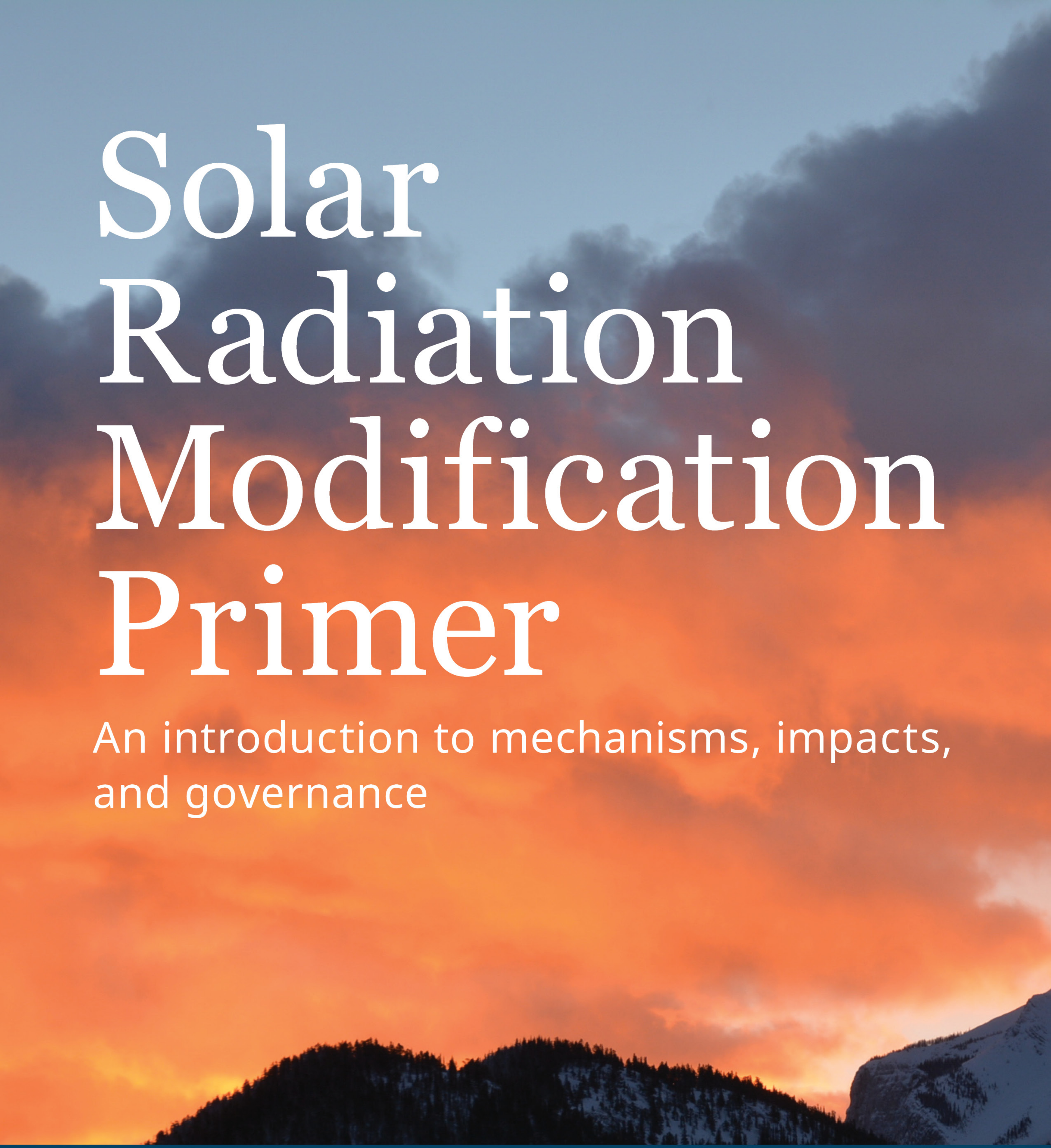

Solar Radiation Modification Primer

An introduction to mechanisms, impacts, and governance

September 2026

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PEMBINA Institute

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These acknowledgements are some of the beginning steps on a journey of several generations. We share them in the spirit of truth, justice, reconciliation, and to contribute to a more equitable and inclusive future for all of society.

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Executive summary

Solar radiation modification (SRM) is a collection of climate interventions that reduce the solar radiation warming the Earth to prevent or minimize dangerous climate change. While the first U.S. government report to recommend the use of SRM interventions was released in 1965, attention to SRM has increased since 2021. SRM has entered the public conversation as a potential intervention to address the widening gap between the growing impacts of anthropogenic climate change and the pace of global emissions reductions. Current emissions reduction policies and actions are leading to a scenario in which global mean temperature approaches 2°C, widely considered a threshold that could prevent some of the most severe impacts of climate change. SRM offers the only known climate intervention that can be deployed at a pace and scale to reduce global mean temperature over years rather than decades, with deployment costs that are multiple orders of magnitude lower than those of full global mitigation.

The potential benefits also come with potential risks and harms for populations across the globe, such as changes in precipitation patterns or increased acid rain. In response, governments and international organizations are increasingly focused on SRM governance. To meaningfully engage in these governance discussions, the Canadian government and environmental non-governmental organizations (ENGOs) need a clearer understanding of the methods, benefits, and risks associated with SRM. They also need to know the status of the research across academic fields from the fundamental science to the impacts on ecology and agriculture — both where there is certainty and where further research is required. This primer is intended to provide ENGOs with an introduction to the broader SRM topic, focusing on understanding the benefits and risks of stratospheric aerosol injection (SAI), the method that holds the most promise.

Key takeaways

- SRM is not a substitute for deep and sustained emissions reductions. In any SRM scenario, continued decarbonization and deployment of carbon removal are required to avoid the long-term risks of dangerous climate change.
- SRM evaluation requires a risk–risk framework. This compares the risks of the intervention with those of non-intervention where the baseline scenario includes continued and increasing climatic impacts. This approach helps assess the governance challenges of introducing new risks.

- While five potential SRM methods exist, the policy conversation is focused on the governance of stratospheric aerosol injection (SAI).
- SAI is the only climate intervention capable of cooling the planet within one to two years. This temperature reduction could produce significant benefits, including fewer extreme heat events, slower ice melt, and lower sea-level rise.
- The principal risks are largely design and governance driven. Termination shock, moral hazard risk, and equity concerns all depend on how SRM is deployed and governed. Known biophysical risks of stratospheric aerosol injection include modest ozone loss, regionally concentrated acid deposition, and altered precipitation.
- The annual SAI costs that could reduce global temperatures by 0.5 to 1°C are estimated in the tens of billions (US$) range. With estimates of the cost to fully decarbonize the global economy around US$9.2 trillion per year, the comparatively low cost of SRM is enough to put deployment within the reach of individual nations.
- Current actions and policies to address climate change present no risk-free scenarios. The global climate is already on a path to potentially cross critical thresholds and tipping points in global temperature. In contrast, SRM constitutes an intervention on a previously untried scale and entails significant benefits and new risks. In this context, no decision is without risks, but it is the responsibility of governments and civil society to navigate these challenges.

1. Introduction

Solar radiation modification (SRM) refers to a set of climate interventions that aim to reduce the amount of solar radiation that warms the Earth. These interventions have been studied for decades but are increasingly part of the climate conversation around the widening gap between how quickly and dangerously the climate is changing and how fast the world can realistically respond. SRM has a unique advantage: it is the only approach known to be capable of cooling the planet over years, not decades. Emissions reductions and carbon removal both work on technical, economic and political timescales that are slower than the accelerating pace of climate impacts. If global temperatures rise rapidly enough to trigger irreversible tipping points, emissions reductions and carbon removal may be unable to prevent catastrophic harm, because the damage would already be locked in by the time those interventions took effect.

