Researching Solar Radiation Modification, Marine Carbon Dioxide Removal, and Glacial Interventions as Climate Risk Reduction Tools

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Executive Summary

Climate change is progressing faster than many projected mitigation pathways can address. Even under ambitious decarbonization scenarios, global temperatures are expected to overshoot the Paris Agreement targets for several decades, exposing societies to increasing risks from extreme heat, sea-level rise, ecosystem collapse, and irreversible cryosphere loss. While rapid emissions reductions should remain the cornerstone of climate policy, growing evidence suggests that mitigation and adaptation alone may not sufficiently reduce the probability of catastrophic climate outcomes.

This policy brief argues that *research into climate interventions such as Solar Radiation Modification (SRM), targeted glacial interventions, and marine carbon dioxide removal (mCDR) should become a formal component of national and international climate policies*. This would enable development of scientific knowledge, governance frameworks, monitoring capabilities, and international institutions necessary to evaluate these approaches responsibly should future conditions make climate interventions a necessity. Another often discussed and less controversial approach, Carbon Dioxide Removal (CDR) is not discussed in this brief. This policy brief treats CDR as a pre-condition to climate change policies as mitigation will not reduce carbon dioxide already present in the atmosphere. While this brief gives an overview of mCDR proposed approaches that need to be studied more, it focuses on more controversial climate interventions, SRM and glacial interventions.

The paper suggests applying *a diversified portfolio to manage climate risks*. Under such a portfolio, climate policy has five components. Mitigation remains the primary mechanism for reducing long-term climate change, and adaptation reduces societal vulnerability to unavoidable impacts. CDR addresses legacy emissions. Solar Radiation Management and glacial interventions are potential *risk reduction measures* during periods of possible climate overshoot.

[1] This paper is part of the project: SEAO2-CDR project. The SEAO2-CDR project is aimed at expanding our understanding of the potential to use ocean-based marine Carbon Dioxide Removal (mCDR) approaches. By integrating scientific, social, legal and commercial knowledge we are developing the tools, mechanisms and guidelines required to ensure that potential mCDR techniques can be developed and assessed in a responsible and transparent manner. SEAO2-CDR has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101081362.

Both SRM and glacial interventions can reduce climate risks in scenarios where conventional mitigation coupled with CDR and mCDR prove insufficient. Ignoring climate interventions research today increases the likelihood that future decisions would occur under crisis conditions with inadequate scientific understanding, weak governance, and limited public oversight.

The Climate Risks: Context

Emerging evidence indicates that current climate policy that relies on mitigation (reducing greenhouse gas emissions) and adaptation (reducing vulnerability) may not sufficiently manage extremely high-consequence climate risks such as tipping points.[2] Even if global emissions rapidly decline, the long atmospheric lifetime of carbon dioxide from historical emissions will continue affecting the climate system for decades. Moreover, the IPCC mitigation scenarios for net-zero assume CDR at scale, but in reality that is far away from feasible implementation.[3]

Accelerating ice-sheet loss, increasing climate extremes, and the possibility of crossing Earth system tipping points highlight the importance of preparing for a *broader range of future scenarios*. As the current evidence suggests that temporary temperature overshoot of the 1.5°C warming limit will be difficult to avoid, managing these climate risks effectively requires that climate policy adopts a diversified portfolio.[4] This approach, widely applied in public health, national security, and disaster preparedness, will prevent emergency decision-making under conditions of limited evidence and stress.

SRM and glacial interventions can buy much-needed time to implement the strategies of mitigation, adaptation, and CDR without crossing Earth System tipping points.

SRM

SRM, sometimes referred to as solar climate intervention or solar geoengineering, comprises a class of proposed technologies intended to reduce global temperatures by increasing Earth's reflectivity (albedo) and thereby decreasing the amount of incoming solar radiation absorbed by the climate system. Incoming shortwave solar radiation is partially reflected back into space by clouds, atmospheric aerosols, snow, ice, and other reflective surfaces. SRM should not be a permanent solution to anthropogenic warming, but rather a

[2] Armstrong McKay, D. I., Staal, A., Abrams, J. F., et al. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science, 377*(6611), eabn7950.
[3] IPCC (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Ed. P.R. Shukla et al., Cambridge University Press.
[4] Ibid.; Bustamante, M., et al. (2023). Ten new insights in climate science 2023. *Global Sustainability*, *7*, e19.

temporary (at least a several decades of potential deployment to shave off peak temperatures) climate risk reduction measure. SRM encompasses several proposed techniques intended to modestly reduce incoming solar radiation (by about a percent) and temporarily offset a portion of greenhouse warming. Increasing planetary albedo by even a small amount reduces the net energy entering the Earth system and can partially offset warming caused by elevated greenhouse gas concentrations.

