision-making options in the context of escalating climate impacts. Others caution that urgency-driven narratives may constrain democratic deliberation, reinforce power asymmetries and sideline broader ethical and political concerns (Biermann *et al.* 2022; Jinnah and Dove 2025; Quagraine *et al.* 2025).

Across this spectrum of views, there is growing recognition—among both critics and proponents—that robust governance frameworks are urgently needed. Such frameworks could help clarify under what conditions SRM-related activities might be considered acceptable or unacceptable, while also establishing guardrails to ensure that decisions are based on rigorous science, guided by transparent deliberation, conducted in an ecologically responsible manner and inclusive engagement.

This includes the need to engage historically marginalized communities, including youth, Indigenous Peoples and those most vulnerable to climate harm. Ultimately, responsible decision-making about SRM requires a shared sense of accountability—not only for what is done, but also for how choices are made, whose voices are heard and whose interests are protected in the face of scientific uncertainty.

In this context, clear decision points should be built into SRM research trajectories—enabling structured pauses for assessment, inclusive deliberation and course correction. Without these safeguards, early-stage activities risk creating lock-in effects, where research momentum or funding architectures narrow future choices or prematurely legitimize deployment pathways.

Summary of findings

- **The current state of scientific knowledge does not support SRM as a viable climate response.** While some SRM proposed methods—notably SAI and MCB—are receiving increasing scientific attention, they remain deeply uncertain in terms of feasibility, effectiveness and safety. They are not substitutes for climate mitigation or adaptation. Nor are they ready for deployment. UNEP underscores that the most effective and essential response to climate change continues to be deep, sustained emissions reductions, coupled with robust adaptation.
- **Across all modelling studies and emerging field research, proposed SRM approaches present significant unresolved risks, including the possibility of unintended consequences, abrupt termination effects and uneven regional impacts.** Modelling to date is heavily reliant on idealized assumptions and remains poorly equipped to predict real-world outcomes. Additionally, regional variability, ecosystem responses and long-term geopolitical effects are poorly understood. To support informed and responsible decision-making, integrated assessment models should more effectively incorporate interactions among biophysical systems, ecosystem responses, human behaviour and policy dynamics.
- **SRM approaches require a comprehensive assessment of their readiness, feasibility, risks, impacts and trade-offs to ensure any future developments can inform decision-making.** To be ethical, legitimate and responsive to real-world concerns, SRM research must address and integrate the natural, ecological, agricultural, and health and social sciences, embed co-design processes and prioritize meaningful public engagement—particularly with vulnerable and historically marginalized communities. Avoiding technocratic, top-down approaches is essential to safeguard equity and trust.
- **The emerging debate around SRM also raises serious questions of justice, global equity and intergenerational responsibility.** Most of the research to date has been conducted in high-income countries, with minimal participation from those most exposed to climate harms. Addressing this asymmetry requires a shift toward reciprocal capacity sharing, regionally-led research and full recognition of diverse knowledge systems—including Indigenous perspectives. Moreover, some deployment scenarios could extend over multiple decades, raising concerns about committed use, multi-generational governance and technological dependency.
- **As discussions continue, there is growing agreement that early and inclusive governance is not optional—it is foundational.** Without transparent, precautionary and globally coordinated governance, any increase in SRM-related activity risks outpacing our institutional capacity to manage it. Precaution does not mean paralysis—it calls for structured deliberation, ethical safeguards and clearly defined boundaries.
- **UNEP stresses that SRM research should not detract attention or resources from the urgent, proven priorities of deep mitigation and adaptation.** Instead, it should be approached as a limited scientific inquiry, subject to transparency, accountability and globally coordinated oversight.
- As the leading global environmental authority, UNEP sets the global environmental agenda, promotes the coherent implementation of the environmental dimension of sustainable development within the United Nations system and serves as an authoritative advocate for the global environment with a mandate to keep the environment under review. In line with this mandate, UNEP will continue to monitor developments in SRM and advise on emerging environmental risks—with a commitment to precaution, scientific integrity and inclusive dialogue.

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