This difference in timescale is the central reason SRM has entered the policy conversation. Tipping points are critical thresholds in the climate system beyond which change becomes self-sustaining: once a threshold is crossed, internal feedbacks drive the system toward a new state regardless of subsequent human action. Because these transitions are effectively irreversible on human timescales, their associated risk depends directly on how high global temperatures climb and how long they remain elevated.[1]

This dynamic makes the speed of an intervention critical, independent of its eventual magnitude. Emissions reductions and carbon dioxide removal address the underlying driver of warming and remain indispensable for long-term climate stability. However, neither can lower temperatures rapidly enough to prevent the system from crossing an immediate threshold; carbon removal in particular requires decades of sustained, large-scale deployment before yielding a measurable reduction in global mean temperature.[2]

Overshoot scenarios, in which global temperatures increase beyond 1.5°C or 2°C, are now more likely than limiting global warming to below these levels. 2°C is widely considered a threshold that could prevent some of the most severe impacts of climate change.[3] Based on current models, the current emissions trajectory, with no increase in mitigation ambitions, would result

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[1] David I. Armstrong McKay et al., "Exceeding 1.5°C Global Warming Could Trigger Multiple Climate Tipping Points," *Science* 377, no. 6611 (2022): eabn7950, https://doi.org/10.1126/science.abn7950.

[2] IPCC, *Summary for Policymakers*. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* H. Lee and J. Romero eds. (2023). https://www.ipcc.ch/report/ar6/syr/

[3] Carbon Brief, "Two Degrees: The History of Climate Change's Speed Limit." December 8, 2014. https://www.carbonbrief.org/two-degrees-the-history-of-climate-changes-speed-limit/

in a mean temperature increase of 2.8 °C by 2100.[4] Recent estimates suggest that the globe will cross 1.5°C warming by the early 2030s.[5] As governments contemplate the reality of inaction and climate change, SRM is increasingly seen as a possible intervention for a world that has failed to achieve its goals.

Environmental groups and governments that want to engage with SRM research and governance need a clearer understanding of the methods, benefits, and risks. This primer introduces these topics and provides a framework for thinking through SRM within the broader climate intervention toolkit.

[4] IPCC, *Summary for Policymakers*.

[5] Piers M. Forster et al., "Indicators of Global Climate Change 2025: Annual Update of Key Indicators of the State of the Climate System and Human Influence," *Earth System Science Data* 18, no. 6 (2026). https://doi.org/10.5194/essd-18-3889-2026

2. Background to SRM

2.1 The emergence of SRM in climate conversations

The first governmental report on possible SRM interventions was the 1965 report *Restoring the Quality of Our Environment* produced by the President's Science Advisory Committee under U.S. President Lyndon Johnson. This report highlighted both surface albedo enhancement and cirrus cloud thinning as potential interventions to address the impacts of climate change.[6] Since 2010, international organizations and governments have been increasingly addressing SRM, with interest and activity rising sharply over the last five years. The Climate Overshoot Commission, the European Union, and the U.K. and U.S. governments have all released reports on SRM.[7]

The 2010 Convention on Biological Diversity Decision, which adopted recommendations on SRM deployment while exempting small-scale scientific research, was the first international recognition of SRM.[8] More recently, governance has emerged as a pressing topic in SRM reports. The 2023 UN Environment Programme report *One Atmosphere* called for four priority actions: establishing a globally inclusive scientific assessment process, exploring a multilateral governance framework, creating a broader framework for governing the stratosphere, and promoting inclusivity in SRM governance and research.[9]

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[6] President's Science Advisory Committee, *Restoring the Quality of Our Environment* (1965). Available at https://nsarchive.gwu.edu/document/31937-document-2-white-house-report-restoring-quality-our-environment-report-environmental

[7] Climate Overshoot Commission, *Reducing the Risks of Climate Overshoot* (2023). https://www.overshootcommission.org/report

European Commission: Group of Chief Scientific Advisors, *Solar Radiation Modification* (2024). https://data.europa.eu/doi/10.2777/391614

Hopkins Van Mil, *Solar Radiation Modification: A Public Dialogue; Public Views on SRM Research and Potential Deployment* (U.K. Natural Environment Research Council, 2026). https://www.ukri.org/wp-content/uploads/2026/05/NERC_280526-PublicDialogueonSRM-Report.pdf.US

U.S. Office of Science and Technology Policy, *Congressionally Mandated Research Plan and an Initial Research Governance Framework Related to Solar Radiation Modification* (2023), https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/06/Congressionally-Mandated-Report-on-Solar-Radiation-Modification.pdf

[8] Conference of the Parties to the Convention on Biological Diversity, *Decision X/33: Biodiversity and Climate Change, UNEP/CBD/COP/DEC/X/33* (October 29, 2010). https://www.cbd.int/doc/decisions/cop-10/cop-10-dec-33-en.pdf

[9] United Nations Environment Programme (UNEP), *One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment* (2023). https://www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment

2.2 SRM in the climate toolkit

Addressing climate change is not a single problem with a single solution. Climate interventions must be viewed as a portfolio, each targeting a different point in the chain of cause and effect that runs from the energy system to its impacts on ecosystems and human welfare.

There are four distinct links in the chain driving climate change and its impacts:

1. Greenhouse gas emissions are produced by human activities.
2. Those emissions accumulate in the atmosphere.
3. The increased concentration of greenhouse gases increases global temperatures.
4. Increased global mean temperatures drive changes in the climate system that harm populations and ecosystems.

Currently, there are four major categories of climate intervention that target each link in the chain.

Emissions reductions are the foundation of climate policy and work to break the chain at the first link by reducing the amount of greenhouse gas emissions entering the atmosphere, primarily through shifts in the energy system. Emissions reduction strategies are being implemented around the globe, including electric vehicles, renewable energy and the electrification of industry. These strategies help reduce the link between human activities and increases in greenhouse gas emissions. Emissions reduction is, and needs to remain, the primary response to climate change to address the fundamental driver of warming.

Carbon dioxide removal (CDR) is focused on reducing the atmospheric concentration of carbon dioxide already emitted in the first stage. CDR, sometimes referred to as 'carbon removal', does not reduce current rates of emissions, but it aims to remove previously emitted CO_2 and store it durably. Deployment of large-scale carbon removal is important because it helps reduce the main cause of climate change by lowering atmospheric CO_2 concentrations. One drawback of carbon removal is the time scale required for both deployment and meaningful reductions in atmospheric CO_2 levels. Even rapid deployment of carbon removal would require decades of sustained removals to produce the necessary reduction in global mean temperatures.

Sunlight reflection helps break the link between atmospheric greenhouse gas concentrations and the temperature increases they would cause. Sunlight reflection lowers the amount of solar energy that can reach the surface of the Earth by increasing the Earth's reflectivity. Reducing the amount of solar energy entering the system lowers the temperature increase observed at a given greenhouse gas concentration. While sunlight reflection can reduce global mean temperatures rapidly compared to other interventions, it does not reduce either new emissions or the concentration of emissions already in the atmosphere.

Adaptation is focused on reducing the harm experienced by populations from climate change. Like emissions reductions, several adaptations are being deployed globally, including permeable pavement, seawalls, and early warning systems for heat waves. Unlike the other intervention categories, adaptation does not reduce the increase in, or the direct impact of, climate change. Instead, adaptation focuses on disrupting the final link in the chain, the on-the-ground harm experienced by populations. Adaptation efforts are limited by the rate and eventual extent of global climate change.