Proposed Intervention Strategies[5]

- *Stratospheric Aerosol Injection (SAI):* The most extensively studied approach involves releasing sulfur dioxide or alternative aerosols into the lower stratosphere using a high-altitude aircraft, balloons, or other delivery systems. Once converted into sulfate aerosols, these particles scatter incoming sunlight and increase planetary reflectivity. Climate models indicate that carefully managed SAI (scattering 1% of sunlight) could reduce global temperatures relatively rapidly by 1°C, potentially within months of deployment, while slowing sea-level rise and reducing heat-related climate impacts such as extreme heat, extreme precipitation and strength of hurricanes. While most research has focused on sulfates mimicking natural injections from volcanoes eruptions, the engineered particles are being increasingly studied (e.g., amorphous silica in the case of Stardust Solutions). The choice of the materials used will determine the risk profile of SAI.
- *Marine Cloud Brightening (MCB):* Marine cloud brightening seeks to increase the reflectivity of low-lying marine clouds by introducing sea salt particles that act as cloud condensation nuclei. Brighter clouds reflect more sunlight and could potentially provide regional cooling, particularly over subtropical oceans. Substantial uncertainty remains regarding cloud responses and long-term effectiveness as well as technological readiness.
- *Cirrus Cloud Thinning (CCT):* Unlike SAI and MCB, cirrus cloud thinning seeks to reduce the warming influence of high-altitude cirrus clouds by encouraging the formation of larger ice crystals that fall more rapidly from the atmosphere. It is a form of cirrus avoidance rather than modification. Because cirrus clouds trap outgoing infrared radiation, reducing their persistence may allow greater heat loss to space. The current understanding of CCT remains considerably less mature than that of SAI.

[5] For an overview of SRM methods see Edward A. Parson, David W. Keith. 2024. Solar Geoengineering: History, Methods, Governance, Prospects. *Annual Review of Environment and Resources* 49:337-366. https://doi.org/10.1146/annurev-environ-112321-081911. Space-based methods have also been proposed to scatter or absorb sunlight before it reaches Earth. However, because these methods are unlikely to be feasible in the next quarter century, they are not helpful in the discussion of urgent climate risks reduction measures.

Current state of research

Current climate model simulations suggest SRM could potentially reduce peak global temperatures, lessen extreme heat events, slow Arctic sea ice loss, and reduce some climate damages during emissions transition. While SRM has the potential to deliver these benefits, it is likely to create changes in regional precipitation, weakening of monsoon systems under some scenarios, alterations to stratospheric ozone chemistry. It is important to note, however, that some of the side effects (e.g., ozone chemistry and acid deposition) arise from the material (sulfate), not from reflecting sunlight as such. Hence, some of the side effects might be minimized if other materials are used. As some of the side effects are problems associated with design rather than fixed properties of SRM, more research can help establish which materials are safer to use. SRM also does not address the problem of continued ocean acidification because atmospheric carbon dioxide concentrations remain unchanged. Furthermore, if SRM (SAI specifically) were to be maintained for decades, and then abruptly discontinued (under a series of unlikely events) while greenhouse gas concentrations remained elevated, a "termination shock" i.e., rapid warming can occur, posing severe ecological and societal challenges. SRM research and potential deployment will also face governance challenges and geopolitical implications that would have to be addressed through transparent decision-making, accountable governance, and international cooperation. Lastly, one important point is worth mentioning regarding the SRM. The Climate Vulnerable Forum recently argued that the planet's albedo is changing and, thus, accelerates global warming. Distinct from any position on climate interventions, the Forum flagged the absence of any albedo or reflectivity item in the UNFCCC process as a governance gap.[6]

Glacial Interventions

Rapid melting of mountain glaciers and polar ice sheets poses one of the greatest long-term climate risks. Unlike SRM, glacial interventions are geographically targeted and aim to reduce localized drivers of ice-sheet instability and glacier retreat. Glacial intervention approaches seek to preserve vulnerable ice masses by modifying the physical processes responsible for accelerated melting. Most proposed interventions seek to reduce contact between warm ocean water and vulnerable glacier grounding lines. The Greenland and Antarctic Ice Sheets together contain enough ice to raise global mean sea level by more than 65 meters if completely melted. While complete melting would require centuries to millennia, accelerating ice loss is already contributing significantly to observed sea-level rise.[7] While glacial interventions are not a solution to anthropogenic warming, it is potentially

[6] https://cvfv20.org/the-earths-energy-imbalance-and-the-reflectivity-crisis/#

[7] IPCC. (2021). *Climate Change 2021: The Physical Science Basis*. Cambridge University Press.

a high consequence climate risk reduction measure. Given the trillions of dollars in projected coastal infrastructure losses associated with sea-level rise and potential relocation of millions of people from the coastal areas (not to mention potential loss of lives), investments in scientific research may produce substantial societal benefits.

Proposed Intervention Strategies

- *Subsea Barriers*: Numerical simulations suggest that underwater berms or sills constructed on the seabed could reduce warm-water intrusion beneath ice shelves, thereby slowing basal melting and delaying glacier retreat.
- *Artificial Pinning Points*: Some ice shelves naturally stabilize when grounded on underwater ridges. Artificially constructed pinning points could potentially replicate this stabilizing mechanism by reducing ice flow toward the ocean.
- *Ice Shelf Stabilization*: Engineering concepts have also explored reinforcing floating ice shelves through localized structural modifications that increase resistance to fracturing and calving.
- *Surface Hydrology Management:* Because surface meltwater can penetrate through crevasses and accelerate glacier flow via hydrofracturing, proposals have examined engineered drainage systems to reduce meltwater accumulation on vulnerable ice shelves.

Current state of research

Although still highly experimental, modeling suggests that some interventions could meaningfully delay ice sheet collapse if technically feasible. Research on glacial interventions remains in its infancy compared with SRM. Existing evidence consists primarily of numerical ice-sheet models, oceanographic simulations, and engineering feasibility assessments. However, substantial uncertainties remain regarding engineering feasibility, construction logistics, environmental impacts, ecological consequences, costs, and long-term effectiveness. Unlike SRM, glacial interventions would require large-scale infrastructure in remote and environmentally sensitive polar regions, presenting significant operational and governance challenges. Thus, research is needed to determine engineering feasibility, environmental impacts, costs, governance and international legal requirements.

Marine CDR

mCDR techniques are gaining attention as potential tools to mitigate climate change by enhancing the ocean's natural capacity to remove and store CO_2. However, the potential

deployment of these techniques raises complex legal, ethical, and policy questions that must be addressed to ensure responsible and effective implementation.

Proposed Intervention Strategies

- *Ocean Alkalinity Enhancement:* this approach aims to accelerate the ocean's ability to absorb and sequester carbon dioxide from the atmosphere by adding alkaline substances to seawater.
- *Ocean Fertilization:* Adding nutrients such as iron would stimulate the growth of phytoplankton that take up CO_2 through photosynthesis.
- *Direct ocean carbon removal:* similar to *land base technologies that capture carbon at site, there are methods that would extract dissolved CO_2 from seawater*
- *Blue Carbon Restoration:* methods involve restoring coastal ecosystems such as mangroves, seagrass meadows, and salt marshes, which can capture and store carbon.
- *Seaweed and Kelp Farming:* These marine plants have the capacity to absorb carbon via photosynthesis.

The mCDR research is a lot less controversial than the SRM and glacial interventions. Nevertheless, more research is needed to establish scalability, environmental impacts, ability to permanently store carbon as well as to analyze the patchwork of existing legal regulations (e.g., BBNJ, the London Protocol) and their applicability to regulation of mCDR, especially in the high seas.

Diversified climate portfolio: SRM and glacial interventions as risk reduction measures

Research on climate interventions should be understood as a sequence of steps such as modelling, lab work, contained testing and outdoor experiments. Each step carries different risks and requires oversight specific to the step. Calls for expanded research are often misunderstood as advocacy for implementation and deployment. In reality, rigorous research provides the evidence needed to determine whether proposed interventions are effective, safe, economically feasible, ethically acceptable, and suitable approaches to achieve climate goals. Moreover, without recognizing the importance of incorporating SRM and glacial interventions in global climate policy, governance frameworks and international agreements to ensure safe, transparent and responsible research and potential deployment are unlikely to be developed.