These four interventions are not alternatives to one another; all must be considered in a comprehensive climate policy. The debate is about the appropriate role of each, the sequencing of deployment, and the risks of overdependence on any one approach at the expense of the others.

2.3 Evaluating SRM: the risk–risk framework

Because the cost of SRM is so low relative to the outsized benefits of limiting global warming, a traditional cost-benefit analysis reveals little. Furthermore, the risks introduced by SRM deployment can't be examined in isolation without a reference to the risks of no or limited action. For a holistic evaluation of SRM, this primer follows a risk–risk framework, which is used for complex interventions that introduce novel risks while reducing primary risks. In it, the risks of a chosen intervention are compared with the risks of non-intervention.[10]

The framework organizes impacts into three categories.

1. **Target risks:** the primary impacts a chosen intervention aims to reduce. For SRM, the primary harm targeted is the increase in global temperatures driven by the accumulation of greenhouse gases in the atmosphere. SRM can reduce several direct impacts, including extreme heat events, ice melt, and sea-level rise. Furthermore, SRM could delay or prevent potentially catastrophic climate tipping points from being reached.

2. **Countervailing risks:** the new risks introduced or increased by the chosen intervention. For example, SAI may introduce and/or increase several biophysical risks such as ozone depletion, acid rain, and altered precipitation.

3. **Co-benefits**: the additional benefits created by the intervention that are not the primary purpose. For SRM, one of the main co-benefits may be providing time to complete mitigation efforts and deploy carbon removal technologies.

[10] Tyler Felgenhauer et al., *Solar Radiation Modification: A Risk-Risk Analysis,* (Carnegie Climate Governance Initiative (C2G), 2022). https://www.c2g2.net/wp-content/uploads/202203-C2G-RR-Full.pdfNULL

The risk–risk framework describes four types of risk trade-offs. These are defined based on whether the populations that are impacted are the same or different, and whether the type of risk is the same or different.

1. A **risk offset** happens when a population faces less of one type of risk, such as when a population experiences fewer extreme heat events with SRM deployment.
2. A **risk transfer** is when one population's risk is lowered while another population experiences an increase in the same risk category. While the regional impacts are still being studied, shifts in precipitation that change risk profiles would constitute a risk transfer under SRM deployment.
3. A **risk substitution** happens when a population experiences less risk in one category while facing increasing risk in another category. Reduced risk of flooding from lower sea level rise while experiencing increases in acid rain is an example.
4. A **risk transformation** is when a population faces divergent risks from the same intervention. For SRM, a risk transformation would be one region benefiting from decreased global temperatures while another region faces disruptions to the monsoon cycle.

This taxonomy gives policymakers and analysts a structured vocabulary for what are nuanced distributional arguments. Further, the framework explicitly focuses on who bears which risks. This primer examines the benefits and risks of SRM using this framework.

3. Overview of SRM methods

Five distinct methods of are currently being examined for reducing the amount of solar energy entering Earth's atmosphere. There are large differences among the methods, as each intervention varies in its deployment location, the natural processes it interacts with, and the new risks it introduces. Understanding how each method is deployed and how it functions is a prerequisite for engaging with the governance and policy questions currently at the focus of international and national discussions.

These five methods are not equivalent candidates, and the sections below should not be read as a menu of comparable options. Assessments of SRM feasibility tend to rely too heavily on the existence of demonstration hardware. A more practical test is functional: whether credible industrial suppliers could bid, with performance guarantees, to deliver a specified radiative forcing by a specified date at a given cost. Against an illustrative benchmark of 0.2 W m^{-2} of global forcing by 2040 at no more than US$15 billion per year, sulphate SAI rates as highly feasible, as multiple suppliers could offer confident estimates drawing on several independent combinations of aircraft and delivery methods. Conversely, space-based methods rate as outright infeasible, while marine cloud brightening, cirrus cloud thinning, and surface albedo enhancement rate low because none currently offers a clear engineering pathway to that benchmark. The critical distinction lies between research and development: engineering a system from demonstrated technologies is relatively predictable, whereas progress in research prior to demonstrated performance is not. While these feasibility judgments are illustrative rather than definitive, this is why SAI dominates governance discussions and why this primer concentrates primarily on it.[11]

3.1 Stratospheric aerosol injection

Stratospheric aerosol injection (SAI) is the method that anchors most policy discussions. SAI is inspired by observations of volcanic eruptions that launch sulphur dioxide into the stratosphere (the second-lowest layer of the atmosphere, around 10 to 50 km above the ground). As sulphur dioxide particles mix in the stratosphere, they oxidize and react with water to form reflective droplets of sulphuric acid, which scatter sunlight away from the planet.[12] In 1991, the eruption of Mount Pinatubo resulted in a 0.3 to 0.5°C decrease in mean global temperature over two years,

[11] Edward A. Parson and David W. Keith, "Solar Geoengineering: History, Methods, Governance, Prospects," *Annual Review of Environment and Resources* 49 (2024). https://doi.org/10.1146/annurev-environ-112321-081911

[12] Science Advice for Policy by European Academies (SAPEA), *Solar Radiation Modification: Evidence Review Report* (2024). https://doi.org/10.5281/zenodo.14283096

after which average temperatures returned to expected levels.[13] SAI deployment would mimic this natural process by using airplanes to inject sulphate aerosol particles (or some other similar aerosol) into the stratosphere.

Deployment in the stratosphere is important for successful SAI intervention. While sulphur can be deployed in both the troposphere (the atmosphere closest to the surface) and the stratosphere, sulphur particles released in the stratosphere are able to persist for one to two years versus only weeks in the troposphere. Building on natural observations, sulphur aerosols are the best-understood material for stratospheric injection. The benefits and risks in the following sections are well understood, as key aspects of the chemistry and optical properties have been studied for decades.[14] To address risks of ozone loss from sulphur deployment, a range of alternative materials are being studied, including calcium carbonate and titanium dioxide. These materials may result in lower impacts on ozone or increased reflectivity, but their overall impacts in the stratosphere require further study.[15]

An important consideration for SAI deployment is the limitations of current commercial aircraft. Commercially available aircraft cannot carry meaningful payloads above 12-13 km, while the required deployment for SAI lies at 15-20 km. Research has demonstrated that even with these technical challenges, SAI deployment could begin with available aircraft, gradually shifting to custom equipment over time.[16] The creation of new purpose-built aircraft would require production and basing on a global scale. However, estimates of the cost for SAI deployment and aircraft development remain relatively low at US$2 to 10 billion annually.[17] The annual SAI costs that could reduce global temperatures by 0.5 to 1°C are estimated in the tens of

[13] Alan Robock, "Volcanic Eruptions and Climate," *Reviews of Geophysics* 38, no. 2 (2000). https://doi.org/10.1029/1998RG000054

UNEP, *One Atmosphere*.

[14] Mark G. Lawrence et al., "Evaluating Climate Geoengineering Proposals in the Context of the Paris Agreement Temperature Goals," *Nature Communications* 9 (2018). https://doi.org/10.1038/s41467-018-05938-3

[15] Lawrence, "Evaluating Climate Geoengineering Proposals in the Context of the Paris Agreement Temperature Goals."

[16] Alistair Duffey et al., "Low-altitude high-latitude stratospheric aerosol injection is feasible with existing aircraft," *Earth's Future*, 13 (2025). https://onlinelibrary.wiley.com/doi/abs/10.1029/2024EF005567

[17] Justin McClellan, David W. Keith, and Jay Apt, "Cost Analysis of Stratospheric Albedo Modification Delivery Systems," *Environmental Research Letters* 7, no. 3 (2012). https://doi.org/10.1088/1748-9326/7/3/034019

Wake Smith and Gernot Wagner, "Stratospheric Aerosol Injection Tactics and Costs in the First 15 Years of deployment," *Environmental Research Letters* 13, no. 12 (2018). https://doi.org/10.1088/1748-9326/aae98d

Jesse L. Reynolds, "Solar Geoengineering to Reduce Climate Change: A Review of Governance Proposals," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 475, no. 2229 (2019). https://doi.org/10.1098/rspa.2019.0255 billions (US$) range,[18] compared with the cost of global decarbonization (estimated at around US$9.2 trillion per year[19]).

3.2 Marine cloud brightening

Marine cloud brightening (MCB) increases reflectivity through a different process and on a smaller scale than SAI. MCB involves spraying fine sea salt particles into the marine atmosphere boundary layer. These particles act as cloud condensation nuclei, causing atmospheric water vapour to condense into a larger number of small droplets. The clouds formed by this process reflect more sunlight than clouds made of larger, fewer droplets. Smaller droplets also help extend cloud lifetime and coverage by suppressing precipitation.[20] As MCB works on marine clouds in a specific region, it is considered a regional intervention and is typically most effective in areas with persistent stratocumulus cloud decks.[21]

Like SAI, MCB is built on real-world observations; in this case, ship-track emissions provide a modelling analogue.[22] MCB is currently being tested in Australia as a regional intervention to assess the potential of protecting the Great Barrier Reef from extreme heat waves. This is a test of a harm reduction measure rather than an SRM intervention.[23] In 2025, a substantial research program, including small-scale field tests of MCB, was conducted by the U.K. government's Advanced Research and Invention Agency.[24]

3.3 Cirrus cloud thinning

Cirrus cloud thinning (CCT) occupies a distinct niche in the SRM portfolio because it targets outgoing heat rather than incoming sunlight. High-altitude cirrus clouds, composed of ice

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[18] UNEP, *One Atmosphere*.

Joshua B. Horton, Wake Smith, and David W. Keith, "Who Could Deploy Stratospheric Aerosol Injection? The United States, China, and Large-Scale, Rapid Planetary Cooling," *Global Policy* (2025). https://doi.org/10.1111/1758-5899.70015

[19] McKinsey, *The Net Zero Transition: what it would cost, what it could bring* (2022). https://www.mckinsey.com/capabilities/sustainability/our-insights/the-net-zero-transition-what-it-would-cost-what-it-could-bring#/

[20] UNEP, *One Atmosphere*.

[21] Jim M. Haywood et al., "World Climate Research Programme Lighthouse Activity: An Assessment of Major Research Gaps in Solar Radiation Modification Research," *Frontiers in Climate* 7 (2025). https://doi.org/10.3389/fclim.2025.1507479

[22] C2G, *Solar Radiation Modification: A Risk-Risk Analysis*.

[23] Southern Cross University, "Taking to the Skies to Shade Corals Using New Technologies," August 26, 2021. https://www.scu.edu.au/news/2021/taking-to-the-skies-to-shade-corals-using-new-technologies.php

[24] Advanced Research and Invention Agency, "Exploring Climate Cooling." https://aria.org.uk/opportunity-spaces/future-proofing-our-climate-and-weather/exploring-climate-cooling

crystals at altitudes of roughly 10 to 16 km, have an overall warming effect. Unlike the clouds in MCB, these cirrus clouds trap outgoing infrared radiation from the Earth's surface more effectively than they reflect incoming solar radiation. CCT aims to reduce this warming effect by seeding these clouds with ice-nucleating particles, causing ice crystals to grow larger and heavier. These thinned cirrus clouds allow more terrestrial heat to escape into space.[25]

3.4 Surface albedo enhancement

Surface albedo enhancement encompasses a range of proposals to increase the reflectivity of terrestrial or ocean surfaces. Examples of this intervention include white roofs, reflective crop varieties, and specialized pavement. These approaches are generally low-risk, easily reversible, and technically feasible in their simpler forms. They are also, with the partial exception of ocean-based approaches, incapable of contributing meaningfully to global temperature management.[26]

Surface albedo enhancement is best understood as a category of local and regional adaptation tools rather than a global temperature strategy. Its relevance for national climate planning lies in its co-benefits and complementarity with other measures, not in its capacity to offset large-scale warming.

3.5 Space-based methods

Space-based solar radiation modification involves placing reflectors, sunshades, or scattering structures between the Earth and the Sun. These would be typically placed at the L1 Lagrange point, approximately 1.5 million km from Earth, to intercept a fraction of incoming solar radiation before it reaches the atmosphere. Space-based methods are not currently being seriously pursued and remain technologically beyond our capability.[27]

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[25] Blaž Gasparini, Zachary McGraw, Trude Storelvmo, and Ulrike Lohmann, "To What Extent Can Cirrus Cloud Seeding Counteract Global Warming?" *Environmental Research Letters* 15, no. 5 (2020)., https://doi.org/10.1088/1748-9326/ab71a3

[26] Royal Society, *Geoengineering the Climate: Science, Governance and Uncertainty,* RS Policy Document 10/09 (2009). https://royalsociety.org/-/media/policy/publications/2009/8693.pdf

[27] National Research Council, *Climate Intervention: Reflecting Sunlight to Cool Earth* (2015). https://doi.org/10.17226/18988

3.6 Comparing SRM methods

The table below summarizes the three primary methods of SRM across dimensions relevant to policy and governance analysis. These methods are the most likely to be technically feasible in the near term.

Table 1. Comparison of solar radiation modification methods

	Stratospheric aerosol injection (SAI)	Marine cloud brightening (MCB)	Cirrus cloud thinning (CCT)
Physical mechanism	Reflects incoming solar radiation via stratospheric aerosol layer	Increases reflectivity of low marine clouds via cloud condensation nuclei	Reduces heat-trapping capacity of high-altitude cirrus clouds; targets outgoing longwave radiation
Geographic scope of effects	Global; aerosols distribute throughout the stratosphere	Regional; concentrated in areas with persistent stratocumulus cloud decks	Regional to sub-continental; most effective at middle and high latitudes
Reversibility	Moderate; effects persist 1–2 years after cessation; termination shock risk	High; effects dissipate within days to weeks of halting	High; ice crystal residence times short
Key risks	Ozone depletion, hydrological disruption, stratospheric heating, termination shock	Precipitation disruption, ENSO interference, ecosystem side effects, rapid rebound on cessation	Over-seeding risk (net warming), model uncertainty, material toxicity
Natural analogue	Yes; volcanic eruptions (e.g., Pinatubo)	Partial; ship tracks provide observational analogue	None
Technological feasibility	High; existing aircraft technology supports development for 20 km deployment; suppliers could offer performance guarantees	Low; laboratory sprayers output ~10^{13} cloud condensation nuclei per second versus 10^{16} needed; no deployable engineering pathway	Low; less mature deployment hardware, though radiative forcing is more sensitive; net thermal effect varies by local meteorology

The rest of this primer focuses on the benefits and risks of SAI, as it is the prominent form of SRM discussed in global governance conversations and the only method with the potential to reduce global warming at the pace and scale required.