Within the framework of a diversified portfolio to manage risks, SRM and glacial interventions occupy a distinct category compared to mitigation, adaptation and CDR. SRM and glacial interventions are potential *risk reduction measures* intended to lessen the probability or severity of high-consequence outcomes during periods of climate overshoot. SRM offers the

potential for relatively rapid global cooling but introduces uncertainties related to atmospheric chemistry, precipitation, geopolitical governance, and termination effects. Glacial interventions, by contrast, are geographically localized and directly target mechanisms contributing to sea-level rise, but face considerable engineering and ecological uncertainties. Neither approach addresses the root cause of climate change nor eliminates the need for emissions reductions.

A diversified portfolio perspective therefore evaluates these interventions not in isolation but as complementary to existing climate strategies. From a risk management standpoint, research on SRM and glacial interventions functions as an investment in scientific preparedness. Analogous to vaccine research during public health planning without expecting a future outbreak or earthquake engineering without expecting seismic disasters, SRM and glacial interventions research will build knowledge before emergencies might arise.

The governance of the expanding research will require careful attention to common concerns such as moral hazard, slippery slope, risk of unilateral action and lack of transparency and accountability. Moral hazard, the possibility that research alone could reduce incentives for emissions mitigation, remain central to the opposition to climate interventions. However, properly designed governance can explicitly position SRM and glacial interventions research as a complement and not an alternative to aggressive decarbonization. Research funding should therefore be integrated within broader climate strategies that prioritize rapid decarbonization. Additionally, linking SAI authorization to emissions reduction performance as well as prohibiting any commercial models such as cooling credits can limit the risk of moral hazard.[8] Slippery slope arguments are often used to oppose climate interventions on the grounds that research will ultimately lead to deployment. However, as the empirical evidence shows some technologies were never developed and deployed despite the research into them. Moreover, viewing research as a sequence of steps can allow for "exit ramps" at any given stage preventing lock in situations. Another worry, the potential of a unilateral action by individual states or non-state actors can be minimized by international collaboration and scientific cooperation to build trust and reduce the risks of a state going rogue. The unilateral action problem is also not supported by the fact that, at least in the case of SRM, an effective deployment will require international collaboration.[9] Additionally, the unilateral-action concern can be addressed by monitoring and attribution - the ability to detect, track and attribute what is in the stratosphere (which will depend on the materials used in SAI). Lastly, any development of climate interventions

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[8] Dye, Jorden. Solar Radiation Modification Primer: An introduction to mechanisms, impacts, and governance. The Pembina Institute, 2026.

[9] Joshua B Horton I, "Geoengineering and the Myth of Unilateralism : Pressures and Prospects for International Cooperation" 6, no. October 2010 (2011): 56–69.

with high stake consequences calls for transparent and accountable governance. In practice, this calls for independent oversight, open publication of results, measurement and monitoring capabilities in place, and meaningful public engagement.

Importantly, the central issue of any development of governance of climate interventions is the discussion of justice and equity. The geographic and intergenerational distribution of burdens and benefits of climate interventions, especially of SRM, is not uniform. It is essential that the regions most vulnerable to climate change risks, have voice and ability to impact decision-making over the research of climate interventions.[10] Some of the main questions that should guide ethical and responsible governance of climate interventions are: who participates, who gains and bears risks, whose knowledge and authority count, and who inherits dependence and termination risks.

In sum, under the diversified portfolio framework, SRM and glacial intervention research should be viewed not as a substitute for mitigation but as complementary components of prudent climate risk management. Developing scientific understanding today will reduce the likelihood that decisions concerning potentially consequential interventions are made during periods of acute climate crisis with inadequate evidence. Governance can evolve alongside research to ensure inclusive international decision-making to allow for the most vulnerable communities to shape future development of climate interventions.