4. Benefits and climate outcomes of SAI

As discussed in section 3.1, SAI offers almost immediate and consequential benefits to the global climate system. These benefits are directly targeted at some of the most pressing issues associated with anthropogenic warming, including rising temperatures, extreme weather events, and global sea ice loss. While the risks introduced by SAI will be covered in the following section, it is important to start with the benefits to understand why such a large-scale intervention is being considered. The benefits of SAI deployment are easy to conceptualize as the inverse of the heat-related impacts of global warming. However, non-heat risks, such as ocean acidification, are not directly reduced by deployment, though the carbon-cycle feedbacks that accompany higher temperature would be partially reversed.

4.1 Effects on global mean temperature

The most consistent finding in the SRM literature is that SAI can quickly cool the planet.[28] Models, supported by observations of volcanic eruptions, show that meaningful global cooling can begin within one to two years of the onset of injection.[29] This speed is what distinguishes SAI from every other climate intervention as well as traditional mitigation and adaptation measures.

The required injection scale depends on the cooling target. Modern Earth system models suggest that somewhere between 8 and 16 million metric tons of sulphur aerosol injected annually could reduce global mean surface temperature by approximately 1°C.[30] Under a moderate SAI scenario targeting roughly 0.5 degrees of cooling, the annual addition of sulphur to the stratosphere would be between 2% and 4% of sulphur emissions in the early 2000s.[31] The relationship between injection rate and cooling is not linear. As injection rates increase, aerosol particles tend to coalesce into larger droplets that scatter sunlight less efficiently and fall out of the

[28] SAPEA, *Solar Radiation Modification*.

National Research Council, *Climate Intervention*.

[29] SAPEA, *Solar Radiation Modification,* 171.

[30] UNEP, *One Atmosphere,* 11.

[31] Paul J. Crutzen, "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" *Climatic Change* 77, no. 3 (2006). https://doi.org/10.1007/s10584-006-9101-y

stratosphere more quickly, yielding diminishing returns. However, our understanding of stratospheric chemistry in this regard is still limited.[32]

The reduction in average global temperatures is the primary benefit of SAI, and temperature increase is considered the target risk that its deployment mitigates.

4.2 Effects on extreme weather

SAI offers several potential benefits for populations affected by increased extreme weather events.[33] SAI is projected to reduce the frequency and intensity of extreme heat events. It is also expected to reduce the intensity of tropical cyclones by lowering sea surface temperatures, reduce wildfire frequency through sustained surface cooling, and moderate the most severe precipitation extremes compared to an unmitigated warming scenario.[34]

For populations on the front line of climate change, these benefits are important considerations in a risk–risk framework. The reduction of extreme weather events is a direct result of lowering global temperatures, and extreme weather is a secondary target risk targeted by SAI deployment.

4.3 Slowing ice melt and reducing sea level rise

Two of the primary drivers of sea level rise are the thermal expansion of water and the melting of ice, both of which are temperature dependent.[35] SRM's cooling effect addresses both drivers by reducing global mean temperature. SAI can slow the rate of sea level rise, and combined with aggressive emissions reduction, could reduce future rise to rates substantially below what mitigation alone could achieve.

For polar ice specifically, multiple Earth system models show that SAI can delay or partially recover Arctic sea ice loss. Permafrost preservation is also a meaningful benefit. SAI could

[32] Ulrike Niemeier and Claudia Timmreck, "What Is the Limit of Climate Engineering by Stratospheric Injection of SO_2?" *Atmospheric Chemistry and Physics* 15, no. 16 (2015). https://doi.org/10.5194/acp-15-9129-2015

[33] David W Keith and Peter J Irvine, "Solar Geoengineering Could Substantially Reduce Climate risks—A Research Hypothesis for the next Decade," *Earth's Future,* 2016. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016ef000465

[34] C2G, *Solar Radiation Modification: A Risk-Risk Analysis,*21, 22, 25.

[35] John C Moore, Svetlana Jevrejeva, and Aslak Grinsted, "Efficacy of Geoengineering to Limit 21st Century Sea-Level Rise," *Proceedings of the National Academy of Sciences* 107 no. 36 (2010). https://doi.org/10.1073/pnas.1008153107

prevent permafrost melt that would otherwise release approximately 13.7 petagrams of stored carbon per degree of warming avoided.[36]

Similar to the impact on extreme weather events, sea ice melt and sea level rise are secondary target risks of anthropogenic climate change that SAI addresses.

4.4 Reducing the risk of crossing tipping points

Among the most serious concerns in climate science is the possibility of crossing irreversible tipping points. Tipping points are thresholds beyond which self-reinforcing feedback drives further change, regardless of subsequent human action. Known examples include the irreversible loss of the Greenland Ice Sheet, the shutdown of the Atlantic Meridional section Overturning Circulation (AMOC), and the die-off of coral reefs.[37]

The first two are the most consequential for Canada. They are among the least reversible of the identified tipping elements; they carry some of the highest assessed probabilities of being triggered this century; and their effects fall directly on Canadian coastlines, fisheries, and regional climate.

Prevention of reaching tipping points has additional significance in Canada, as roughly 50% of the country's land mass is permafrost and it hosts the third-largest area of glaciers in the world.[38] Permafrost represents an important tipping point, as its loss drives new emissions of both carbon from the decomposition of previously frozen material and methane from the release of trapped stores. It is estimated that global permafrost contains 50% more greenhouse gases than are currently in the atmosphere.[39]

By keeping temperatures lower during the decades when greenhouse gas concentrations remain high — that is, in the absence of deep, rapid, and sustained reductions in global emissions combined with large-scale carbon removal — SAI may reduce the probability of triggering these cascading processes.[40] Because these tipping points are irreversible once crossed, temporary

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[36] Y. Chen, A. Liu and J. C. Moore, "Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering," *Nature Communications,* 11, no. 1 (2020). https://doi.org/10.1038/s41467-020-16357-8

[37] Timothy M. Lenton et al., eds., *The Global Tipping Points Report 2025* (2025). https://doi.org/10.5281/zenodo.18163977

[38] Natural Resources Canada, "Geoscience: Climate change." https://natural-resources.canada.ca/science-data/science-research/geoscience-climate-change

[39] "Permafrost," in Timothy M. Lenton et al., eds., *The Global Tipping Points Report 2023* (2023). https://report-2023.global-tipping-points.org/section1/1-earth-system-tipping-points/1-2-tipping-points-in-the-cryosphere/1-2-2-current-state-of-knowledge-on-cryosphere-tipping-points/1-2-2-4-permafrost/

[40] UNEP, *One Atmosphere.*

interventions that delay their breach have lasting value even if they do not permanently resolve the underlying problem.

The relationship between temperature and tipping-point risk varies across different Earth systems. Elements governed primarily by surface temperature and sea-ice extent respond directly to atmospheric cooling. Other elements are driven by ice-sheet dynamics, such as grounding-line retreat, basal melt fed by committed ocean heat, and marine ice-cliff instability. These processes carry their own physical momentum. Where such a dynamical threshold has already been crossed, lowering surface air temperatures may slow ice loss without reversing it, as ocean heat content responds to surface cooling only over decades.[41]

Therefore, the defensible claim is that SAI could reduce the probability of crossing thresholds that have not yet been breached. It cannot be claimed that SAI would restore systems that have already begun to destabilize.[42]

4.5 Additional considerations

4.5.1 Regional distribution of benefits

While SAI is a global intervention and all populations would benefit from reduced extreme weather events and lower global mean temperatures, the concentration of SAI's climate benefits is not uniform. Regions most exposed to the primary hazards of climate change may stand to gain the most from SRM.[43] Tropical populations facing potentially uninhabitable heat by mid-century, low-lying coastal states facing accelerating sea-level rise, and cyclone-exposed areas all fall into this category. This distribution concentrates the greatest impact and benefit in island nations and the Global South.

High-latitude regions sit in a different position. A uniform global SAI intervention overcools the tropics relative to the poles. This distribution means that polar and near-polar regions will remain warmer than they were under pre-industrial conditions once global mean temperature is restored.[44]

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[41] Baylor Fox-Kemper et al., "Ocean, Cryosphere and Sea Level Change," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Valérie Masson-Delmotte et al., eds. (2021). https://doi.org/10.1017/9781009157896.011.

[42] UNEP, *One Atmosphere*.

[43] Ben Kravitz, et al., "Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP)," *Journal of Geophysical Research: Atmospheres* 118, no. 15 (2013). https://doi.org/10.1002/jgrd.50646

Peter J. Irvine, Andy Ridgwell, and Daniel J. Lunt, "Assessing the regional disparities in geoengineering impacts," *Geophysical Research Letters* 37, no. 18 (2010). https://doi.org/10.1029/2010GL044447

[44] "Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP."

4.5.2 SAI in overshoot scenarios

Overshoot scenarios refer to emission and climate trajectories that exceed the target of 1.5 to 2°C of global warming before being drawn down to lower levels. In a world on track to reach 3°C, SAI is one of the very few options capable of acting on a timescale relevant to preventing the worst near-term impacts.

The peak-shaving model is the dominant SAI deployment frame. Under this model, SAI is deployed when temperatures approach a critical threshold to cap warming at that level. At the same time, emissions reductions and carbon removal continue to address the underlying accumulation of greenhouse gases. The goal is to prevent irreversible tipping points from being crossed during the decades when concentrations remain elevated. In a peak-shaving scenario, moderate SAI deployment could keep a 1.5°C world within reach even when greenhouse gas concentrations would otherwise push temperatures toward 2.5°C or higher.[45]

The main challenge in overshoot scenarios is the need for a managed exit strategy. In the peak-shaving model, SAI is phased out gradually as emissions are reduced and carbon removal lowers atmospheric concentrations. Using a managed phase-down, alongside declining greenhouse gas forcing, could avoid the termination shock that an abrupt halt would cause (see Section 5.1).

"Assessing the regional disparities in geoengineering impacts."

[45] SAPEA, *Solar Radiation Modification*.

5. Risks and uncertainties of SAI

While producing significant benefits, SAI deployment also introduces novel countervailing risks and shifts the climate risks experienced by populations. Understanding these risks is key to all governance conversations and to ensuring that decisions on deployment and research reflect a holistic view of the impacts.

The risks of termination shock, moral hazard and equity have emerged in the global discussion as the primary concerns expressed by environmental groups and opposing academics.[46] However, in contrast to the biophysical risks inherent in SAI, these risks are primarily driven by potential SAI deployment design and governance.[47]

Every risk must be evaluated against a realistic baseline, which is not a stable pre-industrial climate but the projected trajectory of a world under current emissions trends. Several risks commonly attributed to SAI are better understood as limitations of the technology rather than newly created harms. For instance, ocean acidification is driven directly by atmospheric carbon dioxide dissolving into seawater rather than by temperature, meaning SAI cannot reverse it. This represents an unmitigated existing risk rather than a newly introduced harm. Even in this case, the net effect is not entirely zero, as holding temperatures down slows climate-carbon cycle feedbacks that accompany warming, thereby modestly reducing atmospheric carbon dioxide compared to an uncooled baseline. Other non-radiative impacts of elevated greenhouse gas concentrations fall into this same category.

Where a risk is genuinely novel or explicitly amplified by SAI, it is identified as such. Conversely, where the deviation from the baseline is minimal, or where honest evaluation indicates SAI offers no mitigation benefit, that limitation is stated with equal clarity.

5.1 Termination shock

SAI works by continuously replenishing a reflective layer that masks the warming effect of accumulated greenhouse gases. Stratospheric aerosols have a residence time of one to two years while greenhouse gases persist for centuries to millennia. If the injection of sulphur stops, the masking effect dissipates within months to a couple of years, and global temperatures rebound rapidly toward the level that accumulated greenhouse gas concentrations would always have

[46] ETC Group, "Briefing for UNEA6 Delegates on Solar Radiation Modification," February 2024, https://etcgroup.org/sites/www.etcgroup.org/files/files/briefing-for-unea6-delegates-on-solar-radiation-modification.pdf

[47] C2G, *Solar Radiation Modification: A Risk-Risk Analysis.*

produced. This rebound would occur at rates of warming that far exceed anything projected for unmitigated climate change.[48]

The severity of termination shock scales directly with two variables: how much warming is being masked and how long it has been masked. A moderate peak-shaving deployment held in place for a decade while aggressive decarbonization proceeds carries a fundamentally different termination risk than a large-scale full-offset deployment maintained for a century while emissions continue.

Three overlapping approaches to reduce the risk of termination shock have been identified.[49]

1. Moderate, temporary deployment under a "peak-shaving," rather than a full-offset, approach, to cap the magnitude of the potential rebound.
2. A gradual phase-out rather than an abrupt termination, to reduce the rate of rebound.
3. Mandatory coupling of any SRM program with binding commitments to emissions reduction and carbon removal, to ensure that the underlying cause of the dependency is being addressed rather than deferred.

Termination shock is often discussed as an inherent feature of SAI, but it is actually the outcome of a specific and unlikely sequence of decisions. Triggering a severe termination scenario requires a compounding series of governance failures sustained over decades: deploying well beyond peak-shaving levels, maintaining deployment long enough for substantial unmitigated warming to accumulate, failing to reduce emissions or deploy carbon removal concurrently, lacking operational redundancy in delivery systems and governing bodies, and executing an abrupt, complete shutdown without a phase-down plan. Each link in that sequence represents an explicit, avoidable choice. While the scenario is vivid and frequently highlighted, the belief that SAI functions as an on-off switch carrying an immediate risk of catastrophic rebound upon deployment is unsupported by the literature.

Ultimately, termination shock highlights the necessity of durable, redundant governance frameworks rather than the inevitability of catastrophic deployment outcomes. Returning to the climate levers, it is important to frame SAI in its proper place: an intervention that allows time for global economies to continue the central work of decarbonization and CDR deployment.

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[48] Christopher H. Trisos et al., "Potentially Dangerous Consequences for Biodiversity of Solar Geoengineering Implementation and Termination," *Nature Ecology & Evolution* 2, no. 3 (2018). https://doi.org/10.1038/s41559-017-0431-0

[49] C2G, *Solar Radiation Modification: A Risk-Risk Analysis*.

Jesse L. Reynolds, "Is Solar Geoengineering Ungovernable? A Critical Assessment of Governance Challenges Identified by the Intergovernmental Panel on Climate Change," *WIREs Climate Change 12*, no. 2 (2021). https://doi.org/10.1002/wcc.690

5.2 Moral hazard

The moral hazard argument holds that developing or deploying SRM will undermine political and public support for emissions reductions. This argument is that SRM deployment may create incentives to delay mitigation efforts by offering a relatively cheap, fast-acting climate intervention that provides cover for continued fossil fuel use, diverting resources and attention from the difficult structural work of decarbonization.[50] It is a prominent objection raised by environmental civil society organizations and by academics opposed to it.[51]

The moral hazard argument does not require that SRM cause mitigation deterrence at the level of public opinion. Rather, the argument advanced only requires that SRM provide sufficient political cover for the actors most motivated and resourced to delay climate policy and action.