Policy Implications

A path toward a more comprehensive climate policy that includes evidence informed discussions on SRM and glacial interventions' feasibility, desirability and acceptability, calls for investment in research on SRM and glacial interventions. To ensure that this research is done in a responsible and accountable way that also minimizes the risks associated with climate interventions:

- Climate interventions research should be explicitly framed as complementary to rapid greenhouse gas emissions reductions. Policy statements, funding mechanisms, and governance frameworks should consistently reinforce that long-term climate stabilization ultimately depends on achieving net-zero emissions. Additionally, authorization to engage in SAI research may depend on mitigation performance.[11] Lastly, stopping at any stage must always be a legitimate outcome to ensure that research is not a presumption in favor of deployment.

[10] The Degrees Initiative is one such example. The non-profit builds research capacity and engages policymakers and scientists in developing countries to evaluate SRM.
[11] Parson, E. A. (2014). Climate engineering in global climate governance: Implications for participation and linkage. *Transnational Environmental Law*, *3*(1), 89–110.

- Governments should establish coordinated interdisciplinary research programs on SRM and glacial interventions involving atmospheric science, glaciology, engineering, ecology, economics, law, political science, and ethics.
- Given the transboundary implications of climate interventions, research should emphasize international collaboration through institutional platforms, such as WMO, UNEP, IPCC, ATS and the Arctic Council (for glacial interventions) among others. A practical first step would be joint research programs and shared data among a group of willing states, with the most climate-vulnerable countries included from the start. Collaborative research will enhance transparency and strengthen global scientific capacity, and governance can develop alongside with the research.
- Governments and international institutions should establish governance frameworks that would define research standards, transparency requirements, public participation mechanisms, international oversight arrangements, and decision-making processes for any future consideration of deployment.[12] Importantly, a responsible governance will require technology to detect, measure and if possible - also attribute aerosols in the stratosphere in the case of SAI - who released what, where and how much. Without it, research standards and oversight arrangements are harder to verify.[13]

Conclusion

Climate change presents an increasingly complex cluster of risks that may exceed the capacity of mitigation, adaptation, and CDR efforts. Research into SRM and glacial interventions should therefore be understood as risk management rather than endorsement of deployment. Developing scientific understanding today will allow future policymakers to make informed, evidence-based decisions under transparent governance rather than responding to climate emergencies with inadequate information. A balanced climate policy portfolio should continue prioritizing emissions reductions while responsibly investigating additional tools that may one day help reduce the probability of catastrophic climate outcomes.

SRM and glacial interventions represent two fundamentally different classes of potential climate interventions. SRM seeks to modify Earth's radiative balance through temporary

[12] Although domestic legislation, what "research standards" and "transparency requirements" can look like in practice, is illustrated in Tracy Hester and Craig Segall's model bill for Texas (30 June 2026). It sets out: (a) permits for releases above a defined threshold; (b) a public register of applications and decisions; and (c) penalties for unpermitted activity. See https://law.uh.edu/eenrcenter/SRM-Texas-White-Paper-final-20260630.pdf.

[13] Waxman, Matthew C. and Spector, Amyad and Kushnir, Doron and Yahav, Robert, From Particles to Policy: Technical Building Blocks for Multi-State SAI Coordination (May 21, 2026). Columbia Public Law Research Paper No. 6814063, Available at SSRN: https://ssrn.com/abstract=6814063.

reductions in absorbed solar energy, while glacial interventions aim to slow specific processes contributing to irreversible ice-sheet loss and sea-level rise. SRM and glacial interventions remain experimental, both involve substantial uncertainties, and neither addresses the root causes of climate change. However, both require rigorous scientific investigation because they may expand future policy options during periods of elevated climate risk. SRM and glacial interventions can buy much needed time to successfully implement the strategies of mitigation, adaptation, and CDR without crossing Earth System tipping points.

Climate policy should integrate aggressive emissions reductions, adaptation, carbon dioxide removal, and responsible research on climate interventions. Whether SRM and glacial interventions ultimately prove feasible, unacceptable, or unnecessary, expanding knowledge will strengthen our capacity to respond to an uncertain climate future. Accepting the necessity of research on climate interventions does not predetermine outcomes of deployment. Instead, it will allow for future decisions to be guided by scientific evidence rather than urgency. Climate intervention research represents preparedness, not commitment. Lastly, preparedness should also mean preparedness for ethical decision, not only preparedness for technological choice. Thus, governance of climate interventions research should be guided by the questions of whose time climate interventions might buy, under whose authority, at whose risk, and for what political purpose.