As a governance concern, the proposed mitigations include a range of policies that can limit bad-faith actors' ability to use SAI as a delaying tactic. Four methods of potentially reducing the countervailing risk of moral hazard have been identified.[52]

1. Formally linking SAI authorization to demonstrated emissions reduction performance.
2. Restricting deployment to partial offset scenarios that cannot be presented as a substitute for mitigation.
3. Prohibiting cooling credits and other commercial models that create fungibility between SRM and emissions reductions.
4. Ensuring that research programs are transparently governed and clearly separated from commercial or fossil-fuel interests.

5.3 Distributive justice and equity

The geographic distribution of SAI's risks and benefits is not uniform, and the non-uniformity follows a pattern that should be central to any serious governance discussion.[53] Regions most vulnerable to unmitigated climate change, the Global South, and tropical and subtropical

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[50] Albert C. Lin, "Does Geoengineering Present a Moral Hazard?" *Ecology Law Quarterly* 40, no. 3 (2013), 673. https://escholarship.org/uc/item/7th0d0pd

Frank Biermann et al., "Solar Geoengineering: The Case for an International Non-Use Agreement," *WIREs Climate Change* 13 (2022). https://doi.org/10.1002/wcc.754

[51] Solar Geoengineering Non-Use Agreement, "Open Letter: We Call for an International Non-Use Agreement on Solar Geoengineering," January 17, 2022. https://www.solargeoeng.org/non-use-agreement/open-letter/

[52] Reynolds, "Solar geoengineering to reduce climate change: a review of governance proposals."

[53] Benjamin K. Sovacool, Chad Baum, and Sean Low, "Climate Protection or Privilege? A Whole Systems Justice Milieu of Twenty Negative Emissions and Solar Geoengineering Technologies," *Political Geography* 97 (2022). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4152361

populations stand to gain the most from SRM's temperature-stabilizing effects. They may also face the greatest risk of transfer from SRM's hydrological disruptions.[54] Ensuring that strong representation from the societies most impacted and most likely to benefit is critical in any global governance conversation.[55]

Indigenous peoples occupy a specific and structural position in this distributional picture. They are on the front lines of both climate impacts and potential SRM risks, particularly where deployment would affect natural systems with which Indigenous communities have deep cultural, spiritual, and subsistence relationships.[56]

The intergenerational dimension adds a further layer for governance considerations. Any current generation that deploys SAI at scale would make a choice that binds future generations to continuous maintenance of the SAI system. Large-scale SRM deployment would constitute one of the most significant restrictions on future generations' decision-making autonomy. The principle of conserving options for future generations is in direct tension with large-scale SRM deployment under conditions where emissions have not been addressed.[57]

5.4 Biophysical risks

In contrast with the design and governance risks identified above, the following biophysical risks are countervailing risks introduced as a direct aspect of SAI deployment. Under a risk–risk framework, the countervailing risks are assessed relative to the target risks that SAI mitigates.

5.4.1 Ozone depletion

The relationship between stratospheric aerosol injection and stratospheric ozone is one of the better-characterized risks in the literature. Sulphate aerosols provide additional surface area for chemical reactions that can deplete ozone.[58] Aerosol-induced heating of the lower tropical stratosphere also increases water vapour transport into the stratosphere, accelerating catalytic

[54] Svoboda, "The potential for climate engineering with stratospheric sulfate aerosol injections to reduce climate injustice."

[55] David E. Winickoff, Jane Flegal, and Asfawossen Asrat, "Engaging the Global South on climate engineering research," *Nature Climate Change* 5, no. 7 (2015). https://doi.org/10.1038/NCLIMATE2632

[56] Kyle Whyte, "Indigenous Peoples, Solar Radiation Management, and Consent," in *Engineering the Climate: The Ethics of Solar Radiation Management,* Christopher J. Preston, ed. (Lexington Books, 2012). Available at https://ssrn.com/abstract=2003187

[57] Sovacool, "Climate Protection or Privilege?"

[58] National Research Council, *Climate Intervention.*

ozone loss.[59] In a significant deployment scenario in which SAI was used to counter a doubling of atmospheric carbon, the recovery of the ozone layer was delayed by decades.[60]

The 2022 *Scientific Assessment of Ozone Depletion*, produced under the Montreal Protocol, remains the most rigorous examination of the question. It concluded that the ozone risk from stratospheric aerosol injection is limited, conditional, and temporary. It is limited because modelled losses under moderate deployment scenarios are modest rather than catastrophic. It is conditional because the magnitude depends heavily on the injection quantity, latitude, altitude, and material choice, with alternative aerosols, such as calcium carbonate, potentially reducing impacts substantially. Finally, it is temporary because stratospheric ozone recovers as aerosol loading declines, meaning SAI would delay the recovery of the ozone hole rather than permanently reopen it. The scale of loss reported in extreme doubled-CO_2 studies reflects a full-offset scenario rather than the moderate peak-shaving deployment that dominates current policy discussions. A further assessment is scheduled for release in late 2026.[61]

5.4.2 Acid rain

Sulphate aerosols injected into the stratosphere have a residence time of one to two years before settling into the troposphere and returning to the surface.[62] The scale of sulphur involved in a meaningful SAI program would be smaller than current global industrial sulphur emissions, and the additional acid deposition would be a small fraction of current anthropogenic levels.[63] This risk is more regionally concentrated than global, as stratospheric circulation transports aerosols poleward before they re-enter the troposphere; high-latitude environments could face disproportionate acidic deposition, with potential consequences for soil chemistry and aquatic systems.[64] The potential to increase acid rain represents a *Risk Substitution* for high-latitude populations.

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[59] P. Heckendorn et al., “The impact of geoengineering aerosols on stratospheric temperature and ozone,” *Environmental Research Letters* 4, no. 4 (2009). https://doi.org/10.1088/1748-9326/4/4/045108

[60] National Research Council, *Climate Intervention.*

[61] World Meteorological Organization, *Scientific Assessment of Ozone Depletion 2022,* GAW Report No. 278 (2022), see especially the assessment of stratospheric aerosol injection. https://csl.noaa.gov/assessments/ozone/2022/

[62] Lawrence, “Evaluating Climate Geoengineering Proposals in the Context of the Paris Agreement Temperature Goals.”

[63] National Research Council, *Climate Intervention.*

The Royal Society, *Solar radiation modification: Policy briefing* (2025). https://royalsociety.org/-/media/policy/projects/solar-radiation-modification/solar-radiation-modification-policy-briefing.pdf

[64] Daniele Visioni et al., “What goes up must come down: impacts of deposition in a sulfate geoengineering scenario,” *Environmental Research Letters* 15, no. 9 (2020). https://doi.org/10.1088/1748-9326/ab94eb

5.4.3 Altered precipitation and atmospheric circulation

The impact of SAI on the water cycle is a key consideration for a risk–risk analysis. SAI weakens the global water cycle by reducing both evaporation and precipitation. A full-offset scenario could reduce global mean precipitation by approximately 4.5%, measured against the wetter, warmer world that SAI would be offsetting rather than against a pre-industrial baseline. A portion of that reduction is the reversal of the intensification of the water cycle that warming itself produces.[65] The risks introduced to the water cycle are highly sensitive to deployment design. Using SRM to halve rather than fully offset warming produces considerably less precipitation disruption across most regions than full-offset scenarios.[66]

Under the risk–risk framework, altered precipitation patterns are a countervailing risk and represent both a risk transfer and risk substitution. Altered precipitation acts as a risk transfer by changing rainfall patterns, potentially protecting crops in one region while introducing new risks in another. It may also represent a risk substitution for countries dependent on monsoons. The impacts and scale of precipitation and monsoon disruptions are still being studied; increasing understanding of precipitation and monsoon seasons is an important step in completing a comprehensive risk–risk assessment of SRM (see Section 5.5).[67]

5.5 Knowledge gaps and areas of current research

Beyond the specific biophysical risks outlined above, four categories of knowledge gaps warrant explicit acknowledgment, as they represent structural limits to what the field currently knows.[68]

An important gap in the literature and in policy is understanding changes in regional precipitation. While the global hydrological slowdown is well established, the direction and magnitude of regional precipitation changes require continued study to properly understand distributional risks. Regional variation in precipitation also depends on the design of an SAI

[65] S. Tilmes et al., "The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP)," *Journal of Geophysical Research: Atmospheres* 118 (2013). https://doi.org/10.1002/jgrd.50868

[66] Peter J. Irvine and David W. Keith, "Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards," *Environmental Research Letters* 15, no. 4 (2020). https://doi.org/10.1088/1748-9326/ab76de

[67] Center for International Environmental Law, *The risks of geoengineering: Accelerating biodiversity loss and compounding planetary crises* (2024). https://www.ciel.org/reports/risks-of-geoengineering/

[68] National Research Council, *Climate Intervention.*

U.S. Office of Science and Technology Policy, *Congressionally Mandated Research Plan and an Initial Research Governance Framework Related to Solar Radiation Modification.*

program, with smaller deployments potentially targeting less cooling, which could increase regional precipitation.[69]

Cloud processes introduce another layer of uncertainty, one that extends beyond SAI to marine cloud brightening and cirrus cloud thinning. One of the largest challenges in accurately modelling the Earth system is creating an accurate representation of clouds and aerosols.[70] Current models do not fully capture microphysics of cloud-aerosol interactions. This limitation is not restricted to SRM and impacts all current climate modelling.[71]

The impacts on agricultural production remain uncertain.[72] SAI reduces total solar radiation while increasing diffuse light. Further research is needed to determine whether the diffuse-light benefit outweighs the harm to crop yields caused by dimming. One prominent study using volcanic natural experiments found that the benefits of diffuse radiation were almost entirely offset by reduced total sunlight for major crop types.[73] Other models suggest that reducing heat and water stress could boost tropical crop yields.[74] As such, the impacts on agricultural systems are among the critical areas for future research as conversations advance.

Biodiversity and ecosystem responses remain underdeveloped in the literature. The National Research Council found that only 14% of research articles addressing sunlight reflection published between 1983 and 2020 examined the impacts of SRM on ecosystems, ecology, health, and agriculture.[75] Increased research in these areas is needed as SAI creates an artificial climate that does not simply reverse warming. This artificial climate would have a distinct atmospheric chemistry, along with modified temperature and precipitation patterns.[76] The implications for species migration, pest dynamics, disease vectors, and ecosystem integrity have been studied only marginally.[77]

These gaps are often cited as grounds for restricting or halting SRM research. However, uncertainty regarding SAI's regional effects, agricultural consequences, and ecological impacts is

[69] Irvine, "Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards."

[70] National Research Council, *Climate Intervention*.

[71] U.S. Office of Science and Technology Policy, *Congressionally Mandated Research Plan and an Initial Research Governance Framework Related to Solar Radiation Modification*.

[72] National Research Council, *Climate Intervention*.

[73] Jonathan Proctor et al., "Estimating global agricultural effects of geoengineering using volcanic eruptions," *Nature* 560 (2018). https://doi.org/10.1038/s41586-018-0417-3

[74] Yuanchao Fan et al., "Solar geoengineering can alleviate climate change pressures on crop yields," *Nature Food* 2, no. 5 (2021), 1.

[75] National Research Council, *Climate Intervention*.

[76] Phoebe L. Zarnetske et al., "Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth," *Proceedings of the National Academy of Sciences* (2021). https://doi.org/10.1073/pnas.1921854118

[77] Samantha Tracy et al., "Stratospheric aerosol injection may impact global systems and human health outcomes," *Elementa: Science of the Anthropocene* 10, no. 1 (2022), 00047. https://doi.org/10.1525/elementa.2022.00047

precisely what research aims to resolve. Declining to study an intervention because its effects are poorly understood guarantees they will remain unknown. Consequently, if deployment is ever seriously contemplated, whether by the international community or a single state acting alone, that decision will rest on a far weaker evidence base than could otherwise be built. The same principle applies to a decision against deployment, which is equally a judgment about outcomes and equally dependent on understanding those consequences. Effective governance relies on knowledge that only rigorous research can produce. Therefore, the case for a transparent, publicly funded, and publicly governed research program is strongest where uncertainties are largest, not where they are smallest.

6. Conclusion

The current realities of global climate change and insufficient efforts to decarbonize the global economy have created a situation in which there is no risk-free decision. In this context, solar radiation modification has entered the global discussion on addressing anthropogenic climate change. SRM's ability to rapidly reduce global temperatures at a cost within the reach of individual nations means that it cannot be ignored. Declining to engage in the conversation will result in decisions on governance and deployment being made without meaningful input from the Canadian government and the ENGO community. Restricting inquiry on the grounds that SRM's effects are uncertain would preserve that uncertainty rather than resolve it, and would leave any future decision, including a decision not to deploy, resting on a weaker evidence base than the one that could otherwise be built. For Canadian ENGOs, these discussions are critical, as Canada faces increasing challenges from extreme heat events, threats to Arctic sovereignty due to melting sea ice, and large areas of at-risk permafrost.

SRM belongs within the broader interventions needed to address climate change and cannot be seen as a replacement for emissions reductions, carbon removal, and adaptation. In its proper role, SRM could temporarily reduce global temperatures while extending the time available for the global economy to decarbonize. This approach requires sustained and increasing commitments from governments to reduce emissions and address the current concentration of greenhouse gases in the atmosphere.

Evaluating SRM as a climate intervention requires examining both the benefits and risks it introduces. The benefits of lowering the global mean temperature are important and include reduced extreme heat events, slower ice loss, and reduced sea-level rise. These benefits would reduce the harms caused by climate change. However, SRM also introduces risks, and weighing these risks in the governance conversation is the central work for governments and ENGOs.

The distribution of benefits and risks from SRM deployment is not uniform worldwide. While the world would benefit from reduced temperatures, the countries shown to benefit most from reduced warming are also the most exposed to changes in precipitation. Further, Indigenous peoples and future generations bring unique considerations to an intervention of this scale and must be included and accounted for in any meaningful governance framework.

Key uncertainties around agricultural impacts, ecosystem responses, and regional precipitation changes still require further study, which is key for any holistic risk–risk assessment of SRM deployment.

Solar radiation management (SRM) is a complex and imperfect response to climate change, carrying significant scientific, ethical, and governance risks that cannot be ignored. However, continued greenhouse gas emissions and delayed mitigation under the status quo also entail profound and potentially irreversible harms. Under current emissions trajectories, there is truly "no-risk-free" pathway forward. SRM should never be viewed as a substitute for emissions reductions, but as a potential supplementary tool whose risks must be rigorously evaluated alongside the escalating risks of climate change itself. Navigating this difficult landscape requires careful research, transparent governance, and inclusive international dialogue, ensuring Canadian policy and civil society are prepared to engage responsibly in the global decisions ahead.